Appendix A
Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin

Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin

Gwyneth Perry[1], Jessica Lundquist[1], and Daniel Moore[2]

[1] Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, USA
[2] Department of Geography and Department of Forest Resources Management, University of British Columbia, Vancouver, British Columbia, Canada

Executive Summary

The Chehalis River Basin is predominantly forested. Forest practices, defined here as forest harvesting and associated practices such as road building and site preparation, influence streamflow in multiple ways. There has been long-standing interest in understanding the effects of forest practices on peak flows (which can result in damaging floods and channel instability) and low flows (which can be critical for aquatic habitat). This report synthesizes many decades of literature focused on forest hydrology in the Pacific Northwest and the relevance of this literature to the Chehalis River Basin.

For the purposes of this review, different areas within the Chehalis are labeled as one of the following: snow-dominated headwaters (~1% of basin area), rain-snow transitional uplands (~20% of basin area), or rain-dominated lowlands (~79% of basin area). We discuss the controlling hydrologic processes and how forest practices affect peak and low flows in each of these area-types. The snow-dominated headwaters are a small portion of the basin, so that changes to flows in this region will only have local effects and not impact the main stem of the Chehalis River Basin (e.g., where lowland population centers are located). Changes to flows in the uplands and lowlands likely affect flows in the main stem.

The literature agrees that in small basins (drainage area <10 km^2), forest harvesting increases the magnitude of "channel-forming flows," defined here as peak flows near or slightly higher than bankfull, corresponding to return periods of about 1.5 to 5 years, and this effect generally persists for 20 years or more following the date of harvest. In snow-dominated headwater basins, uniform harvesting of forests can lead to a more homogeneous snowpack, resulting in synchronized melt and increased snow-dominated peak flows. In both the snow-dominated headwaters and the rain-snow transitional uplands, decreasing forest cover is likely to increase storm-coincident snowmelt during rain-on-snow events and increase resulting peak flows. In addition, higher soil moisture, particularly in the fall, due to decreases in evapotranspiration and interception, acts to increase rain-dominated peak flows in the uplands. Forested, rain-dominated lowlands experience similar increases in peak flows as in uplands. Additionally, in all areas, subsurface flow interception by roads acts to increase peak flows. It is not clear if changes in peak flows in the uplands and lowlands would be isolated to their region of origin, or if downstream reaches in this large basin would experience integrated effects.

There is further agreement in the literature that in small drainages, low flows increase in magnitude following harvest. Low flows often revert to pre-harvest levels within 5-10 years post-harvest and may even shift to deficits as vegetation regrows. With respect to low flows, the effect of forest practices is similar across hydrometeorologic regime. Decreased forest cover leads to decreased evapotranspiration, resulting in increased soil moisture and subsequently, increased low flows.

Increases in "channel-forming flows," and resulting stream channel alterations, can be detrimental to fish habitat in the uplands and headwaters of the basin. Only a few studies were able to draw definitive conclusions on changes in post-harvest extreme flows (those with return periods greater than 10 years), due to the rarity of these events and the nature of the statistical analysis used. In order to draw specific conclusions about the effects of forest practices for the Chehalis River Basin, we recommend a spatially-distributed, physically-based hydrologic modeling approach, possibly complemented by an empirical analysis of trends in streamflow, climatic drivers and land cover. A modeling approach would provide more definitive answers to whether or not forest harvesting and road building in the basin result in increased peak flows in the main stem of the Chehalis River Basin, and increased extreme peak flow events. Model results may also be able to influence future forest practices in the basin.

Table of Contents

1. Introduction

Statement of Purpose: This effort is being conducted to support environmental review of the Chehalis Basin Strategy led by the Washington Department of Ecology under the State Environmental Policy Act. It involves the following activities. (1) Review existing current literature, including peer reviewed studies and other relevant data on the relationship between forest practices and (a) frequency and magnitude of high stream flows, (b) magnitude of summer low flows, and (c) interpret for its applicability to the Chehalis River Basin. (2) Review existing state rules and regulations regarding forest management and timber harvest and how these relate to changed forest conditions over time as described in literature reviewed. Additional data generation and modeling, etc. are not part of this scope.

Forest practices, defined here as forest harvesting and associated practices such as road building and site preparation, influence streamflow in multiple ways. There has been long-standing interest in understanding the effects of forest practices on peak flows (which can result in damaging floods and channel instability) and low flows (which can be critical for aquatic habitat). This report synthesizes many decades of literature focused on forest hydrology in the Pacific Northwest and the relevance of this literature to the Chehalis River Basin.

This review focuses on both peak and low flows. In relation to peak flows, the potential effects of forest practices are considered in relation to three categories: "channel-forming flows," defined here as peak flows near or slightly higher than bankfull, corresponding to return periods of about 1.5 to 5 years; "high flows," which have return periods between about 5 and 10 years; and "extreme high flows," defined as those peak flows with return periods greater than 10 years, and which have sufficient power to cause damage to property. In relation to low flows, the focus is on periods of persistent low flow (e.g., 7 days to a month) toward the end of the summer dry season (August and September).

Methods for studying the effects of forest practices generally fall into the following categories: (1) stand-level process-based studies, which typically focus on water and/or energy budget analyses (e.g., Berris and Harr, 1987); (2) stand-level chronosequence studies, in which some response variable (e.g., interception loss or snow accumulation) is measured at stands with a range of ages, and which assume that variations in space represent variations through time at a single site (e.g., Hudson, 2000); (3) paired-catchment experiments, which involve both treatment and control catchments and monitoring both before and after treatment (e.g., Harr et al., 1982); (4) time-series analysis, which attempts to extract a signal associated with land cover change from multi-year streamflow data from one or multiple catchments (e.g., Bowling et al., 2000); and (5) computer simulation, in which the effects of forest practices can be virtually imposed or removed, and their hydrologic effect inferred by comparison of simulations of "treatment" and "control" scenarios (e.g., Tague and Band, 2000 and WFPB, 2011) or by using the calibrated model as a "virtual control" (e.g., Bowling et al. 2000). In relation to catchment-scale response, paired-catchment experiments are generally considered the most rigorous approach (e.g., Moore and Wondzell, 2005). However, they typically focus on small catchments (usually less than 1 km^2 in area), and time-series analysis and model-based analyses are more appropriate for larger catchments.

In section 2, we provide an overview of the Chehalis River Basin and the important characteristics that influence forest hydrology. This includes a description of the climate and various climatic zones (rain, rain-snow transition, and snow), as well as forest structure and practices.

The forest-hydrology literature review is presented in section 3, in which we draw upon both stand-level and catchment-scale studies to make inferences about the effect of forest practices on runoff generation

(3.1) and on peak and low flows for each hydrometeorologic regime of the Chehalis River Basin (3.2): snow-dominated headwaters, rain-snow transition uplands, and rain-dominated lowlands. Section 3.3 addresses post-harvest hydrologic recovery. In section 3.4, we focus on the challenge of drawing inferences regarding the potential influences of forest harvesting on the lower reaches of the Chehalis River, where concerns about flooding are particularly acute. Section 3.5 covers the importance of "channel-forming flows." The focus of section 3.6 is the ongoing debate about the effects of forest practices on "extreme high flows."

In section 4, we draw conclusions and identify avenues for further research to clarify the extent to which forest practices have modified streamflow in the Chehalis River basin.

2. Basin Description

The Chehalis River Basin is mostly forested and has a maritime climate. The basin can be divided into four regions: Southern Olympic Mountains, Willapa Hills, Black Hills, and Cascade Foothills. For the purposes of this review, portions of each region are labeled as one of the following: snow-dominated headwaters, rain-snow transitional uplands, or rain-dominated lowlands.

2.1 Climate and Streamflow Characteristics

The Chehalis River Basin, encompassing 2.6 km^2 (2700 square miles), begins in the Willapa Hills, and draws from the Black Hills, the Cascade Foothills and the southern Olympic Mountains (Burnett et al. 2014). Figure 1 below shows these four areas, as they are referred to in this paper. In section 3, we divide the basin into three descriptive area types, according to the controlling hydrologic processes: headwaters (~1% of total basin area), uplands (~20% of basin area), and lowlands (~79% of basin area). Referring to Figure 1, snow-dominated headwaters are shaded dark blue, which include small portions of the Southern Olympics and the Cascade Foothills, as well as a very small part of the southern Willapa Hills. Uplands include all light blue shaded portions of the basin. Lowlands are all light green shaded parts of the basin, mainly valleys and foothills of the upland areas, including the most populated areas, Centralia-Chehalis and Aberdeen-Hoquiam.

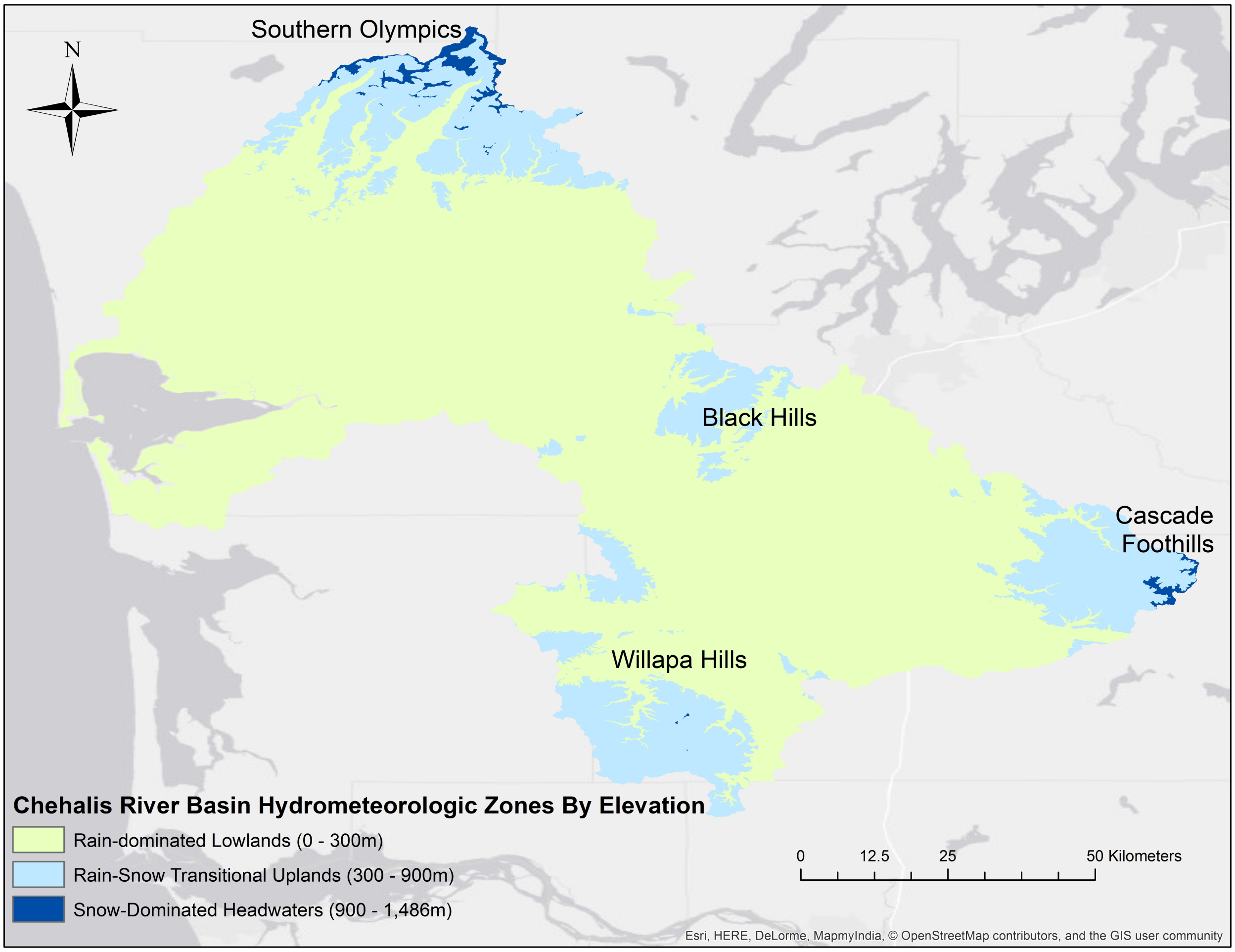

Figure 1. Chehalis River Basin Hydrometeorologic Zones

The Chehalis River Basin has a temperate marine climate with cool, wet winters and warm, dry summers (Gendaszek 2011). The lowest stream flows occur in August and September. Groundwater contribution to streamflow ranges from 45% in November to 89% in July (Gendaszek 2011). Average annual precipitation ranges from about 1000 mm (40 inches) near Centralia-Chehalis to over 2500 mm (100 inches) in the headwaters of the Upper Chehalis Basin, and over 6000 mm (236 inches) in the headwaters in the Southern Olympics (see Figure 2). Basin-average annual precipitation is about 2000 mm (80 inches), with approximately 1% of that accumulating as basin-average snow water equivalent (estimated from modeling studies by Guillaume Mauger, University of Washington Climate Impacts Group). Elevation ranges from sea level to over 1000 m (Rodgers & Walters 2012). Approximately 79% of the total basin area is comprised of rain-dominated lowlands (shaded light green in Figure 1). Snow accumulates mainly above 300 m (984 ft) and is transient between 300 and 900 m (984 – 2953 ft) (~20% of the total basin area, shaded light blue in Figure 1) (Rodgers & Walters 2012). Snow-dominated regions comprise only approximately 1% of the total basin area; there are three small snow-dominated areas (shaded dark blue in Figure 1), including some in the highest elevation Cascade foothills, Stillman Creek drainage (southern-most Willapa Hills) and Southern Olympics (Rodgers & Walters 2012). Since there is a small area that accumulates snow, on average, there is low risk of rain-on-snow (ROS) processes causing major flooding in the Chehalis River Basin. However, as was observed in the January 2009 flood, there is potential for snow to accumulate down to sea level and experience ROS, and the rain-snow transitional uplands correspond with the regions of higher precipitation (Fig. 1 and 2). ROS is discussed further in section 3.2.

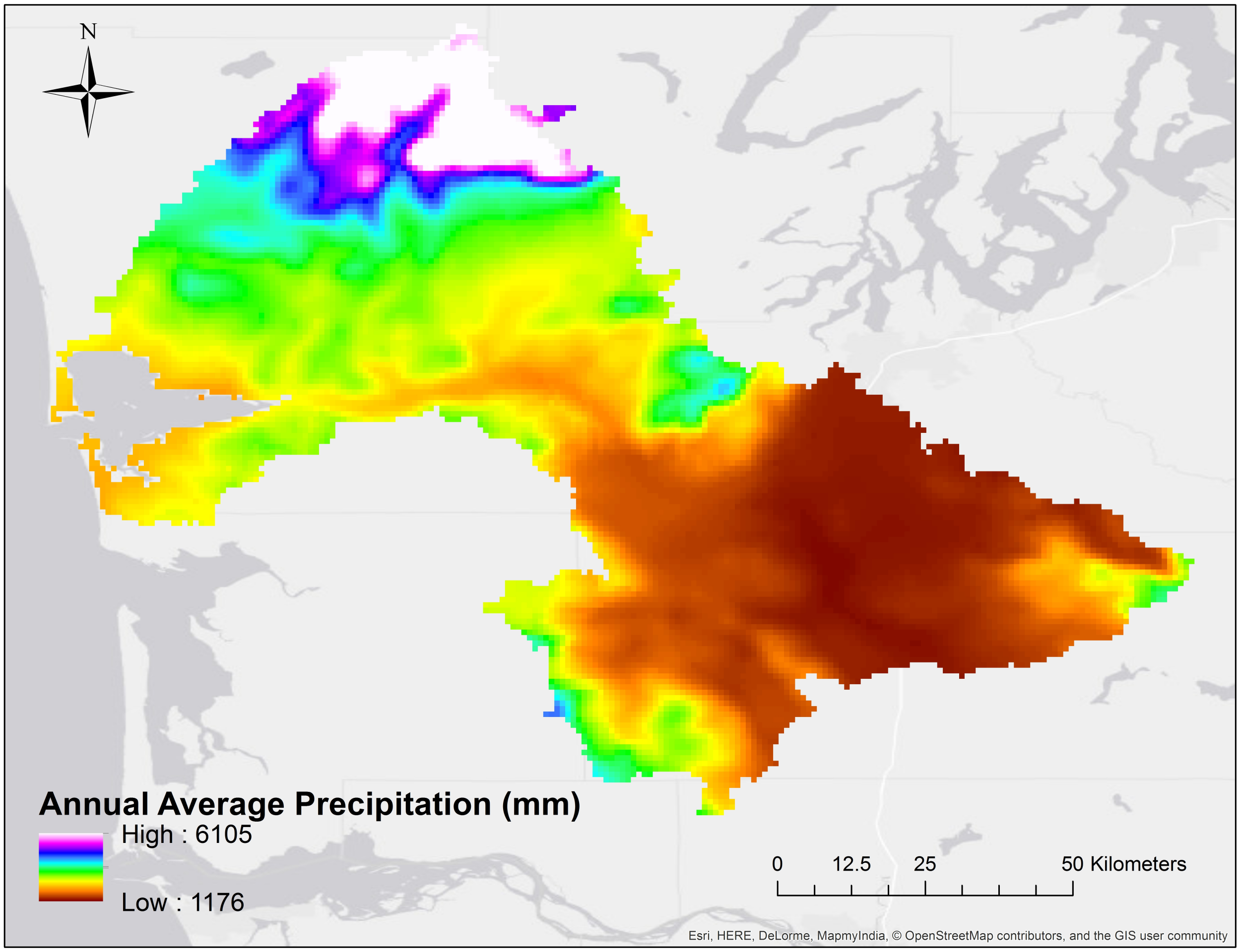

Figure 2. PRISM Annual Average Precipitation in the Chehalis River Basin (mm)[1]

Historically in the Chehalis Basin, minor flooding occurred every 2-5 years, and major flooding occurred approximately every 10 years, on average. However, floods are perceived to be happening more frequently (Kramer 2012; Burnett et al. 2014), as the 100 year flood, estimated in 1968, has been exceeded three times in the past 20 years (U.S. Army Corps of Engineers 1968; National Weather Service 2016). With climate change, the basin is predicted to experience an increase in peak flows, hotter and drier summers, and wetter winters (Burnett et al. 2014).

Flooding typically occurs in the fall and winter, November to March, mostly as a result of heavy rain, but also some rain-on-snow events, with the largest floods caused by atmospheric rivers (Kramer 2012; U.S. Army Corps of Engineers 1968). Depending on the track of the atmospheric river, flooding in the basin may originate from one or more of the following regions: Willapa Hills, Cascade foothills, or Black Hills

[1] 800-m resolution, 30-year climatology. Copyright © 2016, PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu Map Created May 1, 2016

and southern Olympics (Kramer 2012). Storms in the Willapa Hills frequently cause flooding in the upper Chehalis as well as downstream throughout the basin; flooding from the Cascade Foothills is generally confined to the Centralia-Chehalis area; storms in the Black Hills and Southern Olympics generally only cause flooding in the lower Chehalis; any flood may be exacerbated by high tides and coastal storm surges (Kramer 2012).

2.2 Forests and Roads

Approximately 84% of the land base of the Chehalis River Basin is forested (Rodgers & Walters 2012; Kramer 2012), 91% of which is subject to the Washington Forest Practices Act (FPA), while the remaining forested land base is federal or tribal land (Kramer 2012). Logging in the basin has occurred since around 1900, often predating streamflow records (Anon 1996; Sullivan & Sherwood 1995). In general, most landowners do even aged harvests (clearcuts) with the required buffers (Dubé 2016). Approximately 70% of the forests are in early to mid-seral[2] hydrologic maturity stage, with about 30% in the late-seral stage (Rodgers & Walters 2012; Batker et al. 2010), meaning most of the basin's trees are less than 40 years old (Powell 2012).

Forest roads in the Chehalis River Basin are generally standard, unpaved roads, and most are surfaced with gravel due to high rainfall, with cross-drain and stream crossing culverts (Dubé 2016). Washington State Forest Practices rules require road drainage to be disconnected from the stream network. However, it is difficult to meet this target in areas of high road use and density (approximately > 3.1 km/km^2 (5 mi/sq. mi)) and/or high stream density (Rodgers & Walters 2012), particularly in areas with a long legacy of road building. Forest roads west of the Cascade crest meet targets less often than those east of the crest (Dubé et al. 2010). Reported forest road densities in western Washington (including many sites within the Chehalis River Basin) range from 1.5 km/km^2 (2.44 mi/sq. mi) to 4.7 km/km^2 (7.63 mi/sq. mi), with an average of 3.65 km/km^2 (5.87 mi/sq. mi) (Dubé et al. 2010). Reported stream densities in western Washington (including many sites within the Chehalis River Basin) range from 0.7 km/km^2 (1.12 mi/sq. mi) to 10 km/km^2 (16.22 mi/sq. mi), with an average of 3 km/km^2 (4.82 mi/sq. mi) (Dubé et al. 2010). Therefore, road effects must be considered in assessing the effects of forest harvesting on streamflow in the Chehalis.

3. Hydrologic Effects of Forest Practices

Forest practices involve a range of activities, including road construction, harvesting, post-harvest site preparation and ongoing silvicultural treatments. These activities influence streamflow generation by (1) changing rain and snow interception, which alters the timing and intensity of water input to the drainage network by rainfall and snowmelt, (2) modifying soil characteristics (e.g., compaction by skidders), which can potentially influence the amount of water that infiltrates the soil, (3) modifying hillslope flow paths by capturing subsurface flow in road ditches and conveying it more rapidly to a stream channel as surface flow, (4) changing transpiration rates. These individual processes can interact. For example, Tague and Band (2001) applied a spatially distributed model to Watershed 3 in the H.J. Andrews Experimental Forest in Oregon, and found that a mid-slope road reduced soil moisture downslope of the road, which in turn, reduced evapotranspiration.

---

[2] Early (grasses, forbs and shrubs dominate), mid (even mix of young trees, grasses, forbs and shrubs), late (mix of young and old trees) → later the seral stage, the more complex the plant community (Powell 2012)

The hydrologic effects of forest practices depend on the relative importance of snowmelt and rain as flood-generating processes. Therefore, the literature is reviewed separately for the three hydrologic zones in the Chehalis catchment: headwaters, which experience seasonally-continuous snowcover; uplands, which experience transient snow during winter; and the lowlands, which are rain-dominated, but which also receive streamflow generated in the uplands and headwaters.

3.1 Effects of Forest Practices on Runoff Processes

Forest harvesting increases soil moisture, due to decreased transpiration post-harvest, which can increase streamflow response to rainfall and snowmelt. Forest roads can potentially increase peak flows by intercepting subsurface flow and conveying it more rapidly to a stream channel.

In hydrology, the term "runoff processes" is commonly used to refer to all the processes that convey water down hillslopes to the stream channel to produce streamflow, including infiltration-excess overland flow, shallow subsurface flow, and saturation-excess overland flow[3]. The term "runoff" is often used in hydrology to refer to the volume of water leaving a catchment as streamflow, regardless of the process by which water reaches the stream channel. Unfortunately, the term "runoff" has the potential to cause confusion because many non-hydrologists equate "runoff" with overland flow, and particularly infiltration-excess overland flow (which is also commonly referred to as "Hortonian overland flow," after the American engineer and hydrologist R.E. Horton).

Infiltration-excess overland flow is rare or non-existent on undisturbed forested hillslopes in the Pacific Northwest because the soils have high infiltration capacities, in large part due to root channels and other preferred pathways (de Vries & Chow 1978; Cheng 1988). Some forest practices, such as hauling with skidders, tractors, or other ground-based equipment, can cause compaction of the soil surface and to depths of 30 cm (11.8 inches) or more (Froehlich et al. 1985; Cullen et al. 1991; Chamberlin 1991), resulting in decreased hydraulic conductivity and soil infiltration capacity (Startsev and McNabb, 2000). However, even following logging, soil infiltration capacities may remain high enough to prohibit generation of infiltration-excess overland flow (Cheng et al., 1975). McNabb et al. (1989) reported infiltration capacities in excess of 11 cm/hr (4.3 in/hr) in a clearcut prior to slash burning in southwest Oregon. Even where local soil compaction can generate infiltration-excess overland flow, much of that water may flow over undisturbed or less-disturbed soil and infiltrate prior to reaching a stream channel.

The most extreme changes in infiltration following forest change are associated with slash burns, which were implemented in the Chehalis at one point (Anon 1996) , are discussed here for illustrative purposes. Slash burns can potentially reduce a soil's infiltration capacity in two ways. First, the removal of the organic layer exposes the mineral soil to raindrop impact, which can detach fine particles and clog soil pores. Second, during hot fires, organic matter in the soil can volatilize and diffuse as vapors towards cooler soil below the surface, where it condenses around mineral soil grains, rendering them hydrophobic (water repellent). Studies in south coastal British Columbia (Henderson & Golding 1983) and in southwestern Oregon (McNabb et al. 1989) found a higher tendency to water repellency in soils in clear-cut areas subjected to slash burning than in unburned clear-cuts. However, even immediately following

---

[3] Infiltration-excess overland flow occurs when the intensity of rainfall (or rain plus snowmelt) exceeds the infiltration capacity of the soil; saturation-excess overland flow occurs where the water table rises to the soil surface, such that rain falling onto the saturated zone cannot infiltrate and flow downslope as overland flow, augmented by seepage of subsurface water (known as "return flow").

the slash burn in early summer, McNabb et al. (1989) measured infiltration capacities of just under 10 cm/hr (4 in/hr). Furthermore, infiltration capacities recovered toward pre-burn levels by the following November (McNabb et al. 1989). For comparison, the 100-year 1-hour rainfall rate (for design purposes) for Washington State ranges from 2.5 to 3.8 cm/hr (1 to 1.5 in/hr) (ICC 2007), well below the infiltration capacities of even the most impacted soils. Therefore, forest practices in this region are unlikely to result in infiltration-excess overland flow.

Forest practices can influence streamflow generation through changes in soil moisture. At least for the first few years following harvest, soil moisture tends to be higher than for pre-logging conditions during summer and early autumn due to the reduction in transpiration, especially in cases where slash burning removes herbaceous and shrubby vegetation (McNabb et al. 1989; Adams et al. 1991). Adams et al. (1991) found that this increase in soil moisture lasted for about four years, after which soil moisture in the clearcut was lower than expected, presumably due to establishment of herbaceous, shrubby and tree species. Under conditions of higher soil moisture, less rainfall would be retained as soil moisture storage, and more would be available to flow downslope to become streamflow. However, this effect should enhance streamflow response only during summer and early autumn, when the differences in soil moisture between clearcut and forest sites is greatest (Harr et al. 1975; Ziemer 1964; Jones 2000).

Roads and their drainage systems have three main effects on streamflow generation: enhanced infiltration-excess overland flow over relatively impervious road surfaces, interception of subsurface flow, and alternative routing of flow to the stream channel via drainage structures (ditches, culverts, etc.) (Coe 2004). The effects of roads on streamflow generation potentially apply to all regions of the basin, regardless of hydrometeorological regime. Interception of subsurface flow and conveyance of that water to the stream channel via drainage structures would result in more rapid catchment response by reducing hillslope travel times, and thus tend to increase storm peak flows. However, the subsurface flow captured by a ditch may be directed onto a slope below a drainage relief culvert and re-infiltrate to become subsurface flow, with little effect on peak flows (Wemple et al. 1996).

In most paired-basin studies, road construction and harvesting overlapped in time, making it difficult to isolate the effects of each. At Caspar Creek in northern California, roads were constructed four years prior to harvesting, occupying about 5% of the catchment area, with no apparent effect on peak flows (Ziemer 1981). At the Alsea Watershed Study (AWS) in the Oregon Coast Range, there was one year of data with roads but no harvest. In that study, Harr et al. (1975) found an influence of roads only for a sub-catchment that had 12% of its area disturbed by roads and landings. No significant changes in peak flows were found for catchments with less than or equal to 5% of the catchment disturbed by roads, consistent with the results from Caspar Creek. However, the small sample of storm events during the road-only period at AWS limits statistical power.

In some small-catchment-scale studies, the authors did attribute an increase in flows to the conversion of subsurface flow to surface flow by roads (Jones & Grant 1996; Wemple et al. 1996; LaMarche & Lettenmaier 1998; Jones 2000; Jones et al. 2000; Alila et al. 2009; Storck et al. 1998; Harr 1976; Bowling & Lettenmaier 2001; Dutton et al. 2005; Wemple & Jones 2003; Harr et al. 1975). Modeling, especially using DHSVM (Wigmosta et al. 2002) has suggested some clearer results (Coe 2004). Intercepted subsurface flows dominate runoff from roads (LaMarche & Lettenmaier 2001; Wemple & Jones 2003; Mirus et al. 2007), and the majority of road runoff can come from only a small fraction of the road network (Wemple & Jones 2003). "Modest" (LaMarche & Lettenmaier 2001) to "low" (Tague & Band 2001) changes in basin outflow have been attributed, through modeling, to road building alone (Luce & Wemple 2001). Road effects can increase with peak flow magnitude (LaMarche & Lettenmaier 1998; Jones et al. 2000; LaMarche & Lettenmaier 2001), but depend on location (e.g., mid-slope versus downslope) and configuration of the road network and drainage system (Jones 2000). Modeling studies suggest that the combined road effects on peak flows from sub-catchments are roughly additive (LaMarche & Lettenmaier 2001). The effect of roads on peak flows depends on storm timing, especially for low frequency events (Alila et al. 2009), with the ability for roads to increase peak flows most apparent in the late winter and spring, when soils are generally saturated (Tague & Band 2001).

3.2 Effects of Forest Practices on Peak and Low Flows

The effect of forest practices on peak flows in small-catchments depends on the hydrometeorological regime, and these effects may or may not converge downstream in the main stem of the Chehalis River Basin. In snow-dominated headwaters, uniform harvesting of forests can lead to a more homogeneous snowpack, resulting in synchronized melt and increased snow-dominated peak flows. Peak flows resulting from rain-on-snow events, which occur mostly in the uplands and headwaters, depend mostly on rainfall intensity and duration, as well as antecedent snow depth. However, decreasing forest cover is likely to increase storm-coincident snowmelt and increase these flows. Additionally, in the uplands and lowlands, higher soil moisture in the fall, due to decreases in evapotranspiration, acts to increase rain-generated peak flows. Peak flows in all three regimes may be increased due to subsurface flow interception by roads.

With respect to low flows, the effect of forest practices is similar across hydrometeorologic regime. Decreased forest cover leads to decreased evapotranspiration, resulting in increased soil moisture and subsequently increased low flows.

The effects of forest practices on streamflow depend on the relative importance of snowmelt and rain as flood-generating processes. Therefore, the literature is reviewed separately for the three hydrologic zones in the Chehalis catchment: headwaters, which experience seasonally continuous snowcover; uplands, which experience transient snow during winter; and the lowlands, which are rain-dominated, but which receive streamflow generated in the uplands and headwaters. Whenever snow is present, there is a chance for a rain-on-snow (ROS) event to occur. First, the hydrologic processes, and interaction of these processes with forests, are discussed for each region. Then the combined effects of forest practices and hydrologic processes on peak and low flows in the Chehalis River Basin are addressed.

3.2.1 Effects of Forests on Hydrologic Processes Controlling Streamflow Generation

The hydrologic processes controlling streamflow generation, and how they interact with forests, are shown in Figure 3 and described below.

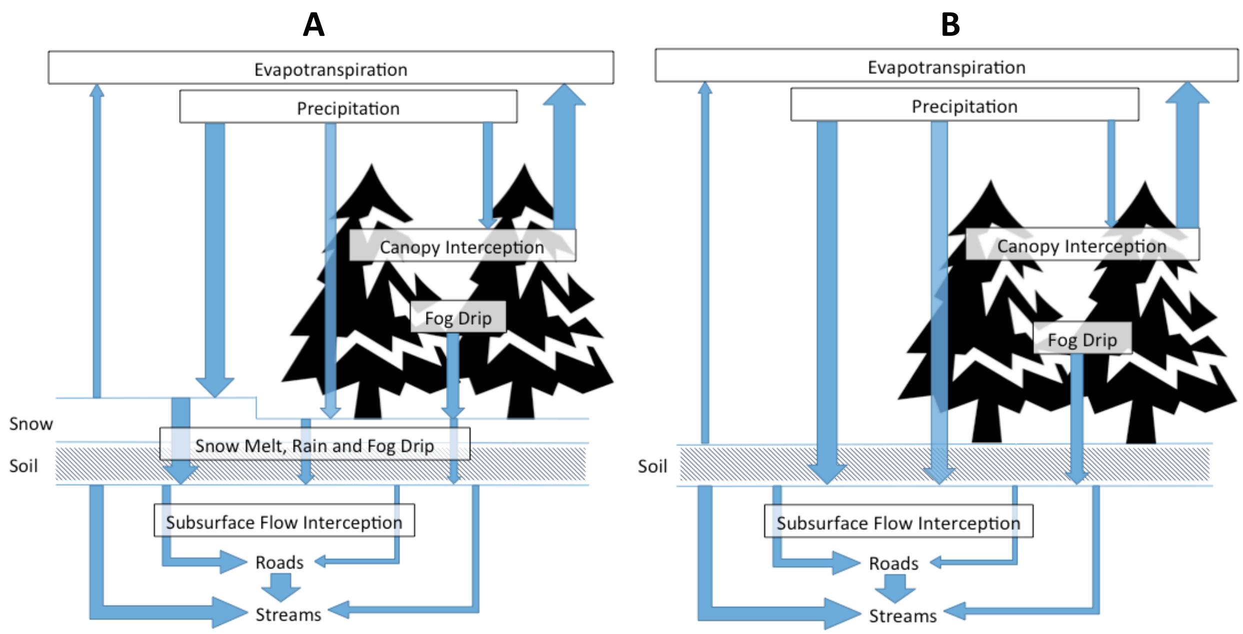

Figure 3. Hydrologic processes with snow (A) and without (B), with disparate dynamics between forest and open. Larger arrows denote larger fluxes of water.

Snow. Due to their small total area, the hydrologic effects of forestry on the snow-dominated headwaters are not likely to have significant impacts downstream; however, they may be important locally, as small headwater streams can provide fish habitat, if the reaches are accessible to fish populations. Processes controlling forest hydrology in these areas are shown in Figure 3A.

The dynamics that control snow accumulation and melt in the forest versus open in the maritime climate of the Chehalis River Basin are interception, wind, solar radiation, and longwave radiation. Overall, forest canopy interception reduces snow accumulation in forests (Anderson & Gleason 1960; Varhola, Coops, Bater, et al. 2010; Varhola, Coops, Weiler, et al. 2010), as intercepted snow is mostly lost to meltwater drip (Storck et al. 2002; Storck & Bolton 1999). Winds can both decrease accumulation through redistribution (Broxton et al. 2015; Dickerson-Lange et al. n.d.) and increase melt rate by increasing sensible and latent heat transfer in the open (Berris & Harr 1987; Lundquist et al. 2013). Open areas receive greater direct solar radiation than forests, leading to generally greater melt rates in the open than the forest (Anderson & Gleason 1960; Varhola, Coops, Bater, et al. 2010; Varhola, Coops, Weiler, et al. 2010), although increased longwave radiation in the forest can lead to greater mid-winter melt rates under the forest canopy (Lundquist et al. 2013). In addition to these dynamics, harvesting leads to decreased evapotranspiration, increasing subsurface flow and interception of such by roads, which then route flow to streams more quickly (Megahan 1983). The manner in which these three factors interact and control accumulation and melt depends on topography, geology, forest characteristics and climate (Varhola, Coops, Weiler, et al. 2010), with climate effects (e.g., average winter temperature and precipitation) dominating (Lundquist et al. 2013).

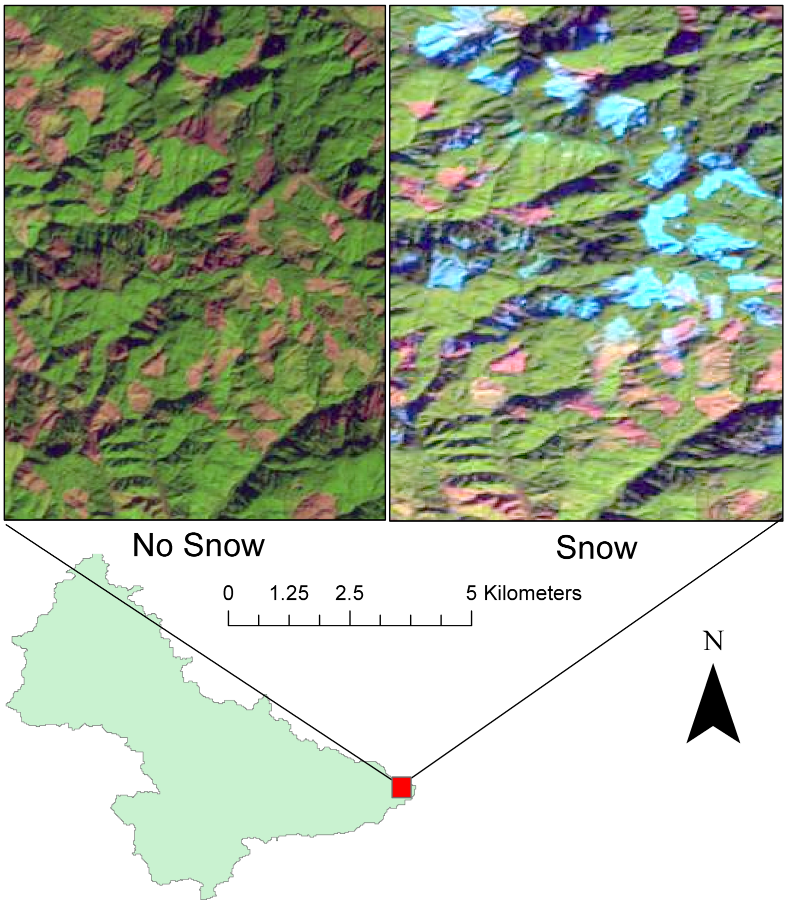

Figure 4. Landsat imagery of headwaters in the Cascade Foothills (~1000 m (3281 ft) elevation, applicable to about 1% of the basin), showing snow presence in clearcuts[4]. No snow image is from September 25, 2000 (snow shown in blue), and the image with snow present is from January 15, 2001.

In the warm maritime climate of western Washington, there is greater snow accumulation in the open (Storck et al. 2002; Lundquist et al. 2013), which results in snow lasting longer in the open than the forest (Dickerson-Lange et al. 2016). In particular, snow lasts longer in small openings in denser forests, where there is both greater accumulation and less wind (Lundquist et al. 2013; Griffen 1918; Anderson & Gleason 1960; Broxton et al. 2015). In the Chehalis River Basin, openings are typically clearcuts on the order of 0.5 km^2 (0.2 sq. mi) (see Figure 4). There will likely be more accumulation, and with the exception of very windy environments, snow will last longer in these openings, but the effects would be more substantial if openings were smaller. As snow lasts longer in the open, it has more potential to experience a ROS event.

Rain-on-Snow. ROS events are most common in both the snow-dominated headwaters and rain-snow transitional uplands of the Chehalis River Basin. Storms centered on the uplands have been known to cause flooding in the downstream lowlands, so the effects outlined may converge downstream. Processes controlling forest hydrology in these areas are shown in Figure 3A and described below.

[4] Landsat imagery downloaded from http://earthexplorer.usgs.gov/

Melting of snow during a ROS event is driven by longwave radiation from low clouds and trees, sensible heat from precipitation, and increases in sensible and latent heat transfer due to wind (U.S. Army Corps of Engineers 1956). In forested conditions, snowmelt is driven by heat transferred to the snowpack from condensation of water vapor at the snowpack surface (U.S. Army Corps of Engineers 1956; Wayand et al. 2015). When forests are removed, wind speed becomes an important factor (Chen et al. 1993), increasing melt rates and runoff (Berris & Harr 1987; Marks et al. 1998). This is especially true for west-southwest oriented slopes, towards which the prevailing winds during winter frontal storms are directed (Harr 1981). In general, wind effects are greater for larger clear-cuts (>100 m diameter) and less for smaller forest gaps (10-50 m diameter), so in snowy areas, forest practices could, in principle, be adapted to both maximize snow retention and minimize midwinter melt (Dickerson-Lange et al. 2016).

Rain. The Chehalis River Basin is approximately 79% rain-dominated lowlands, with the transitional uplands frequently experiencing rain only events as well. Processes controlling hydrology in rain events are shown in Figure 3B.

During rain events, trees intercept rainfall, part of which is lost to evaporation, with diminishing effects as the rainfall intensity and duration increase (Anderson et al. 1976). This region's primary forest type (Douglas-fir, Western Hemlock) has the highest rainfall interception rate of all North American conifers studied (Helvey 1971). As discussed above, rain dominated regions will also be impacted by lower soil moisture in the late summer and fall and hence, greater runoff at these times.

3.2.2 Peak Flows

Snowmelt-generated peak flows. In a maritime climate, peak flows in snow-dominated headwater catchments are driven by rain-on-snow (ROS) events in the fall and winter (discussed in the following subsection), and to a lesser extent, snowmelt in the spring, possibly augmented by rainfall. In the Chehalis River Basin, only very small headwater streams are likely to experience snowmelt-generated peak flows. The effects of forest practices on these flows are presented here for completeness, and the studies cited focus on drainages that have higher elevation and are colder than the Chehalis River Basin.

Both paired-catchment analyses and computer simulations indicate that peak flows associated with seasonal snowmelt increase after forest harvesting (Schnorbus & Alila 2004; Whitaker et al. 2002; Macdonald et al. 2003; Cristea et al. 2013; Schnorbus & Alila 2013; Harr & McCorison 1979; King 1989; Hubbart et al. 2007). Heterogeneous forest cover, such as old growth forest, leads to a more heterogeneous snowpack (Clark et al. 2011; Berris & Harr 1987), which spreads snowmelt out over a longer time period (Lundquist & Dettinger 2005; Lundquist et al. 2005), as some stands receive more direct solar radiation than others (Musselman et al. 2012). The Chehalis River Basin is comprised of mostly young, more homogeneous, forests. However, there are still some more mature and old growth forests at the highest elevations (Rodgers & Walters 2012). Decreasing snowpack heterogeneity, as a result of forest harvest, leads to more synchronized snowmelt (Lundquist & Dettinger 2005; Lundquist et al. 2005), and higher peak flows (Du et al. 2016). The literature reports increases in peak flows resulting from snowmelt ranging from insignificant to 50% (see Figure 8 in Grant et al. 2008). Again, it should be noted that these increases apply only to the smallest headwater stream drainages in the Chehalis.

Rain-on-snow events. Since the runoff dynamics of ROS events are different from those controlling either just rain or snowmelt alone, peak flows resulting from these events are treated separately here. Higher flows have been observed from a clearcut than from forest during ROS (Lettenmaier et al. 1991). Forest harvesting has two influences, described in section 3.2.1. First, clearcuts are more likely to have snow on the ground during rain events due to the decreased canopy interception (Beaudry and Golding, 1983; Berris and Harr, 1987; Hudson, 2001). Second, there is greater turbulent energy available for melting snow in a clearcut, and thus higher melt rates. A series of snowfalls, separated by the melting of intercepted snow, maximizes the difference in snowpack depth and water-equivalent between the forest and open (Berris & Harr 1987; Storck et al. 1998). ROS events occur both in the headwaters and uplands, and synchronous snowmelt across a wide range of elevations, during these events, can increase their severity. Snowpack presence can delay peak flow at low elevations, and speed up time to peak flow at high elevations, potentially synchronizing flows and increasing the severity of a ROS event in a larger basin (>10 km^2) (Perkins & Jones 2008; Jones & Perkins 2010). Such a ROS event is unlikely to occur, but was observed in the January 2009 flood in the Chehalis River Basin.

Maximum basin-total snowmelt contributions from ROS events in the Snoqualmie River Basin, with climate similar to the Chehalis, were found to range from 11 to 47% (Wayand et al. 2015). Over 65% of the Snoqualmie River Basin area is above 300 m (984 ft) in elevation (Gustafson 2003b), and therefore likely to experience rain on snow. For comparison, ~25% of the Upper Chehalis River Basin area (Gustafson 2003c), and <15% of the Lower Chehalis River Basin area (Gustafson 2003a), are above 300 m (984 ft). Therefore, snowmelt contributions during ROS events in the Chehalis River Basin will likely be much less than the range reported for Snoqualmie. While rainfall, not snowmelt, dominates volumetric contributions to ROS event flows, snowmelt cannot be ignored (Wayand et al. 2015; Hess 1984). Additionally, peak discharge is not directly related to precipitation rate, but rather to a multiple-day sum of precipitation and net snowpack outflow, where the highest magnitude events occur when snowpack continuously melts and can feed streams synchronously with rainfall runoff (Jennings & Jones 2015; Shafer et al. 1984). Forest cover was found to reduce basin-wide snowmelt contributions by 20 to 50% in a modeling study in the Snoqualmie River Basin (Wayand et al. 2015). Again, snowmelt contributions in the Chehalis River Basin would be much lower. Additionally, the magnitude of snowmelt reduction varies between storms (Wayand et al. 2015; Connelly 1992)[5]. In some cases, the presence of forest roads, more than the removal of trees, increases peak flows from ROS events (Storck et al. 1995).

Rain-generated peak flows. There is general agreement in the literature that rain-generated peak flows with return periods less than 6 years increase after forest harvesting (Rothacher 1970; Harr et al. 1975; Harris 1977; Harr & McCorison 1979; Bowling et al. 2000; Beschta et al. 2000; Jones & Grant 2001a; Grant et al. 2008; Hibbert 1967). Increases in peak flows, especially in the fall, result from decreased evapotranspiration and interception loss, possibly in combination with the effects of roads (Harr et al. 1979; Jones 2000; Elliott & Brook 2007; Chamberlin et al. 1991). However, some studies found no statistically significant change (Rothacher 1965; Harr et al. 1982; Harr & McCorison 1979), especially later in the rainy season (Chamberlin et al. 1991), when differences in soil moisture between forests and open areas are insignificant (Hess 1984; Harr 1976). Changes in peak flows are basin specific and range from insignificant to 42% (see Figure 8 in Grant et al. 2008). The magnitude and statistical significance of increases in peak flows differ between study sites based on the climate, harvest type and design, and analysis method (e.g. chronological pairing vs. frequency analysis, data processing, and statistical tests), and greater uncertainties exist with increasing basin and event size. Many of the differences between studies are born from subjective decisions, which are discussed in section 4.3.

---

[5] Similarly, the ENSO cycle was found to control streamflow variability, while forest harvesting could heighten the effects (wetter years more runoff, drier years less runoff) (Burt et al. 2015).

When considering the effect of streamflow generated in the uplands and headwaters, it is reasonable to infer that the effects of forest change would decrease in the downstream direction, as a consequence of increased opportunities for surface and subsurface detention and retention, desynchronization of snowmelt, and lowland vegetation uptake (Abdelnour et al. 2011; MacDonald & Coe 2007). Indeed, Grant et al. (2008) stated that "[n]o hydrologic mechanism exists by which peak flow increases, when measured as a percentage change, can combine to yield a higher percentage increase in peak flows in a larger basin." Still, a number of both model-based and empirical analyses suggest that large watersheds do experience post-harvest changes in peak flows in maritime regions dominated by rain and rain-on-snow (Jones & Perkins 2010; Perkins & Jones 2008; Seibert & McDonnell 2010; Jones & Grant 1996).

There are some limitations associated with the studies listed above. First, for empirical studies, it is difficult to establish a large-scale paired basin experiment, as most basins have experienced or will experience some forest cutting, producing a lack of a true control, and differences in meteorology (rain rates), topography, and geology become more important with increasing basin size. Additionally, atmospheric river events, the cause of most storm events in the Pacific Northwest, have quite a narrow focus (bands of rain ~400 km (249 mi) wide[6]), making it less likely that large neighboring watersheds would experience the same duration or intensity from the same storm (Neiman et al. 2011). All of these factors act to reduce the statistical power of empirical analyses of streamflow changes. Secondly, modeling-based studies often remove an unrealistically high percentage (e.g., simulated universal clear cut) of trees or high density of roads (in terms of Forest Practice rules).

Bowling et al. (2000) analyzed streamflow trends for 23 catchments in western Washington, including the Chehalis. Univariate trend analysis for the period 1930 to 1996 did not reveal significant trends for peak flows or mean annual flow for the Chehalis River, but did result in findings for low flows, as discussed in the section below. Bowling et al. (2000) also used the model DHSVM, applied to three catchments in the Snoqualmie River basin and calibrated to land cover for 1983-86, as a "virtual control." This analysis detected increases in peak flows, which were attributed to land-cover change.

3.2.3 Low Flows

Natural controls on low flows include geology, soils, and topography (Tague & Grant 2004), on top of which changes in climate and land use are imposed (Johnson 1998). For example, lower permeability bedrock geology and shallow soils generally lead to lower low flows (Johnson 1998). As discussed previously, there is limited snow in the Chehalis River catchment, and it is unlikely that snow would accumulate deep enough or last long enough to influence summer low flows, even in the snow-dominated headwaters. Therefore only the effects of increased soil moisture are discussed here. As discussed in section 3.1, soil moisture increases after forest harvest, due to decreased transpiration. In the Pacific Northwest, low flows are particularly sensitive to these changes in soil moisture. Additionally, low flows are sensitive to changes in soil moisture and transpiration from riparian vegetation (Moore & Wondzell 2005), and particularly to transpiration from young forests (Moore et al. 2011). Although transpiration increases with increasing root depth (Mackay & Band 1997), transpiration from old growth forests (ca. 450 years old) is significantly less than that from young forests (ca. 40 years old) (Moore et al. 2004; Hicks et al. 1991).

[6] http://www.esrl.noaa.gov/psd/atmrivers/questions/

The majority of the literature, for both rain and snow-dominated regimes, concludes that low flows increase after logging due to increased soil moisture as a result of decreased evapotranspiration (Harr et al. 1982; Ingwersen 1985; Keppeler & Ziemer 1990; Hicks et al. 1991; Bowling et al. 2000; Abdelnour et al. 2011; Harr 1976; Chamberlin et al. 1991; Rothacher 1965; Rothacher 1970; Adams et al. 1991; Surfleet & Skaugset 2013; Pike & Scherer 2003; Ziemer 1964). However, in coastal forests, such as those in the lowlands near Aberdeen-Hoquiam, low flows can be controlled by significant fog-drip, which would decrease post-harvest (Harr 1980; Harr 1982; Ingwersen 1985; Jones 2000). Low flows in the coastal areas of the Chehalis River Basin are likely augmented, but not controlled, by fog-drip.

Results from the literature reviewed are basin specific and changes in low flows range from insignificant to over 140% (8 mm (0.3 inch)). Increases typically diminish 5-10 years after harvest, and may even become deficits with growth of new vegetation (Ingwersen 1985; Keppeler & Ziemer 1990; Hicks et al. 1991; Surfleet & Skaugset 2013; Perry 2007; Adams et al. 1991; Salemi et al. 2012; Pike & Scherer 2003; Ziemer 1964; Fowler et al. 1987).

Bowling et al. 2000 found a statistically significant negative trend in low flows for Chehalis River ($p < 0.1$) for the period between 1930 and 1996, which was attributed to the effects of the Pacific Decadal Oscillation (PDO) rather than land cover change. To filter out the effect of the PDO, Bowling et al. (2000) conducted a paired-catchment analysis, using catchments with the lowest rates of vegetation change as the controls (this analysis did not include the Chehalis). Only minimum flows yielded significant trends, which suggested that minimum flows have increased in association with increased forest harvesting, consistent with a reduction in evapotranspiration.

3.3 Hydrologic Recovery

Hydrologic recovery refers both to the processes by which hydrologic functions return to pre-harvest levels, and to the degree of recovery, where a fresh clear-cut would be assigned 0% recovery and a mature stand 100%. At the stand level, the effects of harvesting on interception loss of rainfall and snow dynamics can persist for several decades. At the catchment scale, increases in low flows persist at least 5 years, and increases in peak flows are typically detectable for up to 20 years, and even longer in some cases.

Following forest harvesting, establishment and development of vegetation will influence hydrologic processes and eventually reduce the magnitude of harvesting-related impacts. The trajectory of recovery will depend on the types of vegetation and their rates of growth and successional processes (Jones and Post, 2004). Recovery rates for stand-level processes can be quantified using a chronosequence approach. Hydrologic recovery (HR) can be computed based on how an individual stand relates to fresh clearcuts and reference stands, with HR ranging from 0% for a fresh clearcut up to 100% for a stand that functions like the original mature/old-growth stand that was harvested.

Relatively few studies have quantified stand-level hydrologic recovery for coastal forests. Hudson (2000) quantified recovery in peak seasonal snow accumulation and post-peak snow ablation rate relative to an old growth stand in the snow-dominated zone of the southern Coast Mountains of British Columbia (latitude 49.5° N). The post-harvest stands had elevations from 970 to 1050 m asl (3182 – 3445 ft), and were naturally regenerated, consisting of a mixture of subalpine fir, western hemlock, mountain hemlock, western red-cedar, and yellow-cedar. Based on a curve fitted to the hydrologic recovery for each stand, tree heights of 4, 6 and 8 m were associated with 53%, 75% and 83% recovery, respectively. Spittlehouse (unpublished)[7] measured interception loss in second-growth stands in the low-elevation rain-dominated zone at Carnation Creek, British Columbia, located on the west coast of Vancouver Island (latitude 48.9° N). Forest stands there are dominated by coastal western hemlock, western red-cedar, Douglas-fir and Sitka spruce. The data suggest hydrologic recovery of 53% and 73% for stand ages of 15-20 and 30-35 years, respectively. We are unaware of any similar studies focused on ROS processes. Based on these stand-level studies, it can be inferred that forestry influences on streamflow may persist for decades following harvest.

A number of paired-catchment studies have included post-harvest monitoring over multiple decades, which sheds light on rates of catchment-scale post-harvest hydrologic recovery. Most studies that addressed low flows reported an increase in streamflow, at least for the first five to ten years following harvesting (Harris, 1977; Harr et al., 1982; Hetherington, 1982; Keppeler & Ziemer, 1990; Hicks et al., 1991). After this initial period, post-harvest trajectories varied among catchments. At HJ Andrews Watershed 3, August water yield remained above predicted levels for about 16 years before returning to pre-harvest levels (Hicks et al., 1991). In HJ Andrews Watershed 1, on the other hand, August water yield was higher than predicted pre-harvest levels for eight years, then dropped below pre-harvest levels for the next 18 years. Hicks et al. (1991) hypothesized that the decreased August water yield was associated with increased evapotranspiration due to the establishment of alder in the riparian zone, which was corroborated by evapotranspiration measurements (Moore et al., 2004).

Several studies have focused on post-harvest recovery of peak flows (Jones and Grant, 1996; Thomas and Megahan, 1998; Jones, 2000; Lewis et al., 2001). Although the results vary somewhat due to different approaches to analyzing the data, there is a consensus that the effects persist for at least 10 years, with some evidence that they can remain detectable for 20 to 30 years.

3.4 Hydrologic Effects of Forest Practices in Larger Catchments

In order to assess whether forest practices have contributed to changes in flood frequency and magnitude in the Chehalis River Basin, it will be necessary to generate a robust catchment-scale index of forest cover hydrological function.

In addition to issues of how to "scale up" research results from stand- and small-catchment-scale studies to larger catchments, an additional challenge in large catchments is how to account for forest practices executed at different locations over multiple decades with varying degrees of recovery (Reid, 1993). One approach to quantifying cumulative effects is by calculating the "equivalent clearcut area" (ECA) (King, 1989), which weights the effective area of each harvest by a factor calculated as 1 – HR/100, where HR is the hydrologic recovery of the cutblock. Calculation of ECA requires that recovery curves be available that are relevant for each stand type, as well as accurate inventories of stand characteristics through time to calculate the degree of hydrologic recovery for each cutblock. Another complication is that ECA does not account for the effects of forest roads. A simpler approach is to use the fraction of a catchment with forest stands less than some threshold age as an indicator. For example, Bowling et al. (2000) used a threshold age of 20 years.

[7] D.L. Spittlehouse, Research Climatologist, British Columbia Ministry of Forests, Lands and Natural Resource Operations. Personal communication, March 23, 2015.

A related challenge in assessing the cumulative effect of recent and proposed harvesting in the context of legacy impacts associated with past harvesting is choosing a reference state. The Chehalis River basin is dominated by second-growth stands and, assuming that forestry continues to be a significant part of the regional economy, it is likely that the forest cover will be dominated by stands at various stages of post-harvest recovery. In order to assess whether forest practices have contributed to changes in flood frequency and magnitude, it will be necessary to generate a robust catchment-scale index of forest cover hydrological function.

3.5 Effects of Forest Practices on "Channel-Forming Flows"

The literature agrees that "channel-forming flows" (near or at bankfull) increase in frequency and magnitude post-harvest, which can be detrimental to fish habitat in the uplands and headwaters of the basin.

Even small percentage increases in mean high flows can cause large frequency increases. Most studies show an increase in "channel-forming flow" frequency post-harvest. These bankfull flows typically occur every 1.5 years, on average, and move the most sediment over time, changing the stream channel gradually over time (Watson & Adams 2010). When these flows become more frequent, the channel experiences more rapid change, including erosion and stream siltation and pollution (Watson & Adams 2010). The stream channel may also "cut down," creating a deeper channel, disconnecting flow from the floodplain and from secondary channels. These effects are potentially detrimental to fish in the uplands and headwaters, including salmonid species that migrate to and spawn in smaller streams (Chamberlin et al. 1991). In fact, "small streams are responsible for a high proportion of salmonid production in a basin, and they influence the quality of habitat in larger tributaries downstream" (Chamberlin et al. 1991).

3.6 Effects of Forest Practices on High and Extreme Peak Flows

The literature agrees that peak flows increase, but the certainty of this change decreases with increasing flows. Extreme flood-inducing flows may or may not be significantly affected by forest practices. Few studies were able to draw definitive conclusions on changes in extreme flows, due to the rarity of the events and the nature of statistical analysis used.

The bulk of the literature concludes that peak flows increase after forest harvesting. The direction is agreed upon, but the magnitude of change is both basin-specific and dependent on the chosen statistical method. Whether or not a change is statistically significant depends substantially on the author's choice of significance level (α to which the p-value is compared) or minimum detectable difference. Simply because a test fails to detect a significant change, does not mean that there is none, and most studies do not report this type II error (probability of failure to reject a false null hypothesis).

Several other subjective decisions can alter the results of a study. The pretreatment of data, chosen analytical approach (chronological event or frequency pairing) and statistical tests used all affect conclusions about the statistical significance of results. For this reason, there is ongoing debate over significance of changes to peak flows, especially within large basins and for extreme events (Jones &

Grant 1996; Jones & Grant 2001a; Jones & Grant 2001b; Thomas & Megahan 1998; Thomas & Megahan 2001; Burton 1997; Troendle & Stednick 1999b; Troendle & Stednick 1999a; Burton 1999b; Burton 1999a; Bathurst 2014; Birkinshaw 2014; Alila & Green 2014c; Alila & Green 2014b; Alila & Green 2014a; Alila et al. 2009; Alila et al. 2010).

Most analyses based on chronological pairing indicate that forest practices can influence peak flows up to about a 6-year return period level (i.e., the channel-forming range) (Grant et al. 2008). In the seminal paper that critiqued that approach, Alila et al. (2009) focused on two catchments relevant to the Chehalis River Basin, watersheds 1 and 3 in the H.J. Andrews Experimental Forest. The analytical approach involved conducting flood frequency analyses using both the observed post-harvest peak flows and the peak flows predicted using the pre-harvest regression (which represent an estimate of what the peak flows should have been had harvesting not occurred). The analysis was conducted using the "raw" observed peak flow series. In addition, to account for the effect of hydrologic recovery through the post-harvest period, a linear trend was fitted to the differences between observed and predicted peak flows. This linear trend was then "removed" from the observed series by subtracting it from the observed post-harvest peak flows, effectively adjusting the post-harvest peak flows upwards (i.e., to estimate what the peak flow would have been had the catchment been harvested in the year immediately prior).

For Watershed 1, the frequency-pairing analysis without adjustment of observed flows for post-harvest recovery indicated a convergence of peak flow frequency curves at a 5-year return period flow. That is, only the "channel-forming" range of peak flows was influenced. On the other hand, after adjusting the observed flows upward to remove the effects of recovery, the curves converged at a return period in excess of 14 years, indicating that harvesting influenced both the high and extreme peak flows as well as the channel-forming flows. For watershed 3, post-harvest peak flows increased following harvest for all return periods with or without adjustment for recovery. Adjusting for recovery is appropriate if one is interested in quantifying the short-term risk associated with forest harvesting in the first years following harvest, before substantial hydrologic recovery occurs. However, if the interest is in risks averaged over a longer time period, then adjusting the flows for recovery will exaggerate the effect of forest practices.

Regardless of the analytical approach chosen, changes in extreme flows are difficult to quantify due to the inherent infrequency of such events and the transient nature of the effects of forest harvesting on peak flows. The same event circumstances are very unlikely to occur twice in a study period. Therefore, the uncertainty around the predicted forest harvesting response increases as the frequency of the storm decreases, simply because effects cannot be observed and repeatedly verified. There are many logical explanations as to why forests would have less effect on streamflow with increasing event size. For example, increased storm intensity and duration may overwhelm interception, infiltration, and soil moisture storage capacity.

Typical statistical analysis approaches used in forest hydrology studies also make it difficult to assess changes in extreme events. To determine how flows change from pre- to post-harvest, temporal data are broken up into sets, and the null hypothesis is usually stated as finding no change in the mean flow. The fact that most methods are testing for a change in mean flow reduces their ability to come to meaningful conclusions about changes in extreme flows. Larger sample sizes have greater statistical power, lower type I error (probability of incorrect rejection of a true null hypothesis), but assume that all peak flows respond to the same forest treatment in the same way, and will be strongly influenced by the more frequent, lower flow, events. On the other hand, small groups can be used to assess the combined effects of forest cover and season, event size, or time post-treatment, but lead to lower statistical power, especially when investigating changes for large, rare events. Additionally, most statistical tests assume normally-distributed data, a requirement that can sometimes be better met by applying a log transformation. Transformations work by compressing one part of the distribution more, so in the case of peak flows, which most often have positive skew (lower values are more common), log transformation would compress higher values on the distribution, artificially lowering their probability of occurrence. This kind of data preprocessing reduces the influence of the largest events (Jones & Grant 2001b), so a bias correction is needed that is not always implemented (Lewis et al. 2010).

Several authors have proposed model analysis as a way around these statistical issues (e.g., Alila and Green, 2014). Hydrologic models can be useful tools to isolate and evaluate streamflow effects of forest changes over large spatial and temporal scales. DHSVM (Wigmosta et al. 1994) in particular has been well established in the Pacific Northwest (Storck et al. 1998; Abdelnour et al. 2011; Du et al. 2016; Jost et al. 2009; Bowling et al. 2000; LaMarche & Lettenmaier 1998; LaMarche & Lettenmaier 2001; VanShaar et al. 2002; Waichler et al. 2005; Zégre et al. 2010; Wayand et al. 2015; Bowling & Lettenmaier 2009). Distributed modeling comes with its own subjectivity because model parameters, representation of basin attributes, and forcing data need to be chosen, such as interception rate, location and amount of harvest, how forests recover/regrow over time, how roads are hydrologically connected to streams, how precipitation and temperature are distributed, and how precipitation is partitioned into rain and snow. All of these can have substantial effects on the basin hydrograph (Wayand et al. 2013; Storck et al. 2002; Storck et al. 1998; Lundquist et al. 2015). These issues continue to be addressed, and model platforms (such as DHSVM) improved upon. A modeling study is the most reliable way to answer specific questions about the effects of forest practices in the Chehalis River basin. We recommend modelers use both a range of parameters, with processes and parameters well-vetted at the forest plot scale, and a range of statistical tests.

Watershed analysis procedures are another technique to evaluate the effects of historic, recent and proposed future harvest on streamflow. Examples include the Interior Watershed Assessment Procedure (for snow-dominate catchments) and the Coastal Watershed Assessment Procedure (for rain- and rain-on-snow-dominated catchments) in British Columbia, Canada, and the Washington Forest Practices Board Standard Methodology for Conducting Watershed Analysis in Washington, USA (WFPB, 2011). These watershed assessment methodologies are based on a number of assumptions and have not been rigorously evaluated over a broad range of catchments (Collins & Pess 1997). More physically-based modeling approaches, as discussed in the paragraph above, are more well-accepted in the literature.

Despite the difficulties discussed above, several studies suggest that we cannot discount the effect of forests on extreme events (Hess 1984; Wayand et al. 2015; Kuras et al. 2012; Schnorbus & Alila 2013; Alila et al. 2009; Harr et al. 1979; Jones & Perkins 2010). This remains a contested and unresolved issue in the forest hydrology community.

4. Conclusions and Recommendations

The literature applicable to the Chehalis River Basin agrees overall on the direction of change in both peak and low flows after forest harvesting and road building. Peak flows increase for the following reasons: decreased evapotranspiration leads to increased soil moisture (especially in the fall), decreased canopy interception leads to an increased amount of rainfall reaching the soil surface, increased snow accumulation and melt rates lead to increased contribution of snowmelt during ROS events, and subsurface flow interception by roads leads to decreased travel time for runoff. At the small-catchment scale, peak flows take about 20 years or more to recover to pre-harvest levels. Low flows typically increase initially due to decreased evapotranspiration, then either revert toward pre-harvest levels or become deficits within 5-10 years. Magnitude and significance of changes to peak and low flows vary between studies and are basin dependent. There is no agreement on whether or not forest harvesting causes significant increases in peak flows in large basins or extreme flow (flood) events.

Forest practices alone likely lead to increased frequency of bankfull flow events in the uplands and headwater portions of the Chehalis River Basin. This could be detrimental to fish habitat in these areas. Additionally, climate change is projected to increase the frequency of these 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 (Warner et al. 2015). For these reasons we recommend studying the combined effects of forest practices and climate change in a modeling framework, as an addition to work currently undertaken by the University of Washington Climate Impacts Group for the Chehalis River Basin. For such an analysis, the methods applied by Bowling et al. (2000) should be applied. Similarly, following Bowling et al. (2000), it would be useful to conduct an empirical time series analysis to relate streamflow variability and trends to climatic and land-use variables.

References

Abdelnour, A. et al., 2011. Catchment hydrological responses to forest harvest amount and spatial pattern. *Water Resources Research*, 47(9), pp.1–18.

Adams, P.W., Flint, A.L. & Fredriksen, R.L., 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Oregon. *Forest Ecology and Management*, 41(3-4), pp.249–263.

Alila, Y. et al., 2009. Forests and floods: A new paradigm sheds light on age-old controversies. *Water Resources Research*, 45(8), pp.1–24.

Alila, Y. et al., 2010. Reply to comment by Jack Lewis et al. on "forests and floods: A new paradigm sheds light on age old controversies." *Water Resources Research*, 46, pp.1–6.

Alila, Y. & Green, K.C., 2014a. A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments. *Water Resources Research*, 48, pp.1–21.

Alila, Y. & Green, K.C., 2014b. Reply to comment by Bathurst on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments." *Water Resources Research*, 50, pp.2759–2764.

Alila, Y. & Green, K.C., 2014c. Reply to comment by Birkinshaw on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments." *Water Resources Research*, 50, pp.2769–2774.

Anderson, H.W. & Gleason, C.H., 1960. Effects of Logging and Brush Removal on Snow Water Runoff. *International Association of Hydrologic Science Publication*, 51, pp.478–489.

Anderson, H.W., Hoover, M.A.R.V.I.N. & Reinhart, K.G., 1976. *Forests and Water. Effects of forest management on floods, sedimentation, and water supply.*, Berkeley, California.

Anon, 1996. *West Fork Satsop Watershed Analysis*,

Bathurst, J.C., 2014. Comment on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments" by K.C. Green and Y. Alila. *Water Resources Research*, 50, pp.2765–2768.

Batker, D. et al., 2010. *Flood Protection and Ecosystem Services in the Cheahlis River Basin*, Tacoma, Washington.

Berris, S.N. & Harr, R.D., 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the Western Cascades of Oregon. *Water Resources Research*, 23(1), pp.135–142.

Beschta, R.L. et al., 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. *Journal of Hydrology*, 233(1-4), pp.102–120.

Birkinshaw, S.J., 2014. Comment on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments" by Kim C. Green and Younes Alila. *Water Resources Research*, 50, pp.2765–2768.

Board), W. (Washington F.P., 2011. *Standard Methodology for Conducting Watershed Analysis under Chapter 222-22 WAC. Version 5.0*,

Bowling, L.C. & Lettenmaier, D.P., 2001. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In M. S. Wigmosta & S. J. Burges, eds. *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*. pp. 145–164.

Bowling, L.C. & Lettenmaier, D.P., 2009. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In M. S. Wigmosta & S. J. Burges, eds. *Land Use and Watersheds: Human influence on hydrology and geomorphology in urban and forest areas*. pp. 145–164.

Bowling, L.C., Storck, P. & Lettenmaier, D.P., 2000. Hydrologic effects of logging in western Washington, United

States. *Water Resources Research*, 36(11), pp.3223–3240.

Broxton, P.D. et al., 2015. Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. *Ecohydrology*, 8, pp.1073–1094.

Burnett, D. et al., 2014. *Chehalis Basin Strategy Governor's Chehalis Basin Work Group: 2014 Recommendation Report*,

Burt, T.P. et al., 2015. Seeing the climate through the trees: Observing climate and forestry impacts on streamflow using a 60-year record. *Hydrological Processes*, 29, pp.473–480.

Burton, T.A., 1997. Effects of basin-scale timber harvest on water yield and peak streamflow. *Journal of the American Water Resources Association*, 33(6), pp.1187–1196.

Burton, T.A., 1999a. Reply to Discussion by C . A . Troendle and J . D . Stednick: "Effects of Basin Scale Timber Harvest on Water Yield and Peak Streamflow." *Journal of the American Water Resources Association*, 35(1), pp.183–184.

Burton, T.A., 1999b. Reply to Discussion by C. A. Troendle and J. D. Stednick: "Effects of basin scale timber harvest on water yield and peak streamflow." *Journal of the American Water Resources Association*, 35(1), pp.183–184.

Chamberlin, T.W., Harr, R.D. & Everest, F.H., 1991. Timber Harvesting, Silviculture, and Watershed Processes. In W. R. Meehan, ed. *Influences of forest and rangeland management on salmonid fishes and their habitats*. American Fisheries Society, pp. 181–205.

Chen, J., Franklin, J.F. & Spies, T.A., 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. *Agricultural and Forest Meteorology*, 63, pp.219–237.

Clark, M.P. et al., 2011. Representing spatial variability of snow water equivalent in hydrologic and land-surface models: A review. *Water Resources Research*, 47(7), pp.1–23.

Coe, D., 2004. *The Hydrologic Impacts of Roads At Varying Spatial and Temporal Scales: A Review of Published Literature as of April 2004*,

Collins, B.D. & Pess, G.R., 1997. Evaluation of forest practices prescriptions from Washington's watershed analysis program. *Journal of the American Water Resources Association*, 33(5), pp.1–12.

Connelly, B.A., 1992. *The cumulative effects of forest management on peak flows during rain-on-snow events*. University of Washington.

Cristea, N.C. et al., 2013. Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. *Hydrological Processes*, 28(12), pp.3896–3918.

Dickerson-Lange, S.E. et al., Snow disappearance timing in warm winter climates is dominated by forest effects on snow accumulation. *Hydrological Processes*.

Du, E. et al., 2016. Evaulating hydrologic effects of spatial and temporal patterns of forest canopy change using numerical modeling. *Hydrological Processes*, 30, pp.217–231.

Dubé, K., 2016. Personal Communication.

Dubé, K. et al., 2010. *Washington Road Sub-Basin Scale Effectiveness Monitoring First Sampling Event (2006-2008) Report*, Olympia, Washington.

Dutton, A.L., Loague, K. & Wemple, B.C., 2005. Simulated effect of a forest road on near-surface hydrologic response and slope stability. *Earth Surface Processes and Landforms*, 30, pp.325–338.

Elliott, L.P. & Brook, B.W., 2007. Revisiting Chamberlin: Multiple Working Hypotheses for the 21st Century. *BioScience*, 57(7), pp.608–614.

Fowler, W.B., Helvey, J.D. & Felix, E.., 1987. *Hydrologic and climatic changes in three small watersheds after timber harvest*,

Gendaszek, A.S., 2011. *Hydrogeologic Framework and Groundwater/Surface-Water Interactions of the Chehalis River Basin, Southwestern Washington*,

Goodell, B.C., 1959. Management of Forest Stands in Western United States to Influence the Flow of Snow-fed Streams. In *Colloque de Hannoversch-Munden*. pp. 49–58.

Grant, G.E. et al., 2008. *Effects of Forest Practices on Peak Flows and Consequent Channel Response : A State-of-Science Report for Western Oregon and Washington*,

Griffen, A.A., 1918. Influence of Forests Upon the Melting of Snow in the Cascade Range. *Monthly Weather Review*, pp.324–327.

Gustafson, D.L., 2003a. Lower Chehalis. *Environmental Statistics Group - Hydrologic Unit Project*. Available at: http://www.esg.montana.edu/gl/huc/17100104.html.

Gustafson, D.L., 2003b. Snoqualmie. *Environmental Statistics Group - Hydrologic Unit Project*. Available at: http://www.esg.montana.edu/gl/huc/17110010.html.

Gustafson, D.L., 2003c. Upper Chehalis. *Environmental Statistics Group - Hydrologic Unit Project*. Available at: http://www.esg.montana.edu/gl/huc/17100103.html.

Harr, R.D. et al., 1975. Changes in Storm Hydrographs After Road Building and Clear-Cutting in the Oregon Coast Range. *Water Resources Research*, 11(3), pp.436–444.

Harr, R.D., 1982. Fog drip in the Bull Run municipal watershed, Oregon. *Water Resources Bulletin*, 18(5), pp.785–789.

Harr, R.D., 1976. *Forest Practices Stream flow In Western Oregon*, Portland, Oregon.

Harr, R.D., 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. *Journal of Hydrology*, 53, pp.277–304.

Harr, R.D., 1980. *Streamflow After Patch Logging in Small Drainages Within the Bull Run Municipal Watershed , Oregon*,

Harr, R.D., Fredricksen, R.L. & Rothacher, J., 1979. *Changes in streamflow folling timber harvest in southwestern Oregon*, Portland, Oregon.

Harr, R.D., Levno, A. & Mersereau, R., 1982. Streamflow changes after logging 130-year-old Douglas fir in two small watersheds. *Water Resources Research*, 18(3), pp.637–644.

Harr, R.D. & McCorison, F.M., 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resources Research*, 15(1), pp.90–94.

Harris, D.D., 1977. *Hydrologic changes after logging in two small Oregon coastal watersheds*,

Helvey, J., 1971. A Summary of rainfall interception by certain conifers of North America. In *Biological Effects in the Hydrological Cycle*. West Lafayette, Indiana: Third International Seminar for Hydrology Professors, pp. 103–113.

Hess, S., 1984. Timber Harvesting and Flooding. *Journal of Soil and Water Conservation*, 39(2), pp.115–117.

Hibbert, A.R., 1967. Forest Treatment Effects on Water Yield. In *International Symposium For Hydrology*. Asheville, North Carolina, pp. 527–543.

Hicks, B.J., Beschta, R.L. & Harr, R.D., 1991. Long-Term Changes in Streamflow following Logging in Western Oregon and Associated Fisheries Implications. *Water Resources Bulletin*, 27(2), pp.217–226.

Hubbart, J.A. et al., 2007. Timber harvest impacts on water yield in the continental/maritime hydroclimatic region of the United States. *Forest Science*, 53(2), pp.169–180.

ICC, 2007. Chapter 16 - Structural Design. *International Code Council, International Bulding Code*. Available at: http://publicecodes.cyberregs.com/icod/ibc/2012/icod_ibc_2012_16_par120.htm [Accessed May 2, 2016].

Ingwersen, J., 1985. Fog drip, water yield, and timber harvesting in the Bull Run Municipal Watershed, Oregon. *Journal of the American Water Resources Association, AWRA*, 21(3), pp.469–473.

Jennings, K. & Jones, J.A., 2015. Precipitation-snowmelt timing and snowmelt augmentation of large peak flow events, western Cascades, Oregon. *Water Resources Research*, 51, pp.7649–7661.

Johnson, R., 1998. The forest cycle and low river flows: A review of UK and international studies. *Forest Ecology and Management*, 109, pp.1–7.

Jones, J.A. et al., 2000. Effects of roads on hydrology, geomorphology, and distrubance patches in stream networks. *Conservation Biology*, 14(1), pp.76–85.

Jones, J.A., 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, Western Cascades, Oregon. *Water Resources Research*, 36(9), pp.2621–2642.

Jones, J.A. & Grant, G.E., 2001a. Comment on “Peak flow response to clear-cutting and road in small and large basins, western Cascades, Oregon” by J. A. Jones and G. E. Grant. *Water Resources Research*, 37(1), pp.179–180.

Jones, J.A. & Grant, G.E., 2001b. Comment on “Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion” by R. B. Thomas and W. F. Megahan. *Water Resources Research*, 37(1), pp.175–178.

Jones, J.A. & Grant, G.E., 1996. Peak flow responses to clear cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research*, 32(4), pp.959–974.

Jones, J.A. & Perkins, R.M., 2010. Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States. *Water Resources Research*, 46, pp.1–21.

Jost, G. et al., 2009. Use of distributed snow measurements to test and improve a snowmelt model for predicting the effect of forest clear-cutting. *Journal of Hydrology*, 376, pp.94–106.

Keppeler, E.T. & Ziemer, R.R., 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in Northwestern California. *Water Resources Research*, 26(7), pp.1669–1679.

King, J.G., 1989. *Streamflow responses to road building and harvesting: a comparison with the equivalent clearcut area procedure*,

Kramer, J., 2012. *Chehalis Basin Flood Hazard Mitigation Alternatives Report*,

Kuras, P.K., Alila, Y. & Weiler, M., 2012. Forest harvesting effects on the magnitude and frequency of peak flows can increase with return period. *Water Resources Research*, 48, pp.1–19.

LaMarche, J. & Lettenmaier, D.P., 2001. Effects of Forest Roads on Flood Flows in the Deschutes River , Washington. *Earth Surface Processes and Landforms*, 26, pp.115–134.

LaMarche, J. & Lettenmaier, D.P., 1998. *Forest Road Effects on Flood Flows in the Deschutes River Basin, Washington*, Seattle, Washington.

Lettenmaier, D.P., Harr, R.D. & Cundy, T.W., 1991. Effect of Forest Practices on Downstream Flooding in the Northwestern U.S. In *International Hydrology & Water Resources Symposium*. Perth, Australia: National Conferences Publication - Instutute of Engineers, Australia.

Lewis, J., Reid, L.M. & Thomas, R.B., 2010. Comment on “forest and floods: A new paradigm sheds light on age old controversies” by Younes Alila et al. *Water Resources Research*, 46, pp.1–4.

Lin, Y. & Wei, X., 2008. The impact of large-scale forest harvesting on hydrology in the Willow watershed of

Central British Columbia. *Journal of Hydrology*, 359, pp.141–149.

Luce, C.H. & Wemple, B.C., 2001. Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surface Processes and Landforms*, 26, pp.111–113.

Lundquist, J.D. et al., 2015. Diagnosis of insidious data disasters. *Water Resources Research*, 51(5), pp.3815–3827. Available at: http://apps.webofknowledge.com.offcampus.lib.washington.edu/full_record.do?product=WOS&search_mode=GeneralSearch&qid=1&SID=3CLnMtUrT9aJkk5cdqR&page=1&doc=1 [Accessed April 1, 2016].

Lundquist, J.D. et al., 2013. Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling. *Water Resources Research*, 49(10), pp.6356–6370.

Lundquist, J.D. & Dettinger, M.D., 2005. How snowpack heterogeneity affects diurnal streamflow timing. *Water Resources Research*, 41(5), pp.1–14.

Lundquist, J.D., Dettinger, M.D. & Cayan, D.R., 2005. Snow-fed streamflow timing at different basin scales: Case study of the Tuolumne River above Hetch Hetchy, Yosemite, California. *Water Resources Research*, 41(7), pp.1–14.

Macdonald, J.S. et al., 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. *Canadian Journal of Forest Research*, 33, pp.1397–1407.

MacDonald, L.H. & Coe, D., 2007. Influence of headwater streams on downstream reaches in forested areas. *Forest Science*, 53(2), pp.148–168.

Mackay, D.S. & Band, L.E., 1997. Forest ecosystem processes at the watershed scale: dynamic coupling of distributed hydrology and canopy growth. *Hydrological Processes*, 11, pp.1197–1217.

Marks, D. et al., 1998. The sensitivity of snowmelt processes to climate conditions ans forest during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, 12, pp.1569–1587.

McNabb, D.H., Gaweda, F. & Froehlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon. *Journal of Soil and Water Conservation*, 44(1), pp.87–90. Available at: http://www.jswconline.org/content/44/1/87.short [Accessed May 2, 2016].

Megahan, W.F., 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. *Water Resources Research*, 19(3), pp.811–819.

Mirus, B.B. et al., 2007. Simulated effect of a forest road on near-surface hydrologic response: redux. *Earth Surface Processes and Landforms*, 21, pp.126–142.

Moore, G.W. et al., 2004. Structural and compositional controls on transpiration in 40-and 450-year-old riparian forests in western Oregon, USA. *Tree Physiology*, 24, pp.481–491.

Moore, G.W., Jones, J.A. & Bond, B.J., 2011. How soil moisture mediates the influence of transpiration on streamflow at hourly to interannual scales in a forested catchment. *Hydrological Processes*, 25, pp.3701–3710.

Moore, R. & Wondzell, S.M., 2005. Physical Hydrology and the Effects of Forest Harvesting in the Pacific Northwest: a Review. *Journal of the American Water Resources Association*, 41(4), pp.763–784.

Musselman, K.N. et al., 2012. Influence of canopy structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest. *Agricultural and Forest Meteorology*, 161, pp.46–56.

National Weather Service, 2016. *National Weather Service Advanced Hydrologic Prediction Service: Chehalis River Near Grand Mound*, Available at: http://water.weather.gov/ahps2/hydrograph.php?gage=cgmw1&wfo=sew.

Neiman, P.J. et al., 2011. Flooding in Western Washington: The Connection to Atmospheric Rivers. *Journal of*

Hydrometeorology, 12, pp.1337–1358.

Perkins, R.M. & Jones, J.A., 2008. Climate variability, snow, and physiographic controls on storm hydrographs in small forested basins, western Cascades, Oregon. *Hydrological Processes*, 22, pp.4949–4964.

Perry, T., 2007. *Do vigorous young forests reduce streamflow? Results of up to 54 years of streamflow records in eight paired-watershed experiments in the H. J. Andrews and South Umpqua Experimental Forests.* Oregon State University.

Pike, R.G. & Scherer, R., 2003. Overview of the potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes. *BC Journal of Ecosystems and Management*, 3(1), pp.1–17.

Powell, D.C., 2012. *A stage is a stage is a stage... or is it? Successional stages, structural stages, seral stages*, Pendleton, Oregon.

Rodgers, C. & Walters, C., 2012. *Draft Chehalis River Basin Report, Forestland Section*,

Rothacher, J., 1970. Increases in Water Yield Following Clear-Cut Logging in the Pacific Northwest. *Water Resources Research*, 6(2), pp.653–658.

Rothacher, J., 1965. Streamflow from small watersheds on the western slope of the Cascade Range of Oregon. *Water Resources Research*, 1(1), pp.125–134.

Salemi, L.F. et al., 2012. Riparian vegetation and water yield: A synthesis. *Journal of Hydrology*, 454-455, pp.195–202.

Schnorbus, M. & Alila, Y., 2004. Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modeling. *Water Resources Research*, 40, pp.1–16.

Schnorbus, M. & Alila, Y., 2013. Peak flow regime changes following forest harvesting in a snow-dominated basin : Effects of harvest area, elevation, and channel connectivity. *Water Resources Research*, 49, pp.1–19.

Seibert, J. & McDonnell, J.J., 2010. Land-cover impacts on streamflow: a change-detection modelling approach that incorporates parameter uncertainty. *Hydrological Sciences Journal*, 55(3), pp.316–332.

Shafer, B.A., Jensen, D.T. & Jones, K.C., 1984. Analysis of 1983 snowmelt runoff production in the upper Colorado River basin. In *52nd Western Snow Conference*. pp. 1–11.

Storck, P. et al., 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. *Hydrological Processes*, 12, pp.889–904.

Storck, P. et al., 1995. *Implications of forest practices on downstream flooding: phase II final report*, Olympia, Washington.

Storck, P. & Bolton, S., 1999. Measurement of differences in snow accumulation, melt, and micrometeorology due to forest harvesting. *Northwest Science*, 73, pp.87–101.

Storck, P., Lettenmaier, D.P. & Bolton, S.M., 2002. Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research*, 38(11), pp.1–16.

Sullivan, K. & Sherwood, K., 1995. *Upper Skookumchuck Watershed Analysis*,

Surfleet, C.G. & Skaugset, A.E., 2013. The Effect of Timber Harvest on Summer Low Flows, Hinkle Creek, Oregon. *Western Journal of Applied Forestry*, 28(1), pp.13–21.

Tague, C. & Band, L., 2001. Simulating the Impact of Road Construction and Forest Harvesting on Hydrologic Response. *Earth Surface Processes and Landforms*, 26, pp.135–151.

Tague, C. & Grant, G.E., 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research*, 40, pp.1–9.

Thomas, R.B. & Megahan, W.F., 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. *Water Resources Research*, 34(12), pp.3393–3403.

Thomas, R.B. & Megahan, W.F., 2001. Reply. *Water Resources Research*, 37(1), pp.181–183.

Troendle, C.A. & Stednick, J.D., 1999a. Discussion "Effects of basin scale timber harvest on water yield and peak streamflow," by Timothy A. Burton. *Journal of the American Water Resources Association*, 35(1), pp.177–181.

Troendle, C.A. & Stednick, J.D., 1999b. Discussion: "Effects of basin scale timber harvest on water yield and peak streamflow" by Timothy A. Burton. *Journal of the American Water Resources Association*, 35(1), pp.1187–1196.

U.S. Army Corps of Engineers, 1968. *Flood Plain Information: Chehalis and Skookumchuck Rivers, Centralia-Chehalis, Washington*, Seattle, Washington.

U.S. Army Corps of Engineers, 1956. *Snow hydrology - Summary report of the snow investigations*, Portland, Oregon.

VanShaar, J.R., Haddeland, I. & Lettenmaier, D.P., 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. *Hydrological Processes*, 16, pp.2499–2520.

Varhola, A., Coops, N.C., Weiler, M., et al., 2010. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392, pp.219–233.

Varhola, A., Coops, N.C., Bater, C.W., et al., 2010. The influence of ground- and lidar-derived forest structure metrics on snow accumulation and ablation in disturbed forests. *Canadian Journal of Forest Research*, 40, pp.812–821.

Waichler, S.R., Wemple, B.C. & Wigmosta, M.S., 2005. Simulation of water balance and forest treatment effects at the H.J. Andrews Experimental Forest. *Hydrological Processes*, 19, pp.3177–3199.

Warner, M.D., Mass, C.F. & Salathé, E.P., 2015. Changes in winter atmospheric rivers along the North American west coast in CMIP5 climate models. *Journal of Hydrometeorology*, 16, pp.118–128.

Watson, D. & Adams, M., 2010. *Design for Flooding: Architecture, Landscape, and Urban Design for Resilience to Climate Change*, John Wiley & Sons.

Wayand, N.E. et al., 2013. Intercomparison of Meteorological Forcing Data from Empirical and Mesoscale Model Sources in the North Fork American River Basin in Northern Sierra Nevada, California. *Journal of Hydrometeorology*, 14(3), pp.677–699.

Wayand, N.E., Lundquist, J.D. & Clark, M.P., 2015. Modeling the influence of hypsometry, vegetation, and storm energy on snowmelt contributions to basins during rain-on-snow floods. *Water Resources Research*, 51, pp.8551–8569.

Wemple, B.C. & Jones, J.A., 2003. Runoff production on forest roads in a steep, mountain watershed. *Water Resources Research*, 39(8).

Wemple, B.C., Jones, J.A. & Grant, G.E., 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin*, 32(6), pp.1195–1207.

Whitaker, A., Alila, Y. & Beckers, J., 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. *Water Resources Research*, 38(9), pp.1–16.

Wigmosta, M.S., Nijssen, B. & Storck, P., 2002. The distributed hydrology soil vegetation model. In V. P. Singh & D. Frevert, eds. *Mathematical models of small watershed hydrology and applications*. Chelsea, Michigan: Water Resources Publications, pp. 7–42.

Zégre, N. et al., 2010. In lieu of the paired catchment approach: Hydrologic model change detection at the catchment scale. *Water Resources Research*, 46, pp.1–20.

Zhang, M. & Wei, X., 2014a. Alteration of flow regimes caused by large-scale forest disturbance: A case study from a large watershed in the interior of British Columbia, Canada. *Ecohydrology*, 7, pp.544–556.

Zhang, M. & Wei, X., 2014b. Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: Implications for forest management and future forest hydrology studies. *Hydrological Processes*, 28, pp.6183–6195.

Ziemer, R.R., 1964. Summer evapotranspiration trends as related to time after logging of forests in Sierra Nevada. *Journal of Geophysical Research*, 69(4), pp.615–620.

Attachment A: Confirmation Letter

CIVIL & ENVIRONMENTAL ENGINEERING
UNIVERSITY of WASHINGTON
College of Engineering

Dear Reviewers,

We thank the reviewers from the Quinault Indian Nation, the DNR, and Washington Forest Protection Association for providing insightful and constructive comments, as this feedback has helped us make this a clearer and stronger document. The following changes have been made:

- Explanation of and direct references to Washington State Forest Practices in the Washington Administrative Code (page 8 and 10).
- Recommendation for the evaluation of current forest practices (RMAPs) and their potential mitigation of streamflow effects through a controlled observational study (page 23, as well in the executive summary and conclusion)

In addition to the above, there are a few general changes to the paper that we would like all reviewers to be aware of. They are the following:

- Figure 1 has been updated (page 6), leading to an update in the % watershed area defined as snow-dominated and rain-snow transition (page 5).
- Figure 2 has been updated to reflect changes in Figure 1 (page 7).
- A new figure, Figure 4, has been added, which displays percent tree canopy cover over the entire basin (page 10).

Thank you again for your time and consideration of this literature review.

Sincerely,

Gwyneth Perry

Jessica Lundquist

R.D. Moore

Attachment B: Comments

Quinault Indian Nation

Quinault Indian Nation

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

May 26, 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 regarding the "Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin," Gwyneth Perry, Jessica Lundquist, and R.D. Moore (Review). We understand this Review was commissioned by Washington State Department of Ecology (Ecology) because of scoping comments recommending analysis of the hydrologic (flooding and low flow) effects of forest practices.

Overall, the QIN agrees with many of the conclusions in the Review, including that forest practices, defined here as forest harvesting and associated practices such as road building and site preparation, influence streamflow in multiple ways, including by: (1) changing rain and snow interception, which alters the timing and intensity of water input to the drainage network by rainfall and snowmelt, (2) modifying soil characteristics (e.g., compaction by skidders), which can potentially influence the amount of water that infiltrates the soil, (3) modifying hillslope flow paths by capturing subsurface flow in road ditches and conveying it more rapidly to a stream channel as surface flow, (4) changing transpiration rates. We agree, these individual processes do interact, with variations dependent on site-specific characteristics. More specifically, QIN agrees that forest harvesting increases soil moisture, due to decreased transpiration post-harvest, which can increase streamflow, which is exacerbated by rainfall and snowmelt. Additionally, forest roads can increase peak flows by intercepting subsurface flow and conveying it more rapidly to a stream channel.

We particularly agree with the recommendation of studying the combined effects of forest practices and climate change in a modeling framework and conducting an empirical time series analysis to relate streamflow variability and trends to climatic and land-use variables. While the results from such a modeling exercise would be useful in the short term, it is clear that Basin-specific qualitative research on forest hydrology is needed to inform reasonable recommendations regarding the proposed PEIS Alternatives. QIN sees limited value in a literature review and generalized conclusions about the impact of forest practices on hydrologic function in the Chehalis Basin provided in the context of the Draft PEIS without a focused, Chehalis Basin-specific analysis of in relation to the proposed PEIS Alternatives.

However, we take this opportunity to point out some short comings.

In short, the conclusions of the Review drawn from the literature review have limited utility in application without consideration of Basin-specific information. For example, while the Review concludes that the removal of the forest results in a hydrological immature condition that alters stream flows, it does not provide any information on how much timber removal results in this alteration. It notes that while hydrologic maturity is often defined at age 20, it also notes that hydrologic maturity had not been achieved at age 35 in one study.

Additionally, the Review recognizes the importance of considering forest roads while investigating the relationship between forest practices and streamflow in the Chehalis Basin, yet does not address the specific regulatory framework addressing roads. The Washington Department of Natural Resources (DNR), Road Maintenance and Abandonment Plans (RMAP) program is a regulatory system used to evaluate forest roads, identify areas that do not meet current forest practice rule standards, and schedule repairs that must be completed by 2021. WAC 222-24-050 & 222-24-051. Washington State Forest Practices rules require road drainage to be disconnected from the stream network and advocate land owners to divert the water on to the forest floor. WAC 222-24-010; and see Washington State Forest Practices Board Manual, Section 3. This is a key parameter that could affect qualitative analysis of issues such as soil moisture, peak stream flow, and overland flow. The Review also fails to recognize that the Forest Practices Rules do not limit logging by watershed, which can result in concentrated impacts when many areas in a given watershed are below the age of hydrological maturity.

Regardless of the regulatory frameworks applying to forest practices in the Basin, the most effective and appropriate analysis relies on consideration of on-the-ground conditions, including: a) road density (miles of road per square mile), b) connectivity (stream parallel roads, stream crossings, culverts, drainage), c) past instances of road failure including blocked culverts, none of which are included in the Review.

The Review does not consider the current trend toward shorter rotation ages and how timber rotation age affects this impact. The Review concludes that clearcut logging has been shown to alter peak flows and summer low flows in small watersheds, but the effects are not as well documented in larger watersheds based on the published literature. While it ascribes these affects to the land classed as hydrologically immature, it does not look at the amount of the watershed in a hydrologically immature condition necessary for the stream flow changes; nor does it put the potential changes into the context of 35-40 year rotations that seem to be more common now, versus 50 year timber rotations that were assumed when the watershed analyses prescriptions were written. On page 19 the Review notes data supporting a 53% recovery in hydrologic maturity at age 15-20 and a 73% recovery at age 30-35 based on data from Carnation Creek in British Columbia. Under this scenario, a 35 year rotation would never allow full recovery of hydrologic maturity on the landscape: the entire watershed would remain in a hydrologically immature state. Additionally, ideally the PEIS would analyze the predicted changes in the hydrograph due to hydrologically immature forests and the resulting changes in stream morphology, as well as fish habitat since the increase in frequency and magnitude of channel forming flows will alter fish habitat.

2.1 Climate and Streamflow Characteristics, Rain-on-Snow

To have greater utility, the actual effects of the rain-on-snow zone in the Chehalis Basin would need to be clarified given the apparent effects on flooding despite the small amount of acreage in the rain on snow zone.

More specifically,

> **Approximately 79% of the total basin area is comprised of rain-dominated lowlands (shaded light green in Figure 1). Snow accumulates mainly above 300 m (984 ft) and is transient between 300 and 900 m (984 – 2953 ft) (~20% of the total basin area, shaded light blue in Figure 1) (Rodgers & Walters 2012). . . Since there is a small area that accumulates snow, on average, *there is low risk of rain-on-snow (ROS) processes causing major flooding* in the Chehalis River Basin.**

2.1, at 6 (emphasis added).

The assertion that this statement makes of how the ROS "zone" is too small to cause major flooding is contradicted by the following statement that references actual ROS events:

> **ROS events are most common in both the snow-dominated headwaters and rain-snow transitional uplands of the Chehalis River Basin. *Storms centered on the uplands have been known to cause flooding in the downstream lowlands*, so the effects outlined may converge downstream.**

Section 3.2.1, at 15 (emphasis added). Additionally, the Review acknowledges climate changes, but does not address the manner in which current and projected changes in precipitation will affect low flows and their interaction with forest hydrology. The Reviews states that, **With climate change, the basin is predicted to experience an increase in peak flows, hotter and drier summers, and wetter winters (Burnett et al. 2014).** Page 7, 2nd Paragraph. Further research on climate change and forest hydrology is needed.

3. Hydrologic Effects of Forest Practices

The observation below raises the possibility that intercepted soil moisture may be directed into the channel faster. Reduced downslope soil moisture could then cause decreased summer flows. Application of such assessments to the greater Chehalis Basin landscape would be particularly useful given the importance of summer low flows to coho and the presence of numerous mid-slope roads..

> **For example, Tague and Band (2001) applied a spatially distributed model to Watershed 3 in the H.J. Andrews Experimental Forest in Oregon, and found**

that a mid-slope road reduced soil moisture downslope of the road, which in turn, reduced evapotranspiration.

4. Effects of Potential Mitigation

The review documents widespread agreement that forest practices increase the rate and quantity of runoff and stream flows. It would be helpful if the review discussed any study of potential mitigation for these impacts, such as increased rotation age, utilization of thinning regimes or smaller harvest areas, or limitations on logging and/or miles of road per watershed. Identifying studies of effective mitigation practices would assist in the PEIS' analysis of impacts of forestry and methods of reducing flood severity and frequency.

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

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

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

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

Comments on *Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin*, written by Perry et al.

Executive summary:

1-Need to qualify that the assessment of the literature did not include any contemporary rules, and is strictly based on limited forest practices. This is a major limitation of the study and its relevance to the Chehalis PEIS.

2-Use of the word “likely” and other statements that are more nuanced. I suggest “may” and “can” be substituted wherever it is stated that flow interception by roads increases peak flows. Current RMAP context should have been provided for emphasis on how this relationship has been reduced/avoided over time.

3-The last sentence needs to be removed.

Introduction

1-The purpose statement captured by item (2) was omitted. Instead, the focus was misplaced on the effects of forest harvest under legacy rules. Those legacies are the very reason the rules have changed.

Basin Description

p. 9, regarding road density. The statements about road density are misleading. RMAPs and contemporary forest practices mitigate these effects and need to be discussed for appropriate context.

Hydrologic Effects of Forest Practices

p. 10. Conveyance of flows from roads can enter the stream network directly or may be routed onto the forest floor. Both of these conditions need to be included and the statement that the conveyance is more rapidly conveyed as surface flow is a broad generality and reflective of past practices. Please see current rules and note effects of RMAPs on the very issues contained in this section.

p. 11. Slash burning should be noted as a practice that is almost non-existent. I would suggest removing the entire paragraph (full paragraph number 2) as it is not relevant and removal of slash burning throughout section should be considered (e.g., paragraph 3 with the topic of soil moisture). RMAPs and contemporary road drainage practices need to be included with the discussion of overland flow.

p. 15-16. Why was the ROS rule left out? It is implemented to avoid the effects discussed in the ROS section.

p. 17. Again, it is important to note that RMAP and contemporary practices target a reduction in the reported responses from legacy forest practices.

p. 18. You captured the literature well on this subject.

p. 19. Hydrologic recovery is an important component in current rules and should be discussed here. The HR discussed on this could be misleading in the statements about the detectability of the effects. Current research in western Washington conducted by CMER is looking at the HR, and will be able to better assess this response when the results are published over the next few years (Type N Hard Rock Study by W. Ehinger).

p. 20-21. Much of this section should be condensed and emphasis should be placed on the confounding variables that make it difficult to draw conclusions that there is a relationship between extreme events and forest practices. When context of contemporary practices, that relationship is next to impossible.

p. 22. A spatially explicit model like DHSVM is a good way to go (as suggested at the outset), but model inputs need to include contemporary rules and legacy effects in isolation and together in a heuristic sense to gain an appreciation for the potential differences.

Conclusions

p. 22. It is important to caveat that current rules were not considered in addressing the peak flow topics, roads, nor the response of the post-harvest environment to contemporary practices.

p. 23. Channel forming flows may not be altered due to forest practices. Legacies of wood removal, little or no buffers, improper BMPs with road construction, etc., have influenced channel characteristics and fish distribution and habitat. However, those practices led to improved rules and RMAPs that restore many of these functions back to uplands and headwaters in the Chehalis Basin (as well as the rest of the State). It is misleading to conclude the report without mention of the current practices.

Overall

The document reads fairly well, but the omission of contemporary rules and separating legacy effects from what is expected in the future is a mistake and misleading for the public.

Washington Forest Protection Association

WASHINGTON FOREST PROTECTION ASSOCIATION
724 Columbia St NW, Suite 250
Olympia, WA 98501
360-352-1500 Fax: 360-352-4621

May 25, 2016

Transmitted via Email

Chrissy Bailey
Department of Ecology
P.O. Box 47775
Olympia, WA 98504-7775
chrb461@ECY.WA.GOV

Subject: Comments on Draft Literature Review on the Potential Forest Practices on Stream Flow in the Chehalis River Basin

Dear Ms. Bailey:

The Washington Forest Protection Association (WFPA) appreciates the opportunity to comment on Draft Literature Review on the Potential Forest Practices on Stream Flow in the Chehalis River Basin ("Draft Review"). The Department of Ecology (Ecology) is currently considering comments on this draft 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.

As stated in the draft review, forest practices in Washington are regulated under a comprehensive system based on the Washington Forests & Fish Report (FFR). The FFR was developed in collaboration with federal, state, Tribes, county governments, and private forest landowners, and implemented through legislation. In 2001, the Forest Practices Board adopted new permanent forest practices rules to address impacts to aquatic species on all private forest lands not covered under an existing habitat conservation plan. In 2006, these forest practices rules were endorsed by the federal government through a statewide Forest Practices Habitat Conservation Plan (FP-HCP).

The FFR resulted in significant changes to existing regulations that improved forest roads and culverts, enlarged buffer zones along stream banks, and identified and protected unstable slopes. Considerable improvements were also made to forest practices permitting processes with the goal of preventing forest practices from causing an increased rate of landslide-related sediment delivery. Currently, topographic and geologic mapping provide landowners and the Department of Natural Resources (Department) with more accurate tools to predict where landslides may occur. An ongoing adaptive management program provides science and technical information to determine whether rules and/or guidance need to be adjusted to achieve resource goals and objectives. The Department has also established a compliance monitoring program to review on-the-ground implementation of the rules.

With that background, WFPA reviewers believe that the Draft Review is quite thorough and covers all of the major concerns with forest harvest and hydrology. We agree that a more basin specific study (modeling) will be required to assess the potential issues raised in the review. The Draft Review seems to be unbiased given the literature and accurate when it states “There is no agreement on whether or not forest harvesting causes significant increases in peak flows in large basins or extreme flow (flood) events.”

WFPA does have concern about the following conclusion: On page 23, the authors state “Forest practices alone likely lead to increased frequency of bankfull flow events in the uplands and headwater portions of the Chehalis River Basin. <u>This could be detrimental to fish habitat in these areas</u>.” (emphasis added). This conclusion is not supported by any citations or specific data. If the science supports the conclusion, the authors need to provide that information. If not, the conclusion needs to be modified or eliminated. The conclusion is also stated in slightly different terms on page 2.

We offer these comments in an attempt to improve the draft review. Thank you for your consideration. 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