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

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## 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 (~3.5% of basin area), rain-snow transitional uplands (~17.5% 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; changes to flows in this region only have local effects and will 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 $km^2$ (3.9 sq. mi)), 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. 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 implementation could be greatly improved if observational studies of the effects of these practices on streamflow were conducted first. 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", as well as 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. For the purposes of this review, the basin is divided into three hydrometeorologic regimes: snow-dominated headwaters, rain-snow transitional uplands, and rain-dominated lowlands.

## 2.1 Climate and Streamflow Characteristics

The Chehalis River Basin, encompassing approximately 7000 $km^2$ (2700 square miles), begins in the Willapa Hills, and draws from the Cascade Foothills, the Black Hills, 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 (~3.5% of total basin area), uplands (~17.5% 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.

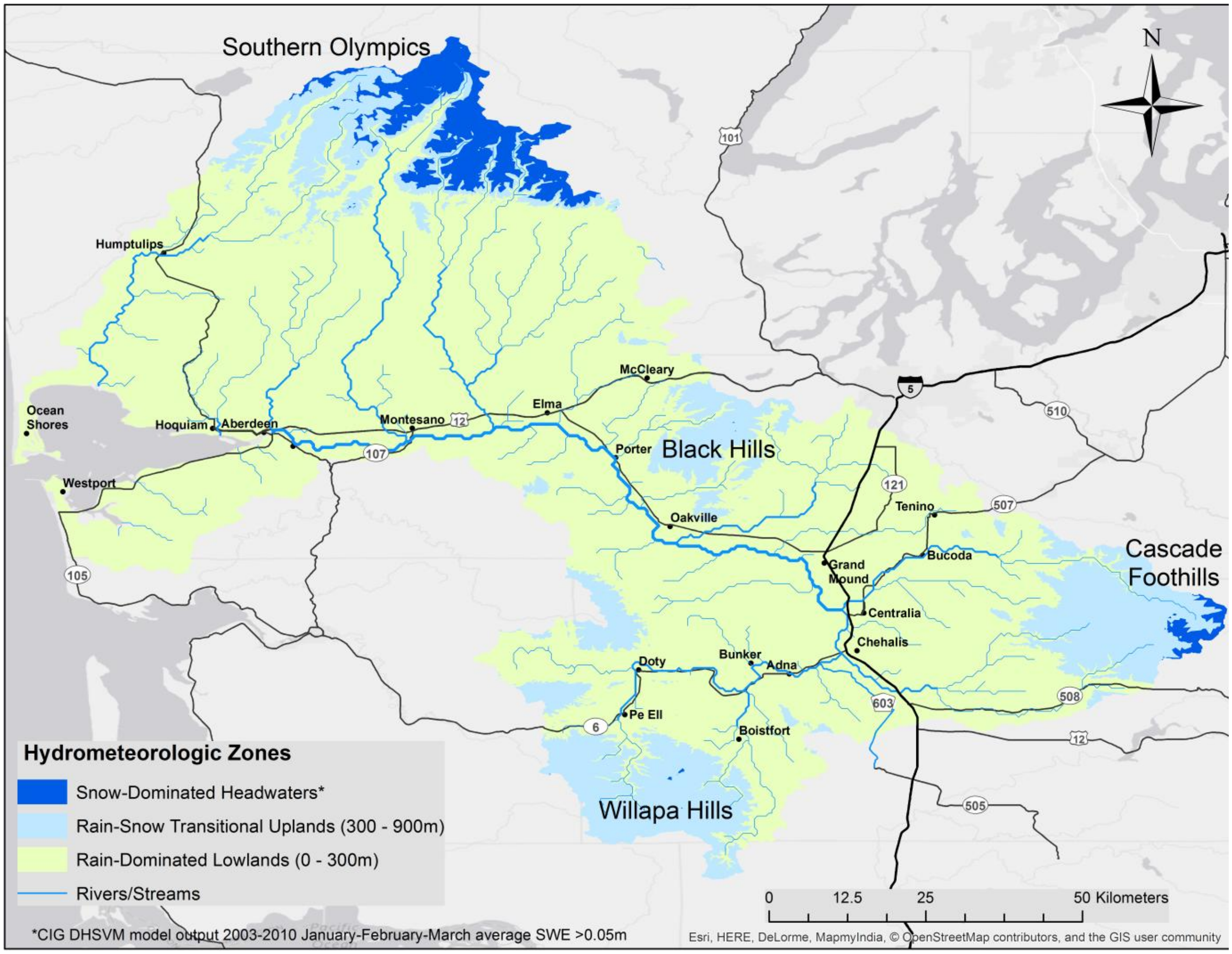


Figure 1. Chehalis River Basin Hydrometeorologic Zones. Snow-Dominated Headwaters are defined as areas with >0.05m snow water equivalent (SWE) on average for January-March, 2003-2010, calculated from outputs of a DHSVM model using WRF forcing data, performed by the University of Washington Climate Impacts Group.

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 on a regular basis. However, as was observed in the January 2009 flood, there is potential for snow to accumulate down to sea level and for the entire catchment to experience ROS on an infrequent basis. ROS is discussed further in section 3.2.

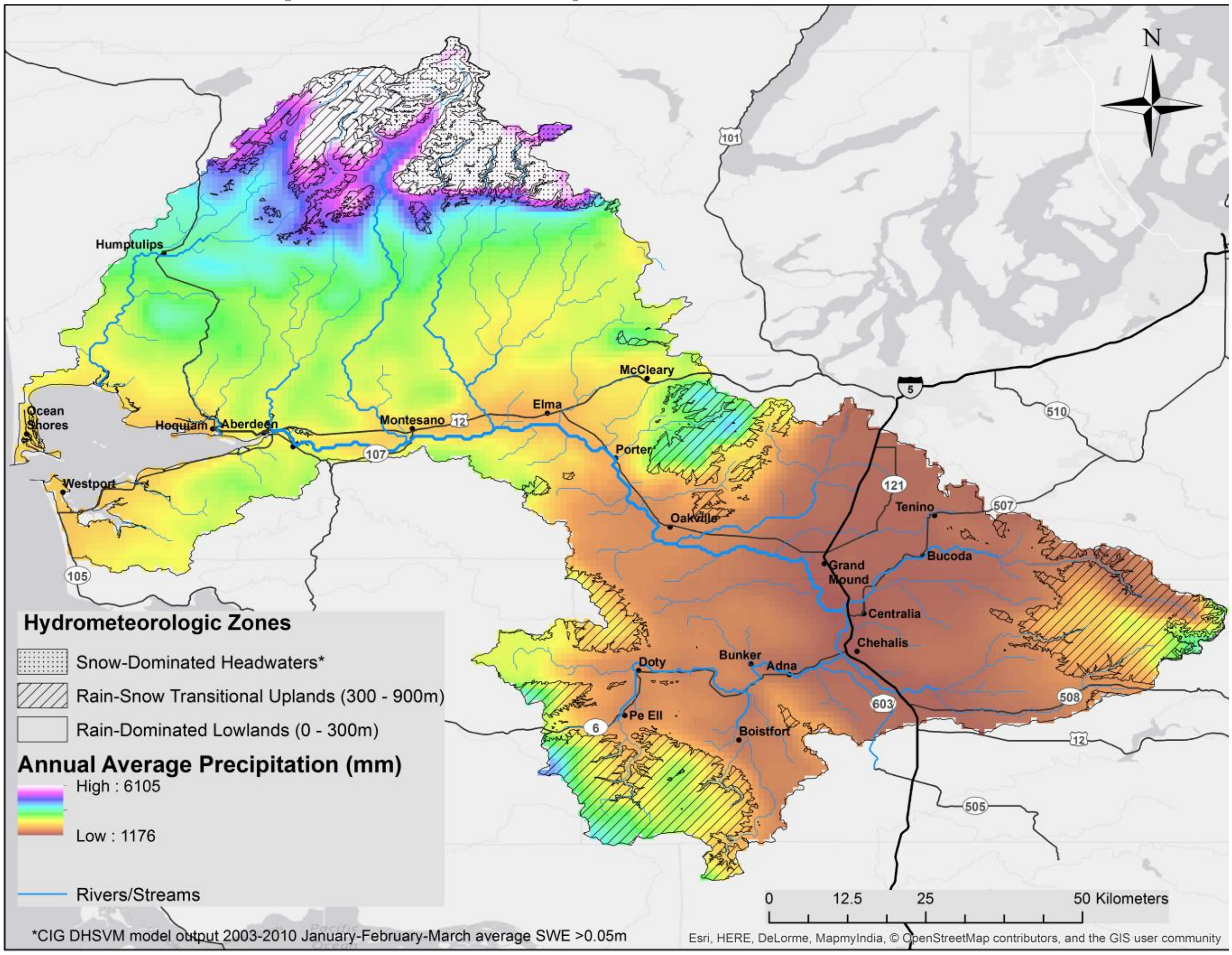


Figure 2. PRISM Annual Average Precipitation in the Chehalis River Basin (mm)[1]

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.

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

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 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) (see Figure 3). 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). Washington State Forest Practices rules limit clearcut size to under approximately 1 $km^2$ (240 acres), but there is no rule limiting total logging by watershed (WAC 222-30-025). Forestland in the Olympic National Forest may be subject to variable density thinning, a method used to accomplish restoration goals[2]. Figure 4 conveys a first order approximation of the amount of forest removed throughout the basin; 12% of the total basin area has less than 10% canopy cover, with average percent tree canopy cover at 73%, 70% and 62% in the snow-dominated, rain-snow transition, and rain-dominated zone respectively. Approximately 70% of the forests are in early to mid-seral[3] hydrologic maturity stage, with about 30% in the late-seral stage (Rodgers & Walters 2012; Batker et al. 2010), meaning most of the basin's forest stands are less than 40 years old (Powell 2012).

[2] http://www.fs.usda.gov/detail/olympic/landmanagement/resourcemanagement/?cid=stelprdb5369534
[3] 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)

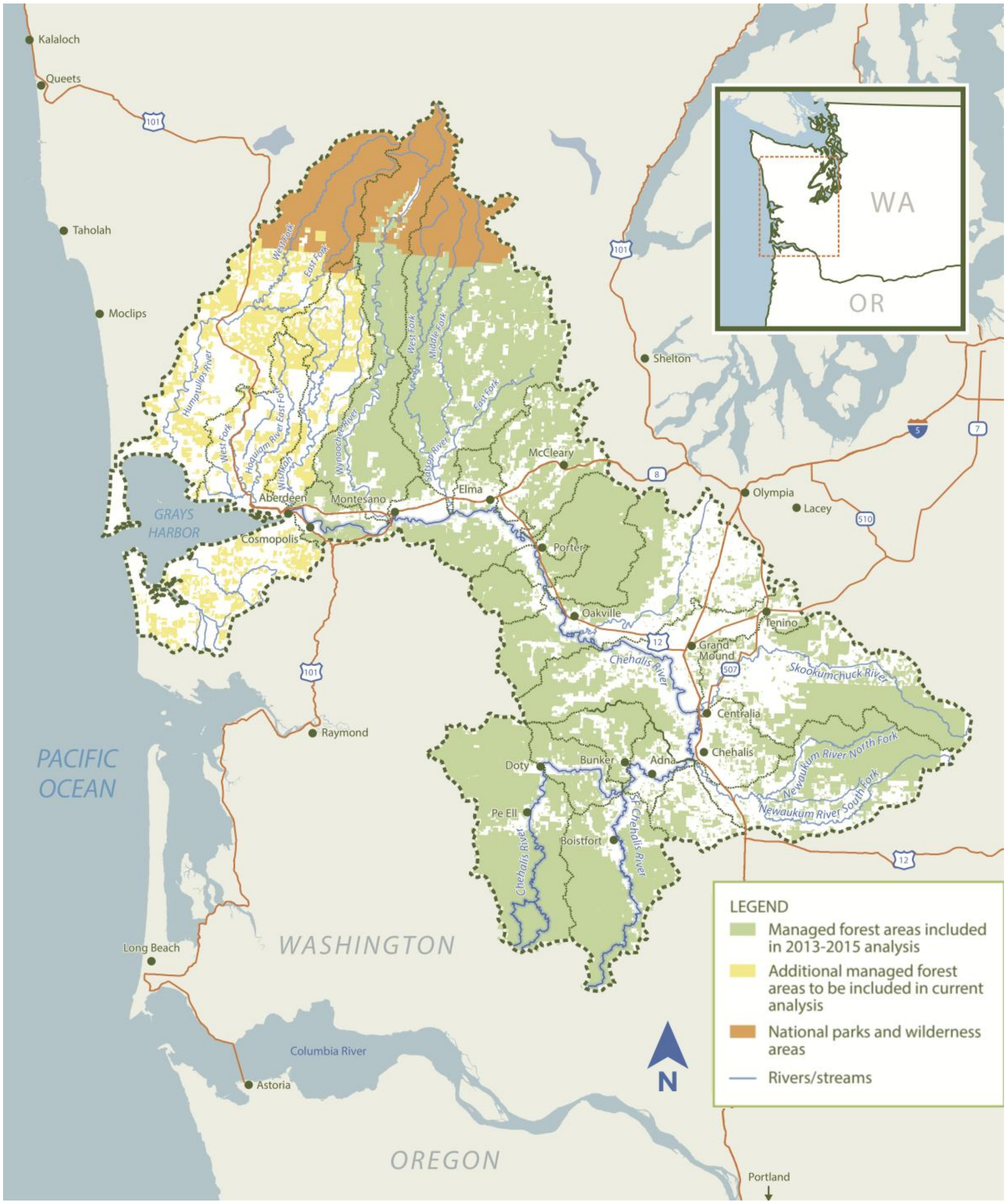


Figure 3. Chehalis River Basin Managed Forests (modified from original by Anchor QEA for Washington Department of Ecology Chehalis Basin Strategy)

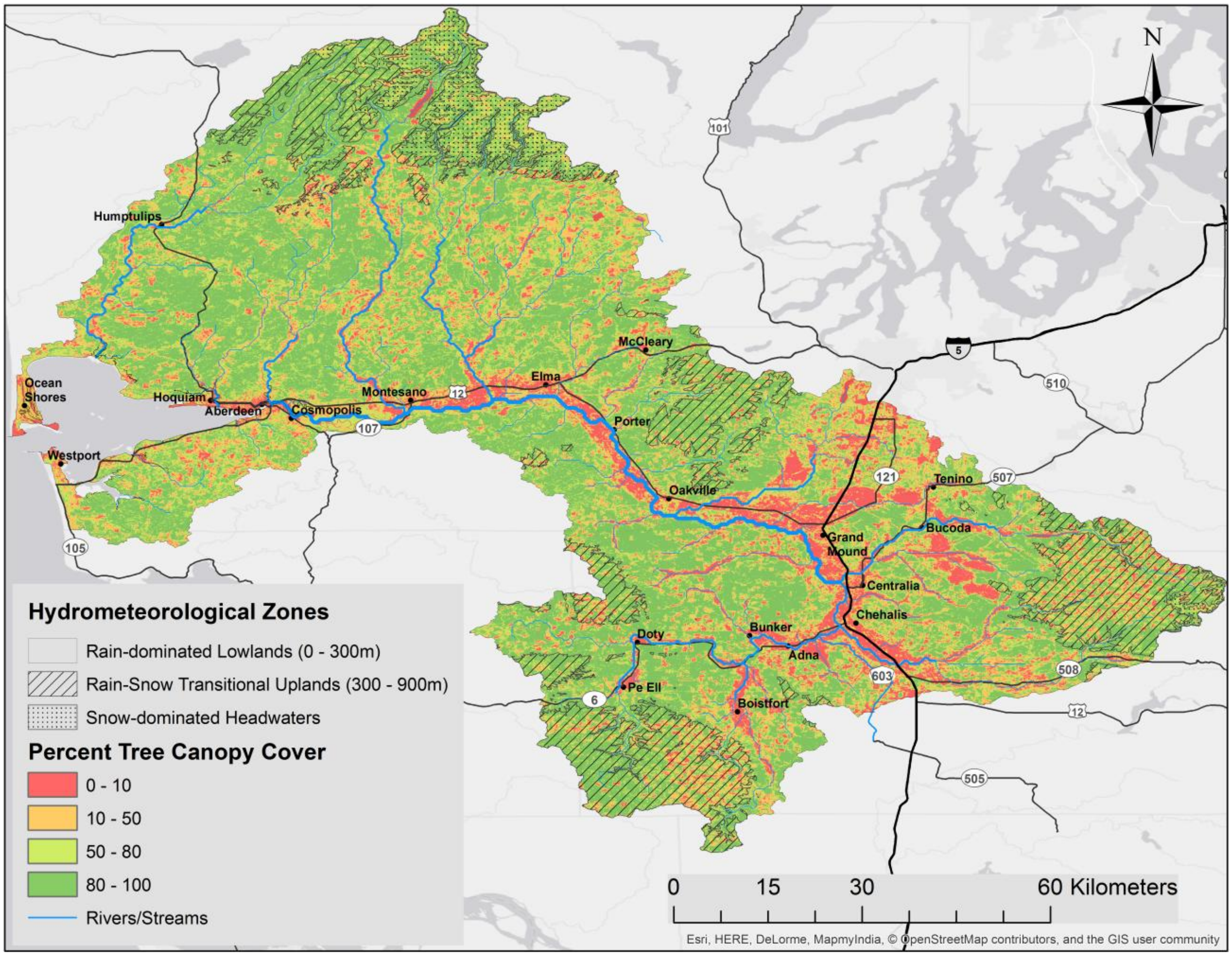


Figure 4. Percent Tree Canopy Cover in the Chehalis River Basin (30 m (98.4ft) resolution)[4]

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, following the Road Maintenance and Abandonment Plans (RMAPs) developed in 2001, with all roads in compliance by 2021 (WAC 222-24-050). Two rules pertaining to runoff from roads are 1) ditches must drain off onto the forest floor before reaching the stream, as close to but not within the 200 ft riparian forested buffer as possible (WAC 222-24-020), and 2) seeps and springs intercepted by roads must be returned to the forest floor as close to the point of origin as reasonably practicable (WAC 222-24-020). However, the objective of these rules is to reduce the sediment loading from road runoff to streams, and the ability of these rules to mitigate the potential increased flow from roads to streams has not been directly studied. Additionally, 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. Currently, forest roads west of the Cascade crest

[4] Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354

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.

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[5]. 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

[5] 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").

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 et al. 1991), resulting in decreased hydraulic conductivity and soil infiltration capacity (Startsev & McNabb 2011). 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 basin historically (Anon 1996) but are not currently a common practice, and are discussed here for completeness. 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 clearcut areas subjected to slash burning than in unburned clearcuts. However, even immediately following 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 1981; 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 hydrometeorologic 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, reducing the effect of the road on peak flows (Wemple et al. 1996). This re-infiltration of ditch flow is the goal of WAC 222-24-020 (see description in section 2.2).

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 hydrometeorologic 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 5 and described below.

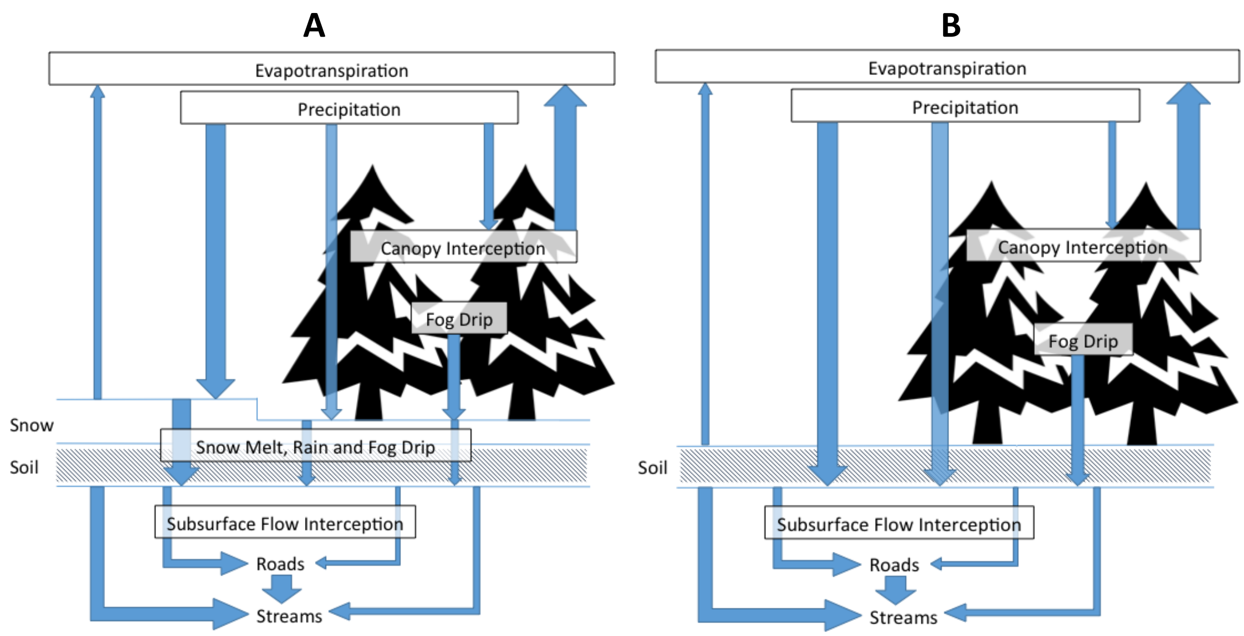


Figure 5. Hydrologic processes with snow (A) and without (B), with disparate dynamics between forest and open. Larger arrows denote larger fluxes of water.

***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 5A and described below. Overall, more snow accumulates, and subsequently lasts longer, in the open than in the forest, due to decreased interception.

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).

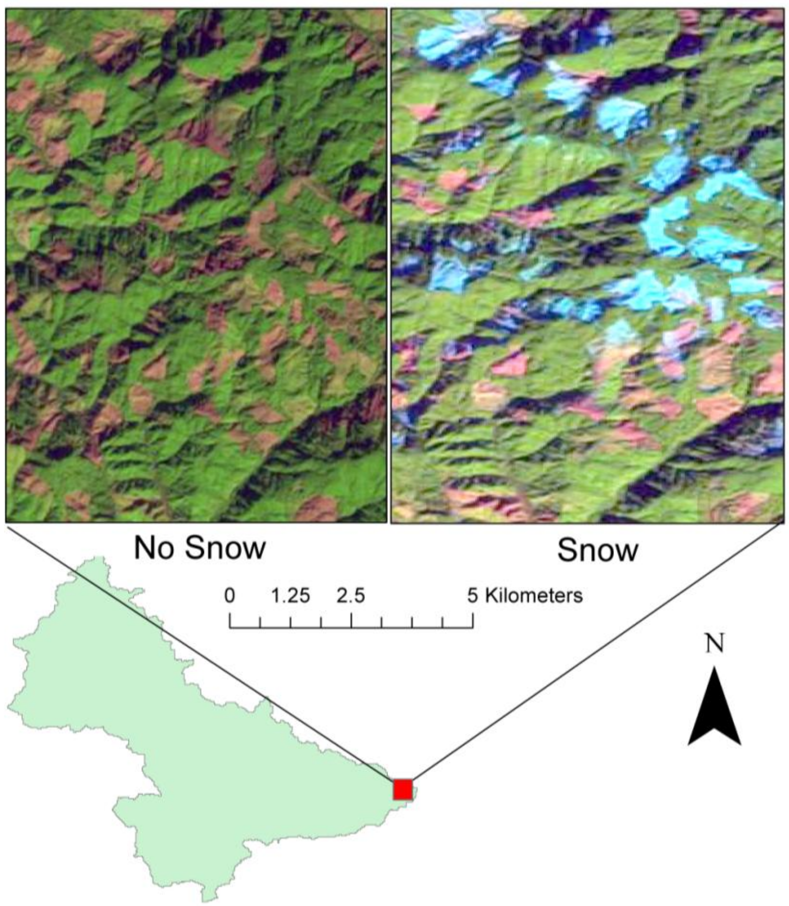


Figure 6. Landsat imagery of headwaters in the Cascade Foothills (~1000 m (3281 ft) elevation, applicable to about 3.5% of the basin), showing snow presence in clearcuts[6]. No snow image is from September 25, 2000, and the image with snow present is from January 15, 2001 (snow shown in blue).

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

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

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 6). 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 5A and described below.

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). When forests are removed, wind speed becomes more of 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 clearcuts (>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 5B.

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 composed 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 on a regular basis, 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 more likely to experience rain on snow. For comparison, only ~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)[7]. 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

[7] 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).

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.

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 major storm events in the Pacific Northwest, have quite a narrow focus (bands of rain ~400 km (249 mi) wide[8]), 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 clearcut) 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. However, because precipitation had a negative trend during this time period, it was difficult to assess whether changes in streamflow were due to the climate or forest cover change. This analysis did find significant effects 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

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

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). 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).

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 daily summer low flows range from insignificant to over 140% (8 mm (0.3 inch) per unit area). 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)[9] 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 unit by a factor calculated as 1 – HR/100, where HR is the hydrologic recovery of the harvest unit. Calculation of ECA requires that recovery curves be

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

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 harvest unit. 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.

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 Further Discussion of Effects of Forest Practices on Peak 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. Most analyses based on "chronological pairing" suggest that forest harvesting has little to no effect on high or extreme peak flows, whereas an analysis based on "frequency pairing" suggests that even extreme peak flows can increase following forest harvesting. Statistical inference regarding the more infrequent events is limited by the inherently small sample size available.

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 ($\alpha$ 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), but have little or no effect on the high and extreme peak flows (Grant et al. 2008). These near-bankfull flows move the most sediment over time, changing the stream channel gradually (Watson & Adams 2010). When these flows become more frequent, the channel may experience 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).

In the seminal paper that critiqued the chronological-pairing 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 simulated 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-dominated 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.

To provide a more definitive assessment of the effects of forest harvesting on Chehalis River streamflow, we recommend a controlled observational study, either within the Chehalis River Basin or within an experimental forest of paired watersheds, such as HJ Andrews, to compare runoff from an area following current forest practices vs. an area not in compliance. This study could evaluate the potential mitigating effect of current forest practices, including the 2001 rules pertaining to forest roads. Furthermore, the results of this study would be valuable for constraining parameters within a physically based model and thus reduce model uncertainty.

Despite the difficulties of interpretation 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. Increased flows alone can be detrimental to fish habitat in these areas, by changing the channel morphology and sediment composition (Chamberlin et al. 1991). 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. Model implementation of the effectiveness of forest management practices on mitigating hydrologic impacts could be greatly improved if observational studies of the effects of these practices on streamflow were conducted first.

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