Chapter 4

Water Quantity

Kevin Bladon and Jeff Behan

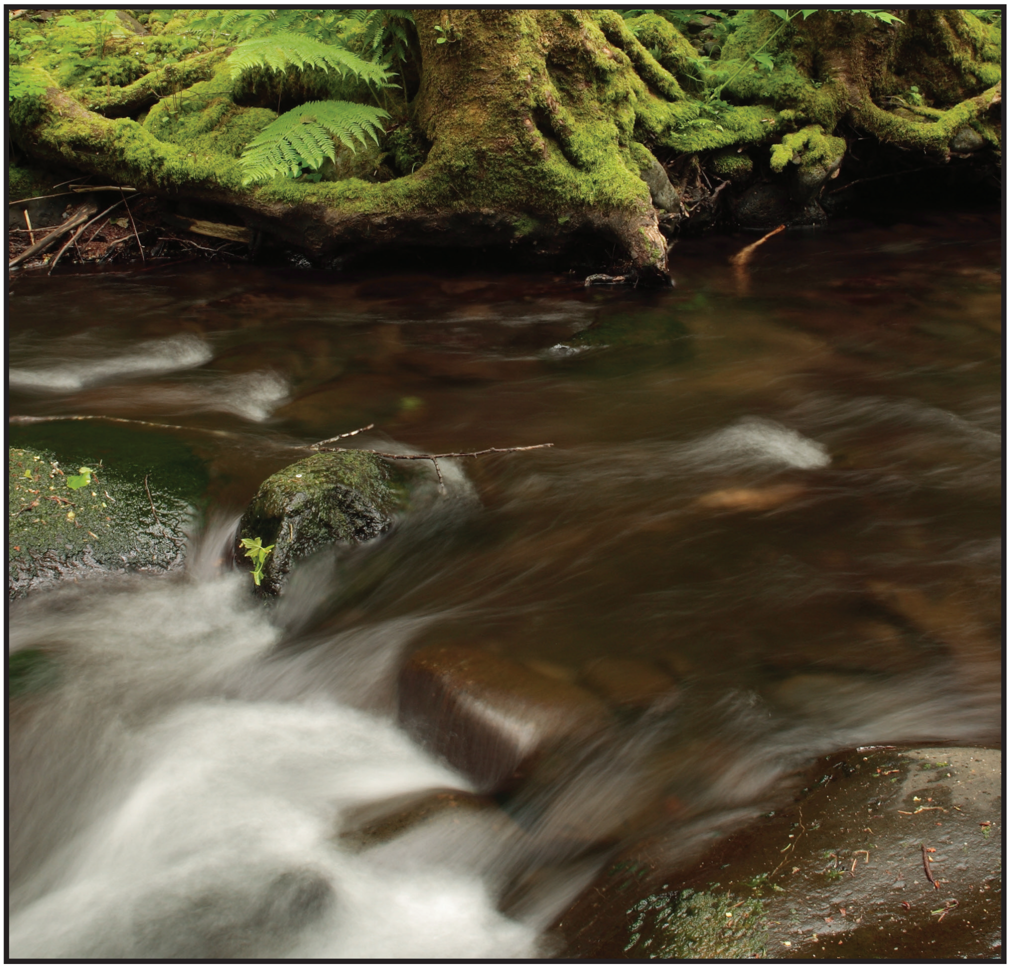


Photo: © Dreamstime

4.1. Introduction

Relationships between forest cover and type, forest management, and the quantity and timing of water produced by forested watersheds have been studied for at least 100 years (e.g., Bates and Henry 1928; Griffin 1918). Motivations for such research have included interest in how active management affects the ways that forested catchments capture, hold and deliver water to community water systems (Neary 2000). To provide a safe and secure water supply to communities, water providers are concerned about maintaining access to a consistent supply of raw water, but also in how episodic high flows and seasonal low flows respond to land use changes in their source watersheds.

In this chapter, we will discuss how active forest management affects water delivery in terms of annual yield of water; peak flows and flooding; low flows; and the timing of water runoff from forested watersheds.

4.2. Overview of literature reviewed

Many studies of the effects of active forest management on the quantity and timing of water delivered from forested watersheds were conducted when forest practices were different than they are today. How relevant is this older research to current practices? The effects of industrial forestry on sediment production and water quality have received more attention and been the focus of more significant changes in forest practices than have effects on water quantity and timing. For example, management practices for riparian areas — such as stipulations for leaving forested buffers along waterways — were modified in the 1970s and 1990s. Rules for forest road location, construction and use have also been revised several times, primarily focused on reducing sediment impacts.

Studies have repeatedly shown that changes in water delivery resulting from forest management are driven primarily by the percentage area of the watershed that was recently harvested. In Oregon, this variable was addressed in Senate Bill 1125 in 1991, and resulting changes to the Oregon Forest Practices Act in 1992 limited clearcuts on non-federal forestland to 120 acres. Adjacent areas in the same ownership cannot be clear-cut until new trees on the original harvest are at least 4 feet tall or four years old and the stand is "free-to-grow." Under these rules, an entire subwatershed can still be logged within a decade. Forest rules that affect the amount and timing of water produced have changed relatively little, especially in comparison to practices targeted toward sediment production. This suggests that older studies on linkages between forestry and water production still have some relevance under current practices.

This review is focused on research conducted since 2000 in the Pacific Northwest, including studies from Northern California to southwestern British Columbia. But research on relevant subtopics is often limited, so evidence is also drawn from older studies, synthesis papers and research from outside this geographic area.

4.2.1. Forest management and annual water yields

The hydrologic response to forest management activities (e.g., road construction, harvesting, post-harvest site preparation and silvicultural treatments) can be highly variable among watersheds due to catchment differences in forest type, soils, geology, topography, climate, hydrological regimes (e.g., rain-dominated, snow-dominated), and management approach (Stednick 2008). Forest management activities can affect hydrologic processes in several ways, including (a) decreased evapotranspiration, (b) decreased precipitation interception, and (c) increased snowpack accumulation due to decreased snow sublimation in the seasonal or transient snow zone (Jassal et al. 2009; Varhola et al. 2010; Hubbart et al. 2015; Winkler et al. 2015). These effects often lead to increased soil water content in the first few post-harvest years, especially during summer and early fall due to decreased transpiration (Harrington et al. 2013; Du et al. 2016). As a result, the deficit in soil water content necessary to exceed the soil field capacity to generate runoff is often reduced. In other words, less precipitation may be needed to produce hillslope runoff and streamflow. Thus, forest management practices often lead to increases in annual water yields and influence flow regimes for some time after harvest (Stednick 1996; Bowling et al. 2000; Brown et al. 2005).

In a recent forest hydrology textbook, Stednick and Troendle (2016) summarized concepts regarding relationships between annual water yield and forest management gleaned from several decades of paired catchment studies. They noted that increases in water yields after harvest are often not detectable unless the catchment (1) receives annual precipitation greater than about 450–500 milimeters and (2) has had at least 20% of the catchment area harvested. In areas that receive less precipitation, a decrease in forest cover will usually increase soil evaporation and transpiration by residual vegetation, rather than increasing net water yield from the basin. In rain-dominated areas, increased water yields after harvest are most prominent during late fall and winter when the soil moisture deficit from the drier summer months is being recharged. In the snow zone, increases usually peak during the late spring to early summer when melting snow recharges the soil moisture. South-facing slopes in the northern hemisphere generally have less dense vegetation and receive more solar energy than north-facing slopes. As a result, water yield increases are usually reduced on south-facing slopes. Compared to clearcuts, forest stands subject to partial cuts usually have less response to harvesting since increased water is used by the remaining vegetation.

Changes in annual water yield following timber harvest depend on the post-harvest climate and antecedent moisture conditions. Water yield response to a given precipitation event reflects soil moisture conditions just prior to the event. Precipitation on wetter soils generally results in greater water yield than will be generated from the same event falling on drier soils, and soils are typically wetter on logged watersheds. In drier forests, or during drier seasons, the difference in antecedent moisture content between forested and harvested catchments might be minimal as will be water yield responses. In wetter forests, differences in soil moisture conditions between forested and harvested catchments prior to a given precipitation event are usually greater, as are differences in water yield that occur in response. Water yield and changes in yield following timber harvest generally increase with increasing precipitation, especially when differences in antecedent soil moisture exist. Where rainfall is high, or when evapotranspiration is low (winter), differences in antecedent conditions for soil moisture between forested and harvested catchments may be attenuated, as will be the difference in water yield response. (Stednick and Troendle 2016.) It should be noted that considerable variability and some exceptions to most of these generalizations can be found in the literature.

Due to the importance of water yields for downstream water supply, aquatic ecosystem health and forest health, there have been several reviews synthesizing literature regarding the effects of forest management activities on annual water yields (Stednick 1996; Brown et al. 2005; Moore and Wondzell 2005). Moore and Wondzell (2005) focused on the rain-dominated regions of the Pacific Northwest and found that for each percentage of the catchment harvested by clear-cut and patch-cut harvesting, water yields increased up to 6 millimeters. They also showed that selective harvesting increased water yields up to 3 millimeters for each percentage of the catchment harvested. Those findings were similar to an older review by Bosch and Hewlett (1982), who found about a 40-millimeter increase in annual water yield per 10% reduction in forest cover after reviewing 94 experimental watersheds. Moore and Wondzell (2005) also showed that increases in water yield were more muted after forest harvesting in snow-dominated catchments, ranging from about 0.25 to 3 millimeters per percentage of catchment harvested. However, most studies reviewed have concluded that annual streamflow changes are generally not detectable until at least 15–20% of a catchment is harvested (Stednick 1996; Brown et al. 2005; Moore and Wondzell 2005). The majority of past reviews have also shown that increased annual water yields can persist for about 10–20 years, with the largest increases occurring during the wet period of the year; autumn and winter in rain-dominated regions. (Harr 1983; Keppeler and Ziemer 1990). Moore and Wondzell (2005) provide an important summary of research results regarding the effects of forest harvesting on annual water yields at the headwater scale (mean catchment area 0.62 square kilometers; range: 0.10–3.04 square kilometers) in the Pacific Northwest, which are relevant to many smaller water providers in Oregon. However, these findings may have less relevance for water providers with larger, basin-scale drinking water sources.

The majority of recent studies have also focused on contemporary forest harvesting effects on annual yield at the headwater catchment scale. For example, Zegre et al. (2010) assessed contemporary forest harvesting, based on the Oregon Forest Practices Act, in catchments ranging in area from 0.23 to 1.56 square kilometers. These results from the Hinkle Creek Paired Watershed Study (2004–2008) on the foothills of the west slope of the southern Oregon Cascades Mountains illustrated that about 9% of the post-harvest median model innovations (i.e., random noise component of the time series model) exceeded the 95% prediction intervals (Zegre et al. 2010). Statistically, this indicated that daily streamflow increased following harvesting, by as much as 31 millimeters for each model. Similar to previous studies, they also found the greatest seasonal increases occurred during winter (485 millimeters), followed by spring (146 millimeters), fall (114 millimeters), and summer (100 millimeters) (Zegre et al. 2010).

Winkler et al. (2017) investigated streamflow response to forest harvesting of two small (4.5 and 4.9 square kilometers), snow-dominated catchments on the Okanagan Plateau of British Columbia and found only a 5% increase in annual water yield after clearcutting of 47% of the logged watershed. However, they identified dramatic changes in the timing and magnitude of April-June streamflow. During spring runoff (April and May) average water yield increased by about 19–29% during the first seven years after harvesting. Winkler et al. (2017) indicated that such changes in runoff timing could increase the risk of channel destabilization during the snowmelt season, and water shortages early in the irrigation season.

Du et al. (2016) also illustrated an effect on water yield following contemporary forest harvesting of a 28-square-kilometer subcatchment in the Mica Creek Experimental Watershed in northern Idaho. However, in their study they parameterized a model (DHSVM) with 10 years (1998–2007) of data and ran a series of virtual experiments to assess various spatial and temporal patterns of forest canopy removal. Model simulations predicted increases in annual water yields of (a) 33% for gradual patch-cutting of 10% of the catchment area every six years, (b) 37% for the 50% forest removal scenario, and (c) 79% for the 100% clear-cut scenario (Du et al. 2016). Interestingly, model simulations also indicated the importance of the spatial location of the harvest within a catchment as annual water yields were about 4% greater if the upper half of the catchment was harvested rather than the lower half of the catchment (Du et al. 2016).

Abdelnour et al. (2011) applied the Visualizing Ecosystems for Land Management Assessments (VELMA) model to elucidate how hillslope and catchment-scale processes control stream discharge in the H.J. Andrews Experimental Forest. This work showed that streamflow response was strongly sensitive to harvest distance from the stream channel. Specifically, they found that a 20% clear-cut area near the catchment divide (average distance of 152 meters to the nearest stream channel) resulted in an average annual streamflow increase of 53 millimeters (4%). In contrast, a 20% clear-cut in the lowlands (average distance of 53 meters to the nearest stream channel) resulted in an average annual streamflow increase of 92 millimeters (8%).

These studies did not investigate the effects of forest harvesting at the larger basin scale, which would be relevant to larger community drinking water suppliers. Specifically, approximately 95 Oregon communities (about 47.5% of state population) have a surface water supply originating in a forested watershed > 10 square kilometers, with a state average of about 426.4 square kilometers and median area of 86.6 square kilometers (Oregon Department of Environmental Quality 2018). Thus, while not directly representative of the PNW, a recent study by Zhang et al. (2017) provides insights into the potential effects of forest harvesting on annual water yields at the large watershed scale. Zhang et al. (2017) studied the effects of forest harvesting in 6 snow-dominated watersheds in British Columbia, Canada ranging from 539–3,185 square kilometers. They showed an increase in mean annual yields of 21–60 millimeters in those large basins with a cumulative equivalent clear-cut area greater than 30%. Not surprisingly, the largest changes in mean annual water yields were observed in wetter years. Overall, the results were inconsistent with no changes in water yields after substantial forest harvesting activity contrasted with significant changes in mean annual water yields with relatively small areas of forest harvesting activity (Zhang et al. 2017).

In summary, existing research is fairly consistent in showing that clear-cut harvests can result in increases in annual streamflow, especially at smaller spatial scales that are most studied. These increases are typically highest just after harvest and then decline over the following decade or two as vegetation regrows. However, attempting to quantify harvesting effects on streamflow is time consuming and expensive, requiring long-term commitments from both researchers and landowners (Stednick and Troendle 2016). Study results vary considerably and are based primarily on research streams from a relatively small number of paired watershed study sites. Existing studies across the Pacific Northwest do not adequately reflect the broad range of climate, geology, topography and vegetation, which drive highly variable hydrologic processes in the region. As such, there are still substantial information gaps, especially at the larger basin scale, most relevant to larger water providers. Given the substantial uncertainty around reliable water supplies in the PNW in coming decades, it is critical to resolve some of this uncertainty through additional empirical and modeling research (Mateus et al. 2015; Vano et al. 2015).

4.2.2. Forest management and peak flows

Peak flows and floods have the potential to produce extensive and costly damage to the structure and function of headwater catchments and downstream infrastructure (Downton et al. 2005; Ashley and Ashley 2008; Tullos 2018). Historically, the PNW has experienced peak flows in the upper 90th and 99th percentile of the contiguous U.S. (O'Connor and Costa 2004). The majority of these large flood events have occurred during winter rain-on-snow events; however, further work is still needed to understand the relationship between rain-on-snow events and floods (McCabe et al. 2007; Jennings and Jones 2015). Regardless, recent research has projected that peak flow magnitudes may increase up to 30–40% in some higher elevation areas of the PNW, including the Cascade Mountains, Olympic Mountains, and Blue Mountains, due to the effects of warmer temperatures on snowpack dynamics (Safeeq et al. 2015).

Given the concerns about naturally occurring high-flow events, the effects of forest management activities on the occurrence and magnitude of peak flows and floods remains a contentious issue, which has led to repeated calls for the forest hydrology community to address (DeWalle 2003; Calder et al. 2007; Alila et al. 2009). The magnitude and occurrence of high-flow events may be influenced by many factors: (a) rapidly changing forest harvesting treatment types; (b) percent of catchment harvested; (c) road location and construction approaches; (d) site preparation; (e) slope stability; (f) vegetation species; (g) forest regrowth rates; and, the differential responses to precipitation across hydrologic zones (i.e., rain-, transient-snow, and snow-dominated)

(Jones and Grant 1996; Grant et al. 2008; Kuraś et al. 2012). As a result of the complex interactions between the many influential factors and the infrequent observations of high-flow events, accurate prediction and assessment of the effects of forest harvesting on peak flows remains a challenge (DeWalle 2003). Knowledge has accumulated and certain trends have been noted, but information gaps remain in the scientific community about the relationship between forest practices and peak flows.

Despite this uncertainty, regulatory agencies and land managers remain tasked with developing strategies to manage forests in ways that mitigate or avoid changes in peak flows. In the face of major revisions to regional-scale forest plans in the PNW, this provided the impetus for the most recent comprehensive review by Grant et al. (2008). The objective of that synthesis document was to provide guidance to forest managers and regulators for evaluating the potential risks of elevated peak flows associated with forest management. In their review, Grant et al. (2008) considered factors such as different forest harvesting treatment, presence of roads and catchment drainage efficiency.

Grant et al. (2008) found that increases in peak flows were generally smaller when a lower percentage of the catchment was harvested. The largest increases in peak flows associated with forest harvesting occurred in catchments that were clear-cut (i.e., 100% harvested). With decreasing harvesting intensity, increases in peak flows were highly variable, ranging from 0 to 40% in the rain zone and transient snow zone, and from 0 to 50% in the snow zone. Unfortunately, there was insufficient research available to assess how this variability in peak flow response may be related to different forest harvesting approaches.

Additionally, Grant et al. (2008) found that forest management activities had less of an effect on the larger, less-frequent peak flow events. While peak flows increased about 90% in harvested catchments over reference catchments during small storm events (recurrence interval less than one year), this effect tended to diminish as an approximate exponential function. This trend of an exponential decrease in peak flow with increasing storm magnitude was considered to be consistent from the site (< 10 square kilometers) to large basin scale (> 10 square kilometers to < 500 square kilometers).

Grant et al. (2008) also found that watersheds in the transient snow zone were more sensitive to the effects of forest harvesting on peak flows compared to watersheds in rain-dominated zones of the PNW. However, the transient snow zone was the hydrologic zone most studied historically. There was not enough research or data (i.e., a lack of modeling or field studies with > 50 % catchment harvested) to make interpretations about the effects of forest harvesting on peak flows in the snow zone.

Importantly for the current review, there were only a couple studies in the PNW investigating the effects of forest harvesting on peak flows at the larger basin scale (Jones and Grant 1996; Thomas and Megahan 1998), which would be most relevant to community drinking water supplies. As such, the results from the Grant et al. (2008) review may only be directly relevant to about 23 Oregon communities (about 3.7% of the state population), which rely on surface water from forested watersheds with an area < 10 square kilometers. For comparison, approximately 95 Oregon communities (about 47.5% of state population) have a surface water supply that originates in a forested watershed > 10 square kilometers, with a state average of about 426.4 square kilometers and median area of 86.6 square kilometers (Oregon Department of Environmental Quality 2018).

The lack of research at the larger basin scale creates uncertainty about how to interpret research results from the small catchment scale. Despite this, Grant et al. (2008)

suggest that elevated peak flows in headwater catchments due to forest management activities are most likely to diminish with increasing basin size. The principal theories supporting the idea that peak flows diminish at the downstream basin scale, include: (a) floodplain storage, (b) transmission losses into the alluvial material of the streambed, (c) channel resistance, (d) low likelihood of sub-catchment peak flow synchrony, and (e) the proportion of basin area disturbed generally decreases with increasing basin size (Archer 1989; Shaman et al. 2004; Calder and Aylward 2006). However, the role of these different factors at attenuating peak flow magnitude at the basin scale is likely to differ depending on specific catchment characteristics, including valley width, channel morphology and complexity, stream slope, hydraulic roughness (e.g. large woody debris), amount of wetlands, and precipitation event characteristics (Woltemade and Potter 1994). As such, additional research on the scaling of peak flows from small headwater catchments to larger river basins is needed to resolve this issue.

Another consideration is that all 21 of the paired catchment studies reviewed by Grant et al. (2008) investigated effects from forest harvesting that occurred from the 1950's to the 1990's. Forest harvesting and best management practices have continued to evolve in the 21st century (Cristan et al. 2016), but there is insufficient research to determine if, or the degree to which, current forest practices may have modified the effects of harvesting on peak flows, compared to past practices. For this review we have searched the literature for research not included in previous reviews and relevant to the PNW. Unfortunately, there have been few studies investigating the effects of contemporary practices on peak flows, especially at the large basin scale.

Jones and Perkins (2010) analyzed more than 1,000 peak-flow events that occurred in the western Cascades of Oregon from 1953 to 2006. Their study sites included data from six small catchments (0.09–1 square kilometers) and six large basins (60–600 square kilometers) covering the transient snow and permanent snow zones. Their findings were mostly consistent with previous research, illustrating that forest harvesting generally had the greatest effect on the smaller, more frequent (less than one-year return interval) peak-flow events. However, they did observe an increase (about 10%–20%) in the magnitude of large peak flows (more than one-year return interval) during rain-on-snow events in the transient and seasonal snow zones. While this is consistent with previous research showing that the largest peak-flow events were associated with rain-on-snow events, their observation of the potential synchronization of peak flows in the small catchment scale illustrates the potential for large floods at the large basin scale associated with forest harvesting (Jones and Perkins 2010). The Jones and Perkins (2010) study represents a new analysis of data not included in a previous review of peak-flow effects; however, the study still relies on data from catchments harvested in the 1960's and 1970's.

Similarly, Du et al. (2016) used 10 years (1998–2007) of data from the upper sub-catchment (28 square kilometers) of the snow-dominated Mica Creek Experimental Watershed in northern Idaho to parameterize the Distributed Hydrology Soil-Vegetation Model (DHSVM). They used the model with this data to simulate clear-cut harvesting of the entire watershed, which predicted about a 68% increase in peak flows (fifth percentile flows). They also ran scenarios with 50% vegetation removal and a gradual patch-cut of about 10% of the catchment. These two scenarios also predicted increases in peak flows of about 19% and 16%, respectively. Interestingly, the modeling exercise by Du et al. (2016) also indicated that forest harvesting away from the outlet or stream channel could produce larger peak flows during snowmelt. They attributed this result to a synchronicity of melt between the high and low elevations, which is consistent with historical research in snow-dominated catchments (Troendle and King 1985). Specifically, the modeling scenarios suggested that harvesting of the upper portion (higher elevation) of the catchment would increase peak flows about 9 % more than scenarios where forest harvesting occurred on the lower portion (lower elevation) of the catchment (Du et al. 2016).

Green and Alila (2012) argued forcefully for a "paradigm shift" from generally accepted methods of comparing floods by equal meteorology or storm input (chronological pairing) to a flood frequency distribution framework (frequency pairing). They maintained that chronological pairing approaches in paired watersheds have yielded inaccurate results that underestimate forestry effects on large flood frequency. Green and Alila (2012) and related work (Kuraś et al. 2012; Schnorbus and Alila 2013) in a low elevation, snow-dominated system in British Columbia found that forest harvesting may substantially increase the frequency of the largest floods. These studies have been contentious within the forest hydrology community, but nonetheless may have relevance for understanding the effects of forest harvesting on peaks flows in the seasonal or permanent snow zones in the PNW and are discussed in more detail below.

Kuraś et al. (2012) used data from a harvested catchment in Penticton, British Columbia to evaluate three modeling scenarios of increasing area harvested (20%, 30%, and 50% clear-cut). The study catchment (241 Creek) was small (4.74 square kilometers), high elevation (1600–2025 meters), and snow-dominated with mature lodgepole pine (*Pinus contorta* Dougl.) and small amounts of Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt). The model results predicted greater effects with increasing catchment area harvested, with an increase of about 9–25% for peak flows with recurrence intervals of 10–100 years after 50% of the catchment was harvested (Kuraś et al. 2012). Key findings from the model simulations by Kuraś et al. (2012) were (a) an increase in peak flows of all sizes after forest harvesting; and, (b) a greater effect on the larger, less frequent peak flows relative to the smaller, more frequent peak flows. These findings are counter to the majority of current forest hydrology literature (Beschta et al. 2000; Troendle et al. 2001; Moore and Wondzell 2005; Birkinshaw et al. 2011).

Similarly, Schnorbus and Alila (2013) used data from the small (4.7 square kilometers), reference catchment (240 Creek) from the same study to model the effects of 11 hypothetical forest harvesting scenarios on peak flows. Again, the model suggested that annual peak-flow magnitude would increase with increasing area harvested, with a threshold of about 20%–30% of catchment area harvested to produce a demonstrable effect on peak flows. Additionally, the model projections from Schnorbus and Alila (2013) were also counter to the majority of past paired-catchment research, indicating a "relative increase in peak annual discharge occurs consistently across the full range of return periods." Schnorbus and Alila (2013) also showed increases in peak flows if forest harvesting occurred in the lower elevation bands of the catchment, which they attributed to greater channel drainage density and increased runoff efficiency at the lower elevations. This important finding of catchment physiographical control over the peak flow response to forest harvesting likely requires additional research in other regions.

More recently, Yu and Alila (2019) adapted the frequency pairing approach to account for "nonstationarities" contained in peak flows that are caused by continuous harvesting and forest growth. Their nonstationary frequency pairing method for evaluating harvesting effects allowed the parameters of peak flow frequency distributions to change in time using physically based covariates. The method was demonstrated in the 37 square kilometers Camp Creek (harvested) and 41 square kilometers Greata Creek (reference) watersheds in the same Okanagan Valley, British Columbia study area utilized by Green and Alila (2012). Yu and Alila (2019) found that both small (return periods less than 10 years) and large (return periods greater than 10 years) peak flows are highly sensitive to harvesting in the midelevation, south-exposed slopes of this snow-zone watershed. They contend that their nonstationary frequency pairing method is advantageous because it: (a) bypasses the need for the calibration equation traditionally used in paired watershed studies, and thus some associated sources of uncertainty; (b) enables use of longer peak flow records by explicitly accounting for physical causes of the nonstationarities, and thus more explicit inferences about effects of harvesting on the larger peak flows; and, (c) allows estimation of harvesting effects on peak flows at different points during the disturbance history of a watershed, thus providing a direct evaluation of hydrologic recovery.

Alila and his colleagues (Alila et al. 2009; Green and Alila 2012; Kuraś et al. 2012; Schnorbus and Alila 2013) acknowledge that their results run counter to prevailing wisdom in hydrological science (i.e., that the effect of forest harvesting must always decrease with an increase in flood event size). These authors attribute the effects they found to increased net radiation associated with conversion from longwave-dominated (infrared) snowmelt beneath the canopy to shortwave-dominated (visible and ultraviolet light) snowmelt in harvested areas, amplified or mitigated by basin characteristics such as aspect distribution, elevation range, slope gradient, amount of alpine area, canopy closure and drainage density. Their work spurred disagreement regarding the use of chronological pairing and frequency pairing approaches (Alila and Green 2014a; Alila and Green 2014b; Bathhurst 2014; Birkinshaw 2014) echoing similar debates over methods and statistical approaches among Jones and Grant (1996), Thomas and Megahan (1998) and Beschta et al. (2000).

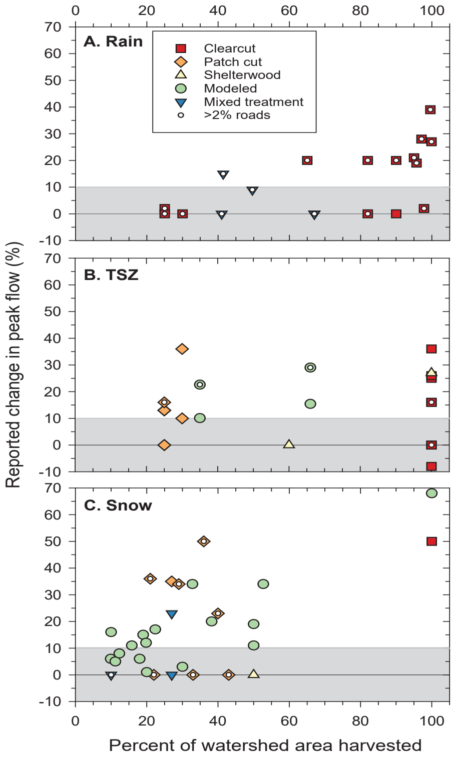


Figure 4.1. A summary of literature findings on the relationship between percent catchment harvested and percent change in peak flows in the (a) rain-dominated zone, (b) transient snow zone, and (c) snow-dominated zones of the Pacific Northwest. Symbol shapes and colors indicate the type of harvesting scenario. Figure modified from Grant et al. (2008) to include additional studies since that publication.

A persistent challenge that contributes to these disagreements is that as peak-flow size increases, frequency of occurrence decreases, so the number of observations and resulting statistical power regarding the largest events are usually limited. In these situations, trends detected and conclusions made can vary substantially depending on methodological and statistical approaches used, even with the same underlying data. While much of the current literature agrees with historical studies that forest harvesting can increase the magnitude of peak flows (Figure 4.1), the majority of research has remained focused on small catchments (less than 10 square kilometers) (Perry et al. 2016). Additionally, existing studies across the Pacific Northwest do not adequately reflect the broad range of climate, geology, topography and vegetation, which drive highly variable hydrologic processes in the region. Moreover, assessing the cumulative effects of legacy impacts from historical forest management activities along with recent or proposed harvesting activities remains a challenge (Perry et al. 2016). Observations have continued to be variable, leading to vigorous debate focused on the analytical approach to quantitatively assessing relatively rare events with few observations (Alila et al. 2009; Lewis et al. 2010). As such, there remain gaps in our understanding of whether forest management activities influence peak flows at a scale relevant to larger downstream drinking water utilities.

Theoretical arguments have been made that peak flows in forested headwaters are unlikely to appear as integrated effects at larger basin scales (Grant et al. 2008; Perry et al. 2016). However, this is not certain as there have been observations in interior British Columbia of peak-flow effects from forest harvesting at the large watershed scale (Lin and Wei 2008; Zhang and Wei 2014). Uncertainties around predicted peak-flow responses to forest harvesting are not likely to be definitively resolved without longer-term research that captures data on these relatively infrequent events in a broader range of managed forests and at larger basin scales.

4.2.3. Forest management and low flows

Low flows, which generally occur in late summer or early autumn, are increasingly of interest in the Pacific Northwest due to a greater occurrence of dry years (Mantua et al. 2010; Arismendi et al. 2013; Luce et al. 2014). Recent evidence suggests declining low flows and a lengthening in duration of the annual low-flow period (Luce and Holden 2009; Leppi et al. 2012). Similar to the preceding subsections, most research on low flows has occurred at the small, headwater catchment scale, and primarily focused on concerns about summer stream temperature and aquatic habitat (Harr and Krygier 1972; Keppeler and Ziemer 1990; Stednick 2008). Research has not yet encompassed a broad range of geology, soils, topography, climate or land uses, which all exert controls on low flows (Johnson 1998; Tague and Grant 2004). Much of the research comes from studies investigating older forest practices, (Rothacher 1970; Harr et al. 1979; Bowling et al. 2000). There remain knowledge gaps around the effects of forest management activities on low flows, especially at large basin scales.

Regardless, there is general agreement in the literature that in small catchments, forest harvesting results in increased low flows in the first 5–20 years after harvesting, but can shift to low flow deficits in the longer term (Moore and Wondzell 2005; Surfleet and Skaugset 2013). This is the case for both rain- and snow-dominated regimes in the Pacific Northwest, where low flows have been shown to increase initially after forest harvesting as a result of decreased interception and evapotranspiration leading to increased soil moisture (Figure 4.2) (Rothacher 1965; Harr et al. 1982; Keppeler and Ziemer 1990; Bowling et al. 2000).

In a recent literature review on the potential effects of forest practices on streamflow in the Chehalis River Basin (6,993 square kilometers), Perry et al. (2016) concluded that low flows in that region may increase for about 5–10 years after harvest. However they also found a broad range of low-flow changes, from insignificant to more than 140% increase, with evidence of low-flow deficits over time as sites revegetated (Ingwersen 1985; Fowler et al. 1987; Adams et al. 1991; Pike and Scherer 2003; Salemi et al. 2012). This latter finding was related to higher rates of transpiration from young, vigorous forests compared to older, mature forests (Moore et al. 2004; Moore et al. 2011). Perry et al. (2016) provide insights into the potential range of effects of forest harvesting on low flows, while noting that the results from the literature reviewed were basin-specific. Additionally, they note the lack of large-scale paired basin studies, principally attributed to the difficult challenge of establishing a true reference given that most large basins

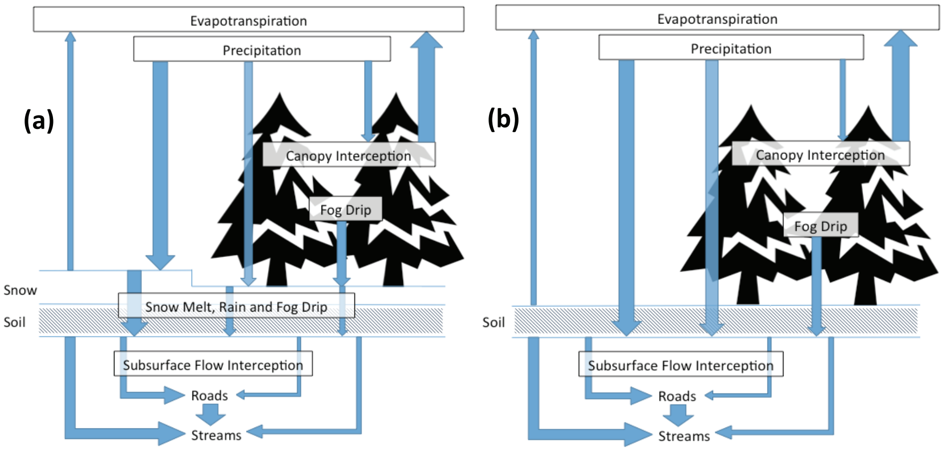


Figure 4.2. Hydrologic processes affected by forest harvesting relative to forested sites in (a) snow-dominated regimes and (b) rain-dominated regimes. Arrow widths denote the relative fluxes of water in each process in harvested compared to unharvested sites. From Perry et al. (2016).

have experienced or will experience some forest harvesting activity (Perry et al. 2016). Some inferences can be made on the basis of smaller-scale studies, but there is a paucity of direct evidence regarding the effects of forest management activities on low flows at the large basin scale.

In the western Cascades of southern Oregon, Surfleet and Skaugset (2013) also observed an increase in summer (August) low flows of about 45% (1.9 millimeters per year) for three years after harvesting of about 13% of a 10.8 square kilometers catchment. More specifically, summer low flows increased by 106% (4.5 millimeters) in the first summer and 47% (2.0 millimeters) during the second summer. However, the effects of forest harvesting on summer low flows were not distinguishable five years after harvesting in all catchments except for the one with the greatest proportion of area harvested. Given the short duration and small spatial scale of the study, it is uncertain whether low-flow deficits occurred in these catchments later as the forest revegetated or whether effects were observable at a larger, basin scale. Regardless, results from this study are consistent with historical research in the same region of southwest Oregon, which showed a 44% increase in summer low flows (Harr et al. 1979). The results are also consistent with model simulations using data from Watershed 10 (WS10) of the H.J. Andrews, which illustrated that the largest relative increases in streamflow after harvesting occurred during the summer low flow period (Abdelnour et al. 2011).

Over the past 20 years, an increasing amount of research has focused on how regenerating forests affect summer low flows for a longer period after harvest (i.e., several decades) when the new stand is fully re-established and growing quickly. Moore et al. (2004) showed that younger, vigorous stands use more water than adjacent older stands, which they attributed primarily to tree age and, to a lesser degree, differences in sapwood basal area and finally species composition. In three small watersheds in southern interior British Columbia, Gronsdahl et al. (2019) found that summer flows were reduced starting about 20 years after the onset of forest harvesting, which they surmised was a result of regenerating forests transpiring more water than the mature forests they replaced.

In a rigorous analysis of 60 years of daily streamflow data from eight paired watersheds in the seasonal snow zone of the Pacific Northwest, Perry and Jones (2017) showed that summer low flows were lower in young, vigorously growing stands compared to older adjacent stands. In particular, they showed that about 15 years after forest harvesting and establishment of Douglas-fir plantations, summer streamflows were in a deficit, which persisted and intensified for about 50 years (Perry and Jones 2017). The average daily streamflow during the summer (July through September) was about 50% lower in catchments with 34- to 43-year-old plantations compared to reference catchments with 150- to 500-year-old forests. This persistent decline in summer low flows was attributed to greater sapwood area, sapflow per unit sapwood area, leaf area in the upper canopy, and less stomatal control to limit transpiration in the young plantation compared to the mature forest (Perry and Jones 2017). While this study provided a much longer time series than previous observations, the potential for longer-term reductions in low flows due to vigorous regrowth following forest harvesting were noted previously in these PNW catchments (Hicks et al. 1991; Jones and Post 2004).

Segura et al. (2020) compared responses of daily streamflow in (a) harvested mature/old forest in 1966, (b) 43- to 53- and 48- to 58-year-old industrial plantation forests in 2006–2009, and (c) these same plantation forests in 2010 and 2014, after harvesting using contemporary forest practices, including retention of a riparian buffer. The work was part of the long-term Alsea Watershed Study in the Oregon Coast Range (Stednick 2008). Segura et al. (2020) found that daily streamflow from a 40- to 53-year-old Douglas-fir plantation was 25% lower on average, and 50% lower during summer, relative to the mature/old forest, and that these deficits lasted at least six months of each year. Contemporary forest practices (retaining riparian buffer strips in clear-cuts) had a minimal effect on streamflow deficits. Two years after logging in 2014, summer streamflow deficits were similar to those prior to harvest (under 40- to 53-year-old plantations).

Consistent with Perry and Jones (2017) and Gronsdahl et al. (2019), Segura et al. (2020) attributed persistent streamflow deficits after logging to high evapotranspiration from rapidly regenerating vegetation, including planted commercial timber species. The authors note that their findings for summer streamflow deficits in young stands in the Oregon Coast Range were similar in magnitude to those detected in Douglas-fir plantations in the western Cascades (Perry and Jones 2017; Jones and Post 2004). This indicates that plantations of similar age have similar evapotranspiration rates relative to mature and old-growth forest reference stands in all of these locations. Overall, Segura et al. (2020) found that 40- to 50-year rotations of Douglas-fir plantations can produce persistent, large summer low-flow deficits, and that clear-cutting with retention of riparian buffers increased daily streamflow slightly but flows did not return to conditions when the old/mature forests were intact. The authors suggest that additional work is needed to investigate how intensively managed forests and expected warmer, drier conditions in the future may influence summer low flows.

Considerable knowledge has accumulated, but understanding of the magnitude, duration, physical processes and downstream consequences associated with the short-term increases in low flows or longer-term decreases in low flows after forest harvesting remains incomplete. Additional research is necessary to examine both the upstream and downstream effects of forest management activities on low flows in a wider range of areas. Similar to the other subsections in this chapter, comparative studies, process studies and modeling are all necessary to fully understand the spatial and temporal impacts. Given current projections for climate and its potential impacts on low flows (Hamlet 2011; Arismendi et al. 2013; Tohver et al. 2014), it is increasingly imperative to maintain current longer-term watershed studies and revive historical studies to capture data from a range of climates, geologies, soils, topographies, forest types and forest ownerships. Doing so will facilitate effective management of the water supply from forests during periods of low flow, which generally coincide with the period of greatest demand by communities.

4.2.4. Timing of water delivery

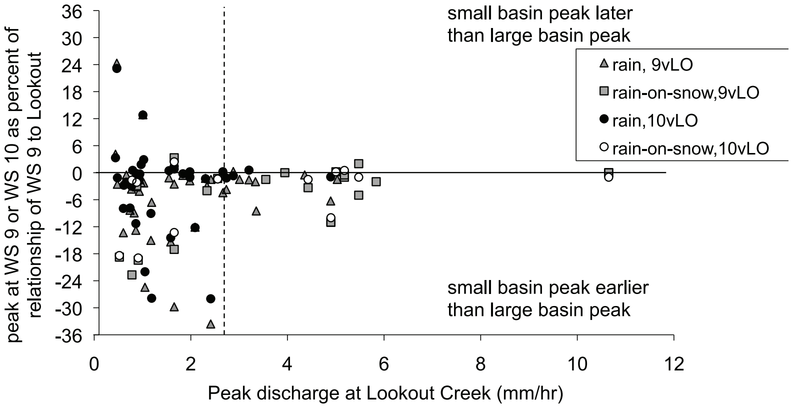
Much of the Pacific Northwest is reliant on a community water supply originating as mountain snow. This includes many community water systems in Oregon, although mostly not in the Coast Range. The melting of the seasonal snowpack in snow-dominated catchments, combined with the onset of spring and early summer rains, generates the rising limb and peak in the annual hydrograph (Kormos et al. 2016). As such, observations and projections of a declining annual snowpack — along with a shift toward earlier spring snowmelt and provision of downstream water supply — have generated considerable concerns (Cayan et al. 2001; Mote 2003; Stewart et al. 2005; Mote et al. 2008; Abatzoglou et al. 2014). Shifts in snowmelt timing violate the critical stationarity assumption for statistical water supply forecast models, producing concomitant challenges for downstream water supply managers (Milly et al. 2008; Barnhart et al. 2016).

Research has clearly shown the important role of forests in the PNW in influencing snow accumulation, ablation and the timing of snowmelt (Marks et al. 1998; Storck et al. 2002; Molotch et al. 2009; Lawler and Link 2011; Gleason et al. 2013). However, predicting the effect of forest cover and the effects of forest harvesting on the timing of snowmelt and resulting streamflow remains complex. This is because the influence of the forest on snowmelt timing is modified by a broad range of factors, including climate, topography and specific forest characteristics (Lundquist et al. 2005; Varhola et al. 2010; Lundquist et al. 2013; Martin et al. 2013; Harpold and Molotch 2015). As such, predicting the net effect of forest management activities on forest cover and snowmelt timing requires integrating multiple forest–snow processes, which all vary in space and time (Dickerson-Lange et al. 2017). Thus, there is considerable variability and associated uncertainty in the literature regarding the effects of forest harvesting on the timing of streamflow, especially at a large basin scales.

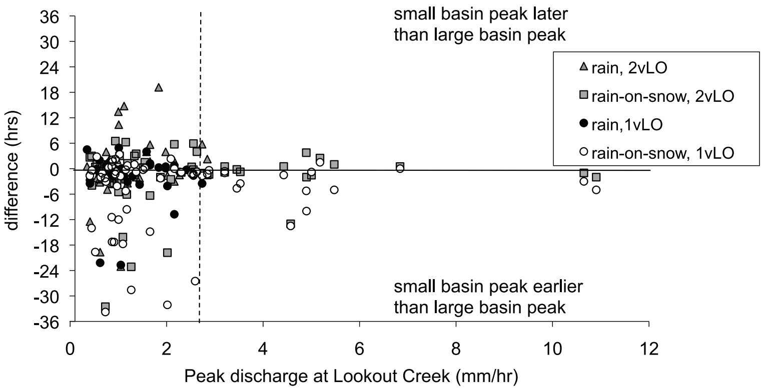
In a recent study, Dickerson-Lange et al. (2017) used observational data to compare snowmelt timing between forested and open areas across 14 sites in the western slopes and crest of the Cascade Range in Washington, Oregon and central and northern Idaho. Overall, they found that forest modification by forest harvesting was a dominant factor influencing the timing of snow disappearance. In particular, at 12 of 14 open, harvested sites, melting of the snowpack was either synchronous in timing or persisted for a longer period of time (up to 13 weeks longer) relative to forested sites (Dickerson-Lange et al. 2017). This effect was most noticeable in warmer, maritime climates of the PNW and was related to greater canopy interception storage capacity, greater snow interception efficiency, and lower wind unloading of snow from the canopy due to greater snow cohesion (Kobayashi 1987; Andreadis et al. 2009; Friesen et al. 2015). However, snow disappearance occurred about two to five weeks earlier at two open sites compared to forested sites, which was attributed to comparatively high wind speeds (hourly average wind speeds 8 and 17 meters per second). The wind effects at those sites was believed to have produced similar snow deposition in the open and the forest sites, but higher ablation rates in the open sites (Dickerson-Lange et al. 2017).

In small, snow-dominated catchments in the Okanagan Plateau of British Columbia, Winkler et al. (2017) also noted a shift in timing of snowmelt associated with forest harvesting activity. They observed an advancement in the date of peak water yield by up to one week in harvested locations with an associated increase in monthly water yields on the rising limb of the snowmelt hydrograph (April and May) along with a decrease on the falling limb (June and July) (Winkler et al. 2017). In this case, the shift in timing of snowmelt and associated streamflow was attributed to synchronization of snowmelt in the high elevation clear-cut areas (south-facing) with snowmelt from the lower elevation,

(a) Post-harvest timing of peak discharges from WS 9 (control) and WS 10 (harvested)



(b) Post-harvest timing of peak discharges at WS 2 (control) and WS 1 (harvested)



(c) Post-harvest timing of peak discharges from WS 8 (control) and WS 6 (harvested)

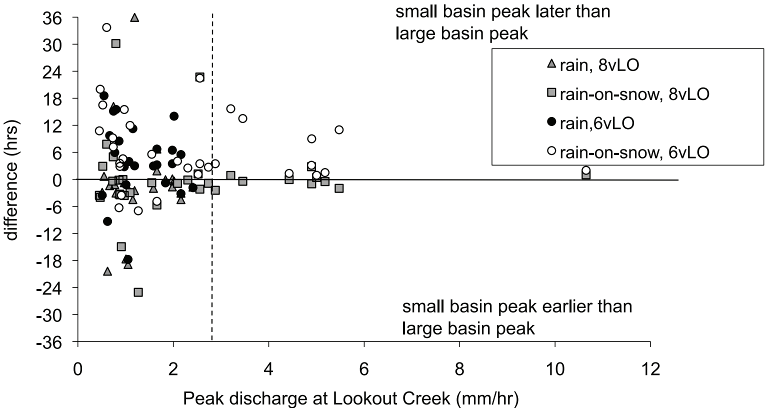


Figure 4.3. Post-harvest timing of peak flows following rain and rain-on-snow events from paired catchment studies in the (a) transient snow zone, (b) transient to seasonal snow zone, and (c) the seasonal snow zone in the H.J. Andrews Experimental Forest, OR (Jones and Perkins 2010).

unharvested forest. Similarly, Zhang et al. (2016) observed an advancement in timing of annual peak flows of approximately nine days at the large watershed scale after forest harvesting in two snow-dominated watersheds of British Columbia. This study was not focused on timing of availability, so results are limited. Additionally, this study occurred in the interior of British Columbia, a drier environment than much of western Oregon, but provides some indication that effects of forest harvesting on timing may be measureable at the large, basin scale.

Alternatively, in their study of the effects of forest harvesting on peak flows in the western Cascades of Oregon, Jones and Perkins (2010) found some evidence of shifts in the timing of peak flows in small catchments, but the timing of large peak flow events in large catchments remained largely unaffected (Figure 4.3). Even at the small catchment scale, the effects of forest harvesting on the timing of peak flows weren't consistent. For example, peak flows occurred about 3–10 hours earlier in harvested catchments in the transient snow zone, but 6–12 hours later in the harvested catchment in the seasonal snow zone (Jones and Perkins 2010).

Shifts in the timing of annual water yields have the potential to produce serious water supply management impacts, especially in community watersheds with limited reservoir storage capacity (Winkler et al. 2017). In communities without reservoirs, shifts to earlier timing of water supply may increasingly disconnect the timing of supply with the timing of greatest demand. Comparatively, in communities reliant on reservoirs, shifts in the timing of availability of streamflow to earlier periods of the year could potentially influence water purveyors to release water in excess of reservoir storage capacity, which would increase the risk of water shortages later in the year when demand is greatest (Winkler et al. 2017). Given the important linkage between forests and the timing of spring and summer streamflow (Whitaker et al. 2002; Lundquist et al. 2005; Lyon et al. 2008), it is critical to improve understanding and predictions of when and where forests will accelerate or delay snowmelt and streamflow timing, especially at the large basin scale (Rutter et al. 2009; Lundquist et al. 2013).

4.3. Conclusions

Relationships between forest cover and type, forest management, and the quantity and timing of water produced by forested watersheds have been studied for at least 100 years. Understanding of these relationships has been enhanced by research, especially long-term, paired watershed studies. We reviewed evidence regarding changes in (a) annual flow, (b) changes in peak flows and flooding, (c) changes in low (base) flows, and (d) changes in the timing of water delivery.

Throughout this chapter, we have noted potential sources of uncertainty in trying to extrapolate from results in the literature regarding forestry effects on these variables to effects on drinking water supplies. Key findings are derived mostly from studies in the upper parts of smaller, headwater catchments, and from a relatively limited number of geographic locations where long-term, paired watershed studies have been maintained. Even where consistent trends are noted across multiple studies, there is often considerable variability in results, with some studies finding large effects and others none at all. This suggests that effects may often be specific to the combination of conditions at a particular location. Studies we found focus on streamflow responses from headwater catchments, rather than at downstream drinking water intakes. Rigorous analysis of hydrologic responses to forest management is complex, time consuming and expensive, especially at larger scales and longer timeframes. Effects that have been quantified at smaller scales may potentially "scale up" to larger watershed scales, but these larger scale effects are rarely studied and thus remain generally speculative. Lastly, conditions in many watersheds reflect the cumulative effects of actions conducted over the span of many decades of evolving forest management practices. In light of this complexity and the variability of climatic, physical and ecological factors in play, the uncertainty that remains in our understanding of the effects of active management on forest hydrology in particular locations should not surprise us.

These caveats noted, a substantial body of evidence has nevertheless accumulated from an increasingly diverse array of research perspectives and methodologies. There will always be local exceptions and multiple contributing factors to any generalized conclusion, but we have some confidence that percent area of the watershed harvested is often the predominant factor affecting changes in annual flow volumes. There is general agreement that in many cases, timber harvesting temporarily increases annual water production, especially in the first few years after harvest, with these increases declining in following years, as vegetation, including planted commercial timber species, establishes and starts growing vigorously. By *volume*, these changes often peak in the fall and early winter. By *percentage*, the largest changes often occur in late summer.

Peak flows and floods have implications for community water suppliers in terms of increased sediment transport, turbidity and mobilization of pollutants, as well as potential damage to water treatment infrastructure. The generally accepted scientific understanding regarding increases in peak flows attributable to forest management and harvesting has been that these effects are most prominent for smaller, more frequent peak-flow events, and tend to decline as peak-flow size and basin size increase. However, since the mid-2000s, the study designs and analysis methods used in much of the research upon which these conclusions are based have been vigorously debated. Several studies using alternative methods in snow-dominated watersheds in British Columbia have found the opposite (i.e., that the frequency of peak flows of all sizes tend to increase after forest harvest and that these effects are most prominent for larger peak flows). Over time, snowpack changes related to climate warming are likely to result in large increases in peak-flow magnitudes in areas such as the Cascades and Blue Mountains. Predicted drivers for such a shift include greater frequency and magnitude of extreme precipitation events, and a growing proportion of winter precipitation falling as rain instead of snow. These forecasts suggest that any effects that forestry activities have on peak flows may intertwine with climate in increasingly complex ways. If, as expected, the frequency and magnitude of floods in Oregon increase under climate change, public and agency interest in mitigating anthropogenic factors that contribute to peak flows may intensify.

Seasonal low flows are of particular interest to water suppliers, because they generally coincide in late summer with the period of greatest demand for drinking and irrigation water. For at least two reasons, we may expect that relationships between active forest management and summer low flows in Oregon may be increasingly important to drinking water providers. First, while there are uncertainties regarding local and regional implications of climate change over time, there is also evidence that along with rising temperatures, dry years are increasing, low flows are declining and the annual low-flow period is lengthening in duration. Secondly, recent research indicates that, in both the Oregon Coast Range and Cascades, stands of conifers established after clear-cut harvests can, once they are 15–20 years old and growing quickly, significantly and persistently reduce summer low flows in comparison to the older stands they replaced. Many watersheds in these regions contain substantial amounts of timberland in this young plantation forest condition. In watersheds that serve as sources for smaller community water suppliers in Oregon and also support significant amounts of industrial forestry, climate trends and forest management may converge to further exacerbate challenges of supplying water during the critical late summer low-flow period.

The weight of available evidence indicates that forest management can affect the volume and timing of water delivered from managed watersheds and, by extension, community water systems that are hydrologically connected downstream. The limitations on existing knowledge described above are such that variability in local conditions can make it difficult to specify these effects for a particular water system. However, linkages between drinking water supplies and forest management (e.g., harvesting a significant percentage of the watershed) can be more readily established in smaller systems that are closer to the source watershed than in larger systems that are further away, with more intervening land uses.

Despite knowledge gaps, we understand enough to foresee that forest management activities in source watersheds will continue to be relevant considerations for water providers, and that effects may be predicted or specified with some degree of confidence in some smaller watersheds. Finally, climate change and associated shifts in snowpack levels and timing, and in the frequency and severity of extreme weather events, will further complicate an already complex set of factors that influence the amount and timing of raw water provided in actively managed drinking water source watersheds.

4.4. References

Abatzoglou, J.T., D.E. Rupp, and P.W. Mote. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. *Journal of Climate* 27: 2125-2142.

Abdelnour, A., M. Stieglitz, F.F. Pan, and R. McKane. 2011. Catchment hydrological responses to forest harvest amount and spatial pattern. *Water Resources Research* 47: 18.

Adams, P.W., A.L. Flint, and R.L. Fredriksen. 1991. Long-term patterns in soil moisture and revegetation after a clear-cut of a Douglas-fir forest in Oregon. *Forest Ecology and Management* 41: 249-263.

Alila, Y. and K.C. Green. 2014a. 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(3): 2769-2774.

Alila, Y. and K.C. Green. 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(3): 2759-2764.

Alila, Y., P.K. Kuras, M. Schnorbus, and R. Hudson. 2009. Forests and floods: A new paradigm sheds light on age-old controversies. *Water Resources Research* 45: W08416.

Andreadis, K.M., P. Storck, and D.P. Lettenmaier. 2009. Modeling snow accumulation and ablation processes in forested environments. *Water Resources Research* 45: 13.

Archer, D.R. 1989. Flood wave attenuation due to channel and floodplain storage and effects on flood frequency. Pp. 37-46 *In*: Beven, K. and P. Carling (eds). *Floods: Hydrological, Sedimentological and Geomorphological Implications*. Chichester, UK: John Wiley and Sons. 290 pp.

Arismendi, I., M. Safeeq, S.L. Johnson, J.B. Dunham, and R. Haggerty. 2013. Increasing synchrony of high temperature and low flow in western North American streams: double trouble for coldwater biota? *Hydrobiologia* 712: 61-70.

Ashley, S.T. and W.S. Ashley. 2008. Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology* 47: 805-818.

Barnhart, T.B., N.P. Molotch, B. Livneh, A.A. Harpold, J.F. Knowles, and D. Schneider. 2016. Snowmelt rate dictates streamflow. *Geophysical Research Letters* 43: 8006-8016.

Bates, C.G. and A.J. Henry. 1928. Second phase of streamflow experiment at Wagon Wheel Gap, Colorado. *Monthly Weather Review* 56(3): 79-85.

Bathurst, J.C. 2014. Comment on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments" by KC Green and Y. Alila. *Water Resources Research* 50(3): 2756-2758.

Beschta, R.L., M.R. Pyles, A. Skaugset, and C.G. Surfleet. 2000. Peakflow responses to forest practices in the western Cascades of Oregon, USA. *Journal of Hydrology* 233: 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(3): 2765-2768.

Birkinshaw, S.J., J.C. Bathurst, A. Iroume, and H. Palacios. 2011. The effect of forest cover on peak flow and sediment discharge-an integrated field and modelling study in central-southern Chile. *Hydrological Processes* 25: 1284-1297.

Bosch, J.M. and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3-23.

Bowling, L.C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research* 36: 3223-3240.

Brown, A.E., L. Zhang, T.A. McMahon, A.W. Western, and R.A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310: 28-61.

Calder, I.R. and B. Aylward. 2006. Forest and floods: moving to an evidence-based approach to watershed and integrated flood management. *Water International* 31: 1-13.

Calder, I.R., J. Smyle, and B. Aylward 2007. Debate over flood-proofing effects of planting forests. *Nature* 450: 945-945.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82, 399-415.

Cristan, R., W.M. Aust, M.C. Bolding, S.M. Barrett, J.F. Munsell, and E. Schilling. 2016. Effectiveness of forestry best management practices in the United States: Literature review. *Forest Ecology and Management* 360: 133-151.

DeWalle, D.R. 2003. Forest hydrology revisited. *Hydrological Processes* 17: 1255-1256.

Dickerson-Lange, S.E., R.F. Gersonde, J.A. Hubbart, T.E. Link, A.W. Nolin, G.H. Perry, T.R. Roth, N.E. Wayand, and J.D. Lundquist. 2017. Snow disappearance timing is dominated by forest effects on snow accumulation in warm winter climates of the Pacific Northwest, United States. H*ydrological Processes* 31: 1846-1862.

Downton, M.W., J.Z.B. Miller, and R.A. Pielke Jr. 2005. Reanalysis of U.S. National Weather Service flood loss database. *Natural Hazards Review* 6: 13-22.

Du, E.H., T.E. Link, L. Wei, and J.D. Marshall. 2016. Evaluating hydrologic effects of spatial and temporal patterns of forest canopy change using numerical modelling. *Hydrological Processes* 30: 217-231.

Fowler, W.B., J.D. Helvey, and E.N. Felix. 1987. Hydrologic and climatic changes in three small watersheds after timber harvest. Research Paper PNW-RP-379. U.S.D.A. Forest Service, Pacific Northwest Research Station, Portland, OR. 13 pp.

Friesen, J., J. Lundquist, and J.T. Van Stan. 2015. Evolution of forest precipitation water storage measurement methods. *Hydrological Processes* 29: 2504-2520.

Gleason, K.E., A.W. Nolin, and T.R. Roth, T.R., 2013. Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophysical Research Letters* 40: 4654–4661.

Grant, G.E., S.L. Lewis, F.J. Swanson, J.H. Cissel, and J.J. McDonnell. 2008. Effects of forest practices on peak flows and consequent channel response: a state-of-science report for western Oregon and Washington. General Technical Report PNW-760. U.S.D.A. Forest Service, Pacific Northwest Research Station, Portland, OR. 76 pp.

Green, K.C. and Y. Alila. 2012. A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments. *Water Resources Research* 48(10): W10503.

Griffin, A.A. 1918. Influence of forests upon the melting of snow in the Cascade Range. *Monthly Weather Review* 46(7): 324-327.

Gronsdahl, S., R.D. Moore, J. Rosenfeld, R. McCleary, and R. Winkler. 2019. Effects of forestry on summertime low flows and physical fish habitat in snowmelt□ dominant headwater catchments of the Pacific Northwest. *Hydrological Processes* 33(25): 3152-3168.

Hamlet, A.F. 2011. Assessing the water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Science* 15: 1427-1443.

Harpold, A.A. and N.P. Molotch. 2015. Sensitivity of soil water availability to changing snowmelt timing in the western US. *Geophysical Research Letters* 42: 8011-8020.

Harr, R.D. 1983. Potential for augmenting water yield through forest practices in western Washington and western Oregon. *Water Resources Bulletin* 19: 383-392.

Harr, R.D., R.L. Fredriksen, and J. Rothacher. 1979. Changes in streamflow following timber harvest in southwestern Oregon. Research Paper PNW-RP-249. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Corvallis, OR. 22 pp.

Harr, R.D. and J.T. Krygier. 1972. Clearcut logging and low flows in Oregon coastal watersheds. Research Note 54. Forest Research Laboratory, College of Forestry, Oregon State University, Corvallis, OR. 3 pp.

Harr, R.D., A. Levno, and R. Mersereau. 1982. Streamflow changes after logging 130-year-old Douglas-fir in 2 small watersheds. *Water Resources Research* 18: 637-644.

Harrington, T.B., R.A. Slesak, and S.H. Schoenholtz. 2013. Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir. *Forest Ecology and Management* 296: 41-52.

Hicks, B.J., R.L. Beschta, and R.D. Harr. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. *Water Resources Bulletin* 27: 217-226.

Hubbart, J.A., T.E. Link, and J.A. Gravelle. 2015. Forest canopy reduction and snowpack dynamics in a northern Idaho watershed of the Continental-Maritime Region, United States. *Forest Science* 61: 882-894.

Ingwersen, J.B. 1985. Fog drip, water yield, and timber harvesting in the Bull Run municipal watershed, Oregon. *JAWRA Journal of the American Water Resources Association* 21: 469–473.

Jassal, R.S., T.A. Black, D.L. Spittlehouse, C. Brummer, and Z. Nesic. 2009. Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands. *Agricultural and Forest Meteorology* 149: 1168-1178.

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

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

Jones, J.A. and G.E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research* 32: 959-974.

Jones, J.A., and R.M. Perkins. 2010. Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States. *Water Resources Research* 46: W12512.

Jones, J.A. and D.A. Post. 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research* 40: W05203.

Keppeler, E.T. and R.R. Ziemer. 1990. Logging effects on streamflow - water yield and summer low flows at Caspar Creek in northwestern California. *Water Resources Research* 26: 1669-1679.

Kobayashi, D. 1987. Snow accumulation on a narrow board. *Cold Regions Science and Technology* 13: 239-245.

Kormos, P.R., C.H. Luce, S.J. Wenger, and W.R. Berghuijs. 2016. Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. *Water Resources Research* 52(7): 4990-5007.

Kuraś, 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(1): W01544.

Lawler, R.R. and T.E. Link. 2011. Quantification of incoming all-wave radiation in discontinuous forest canopies with application to snowmelt prediction. *Hydrological Processes* 25(21): 3322-3331.

Leppi, J.C., T.H. DeLuca, S.W. Harrar, and S.W. Running. 2012. Impacts of climate change on August stream discharge in the Central-Rocky Mountains. *Climatic Change* 112: 997-1014.

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

Lin, Y. and X.H. Wei. 2008. The impact of large-scale forest harvesting on hydrology in the Willow watershed of Central British Columbia. *Journal of Hydrology* 359: 141-149.

Luce, C., B. Staab, M. Kramer, S. Wenger, D. Isaak, and C. McConnell. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. *Water Resources Research* 50: 3428-3443.

Luce, C.H. and Z.A. Holden. 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948-2006. *Geophysical Research Letters* 36: L16401.

Lundquist, J.D., M.D. Dettinger, and D.R. Cayan. 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): W07005.

Lundquist, J.D., S.E. Dickerson-Lange, J.A. Lutz, and N.C. Cristea. 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: 6356-6370.

Lyon, S.W., P.A. Troch, P.D. Broxton, N.P. Molotch, and P.D. Brooks. 2008. Monitoring the timing of snowmelt and the initiation of streamflow using a distributed network of temperature/light sensors. *Ecohydrology* 1: 215-224.

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102:187-223.

Marks, D., J. Kimball, D. Tingey, and T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrological Processes* 12: 1569-1587.

Martin, K.A., J.T. Van Stan, S.E. Dickerson-Lange, J.A. Lutz, J.W. Berman, R. Gersonde, and J.D. Lundquist. 2013. Development and testing of a snow interceptometer to quantify canopy water storage and interception processes in the rain/snow transition zone of the North Cascades, Washington, USA. *Water Resources Research* 49: 3243-3256.

Mateus, C., D.D. Tullos, and C.G. Surfleet. 2015. Hydrologic sensitivity to climate and land use changes in the Santiam River Basin, Oregon. *JAWRA Journal of the American Water Resources Association* 51: 400-420.

McCabe, G.J., M.P. Clark, and L.E. Hay. 2007. Rain-on-snow events in the western United States. *Bulletin of the American Meteorological Society* 88(3): 319-328.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: whither water management? *Science* 319: 573-574.

Molotch, N.P., P.D. Brooks, S.P. Burns, M. Litvak, R.K. Monson, J.R. McConnell, and K. Musselman. 2009. Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology* 2:129-142.

Moore, G.W., B.J. Bond, J.A. Jones, N. Phillips, and F.C. Meinzer. 2004. Structural and compositional controls on transpiration in 40- and 450-year-old riparian forests in western Oregon, USA. *Tree Physiology* 24: 481-491.

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

Moore, R.D. and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. *JAWRA Journal of the American Water Resources Association* 41: 763-784.

Mote, P., A. Hamlet, and E. Salathe. 2008. Has spring snowpack declined in the Washington Cascades? *Hydrology and Earth System Sciences* 12: 193-206.

Mote, P.W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* 30(12): 1601 doi:10.1029/2003GL017258

Neary, D.G. 2000. Changing perspectives of watershed management from a retrospective viewpoint. Pp. 167-176. *In*: Ffolliott, P.F.; M.B. Baker, Jr., C.B. Edminster, M.C. Dillion, and K.L. Mora (eds.) *Land Stewardship in the 21st Century: the Contributions of Watershed Management*. Proceedings, Tucson, AZ, March 13-16, 2000. RMRS-P-13. USDA Forest Service, Rocky Mountain Research Station, Tucson, AZ. 445 pp.

O'Connor, J.E. and J.E. Costa. 2004. Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 square kilometers in the United States and Puerto Rico. *Water Resources Research* 40(1): W01107.

Oregon Department of Environmental Quality, 2018. Surface water drinking water source areas in Oregon. Oregon Department of Environmental Quality, Water Quality Division, Salem, OR. https://www.oregon.gov/deq/FilterDocs/swmap.pdf accessed 4/29/2020.

Perry, G., J. Lundquist, and R.D. Moore. 2016. Review of the potential effects of forest practices on stream flow in the Chehalis River Basin. Appendix A. Chehalis Basin Strategy Draft Programmatic Environmental Impact Statement (EIS). Washington Department of Ecology, Olympia, WA, 46 pp. https://fortress.wa.gov/ecy/publications/parts/1706017part27.pdf accessed 4/29/2020.

Perry, T.D. and J.A. Jones. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. *Ecohydrology* 10(2): eco.1790.

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

Rothacher, J., 1965. Snow accumulation and melt in strip cuttings on the west slopes of the Oregon Cascades. Research Note PNW-RN-23. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 7 pp.

Rothacher, J., 1970. Increases in water yield following clear-cut logging in Pacific Northwest. *Water Resources Research* 6: 653-658.

Rutter, N., R. Essery, J. Pomeroy, N. Altimir, K. Andreadis, I. Baker, A. Barr, P. Bartlett, A. Boone, H.P., Deng, H. Douville, E. Dutra, K. Elder, C. Ellis, X. Feng, A. Gelfan, A. Goodbody, Y. Gusev, D. Gustafsson, R. Hellstrom, Y. Hirabayashi, T. Hirota, T. Jonas, V. Koren, A. Kuragina, D. Lettenmaier, W.P. Li, C. Luce, E. Martin, O. Nasonova, J. Pumpanen, R.D. Pyles, P. Samuelsson, M. Sandells, G. Schadler, A. Shmakin, T.G. Smirnova, M. Stahli, R. Stockli, U. Strasser, H. Su, K. Suzuki, K. Takata, K.Tanaka, E. Thompson, T. Vesala, P. Viterbo, A. Wiltshire, K. Xia, Y.K. Xue, and T. Yamazaki. 2009. Evaluation of forest snow processes models (SnowMIP2). *Journal of Geophysical Research-Atmospheres* 114: D06111.

Safeeq, M., G.E. Grant, S.L. Lewis, and B. Staab. 2015. Predicting landscape sensitivity to present and future floods in the Pacific Northwest, USA. *Hydrological Processes* 29: 5337-5353.

Salemi, L.F., J.D. Groppo, R. Trevisan, J.M. de Moraes, W.D. Lima, and L.A. Martinelli, L.A., 2012. Riparian vegetation and water yield: A synthesis. *Journal of Hydrology* 454: 195-202.

Schnorbus, M. and Y. Alila. 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: 517-535.

Segura, C., K.D. Bladon, J.A. Hatten, J.A. Jones, V.C. Hale, and G.G. Ice. 2020. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. *Journal of Hydrology* 585: 124749.

Shaman, J., M. Stieglitz and D. Burns. 2004. Are big basins just the sum of small catchments? *Hydrological Processes* 18: 3195-3206.

Stednick, J.D. (ed). 2008. *Hydrological and biological responses to forest practices: The Alsea Watershed Study*. New York, NY: Springer Science +Business Media, LLC. 330 pp.

Stednick, J.D. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176: 79-95.

Stednick, J.D. and C.A. Troendle. 2016. Hydrological effects of forest management. Pp. 192-203 *In*: Amatya, D., T. Williams, L. Bren, and C. de Jong (eds) *Forest Hydrology: Processes, Management and Assessment*. Boca Raton, FL: CABI. 307 pp.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18: 1136-1155.

Storck, P., D.P. Lettenmaier, and S.M. Bolton. 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): WR001281.

Surfleet, C.G. amd A.E. Skaugset. 2013. The effect of timber harvest on summer low flows, Hinkle Creek, Oregon. *Western Journal of Applied Forestry* 28: 13-21.

Tague, C. and G.E. Grant. 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research* 40: W04303.

Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. *Water Resources Research* 34: 3393-3404.

Tohver, I.M., A.F. Hamlet, and S.Y. Lee. 2014. Impacts of 21st-century climate change on hydrologic extremes in the Pacific Northwest region of North America. *JAWRA Journal of the American Water Resources Association* 50: 1461–1476.

Troendle, C.A. and R.M. King. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. *Water Resources Research* 21: 1915-1922.

Troendle, C.A., M.S. Wilcox, G.S. Bevenger, and L.S. Porth. 2001. The Coon Creek water yield augmentation project: implementation of timber harvesting technology to increase streamflow. *Forest Ecology and Management* 143: 179-187.

Tullos, D. 2018. How to achieve better flood-risk governance in the United States. *Proceedings of the National Academy of Sciences* 115: 3731-3734.

Vano, J.A., B. Nijssen, and D.P. Lettenmaier. 2015. Seasonal hydrologic responses to climate change in the Pacific Northwest. *Water Resources Research* 51: 1959–1976.

Varhola, A., N.C. Coops, M. Weiler, and R.D. Moore. 2010. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology* 392: 219-233.

Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. *Water Resources Research* 38: 1172.

Winkler, R., D. Spittlehouse, and S. Boon. 2017. Streamflow response to clear-cut logging on British Columbia's Okanagan Plateau. *Ecohydrology* 10(2): eco.1836.

Winkler, R., D. Spittlehouse, S. Boon, and B. Zimonick. 2015. Forest disturbance effects on snow and water yield in interior British Columbia. *Hydrology Research* 46: 521–532.

Woltemade, C.J. and K.W. Potter. 1994. A watershed modeling analysis of fluvial geomorphologic influences on flood peak attenuation. *Water Resources Research* 30: 1933-1942.

Yu, X.J. and Y. Alila. 2019. Nonstationary frequency pairing reveals a highly sensitive peak flow regime to harvesting across a wide range of return periods. *Forest Ecology and Management* 444: 187-206.

Zegre, N., A.E. Skaugset, N.A. Som, J.J. McDonnell, and L.M. Ganio. 2010. In lieu of the paired catchment approach: Hydrologic model change detection at the catchment scale. *Water Resources Research* 46: W11544.

Zhang, M., X. Wei, and Q. Li. 2017. Do the hydrological responses to forest disturbances in large watersheds vary along climatic gradients in the interior of British Columbia, Canada? *Ecohydrology* 10: e1840.

Zhang, M.F. and X.H. Wei. 2014. 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: 544-556.

Zhang, M., X. Wei, and Q. Li. 2016. A quantitative assessment on the response of flow regimes to cumulative forest disturbances in large snow-dominated watersheds in the interior of British Columbia, Canada. *Ecohydrology* 9: 843-859.