Review of forest practices to buffer the effects of climate change on stream flow, and water quality

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Executive Summary

This report[1] tracks past and recent literature relating landcover to stream response, and provides guidelines for forest practices that may be implemented to reduce flood flows, raise low flows, and maintain water quality within the context of the wider landscape and stand-scale hydrologic processes in the Snohomish watershed. Forests translate mild wet winters and dry hot summers in the Pacific Northwest to the flows and water quality we experience. Rising temperatures, wetter springs, and drier summers over the last century reduce snow, hasten its melt, and create even drier hotter summers, thereby increasing fire and reducing water supply to aquatic ecosystems. The purpose of this project is to model various forest treatment practices at the stand level to affect changes in stream flow, particularly low flow during the dry season in the Snohomish River Basin.

Forest practices clearly affect water flow timing, flood flows, low flows, and water quality. The effects of geology and precipitation dominate, while forest practices are nested within these. Most evidence shows ≤10-year peak flows respond to harvest most in the fall. Peak flow responses to harvest can be >100% and last >20 years. Because statistical power is limited and forests regrow after experimental treatments, effects of harvesting on large floods are hard to observe. There is theoretical evidence that runoff synchrony is increased with larger road networks and homogeneous canopy structure and that the frequency and magnitude of all flood magnitudes can increase.

The timing and magnitude of peak soil moisture and its drying rate are linked to forest practices and low flows. The forest canopy can intercept ~60% of snow leading to 30 to 40% sublimation losses. In small gaps in the western Pacific Northwest, snow accumulates more and persists from no longer to up to 13 weeks longer than under forest canopy, but upper limits of 25 days are more common. Rain interception by the canopy accounts for 20 to 25% of annual precipitation and may lead to decreased soil moisture prior to onset of soil drying. Transpiration can be >60% of precipitation in conifer forests and >50% in hardwoods. The most effective way to increase low flows through forest management practices is probably by reducing transpiration to slow soil drying, either by creating lasting non-forest conditions or by promoting old growth structure with heterogeneous horizontal and vertical leaf distribution. Another way to increase low flows may be to plant more hardwoods on hillslopes because they have lower maximum leaf area and interception capacity than conifer forests. The best strategy for

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reducing transpiration is to focus harvests and thinning in regions of mid-seral forests, converting some of the younger end of the spectrum to early-seral forest and some of the older end to old growth.

Contemporary riparian buffers moderate acute effects of harvest on stream temperature and sediment delivery to streams. Conversely, dense riparian buffers of large trees also reduce low flows. Shade is regained quickly following harvest along small streams, while transpiration demands could theoretically be reduced for longer periods by creating heterogeneous canopies with more tree species. Water cools within 100s to 1500 meters downstream if shading reduces heat input or hyporheic exchange is increased, so alternating patterns of harvest along a stream's length and input of wood can reduce impacts of riparian treatments on temperature. In areas with buffers, 30 m to 1-tree-height widths appear adequate to protect against temperature and sediment increases with harvest. Sediment mobilization is increased with harvests and roads. If particularly problematic roads are stabilized, disconnected from streams, or decommissioned a majority of sediment problems can probably be stopped.

An integrated landscape strategy using variable density harvest (VDH) that leaves ≥30% forest cover at watershed scales and variable density thinning (VDT) may be able to balance hydrologic objectives without overly compromising others. Dispersing practices in some areas and concentrating in others creates heterogeneity at multiple scales to delay runoff synchrony and reduce transpiration. VRH and VDT also provide a safety margin for processes we are less certain about. For example, fog drip may contribute significantly to valley bottom forest flows, especially in the fall by raising soil moisture prior to rains. Leaving significant retention and strong dominant trees in these areas may be beneficial if fog contributions outweigh transpiration losses. Hazards for these forests are from disturbance, including but not limited to, fire and insects. The diversity of forest structure and tree species introduced in the guidelines of this report offer a margin of safety as each respond at different times and with different intensities to these disturbances.

Finally, in Section 5, a variety of methods, models, and previous assessments are reviewed for their applicability to this project. Section 5.1 identifies methods for predicting locations on the landscape for wetland restoration and water storage, including the Wetland Intrinsic Potential tool and Hydrologic Sensitivity Index. Determining the best way to integrate the hydrologic, forest growth, and wetland models remains an important task in this study. To assess the effect of alternative forest management practices on basin hydrology, Section 5.2 reviews a set of potential distributed hydrologic models. Each model 1) includes representations of the major hydrologic processes and 2) has been applied to watersheds in the west Cascades in Washington state. DHSVM and/or VELMA have been identified as the most likely models to use for this study. In general, hydrologic models simplify forest vegetation and growth. Forest growth models, such as the USDA Forest Vegetation Simulator (FVS), specialize in predicting change in forest attributes at stand levels over time in response to treatments and growth. Integrating FVS predictions with hydrologic models may improve model sensitivity to forest management. Simulated forest conditions will also be useful for quantifying vegetation-based Indicators. Section 5.3 summarizes other forest and water monitoring and assessment programs to identify relevant management and policy processes, assessment techniques, indicators, datasets, and tools. Many of the assessments are broader in scale than NTA0970 and these generally do not include stream flow metrics. However, particular indicators and tools are identified which may be useful. Flow information is provided by federal, state, and county agencies, however, often only on a station-by-station basis, so it is unclear where and how much overlap there is between these levels. The

Puget Sound Partnership Vital Signs program appears to be the only one providing a regular assessment of flow conditions, and it shows declining trends for the four stations in WRIA07. Further compilation and review of individual grey literature studies could be useful. For example, Hume et al. (2015) analyzed areas of importance and degradation for streamflow and habitat in WRIA07. Their simpler GIS-based flow model may provide a useful comparison for NTA0970 work, and some of the underlying GIS layers and their prioritization approach may be applicable as well.

Common terms used in this report

Variable Retention Harvest (VRH)- Pattern of harvest where aggregated and dispersed retention are used in varying amounts according to management goals. One goal of variable retention harvest is to initiate a new cohort of trees.

Variable Density Thinning (VDT)- Thinning to non-uniform tree density where the goals include creating structural complexity but not initiating a new cohort of trees

LiDAR- Light detection and ranging is a method of quantifying canopy structure and topography using a laser and global positioning system. Resolution of this technology can often reach sub-meter accuracy.

DEM- Digital Elevation Model is a model derived from photographs or LiDAR that shows accurate topography of a landscape in the x, y, and z dimensions.

Distributed Hydrologic Model – A spatially explicit model that uses gridded (raster) inputs to predict hydrologic processes for a watershed over a period of time at a defined time step.

Forest Growth Model – An empirical model that predicts tree diameter at 4.5 feet above the ground (DBH), height, live crown length, and frequency at (typically) five-year time steps for a list of trees representing one acre. The spatial arrangement of trees is not explicitly modeled. Tree competitive position and growing space is represented using tree DBH percentile, total stand density, and site productivity and carrying capacity.

Process (also Physical or Mechanistic) Model – A mathematical representation of real physical processes or phenomenon. These models typically require an expert to initialize and run but can provide useful information for a wider range of study questions compared to empirical models.

Empirical (also Statistical) Model – A regression or correlation model between concurrent input and output variables. These are observation-based models that do not consider the physical processes underlying the relationship between input and output data. Typically simple to apply but with low explanatory depth and not applicable outside the area where the model was developed.

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Report Objectives

This report is compiled for the Tulalip Tribes to track scientific literature on effects of forest management practices on peak flows, low flows, and water quality as part of the NTA 0970 Forestry and Water Storage and Climate project. This project intends to identify priority locations for water storage/recharge in the Snohomish Basin and assess different forest actions for their potential to improve basin hydrology for salmon and treaty resources under climate scenarios. We define forest practices as those related to growing and harvesting timber, so include road building and maintenance, planting, tending, and harvesting trees as well as environmental mitigation associated with those practices. An additional goal of the report is to synthesize the literature into a set of guidelines most likely to reduce floods, increase low flows, and maintain high-quality water in the Snohomish watershed in the western North Cascade Mountains. Therefore, much of the literature used in this report comes from the western Pacific Northwest. These guidelines can then be modeled as a subsequent part of this project at the watershed scale to understand how forest practices are likely to modify runoff attributes.

Forest practices need to be implemented on a landscape level to realize watershed gains, or if not possible, efforts need to be concentrated in particularly beneficial places. To understand how forest practices alter hydrologic processes, we must first understand the broader context they are subject to, and then the local processes they modify. Thus, the first two sections address forests within the broader context of forest development and the legacies of forest practices (**Section 1**) and the hydrologic schema (**Section 2**) of the western Pacific Northwest. **Section 3** provides guidelines for how forests can be managed to reduce flooding, increase low flow, and ensure high water quality and includes supporting scientific evidence. **Section 4** integrates management guidelines from other sections into one cohesive framework. References are included at the end of the section for easier reference in addition to the complete bibliography at the end of the report.

Some guidelines can conflict, so an attempt was made to find middle ground in the integrated strategy based that does not optimize any one goal at the expense of others. Although the guidelines are designed to provide well-regulated flows of quality water in the western Pacific Northwest, current and future management goals are and will be broader. Therefore, we also briefly evaluate how sustainable these strategies are when considering other values, such as resistance and resilience to fire, biodiversity, and cultural resources.

The last section of the report (**Section 5**) provides information to support modeling the forest harvest guidelines from the forest practices literature review. This includes identifying models, with their inputs, strengths, and weaknesses for wetlands and for distributed hydrologic processes. The last portion of this section provides an overview of other aquatic and terrestrial assessments, datasets, tools and indicators for evaluating models.

In addition to the main body of the report, we include several Appendices. We include a glossary of technical terms near the end of the document because it spans so many disciplines (see

Glossary of technical terms). A concise list of forest practices and their implications are summarized in **Appendix 1. Appendix 2** includes several tables of values and references for processes such as interception and transpiration that may be useful for setting boundaries inputs for modeling hydrologic response to forest practices. **Appendix 3** demonstrates an example of how moving proportional forest area from dense forest to early-seral forest and old-growth structure may increase low water yields in the Snohomish watershed. **Appendix 4** provides tables that summarize assessments from **Section 5**, with an additional emphasis on how indicators are combined and scored.

Floods and low flows have been reviewed in detail for the Pacific Northwest in a number of academic publications. Readers are also referred to: Andréassian, 2004; Bosch and Hewlett, 1982; Brown et al., 2005; Coble et al., 2020; Goeking and Tarboton, 2020; Grant et al., 2008; Gribovszki et al., 2010; MacDonald and Stednick, 2003; Moore and Wondzell, 2005; Pike and Scherer, 2003; Salemi et al., 2012; Stednick, 1996. We created a selected annotated bibliography (**Appendix 5**) to point interested readers to more details than are summarized within this report. Additionally, other reports have done an excellent job of summarizing more information than was presented here (see Perry et al., 2016; Souder et al., 2020). The unique contribution of this report is to offer specific guidelines, conceptual frameworks, photographs, and tables with ranges of variability for forest management in the western Pacific Northwest.

Section 1. Forest Practices and Setting

The study region of interest in this report is the west slope of the North Cascades in the Snohomish river basin. In this region of the Pacific Northwest, the forested landscape is a patchwork of forests in varying stages of development following disturbance, mostly from past harvesting and reforestation practices (**Figure 1.1**), but also from re-generation following natural disturbance such as stand replacing fire (Donato et al., 2020; Henderson et al., 1989 p. 12-20), wind (Knapp and Hadley, 2012), ground disturbances such as landslides (Sidle et al., 2006), and Native American burning practices (Storm and Shebitz, 2006; Whitlock and Knox, 2002, Boyd, 1999).

Figure 1.1: Contemporary forest cover along the Tolt River, snapshot acquired from google maps March 2021.

Forests in the region are mostly dominated by Douglas-fir and its associates, including western hemlock, western red cedar, grand fir, and western white pine. Other conifers include Sitka spruce near the coast, and pacific silver fir and noble fir at higher elevations. Common hardwood species are bigleaf maple, red alder, black cottonwood, and pacific madrone on some coastal islands. At higher elevations, important conifers also include mountain hemlock and subalpine fir (Franklin and Dyrness, 1973). The literature search for this review was primarily done for Douglas-fir forests because they make up the vast majority of land subject to forest practices in the region.

Native American land management and natural processes shaped the forest before commercial logging began. Native Americans were managing this landscape using fire to maintain a mosaic that provided food-rich openings, materials for sustenance such as for basketry, and by taking planks and bark from live trees, as well as whole trees for house and canoe building. (Boyd, 1999; Mobley and Eldridge, 1992). Native burning in forested regions are well-documented in the San Juan Islands (Bakker et al., 2019). Much of the mountainous Cascade forests were shaped by fire and wind. Because these forests were usually moist, fires causing significant damage were rare unless coincident with strong dry east winds (Henderson et al., 1989). When fire did occur during such winds they could span >500,000 ha (Donato et al., 2020) and normally killed significant over- and under-story trees. Winds can periodically be the largest tree-killing events (Franklin and Donato, 2020) and primarily kill overstory trees. Native management, and natural fire and wind in the mountainous West Cascades created forests primarily

>200 year old interspersed with meadows and huckleberry fields by the time colonizers first arrived (Boyd, 1999; Franklin and Donato, 2020).

After severe disturbances that kill most overstory trees, forests in this region follow a basic trajectory that can be broken into four periods. The following description is simplified and idealized; in reality, forest development has considerable variability depending on the physical and biological legacies after disturbance. The main stages of development include: early-seral ecosystems, mid-seral young forests, late-seral mature forests, and late-seral old forests. Tree stature, spatial arrangement, species composition, and canopy properties vary greatly between the types of forests, thus are relevant to managing for ecosystem function.

1) **Early-seral ecosystems**: After natural disturbance, this period has abundant dead wood, is dominated by herbaceous and shrubby plants, and has high biodiversity. These systems last between 2-20 years in production forestry (Ulappa et al., 2020) and 30-100 naturally in the Pacific Northwest (Freund et al., 2014). Trees are NOT the dominant vegetation (**Figure 1.2**).

2) **Mid-seral young**: Period dominated by small to large trees with dense crowns so nearly all leaves are in the upper canopy (Franklin et al., 2018). Understories are depauperate and competition between trees is intense (Franklin et al., 2002, **Figure 1.2**). This period ends when trees are approximately 70 to 80 years old.

3) **Late-seral mature**: As forests mature, height growth slows, dead and fallen trees create gaps, and understory trees and other plants establish (**Figure 1.3**). Horizontal and vertical complexity begin and cause of tree death switches from inter-tree competition to external causes (e.g. fungi, wind). Overstory trees in this stage range from ~80 to >200 years (Franklin et al., 2018, 2002).

4) **Late-seral old**: As forests reach old growth, they develop gaps, leaf area is concentrated in the low canopy, trees are of many ages and sizes, and the largest are usually battling decay (**Figure 1.3**). Trees that pioneered after the disturbance can become rare. This stage has the second highest biodiversity and lasts until the next disturbance (Franklin et al., 2002).

Figure 1.2: Examples of non-forest (top) with wet meadows (upper left) and early seral habitat (upper right). Bottom shows young plantations (bottom left) and young forest (bottom right).

Figure 1.3: Images of late-seral forests, with mature forest (top) and old growth (bottom).

Initial logging left many unmerchantable trees, but by the time of WWII, staggered 16 to 24 hectare clear cuts were being used to create access roads into unlogged forest (Franklin and Donato, 2020; Franklin and Forman, 1987). By the 1960s clear cutting, clearing of logging slash, and replanting were well established common practices. Dispersed retention of minimal overstory trees (shelterwood) was also practiced to ensure regeneration in harsh sites with the intention of logging the large trees at a later date (Grant et al., 2008). By the 1970's, environmental concerns on public lands forced adoption of alternatives to clear cutting. Alternatives included leaving individual trees and snags, as well as aggregated and dispersed retention (Franklin and Donato, 2020). Some of the most quickly adopted changes protected the aquatic system, including leaving dead wood in stream channels rather than removing it, and including riparian buffers to mitigate temperature and sediment increases (Franklin et al., 2018).

Various types of retention were formalized on Federal land in 1994 with the Northwest Forest Plan designed to maintain viable populations of the spotted owl (Thomas et al., 2006). It mandated retention on federal land along riparian areas and on hillslope positions within designated areas. Elements of this have been adopted across all ownerships through federal plans or state mandates. Currently, most municipal and state lands are managed using variable retention harvests (i.e. aggregated and dispersed retention and establishment of a new tree cohort), federal lands using variable density thinning (where a new cohort of trees is not established explicitly), and private timber lands that largely retain the minimum required by law (Franklin et al., 2018). Examples of different harvest styles are shown in **Figure 1.4**. Tribal lands were historically managed intensively under the Bureau of Indian Affairs and are now managed by Tribes in a wide variety of ways. The forest landscape is now largely a patchwork of replanted forests in various stages of development that are collectively younger than pre-colonization forests (**Figure 1.1**).

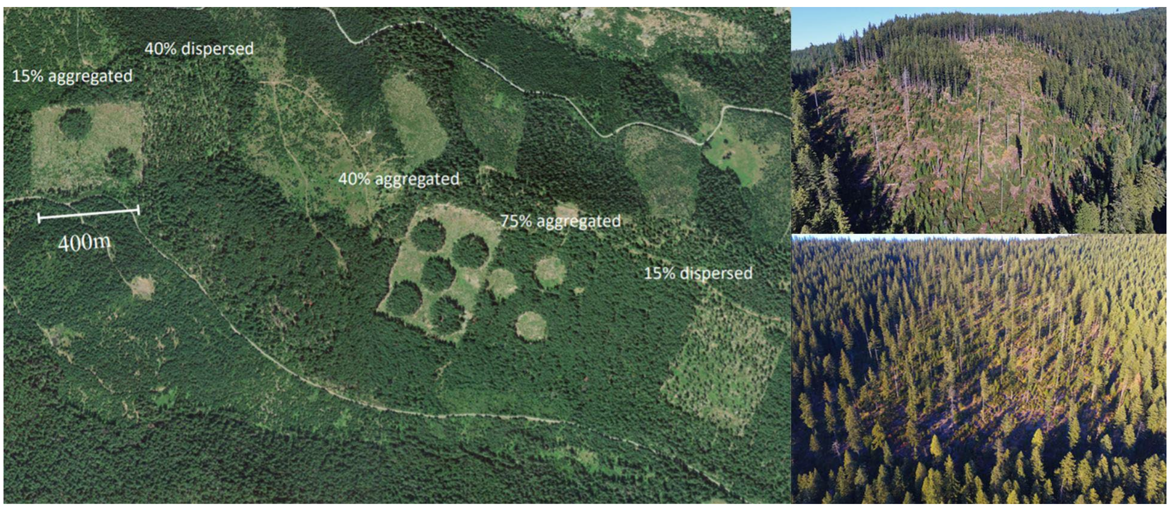

Figure 1.4: Examples of aggregated and dispersed retention harvests left. 15% aggregated and 40% dispersed from left are shown in more detail to right. Images from Harris and Betts (2017).

Current forest practices and some regulations (e.g. “free-to-grow”) are designed to re-establish conifer plantations quickly and thus truncate the pre-forest stage by decades via burning slash, spraying herbicides and planting trees. The result of these actions is that the complex pre-forest that once covered 3-30% of forested land in the west cascades during Holocene periods of similar fire regime (≤5,000 years age) is now <1% in western Washington (Donato et al., 2020; Whitlock et al., 2015, **Table 1.1**). Other underrepresented ecosystems are moist meadows and huckleberry fields that once probably covered ~5% of now forested area (Takaoka and Swanson, 2008). These areas were, and in some areas continue to be, maintained by indigenous land management practices such as burning and weeding, or by high-elevation snow fields (Franklin et al., 1971). **Table 1.1** summarizes the percent area of land currently within different development stages in western Washington in comparison to historical percentages prior to extensive logging, while **Table 1.2** shows estimates of forest in different classes in 2017 in the Snohomish watershed. Policies governing where and when forests were harvested have impacted current spatial arrangements of forest patches in different stages of development. The spatial arrangement of forest will be a large control on the ability to use forest practices to alter hydrologic responses at watershed scales.

Table 1.1: Percent land in forest classes adapted from Table 3 of Donato et al. 2020 based on simulations of natural fires in western Washington forests. Excludes tribal lands. Early-seral defined here as complex post-fire habitats with abundant dead wood.

Ownership	**Private**	**State**	**US Forest service**	**National Park Service**	**Natural range**
% land	30%	9%	55%	5%	—
Early-seral	0%	0%	0.2%	0%	1-30%
Mid-seral	73%	66%	50%	54%	8-36%
Late-seral (mature and old)	11%	25%	44%	44%	47-90%
Young plantation	16%	9%	5.8%	2%	0%

Table 1.2: Forested land in the Snohomish (WRIA 7) watershed broken down by forest cover class and ownership. Data are from the LEMMA group (Ohmann and Gregory, 2011) for forest inventories completed in 2017.

STRUCCOND	**Description**	**Federal**	**County/State**	**Tribal**	**Private**	**Total**
Open	Canopy cover <10%	3.4%	0.8%	0.1%	2.1%	6.4%
Sparse	Canopy cover 10-40%	1.6%	1.0%	0.1%	3.2%	5. 9%
Sapling/pole	Canopy >40%, Quadratic mean diameter <25 cm	7.9%	5.4%	0.5%	8.7%	22.4%
Small/medium	Canopy >40%, Quadratic mean diameter <25–50cm	14.8%	11.4%	0.4%	15.2%	41.9%
Large tree	Canopy >40%, Quadratic mean diameter <50–75cm	10.5%	3.0%	0.2%	2.9%	16.6%
Large/giant tree	Canopy >40%, Quadratic mean diameter >75cm	5.4%	1.1%	0.0%	0.5%	7.0%
Total		**44%**	**23%**	**1%**	**33%**	**100%**

Forest practices generally follow a management cycle of design, harvest, site preparation and planting, and tree tending (**Figure 1.5**). These practices fundamentally alter forest structure (spacing, number, and sizes of trees) and composition (relative quantities of which species are present). The time to complete one cycle (rotation age) will vary greatly depending on management philosophy. Two end members of the forest management continuum are: 1) **Production forestry**, with the goal of maximizing return on investment, and 2) **Forest restoration**, with the goal of restoring ecological integrity as a means to maximize ecosystem function (i.e. services) and timber harvest allowed only if consistent with reaching this goal. Production forestry typically operates on a 40 to 60 year rotation and its product is timber, while restoration has no explicit cycle unless harvest is planned in future restoration efforts.

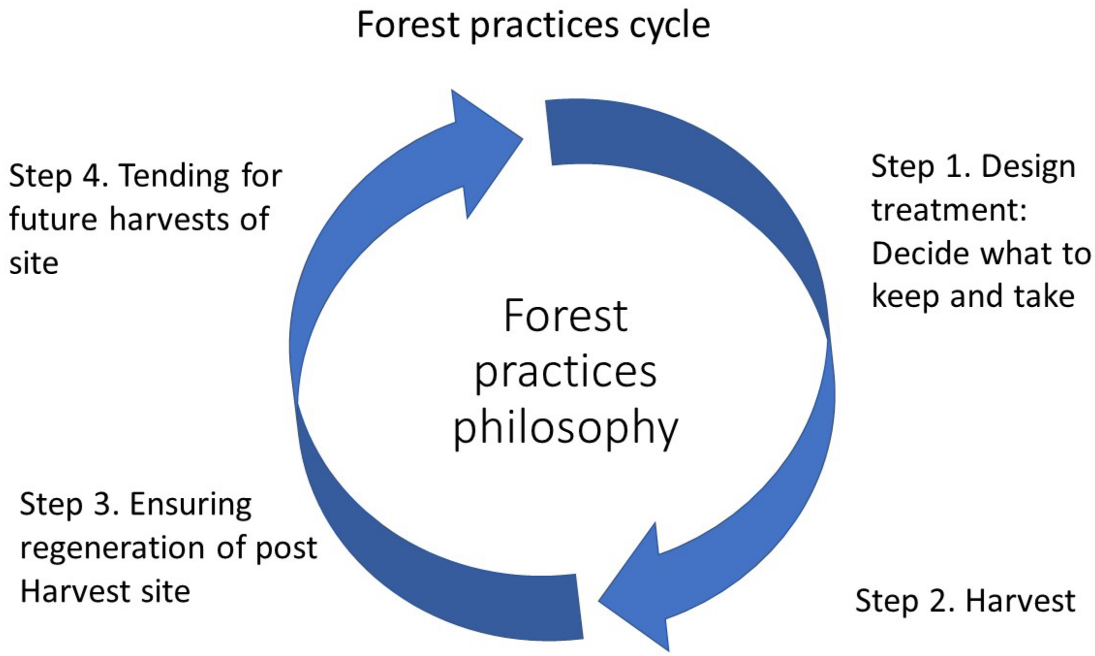

Figure 1.5: The forest management cycle consists of steps to harvest and create a new forest. The techniques used at each step and outcomes of forest practices depend on the management philosophy guiding silviculture.

Tulalip goals are both economic and ecologic, so are best suited to the management philosophy of Ecological Forest Management (Franklin et al., 2018), which spans a wide range between production and restoration forestry. Modern forest practices recognize the benefit of managing for multiple values and there are now many techniques (e.g. VRH) which attempt to regain some of the lost ecosystem functions from a pure production mindset, including retention of desirable habitat features such as snags, habitat trees and hardwood patches (**Figure 1.6**) that are not possible with clear cuts. In Appendix 3 we summarize forest practices and their ecological effects within the framework of the management cycle presented in **Figure 1.5**. We also include mitigation measures often required throughout the harvest cycle which introduces much complexity to forestry plans, especially ones on government land.

Figure 1.6: Elements of preharvest stand can be retained post-harvest. These can include individual elements like a tree killed to make a snag (left), particularly complex habitat trees (center), or areas of special interest like a gap with advanced regeneration of hardwoods (right).

Ecological forestry recognizes multiple values by not maximizing a single response, but instead, ensures the highest probability of a desired outcome while maintaining other values such as biodiversity and cultural resources. The principles of Ecological Forestry and silviculture based on these principles (Box 1) can be used to prepare forests to meet multiple objectives in a warmer world. These principles do not mean we need every ecosystem service everywhere, but that at large scale, we need all ecosystem parts (eg. meadows, old growth, social/cultural goals, habitat). Therefore, production forestry can be embedded within an ecologically managed landscape if it does not compromise composite ecosystem integrity. **Figure 1.7** shows an example of how ecological forestry could be incorporated into timber harvest patterns at the stand scale using VRH. Below we provide a short example for how ecological forestry could be used for riparian management by referencing a natural range of variability table (**Table 1.3**).

Box 1: Ecological forestry (Franklin et al. 2018 p18-19,92-93)

Philosophical principles

1. Restore the integrity of forests and associated ecosystems (keep all the parts!)
2. Develop policies and techniques to sustain a broad array of ecosystem service (do not optimize)
3. Be aware of changing science, techniques, and social goals and concerns
4. Manage to reduce risks and increase future options

Silviculture (Forest management system)

1. Maintain continuity of structure, function, and biota between harvests (using biological legacies)
2. Create structural complexity at multiple scales and biological richness
3. Management activities at times that reflect ecological processes
4. Planning and activities in context of larger scales
5. Emphasize activities to reduce risk to important values to increase future societal options

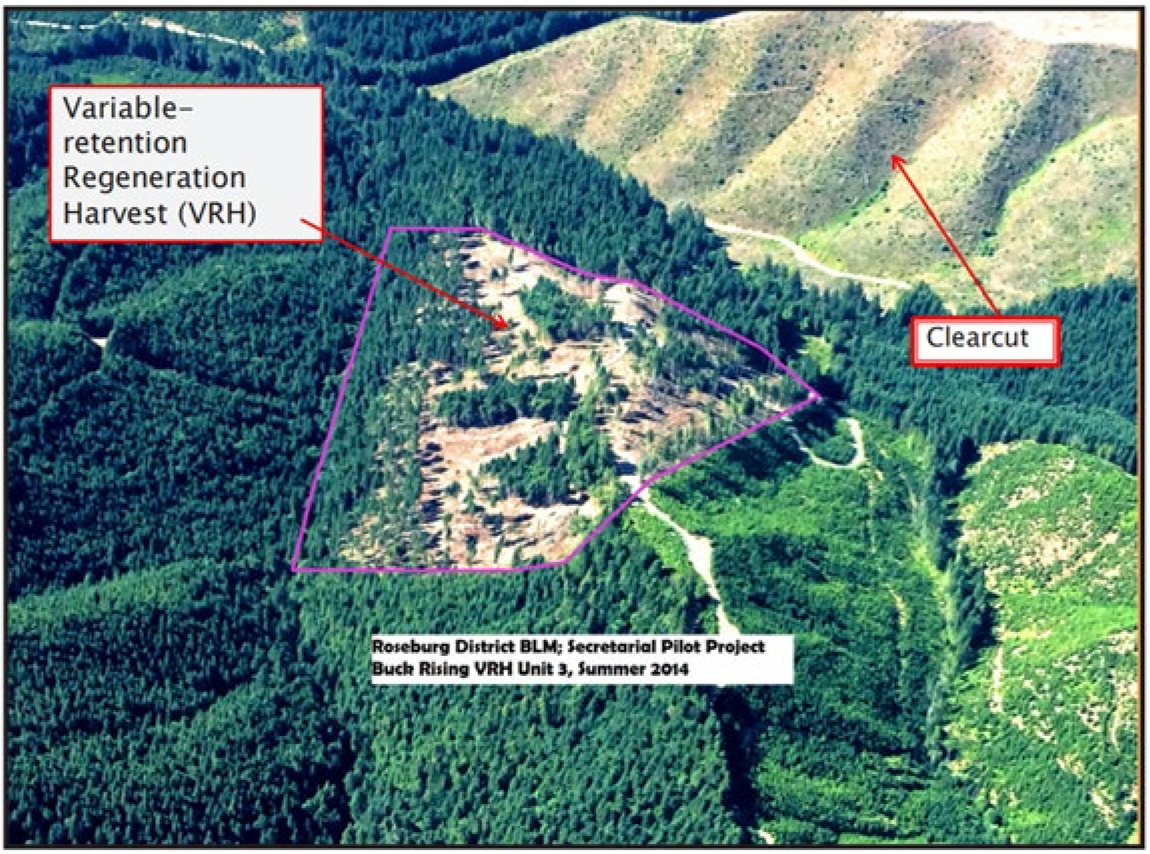

Figure 7.7: Contemporary harvests in Oregon. Management for ecological and economic objectives using variable retention harvests is in foreground while management to maximize return on investment with clear cutting, herbicides, and eventually planting in the background. Figure from Harris and Betts (2017).

Example of Ecological Forestry in a Riparian Zone

One major policy change after the 1960's was the addition of riparian buffers into production plans to mitigate sediment delivery to the streams and to regulate stream temperatures (Richardson et al., 2012). Natural riparian areas are not homogenous but are defined by disturbance with highly variable forest composition and structure due to frequent disturbances (Table 1.3). However, many of the riparian buffers in the western Pacific Norwest are problematic because they are carved from low-diversity rapidly transpiring plantations of Douglas-fir, or simplified alder thickets (Emmingham, 2000), thus have low species and structural diversity and low amounts of dead wood for habitat and stream inputs. Although the buffers are shading and limiting sediment into the streams (Jackson et al., 2001), they are not reaching their potential for ecological benefits (Gregory et al., 1991). Managers can address the problem of low structural and compositional diversity within legacy stream buffers with an ecological management strategy using these three underlying principles:

1) Recognize the importance of large dead wood in and out of the stream
2) Recognize the importance of hardwood and herbaceous individuals and patches
3) Identify important reciprocal inputs between land and water in relation to nearby land use

Following an Ecological Forestry mindset, appropriate buffer prescriptions can be devised by consulting the historic range of variability (**Table 1.3**) suited to the Pacific Northwest. Targets within historic ranges can be chosen and adjusted based on site conditions. For example, they may free growing space around already dominant or habitat trees, utilize existing gaps to encourage hardwood patches, and tip leaning trees into the stream (**Figure 1.8**).

Table 1.3: Natural range of variability of target attributes for riparian areas associated with small to medium sized streams in Douglas-fir western hemlock forests.

Attribute	Target range	Sources
Large trees	≥50 cm diameter for stream input, snags, and live trees	(Pollock and Beechie, 2014)
Wood in the river	12-25% coverage 0.2-0.8 pieces/meter >10 cm diameter	(Anderson and Sedell, 1979; Bilby and Ward, 1989)
Logs	6.5-18.5% cover	(Pabst and Spies, 1999)
Snags	>3/ha hardwood within 32m of stream >19/ha conifer within 32m of stream	(Pabst and Spies, 1999)
Hardwood composition	30-80% of basal area (higher in flood plain), 20-60% canopy cover	(Barker et al., 2002; Nierenberg and Hibbs, 2000)
Overstory canopy	70-87%	(Brosofske et al., 1997; Pabst and Spies, 1999)
Open patches	>20% ground area	(Nierenberg and Hibbs, 2000)
Environmental buffering	fish bearing, ≥30-60m non-fish bearing ≥15-30m	(Anderson et al., 2007; Brosofske et al., 1997; Rykken et al., 2007)

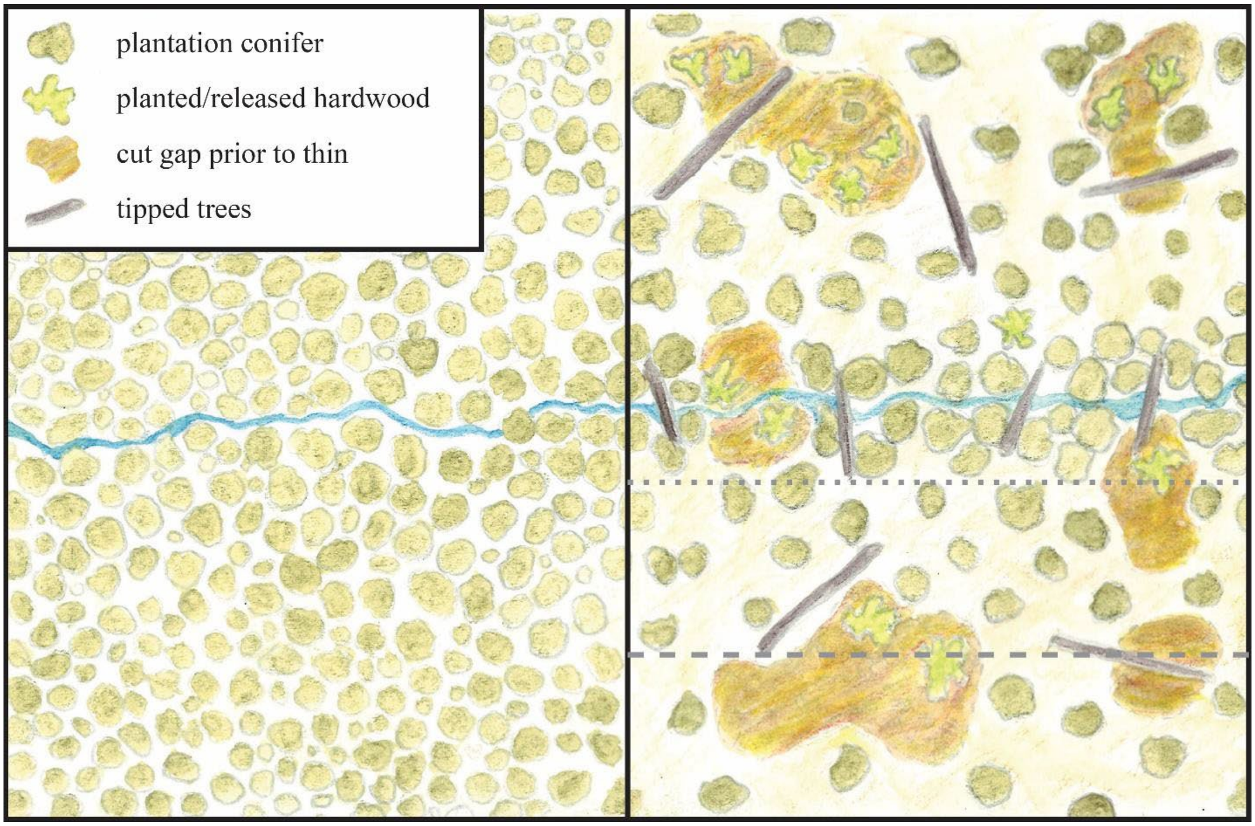

Figure 1.8: Conceptualization of ecological riparian buffer treatment in a conifer plantation. Left is untreated plantation, right is ~10 years post treatment. Dotted line is inner 15m with tipped trees from outer 5m. Dashed line separates light and moderate thinning. If adjacent areas are thinned rather than cleared, then a narrower buffer may be credible.

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Section 2. Forest Cover and the Water Balance

This section provides landscape-scale background for how forest manipulation alters stream flows by placing forests within the context of the water balance. It is useful to conceptualize forest cover as a filter through which precipitation must pass to reach the ground and as a straw that draws water from the root zone before it contributes to streamflow. Through these processes, forests regulate the rate at which rain reaches the ground and the amount of soil moisture discharged as runoff. In section 2.1 we begin by focusing on how the forest canopy regulates water through changes in leaf area. Section 2.2 discusses how forests interact with surface and subsurface moisture. In section 2.3, we discuss subsurface processes and connect forest-regulated processes within the geologic context of hillslopes and groundwater recharge. In section 2.4 we briefly touch on hydrograph phases and the need to integrate hillslope and valley-bottom processes in strategies to alter flows.

Precipitation (which controls water inputs) and geology (which controls water storage and routing), are likely an order of importance higher than forests (which use available water) for determining stream flow response (Safeeq et al., 2013; Tague and Grant, 2004). Thus, geologic and climatic context must be considered in forest practices which seek to influence stream flow. In some geologic settings (discussed below), forest manipulation on the hillslopes may have a more limited effect than others. Climate modeling and empirical data shows future streams will be drying earlier with the largest changes in low flows occurring in July (Luce and Holden, 2009; Safeeq et al., 2013; Stewart et al., 2005) as well as 20 to 40% increases in peak flows in the North Cascades by 2080 (Safeeq et al., 2015). **Table 2.1** shows some key attributes of climate change relevant for streamflow. For more specific data and climate modelling including the Snohomish basin we refer the reader to summary tables from the University of Washington's Climate Impacts Group's state of knowledge report (Mauger et al., 2015).

Table 2.1: Summary of key changes related to streamflow in the Puget Sound area from (Mauger et al. (2015)

Variable	**Trends**
Observed change (1895-2014)	
Temperature	Nighttime: +1℃, Daytime:+0.7℃, max: +0.4℃ More frequent warm nights, day heat waves not different
Precipitation	Annual not different, spring +2.3% per decade, no other changes due to high variability Heavy 24-hr rains: occur 2 d year^{-1}
Runoff	Annual trends weak, but lower flows in dry years
Predicted change	
Temperature	2 to 10 times historic change and warming in all seasons by 2080
Precipitation	Summer precip: -22%, high variability in other seasons Heavy 24-hr rains: expected 4 to 9 d year^{-1} by 2080
Snowpack/Runoff	Snowpack: -20 to -40% by 2040 Shift to earlier water year, most change in transient snow zone Higher winter and lower summer flows More intense flooding and lower low flows Land use change may have more impact than climate

In order to assist in modeling efforts and to present consistent terminology for water balance processes within this section, we present a conceptual flow chart (**Figure 2.1**) labeling the processes that route water through various abiotic (grey) storage units. Processes are colored green if they can be directly changed with forest practices and blue if they are indirectly or not changed with forest practices. Terms used in the diagram to describe flow paths and water storage reservoirs are defined in the glossary and used in subsequent sections. Approximate proportions of annual precipitation flowing between water storage units are represented by the thickness of arrows.

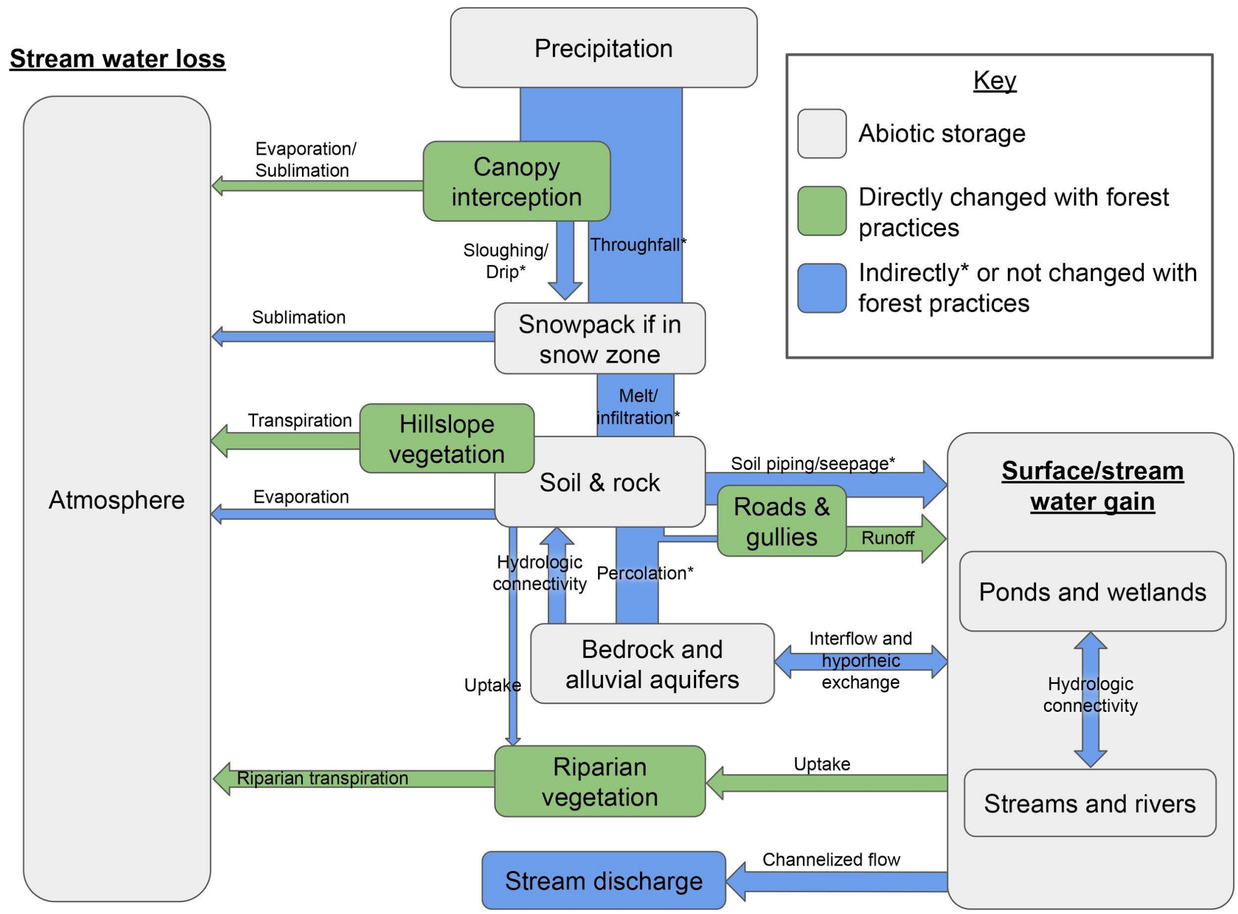

Figure 2.1: Conceptual model of how forests augment hydrologic processes and water storage. Process terms are described in the glossary.

2.1 The Forest Canopy

The forest canopy undergoes predictable development that alters hydrology. After severe disturbance, there are typically decades where herbs, shrubs, and tree seedlings or resprouts are the dominant vegetation. In this period, the leaf area index (LAI), defined as the one-sided leaf area per unit ground area, is low. This period therefore has low interception and transpiration. As trees enter the mid-seral stage and the canopy closes, leaf area rapidly increases and is concentrated in the upper canopy (Franklin et al., 2002) blocking the most light from the understory (Kaylor et al., 2017). This and following stages have relatively high interception and transpiration. During the late-seral mature phase, leaf area is likely at a maximum and an increasing proportion is held in understory trees as overstory trees die (Sillett et al., 2018; Van Pelt et al., 2016). In late-seral old forests, leaf area is comparable to mature forests, however most is now held in the low canopy in understory trees and lower positions on old trees as their crowns deepen to take advantage of new gaps (Franklin and Waring, 1980; Van Pelt et al., 2016).

Water loss through interception and transpiration is directly related to LAI and is often modeled with it (Goeking and Tarboton, 2020 p.186; Vose et al., 2003 p.267) because leaves catch precipitation that then evaporates and they transpire water during photosynthesis (i.e. evapotranspiration). However, forests with similar leaf area can have different interception and transpiration rates (Moore et al., 2004) because of shifts in where leaf area is deployed, the species deploying it, and declining water use per unit of sapwood (sap flow density) as trees age. For example, LAI can reach maximum levels early in young monocultures (Vose et al 2000), then vary as stands develop and LAI is redistributed among other species in different canopy positions (Thomas and Winner, 2000, **Table 2.2**). Old forests with large trees towering above younger trees and gaps have more leaf area in shaded non-dominant trees, shrubs, and herbs than in a younger forest with a single canopy layer (**Figure 2.2**). Additionally, more rain reaches the understory through gaps in old forests (Pypker et al., 2005, **Appendix 4**) where evaporation is less and plants transpire relatively slowly. On aggregate, old forests transpire less water than young forests despite having similar leaf area (Moore et al., 2004), so leaf area is a better measure of transpiration capacity than actual transpiration as forests age (Vose et al., 2003).

Table 2.2: Leaf area of Douglas-fir dominated forests for stands in Washington and Oregon. DF = Douglas-fir, WH = western hemlock, and WRC = western red cedar. Totals in **bold**. Data from Sillett et al., (2018), Velazquez-Martinez et al., (1992), Turner et al., (2000 and Weiskittel and Maguire, (2007)

	LAI (ha ha^{-1})						
Stand age	**DF**	**WH**	**WRC**	**Hardwood**	**Other**	**Total**	**Notes**
20-30	10.7	–	–	–	–	**10.7**	Plantation
20-80	5-6	–	–	–	–	**5-6**	thinning and disease
100	6.3	0.0	0.0	1.8	0.2	**8.3**	Natural
160	3.8	0.1	0.1	2.9	0.3	**7.1**	Natural
200	6.7	0.9	0.0	2.8	2.0	**12.3**	Natural
280	4.0	2.8	0.2	1.5	0.2	**8.7**	Natural
350	6.4	1.4	0.2	2.8	1.2	**12.0**	Natural
480	4.0	5.0	3.1	0.6	0.3	**12.9**	Natural
550	2.1	4.6	1.8	0.9	0.8	**10.2**	Natural
630	4.0	3.4	0.3	0.5	0.4	**8.7**	Natural
650	3.4	2.4	3.1	4.9	0.9	**14.7**	Natural

Figure 2.2: Leaf area in younger forests (left) with few gaps is distributed near the top of the largest individuals, while leaf area in older forests is more evenly distributed in less well-illuminated positions and in understory species (right). Figure adapted from (Sillett et al., 2020).

Conifer versus hardwood cover also matters for tree water usages in the Pacific Northwest. Evapotranspiration is higher for conifers than hardwoods and increases with precipitation (mm mm^{-1}) at a rates of ~0.70 and ~0.45 respectively (Ford et al., 2010 Fig 1 within). Many studies show conifers use more water on an annual basis than hardwoods (e.g. Bosch and Hewlett, 1982; Nippgen et al., 2016; Sahin and Hall, 1996; Swank and Douglass, 1974). Conifers transpire ~19% of annual transpiration in winter (Moore et al., 2011a) at the same time as ~80% of their annual interception (Link et al., 2004). During this time, hardwoods are leafless, intercepting little (e.g. Maule, 1934), and transpiring none, thus runoff ratio (runoff/rain) in hardwoods in winter is 30% greater (Nippgen et al., 2016). Hardwoods can transpire more per unit sapwood area during the growing season (Moore et al., 2011a, 2004), so hardwoods may use more water in summer than a similarly statured conifer.

Forest structure also has strong effects on snow through the processes of interception, wind redistribution, and energy transfer. Forest canopy can intercept 60 to 80% of snowfall during storms, of which 14% can be lost by sublimation in maritime climates, the remainder either melts or sloughs to the ground (Storck et al., 2002). By the time of melt, openings can accumulate 30 to >300% more snow than under forest canopy (Dickerson-Lange et al., 2017; Martin et al., 2013; Pomeroy and Schmidt, 1993). Groups of deciduous hardwoods act like openings, accumulating similar amounts of snow (Maule, 1934). Wind can redistribute snow from openings into shade and prolong its presence under canopy in spring (Dickerson-Lange et al., 2017). Melt-rates during warm winter periods are higher under forest because long-wave radiation emitted by trees dominates melt energy, while melt rates are higher in the open in the spring because short-wave radiation from the sun dominates (Lawler and Link, 2011; Lundquist et al., 2013). Therefore, more area in openings exposes higher volume of snow to melt at the same time (Marks et al., 1998). **Table 2.3** synthesizes the generalized responses of interception and evapotranspiration to different forest conditions.

Table 2.3: Relative interception and transpiration loss from forests in different stages of development and for hardwoods vs deciduous trees

Forest condition	Interception loss	Evapotranspiration
Early-seral, non-forest, gaps	Low	Low
Mid-seral conifer (young and mature)	High year round	High
Late-seral old conifer	Intermediate	Intermediate
Hardwoods	Low-intermediate, seasonal	Lower annual, higher spring

It is generally true that more vegetation intercepts and transpires more water, so non-forest has higher water yields than any forest stage (e.g. Farley et al., 2005; Zhang et al., 2001). There are at least two exceptions. First, up to 40% of continental precipitation is from transpired water, so at large scale, trees pumping water into the atmosphere benefit water yields downwind (Creed et al., 2019; Ellison et al., 2012). Second, condensation and fog drip contribute significantly to water yields in fog-prone basins. Here, cutting actually decreases water yield up to 30% (Harr, 1982; Ingwersen, 1985). Since we are advocating an ecological approach, these concerns are accounted for by leaving considerable trees at any given time. If good data or models exist for where fog is common and fog contributions are expected to exceed transpiration loss, such areas should be managed for old-growth structure with emergent crowns to expose the most leaves to condensation or at least have constant canopy cover if other objectives make this impossible.

2.2 Surface runoff and Subsurface Moisture

The Pacific Northwest is characterized by cool wet winters when soils saturate (recharge) and plant demands are low, followed by dry summers (<10% precipitation) when plant and evaporative demand exceed subsurface water supply (i.e. water deficit) (Mauger et al., 2015). Precipitation generally falls into three zones along elevation bands, the snow zone, the transient snow zone, and the rain zone (**Table 2.4**) which supply peak runoff at different times. Stream discharge from rain rises and falls quickly after storms (e.g. Perkins and Jones, 2008). In transient snow watersheds, snow may accumulate and then get rained on during warm winter weather, producing large floods (described more below). Because temperatures hover near freezing, melt and streamflow in these watersheds is very sensitive to temperature (Grant et al., 2008; Hamlet and Lettenmaier, 2007; Safeeq et al., 2015). Snow watersheds accumulate precipitation then release water as seasonal temperatures rise. When rain or meltwater from snow exceeds infiltration or percolation rates into the soil, it will collect on or near the surface and run-off whether or not the subsurface is completely saturated. Instantaneous rainfall exceeding infiltration is unlikely in our forests where infiltration is high (Ilstedt et al., 2016; Perry et al., 2016), but not on compacted road surfaces (MacDonald and Coe, 2008). Surface and subsurface water that quickly exits watersheds contribute to peak flows whereas infiltrated water is released much slower and contributes to subsurface moisture recession and base flows.

Table 2.4. Precipitation zones in the Snohomish basin

Zone	**Elevation Range** (Grant et al 2008)	**% Forested**	**Timing of Recharge** (Safeeq et al., 2014 Figure 6 within)
Snow Zone	>1500m	Medium	April-July
Transient Snow Zone	400-1500m	High	Variable
Rain Zone	0-400m	High	Oct-Jan

Roughly 60% of large winter peak flows in the Pacific Northwest are from rain-on-snow events (Jones and Grant, 1996). The largest floods occur when warm air and copious rain contact large snow accumulations (Marks et al., 1998) during atmospheric river storms (Harr, 1986; Neiman et al., 2011). Run-off from these storms contain ~10 to 50% snowmelt along with rainwater (Marks et al., 1998; Wayand et al., 2015). Floods can also be caused by copious rain below the snow zone, but are smaller than the rain-on-snow events. In both cases, rain or melt-rate exceed soil recharge rates and become surface runoff or are piped quickly to streams in shallow subsurface pathways. Rain-on-snow events occur ~9.2 days year^{-1} but occur as many as 30 days year^{-1} and during flood events with ~20-year recurrence intervals, precipitation rates are as much as 83 mm day^{-1} (Safeeq et al., 2015). Watershed attributes such as soil compaction, road-to-stream connectivity, and synchrony of runoff increase the rate at which surface water reaches streams and will increase peak flows (**Figure 2.3**).

Roads increase compaction (reducing infiltration), bring subsurface flows to the surface in road cuts, and extend the surface runoff network, all of which increase runoff rate. Road density in western Washington forest lands ranges from 1.5 to 4.7 km km^{-1} and up to 50% of road runoff has entered streams in the past (Bowling et al., 2000; Dubé et al., 2010). Direct runoff to streams is likely smaller subsequent to 2001 guidelines stipulating road runoff be diverted by 2021 before reaching riparian zones (WAC 222-24-020), but their effects have not yet been evaluated. Infiltration in forest soils normally exceeds precipitation (Perry et al., 2016), but compacted road surfaces convert water that would have infiltrated to runoff. Mid-slope roads intercept the most subsurface water flow, converting it to surface flow, and if road ditches are not up to current guidelines, can divert it to streams (Jones et al., 2000). Ridge roads have the least cumulative water gain above them, while valley bottom roads intercept flows already destined for runoff and cross fewer drainages (Jones et al., 2000). Collectively roads can increase surface drainage networks 25 to 50% (Wemple et al., 2001), with the effect of synchronizing flow (Jones and Grant, 1996). Roughly 38% of surveyed area has road lengths exceeding 25% of steam length in western Washington (Dubé et al., 2010).

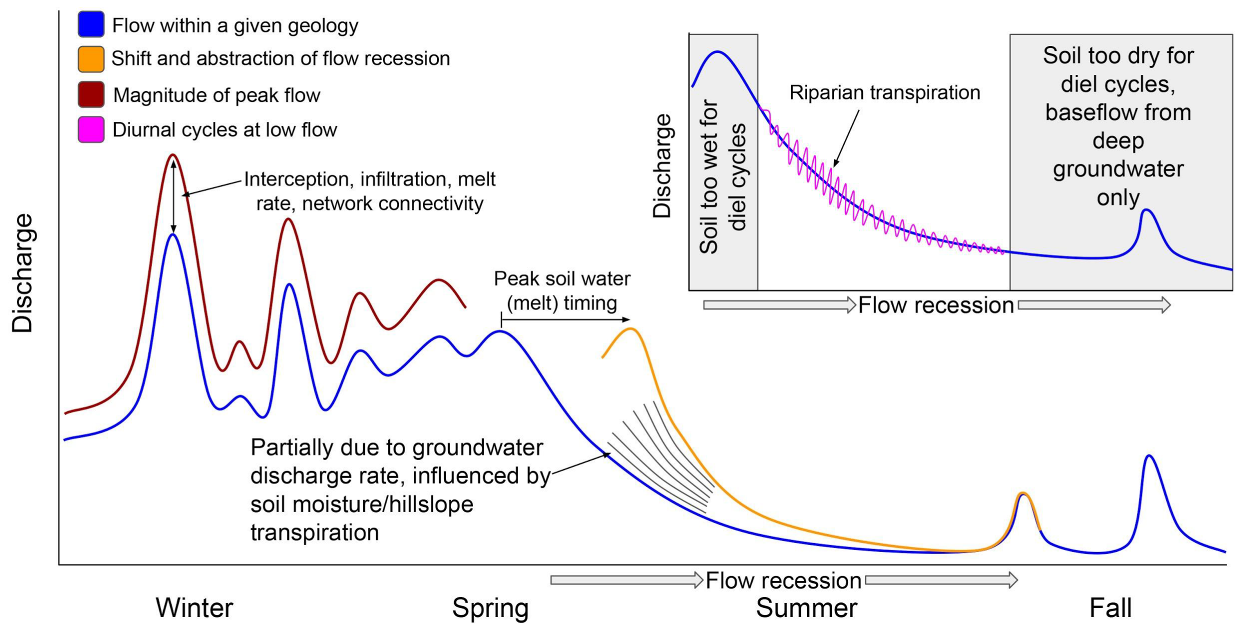

Figure 2.3: Conceptual model of hydrograph variability is related to hydrological processes. Magnitude of high flows is related to processes controlling interception, infiltration, and surface runoff (network) connectivity. Peak soil moisture sets the point at which hydrograph recedes in spring, while transpiration changes the shape of the recession curve as well as magnitude of diel cycles.

Snow retention and disappearance date is related to peak soil moisture (Harpold et al., 2015; Molotch et al., 2009), and therefore onset of moisture depletion and timing of flows (Safeeq et al., 2013). The date snow disappears is controlled by snow accumulation more than melt rate (Dickerson-Lange et al., 2017), thus is most closely tied to interception (Storck et al., 2002). Therefore, increasing snow retention and delaying melt may encourage higher flows during hydrograph recession (**Figure 2.3**). However, since hydrograph recession from snowmelt is normally exponential, even moderate delays to the start of the snowmelt will not elevate low flows near the end of the summer or fall when higher base flows are most needed (**Figure 2.4**).

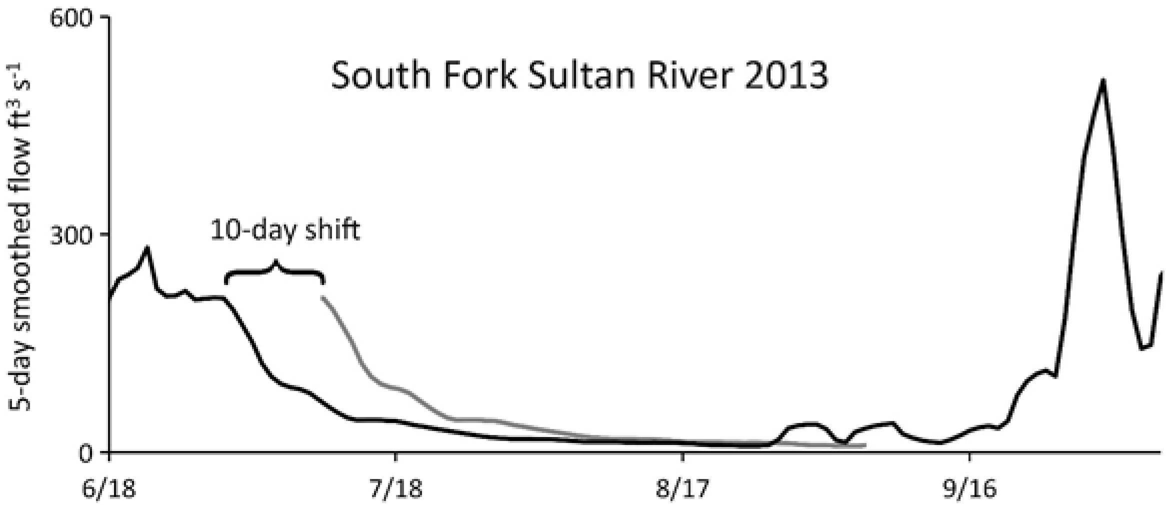

Figure 2.4: Hydrograph of the South Fork Sultan river showing exponential flow recession to base flows and theoretical 10-day shift in timing of last snowmelt.

Although relationships between aspect and snowmelt processes at different elevations, solar angles, and seasons are complex, a general trend is that north aspects will retain snow longer in canopy gaps than south aspects. In winter, radiation emitted from trees rather than from the sun dominates total energy inputs and total energy is low (Lawler and Link, 2011; Lundquist et al., 2013). Because of low total radiation, winter snowmelt on south-facing gaps are unlikely to overcompensate for higher snow accumulation in gaps unless snowfall is low (Strasser et al., 2011). Winter melts will probably also vary less with aspect in the transient snow zone of the western Pacific Northwest where cloudy skies, warmer temperatures, and high humidity can mute elevation and aspect differences (Harpold and Brooks, 2018; Musselman et al., 2015; Seyednasrollah and Kumar, 2014; Varhola et al., 2010). During spring through summer, increasing sun angle and clearer skies means solar radiation dominates (Musselman et al., 2015). The switch from tree-emitted-energy dominance to solar-radiation dominance can happen in medium-sized gaps (4 tree-heights in diameter) as early as late January on south aspects, and by March on north aspects at 47 degrees latitude (Seyednasrollah and Kumar, 2014). Regardless of when the switch occurs, most snowmelt is after it, so shade is most important at this time. Gaps in north aspects receive ~30% less radiation by April than gaps on south aspects (Seyednasrollah and Kumar, 2014 Figure 9d within) and smaller canopy gaps receive less than large openings (Musselman et al., 2015). Despite this general gap size trend, larger gaps on north aspects will retain snow longer than larger gaps on south aspects because a larger proportion of their area is exposed to less radiation than they would be in the open (60-80% vs ~35%) do to edge shading (Seyednasrollah and Kumar, 2014 Figure 10 within).

Aspect can moderate soil moisture drawdown after snowmelt so actions to increase soil moisture on northerly aspects will probably contribute more to soil moisture during hydrograph recession than actions on southerly aspects. Transpiration scales with moisture (Zhang et al., 2001) and will use available water during summer until lack of soil moisture limits further transpiration (Bond et al., 2002). Because transpiration is controlled more by soil moisture than radiation (Stoy et al., 2006; Troendle and Olsen, 1994), reductions in solar radiation with aspect are less important if covered by forests with high leaf area. Additionally, northern aspects often have more vegetation than southerly aspects (MacDonald and Stednick, 2003). Despite this, north aspects can retain 5 to 25% more soil moisture (Geroy et al., 2011; Moore et al., 2011a) and this increased moisture explains why transpiration is counterintuitively higher on north aspects (Hassler et al., 2018). Thus, gains from reducing vegetation (i.e. transpiration) on north aspects is likely disproportionally important.

Subsurface soil and rock moisture (unconsolidated rock below soil but above the groundwater tables) accumulates during the wet season, and combined with vegetation cover, mediates the initiation and magnitude of groundwater recharge and runoff (Moore et al., 2011b; Safeeq et al., 2013; Stoy et al., 2006; Tashie et al., 2019). Recharge rates to the groundwater table are typically much lower in forested areas than non-forested because the trees use most of the soil and rock moisture for transpiration (Carroll et al., 2019). Vegetation change alters runoff more in wet versus dry climates and in wet versus dry years because wetter soil allows it to transpire for longer during the growing season (Bentley and Coomes, 2020; MacDonald and Stednick, 2003). Water uptake from transpiration dries soil in the root zone, so reduces percolation to aquifers supplying low flow (Fan et al., 2017), especially in early summer (Tashie et al., 2019, **Figure 2.3**). During the summer months, evaporative demand is high, groundwater levels decline slowly, runoff is small, and large changes in soil and rock moisture occur (Rempe and Dietrich, 2018). The pattern and magnitude of soil and rock moisture decline shows little variability between wet years and drought years because it’s drying is regulated by tree transpiration rather than quantity of annual precipitation (Rempe and Dietrich, 2018). Lateral flow of water through unsaturated zones (zones above water table) is typically short, ranging from 1 to several hundred meters (Klaus and Jackson, 2018) and stops as soils dry (Grayson et al., 1997; Jencso et al., 2010). In sum, any soil moisture not transpired by plants percolates deeper into the subsurface and is discharged into the streams as baseflow (Klaus and Jackson, 2018).

In a review of 78 studies of streamflow response to disturbance, most attribute diminished low flows to increases in transpiration with vegetation recovery rather than interception (Geoking and Tarbaton 2020). While forests can intercept and transpire similar amounts of annual precipitation (20 to 25%), nearly 80% of interception occurs during large storms when soils are already moist (Link et al., 2004), while most transpiration occurs in spring and summer as soils dry (e.g. Moore et al., 2011a). Therefore, increases in low flows from decreases in transpiration are proportionally more than for reductions in interception (MacDonald and Stednick, 2003).

During low flows, diel (24-hr) stream fluctuations (**Figure 2.3** inset) track tree water demand (with a time lag) in late spring and summer until the water table lowers below the root zone (Lundquist and Cayan, 2002; Moore et al., 2011b). Diel fluctuations account for 1 to ~10% of accumulated streamflow (Bond et al., 2002; Salemi et al., 2012) and can stop if riparian vegetation is removed, even if upslope vegetation is untouched (Dunford and Fletcher, 1947). Summer transpiration loss can be accounted for by only 0.1-0.3% of land area in narrow bands along streams (Bond et al., 2002). Thus, riparian transpiration may have significant impacts on low flows relative to hillslopes.

2.3 Subsurface Water Storage and Flow

Understanding how flows might respond to forest management is typically done with paired watersheds that ignore subsurface storage, but our understanding will benefit from accounting for storage impacts on flows (McDonnell et al., 2018; Shaw et al., 2013). One approach taken by Fonley et al., (2019) was to 'do hydrology backwards' and model evapotranspiration from estimates of water contained in subsurface storage reservoirs. Storage units and the processes that link them can be best visualized at the scale of a hillslope. **Figure 2.5** shows discharge into a stream from a hillslope with an emphasis on subsurface pathways and the role vegetation plays in regulating these pathways.

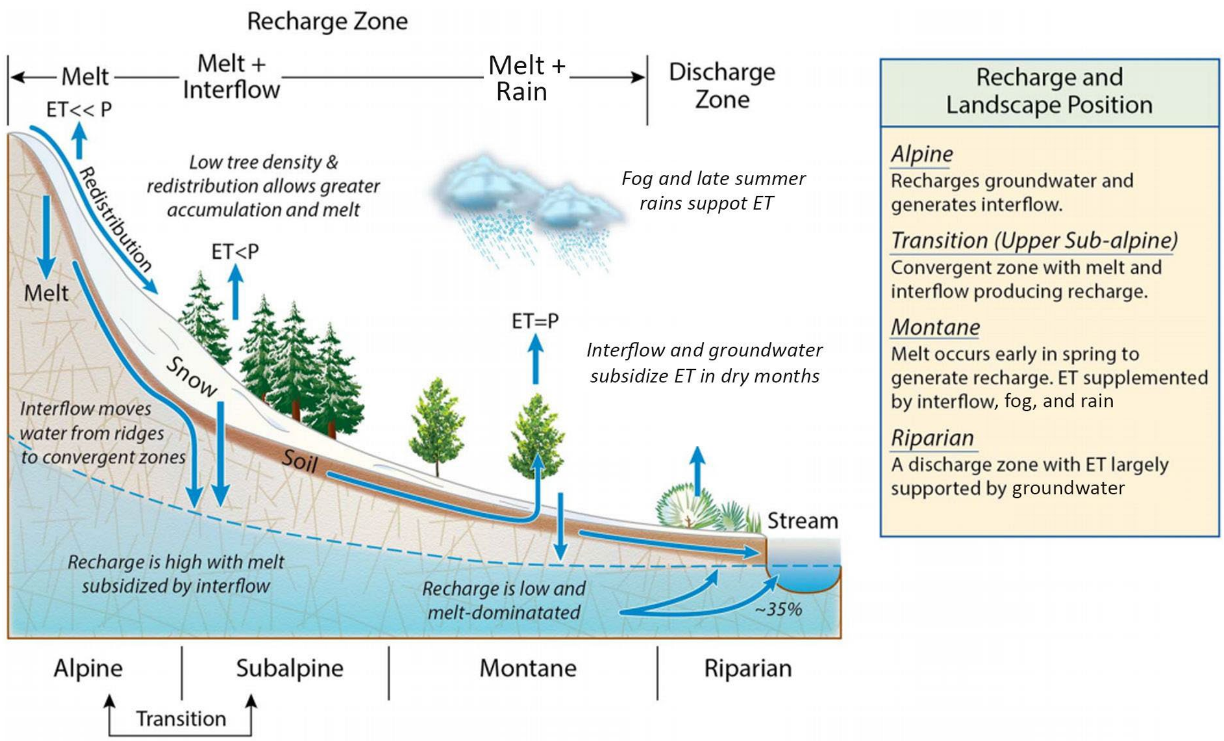

Figure 2.5: Water recharge and distribution on a hillslope. Figure modified after a snow-dominated watershed in Colorado by Carroll et al. (2019) to include fog and rain. In the western Pacific Northwest, more montane recharge is from winter rain as well as snowmelt.

Interflow is the term for the lateral water movement through the soil and fractured bedrock above the water table whereas groundwater is the term for water that is below the water table. Interflow is not continuously connected to the valley except rarely, during the wettest of storms (Stieglitz et al., 2003). Typically, only the hillslopes closest to the valley bottom contribute water to the streams in this manner (Carroll et al., 2019; Jencso et al., 2010; Klaus and Jackson, 2018). Soil seepage and soil piping are types of interflow that route water more slowly through macro pores and or more rapidly through subsurface soil pipes, respectively. Seepage and piping route storm water into surface convergent zones where it becomes concentrated surface flow, or run-off. Run-off processes are concurrent with saturation of the ground during the storms, melt of snowpack, or convergence of subsurface water due to topography (Carroll et al., 2019; Lundquist and Flint, 2006; Perkins and Jones, 2008).

Water percolates in topographic convergent zones until it reaches the groundwater table, which is the boundary between where pore spaces and voids are completely filled with water (saturated zone) and where pore spaces include both water and air (unsaturated zone). In the Cascades, stream responses are either defined by shallower (westerly), or deeper (easterly) groundwater pathways (Nickolas et al., 2017; Safeeq et al., 2014; Tague and Grant, 2009, 2004). The deeper pathways dominate the hydrograph signature at the low end of flows while shallower pathways dominate the hydrograph signature at peak flows (Tague and Grant, 2009). Old fractured bedrock acts as a capacitor, dampening peaks and releasing water later into the year while younger, less weathered bedrock and shallower soils have “flashier” hydrographs regressing quickly to baseflow (Tague and Grant, 2004). Counterintuitively, deeper pathways make absolute low flow 4 to 5 times more sensitive to recharge because there is flow in the late summer and fall to augment, whereas in flashy systems, low flows bottom out lower and earlier (Tague and Grant, 2004). Groundwater aquifers discharge water downslope at different timescales ranging from days to centuries (Smerdon and Redding, 2007; Winkler et al., 2010) and regulate the recession of flows and the water available to streams between storms and during the dry season (Shaw et al., 2013). Water inputs from intermediate flow paths such as seepage and transpiration regulate the rate of recession of peak flows and seasonal recession to baseflow levels (Tashie et al., 2019, **Figure 2.3**).

In basins with snow, most groundwater recharge is topographically controlled in the snow zone above or just below the tree line (Carroll et al., 2019). Here snow and snowmelt collects into surface depressions and convergent zones and then slowly percolates into the water table over the summer. Within a basin, more discharge per unit drainage area at low flow indicate deeper groundwater contributions (e.g. Tague and Grant, 2009 Fig 4b within). Early snowmelt in deep groundwater basins tends to reduce summer low flows, while early snowmelt with shallow groundwater systems tends to make onset of summer low flows earlier (Tague and Grant, 2009). If a basin has more shallow surface flows, then manipulating forest cover to reduce transpiration will have greater effect closer to the stream and in early summer. Basins with deeper groundwater are more sensitive to changes in snowpack and snowmelt than solely rain fed systems by an order of magnitude (Jefferson et al., 2008; Mayer and Naman, 2011; Safeeq et al., 2013). So, for sections of hillslope with snowmelt, forest practices that encourage snow accumulation and depressions in which meltwater can pool and then percolate rather than quickly running off, should help reduce peak flows and contribute to higher regional groundwater tables.

Isotope signatures suggest generally shallower paths for moisture in west-facing basins of the North and Middle Cascades. These basins intercept storms from the Pacific Ocean such that precipitation increases with elevation. Higher elevations initially have fewer ocean signature isotopes than lower elevations. Soil water then percolates and mixes to various degrees with groundwater, and glacial or snowmelt before being discharged as streamflow. Isotopic signatures in the Snoqualmie drainage, which is the southern branch of the Snohomish system, are tightly coupled to watershed elevation suggesting less mixing and shallow flow paths, while isotopic signatures to the north in the Skagit are diluted, likely from glacial and snowmelt (McGill et al., 2020). When summer isotopic signatures are strong, it suggests that source water is from lower elevations (i.e. less from upland snow). This appears to be the case in the Snoqualmie, so base flows will be less affected by snowmelt changes there than a river like the Skagit (McGill et al., 2021).

2.4 Streamflow Phases

Streams and Rivers in the Pacific Northwest have four discharge phases during a year which we graphically show in **Figure 2.6** and summarize below:

1) **Phase I**: Winter rain and snow accumulation. Moderate to low flows punctuated by brief but intense rain-on-snow events in the transient snow zone. Soil and rock moisture is increasing in lower elevation and frozen in higher elevations. (~Dec-Mar)
2) **Phase II**: Spring snowmelt with high soil and rock moisture and sustained higher flows punctuated with runoff peaks from snowmelt from lower elevation snow due to higher temperatures and spring rains. High elevation snowpack still accumulates. In rain-dominated watersheds with limited to no snow zones, the snowmelt phase disappears, so a higher proportion of runoff occurs earlier. Rains cause near instantaneous spikes followed by exponential flow recession to an underlying flow (~Mar-June)
3) **Phase III**: Summer recession with smoothly declining flow as melt water is routed through stream networks and streams regress to stable base flows based on groundwater tables and pathways. Soil and rock moisture storage is depleted by plant evapotranspiration. High elevation snowpack is slowly depleted (June-September) and deeper groundwater tables are slowly recharged from high elevation depressions. (~Jun-Sept)
4) **Phase IV**: Fall rains create runoff spikes followed by exponential regression to base flow. Baseflow supported by groundwater storage and augmented by rain and fog (~Sept-Dec)

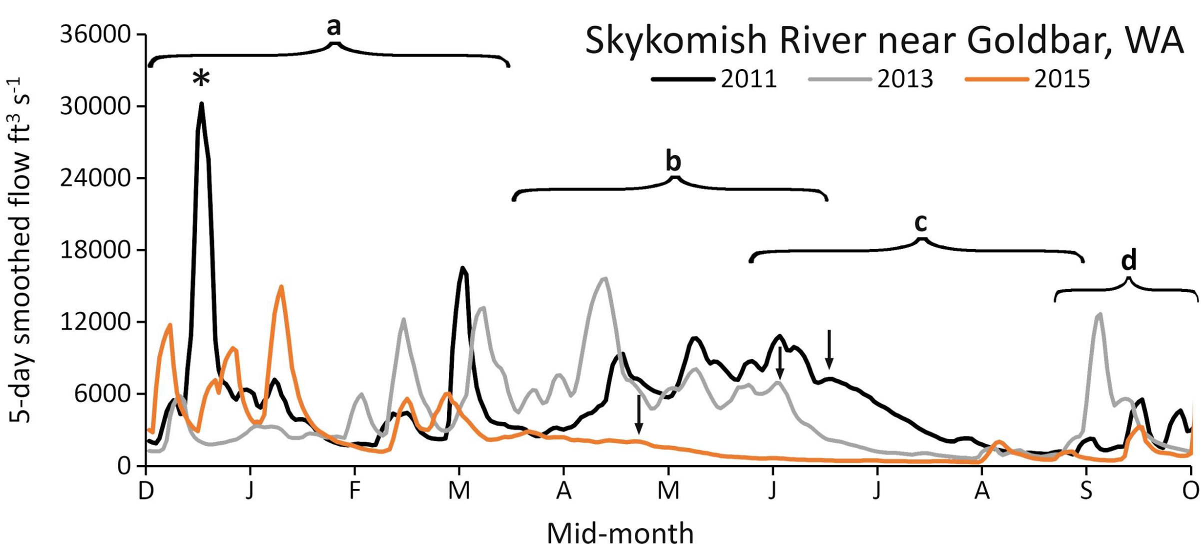

Figure 2.6: Hydrographs of the Skykomish river from the wettest (2011), intermediate (2013), and

driest (2015) years in recent record. A period of snow accumulation, periodic melt peaks, and large rain-on-snow events (*****) occur in winter (**a**). During snowmelt, melt peaks augment higher baseflow (**b**). After snow disappearance (arrows) there is a period of hydrograph recession to baseflows (**c**), followed by fall rains with sharp peaks and rapid recession to baseflow (**d**).

Surface topography and geomorphology can strengthen or lessen a forest's ability to regulate flows depending on the shape of the stream network, the geomorphology of the stream and subsurface water storage capacity (Jensco et al. 2010). For example, incised channels can lower water tables (Poole and Berman, 2001). Extensive review of these controls is outside the scope of this document, but should be fully considered before implementation of management plans. For example, long narrow drainages ("linear") have subdued and delayed runoff compared to short and highly dissected drainages ("dendritic") (Bierman and Montgomery, 2014 p.127). Groundwater pathways can either supplement ("gaining" reach) or remove ("losing" reach) streamflow, which is particularly important for low flow volumes that change a lot proportionally with even small inputs and outputs.

Section 2 References

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Section 3. Forest Management for Water

This section of the report identifies specific forest management strategies most likely to succeed at reducing floods (**Section 3.1**), increasing low flow (**Section 3.2**), and maintaining water quality (**Section 3.3**). Each section begins with a highlight box followed by a summary of guidelines or suggestions relating to the topic. This is followed by supporting evidence justifying specific recommendations based on current literature. Some guidelines are based on fundamental processes outlined in the introduction, as well as specific supporting evidence.

Flow increases are variously reported in absolute terms as mm precipitation or in relative terms as % of flow. How these are reported alter how impactful the results appear. For example, peak flow change following harvest is usually large in volume and moderate in percent, while low flow changes are always small in volume but a large percent (Jones and Post, 2004; MacDonald and Stednick, 2003). In the literature, it is left to the reader to determine if a small but high percent increase is biologically meaningful. Here we report changes in relative terms with the assumption of annual precipitation of 1500 to 2000 mm and low flows in small streams <10 L s^{-1} per square km of drainage area.

Much literature is dedicated to how forest practices affect annual flows, which we briefly discuss here before reviewing floods and low flows. Minimum levels of forest harvest to elicit streamflow response varies among ecosystems from 15 to 50% (Stednick, 1996), but the consensus is that >20% of forest needs to be harvested (Bosch and Hewlett, 1982; MacDonald and Stednick, 2003). This is inferred from small paired watershed studies where two watersheds are calibrated, then one is harvested. In large watersheds (>1000 km^2), true calibration of control and treatment watersheds is impossible, so our knowledge relies on observational correlations. Such studies show higher (30 to 62%) thresholds, likely because each watershed has more variable geology, climate, and vegetation, and thus, higher streamflow buffering (Andréassian, 2004; Lin and Wei, 2008; Zhang et al., 2017; Zhang and Wei, 2012). Annual flow responses to proportion cut in large watersheds also attenuate, which cannot be shown in small watersheds (Zhang et al., 2017). After thresholds are met, the flow increases with % land harvested at rates of 1.7 to 6 mm per 1% harvest (Brown et al., 2005; Moore and Wondzell, 2005), and increases with increasing precipitation (Harr, 1983). For example, the effect of clearing vegetation is negligible below ~450 mm precipitation and rises with higher precipitation (Brown et al., 2005) until saturated around 2500 mm (Zhang et al., 2001). Maximum responses of annual flows to harvest occur between fall rains and winter storms when soils are more saturated (Harr, 1983).

3.1 Floods and Forest Practices

<u>Highlights</u>

Key processes:
- Increased snowmelt and rain runoff synchrony increase flood responses
- Heterogeneous canopy structure decreases snowmelt synchrony
- Rapid routing of water to streams increases flood responses

Key management implications:
- Gaps <2 tree heights in diameter in transient and snow zones reduces snowmelt in spring
- Create heterogeneous canopy structure to desynchronize melt

- Concentrating practices may reduce broad-scale cumulative effects
- Carefully plan to minimize roads, especially mid-slope roads
- Use skylining to minimize temporary roads and harvest compaction
- Continue to engineer roads to minimize connection to streams

Guidelines

Forest management efforts focused in the transient-snow zone will have the largest impacts on flooding, followed by efforts in the snow zone. Create canopy structure heterogeneity at multiple scales to desynchronize snowmelt timing. Management at small scales should use variable retention harvesting to create local heterogeneity. If close to large open areas, create shaded gaps from 0.5 to 2 tree heights in diameter to delay snowmelt longest. Buffers between such gaps should be at least one tree height wide to reduce edge effects of wind and temperature and reduce air mixing (Chen et al., 1993). At large scales, desynchronizing sub-basins will reduce flood effects downstream. Therefore, it is best to not apply the same practices everywhere. Concentrating more intense practices will intensify floods locally and may allow managers to create different forest structure in alternate basins.

Although the effects of roads on floods are ambiguous, the precautionary principle suggests assuming roads are important to flooding. It is best to use forest practices that lessen compaction, channelization, and connectivity to streams to reduce runoff rate. Careful planning and new tools can reduce road building and maintenance through optimization (Ross et al., 2018) and by using methods such as skylining (Appendix 3) to eliminate their need. Localized rutting and compaction from equipment and skid trails can increase runoff from harvests (Horn et al., 2007; LaMarche and Lettenmaier, 2001; Zemke et al., 2019). Practices such as logging when there is snowpack, shovel logging where a machine on a bed of branches "leap frogs" piles of logs to pickup points (log decks), and favoring lighter tracked equipment over rubber-tired equipment can reduce negative soil disturbance (Cambi et al., 2015; Horn et al., 2007). Out-sloping roads 3 to 5% and frequent water bars, rolling dips, and relief culverts can help by diverting captured water downslope before it reaches stream networks (MacDonald and Coe, 2008). Using a ripping tool to decommission temporary roads is also effective at stalling road surface flows for long enough for it to infiltrate (Sosa-Pérez and MacDonald, 2017).

Supporting Evidence

We briefly review harvest effects on peak flows before flood flows. Peak flows are the largest flows within any given time-frame regardless of magnitude whereas flood flows will be near or above bank-full width and occur coincident with rain and rapid snow melt (i.e. large winter-spring peak flows). For example, forest harvest increases peak flows during fall rains, but these flows are not inherently large (Harr, 1983; Jones, 2000; Ziemer, 1981). Peak flow increases with forest harvest are triggered above 25 to 30% harvested area (Grant et al., 2008; Moore and Wondzell, 2005) and generally range from 13 to 40%, although some negative peak flow responses and some >100% occur (Bowling et al., 2000; Grant et al., 2008; Moore and Wondzell, 2005; Stednick, 2008; Storck et al., 1998). Consistent detected peak flow responses are limited to <10-year events and persist for ~20 years (Bowling et al., 2000; Harr, 1983; Hicks et al., 1991; Jones, 2000). As with annual flows, peak flow is buffered at large scale by spatial variability that can reduce discharge, sometimes as much as 50% (Grant et al., 2008; Woltemade and Potter, 1994). Because large landscapes are buffered by areas less prone to extreme responses, the maximum proportional responses seen in small watersheds are likely also maximums at larger scales.

Flood flows have a disproportionate effect on rearranging or scouring stream channels (e.g. Swanson et al., 1998). The largest post-harvest peak flows can increase by 10-30% and last ~5 years following clear-cutting but are generally confined to smaller basins and are hard to predict (Berris and Harr, 1987; Grant et al., 2008; Jones and Grant, 1996; Jones and Perkins, 2010; Seibert and McDonnell, 2010). In the western Pacific Northwest, this is exacerbated by relatively high humidity and warm temperatures, which increase melt synchrony (Harpold and Brooks, 2018). However, such melt synchrony may diminish as climate warms. For example, with less snow to melt during spring (Mote et al., 2018) and warmer temperatures occurring earlier when sun angles are low, less snow will be exposed to sun at the time of melt (Lundquist et al., 2004). Trees surrounding snow accumulations in openings delay melt by reducing warm air mixing during rain-on-snow events and shading snow during spring melt, with the most persistent snow in 0.5-2 tree-height gaps (Golding and Swanson, 1978; Lawler and Link, 2011; Sun et al., 2018). Likewise, more heterogenous canopy structure desynchronizes snowmelt and delays its disappearance because various shade and snow accumulations melt at different times and rates (Berris and Harr, 1987; Lundquist and Dettinger, 2005).

Detecting changes in floods is complicated by simultaneous changes in the magnitude and frequency, high precipitation variability, and flood rarity. Most studies show no significant effect of forest practices on the largest most infrequent flows based on paired events in separate watersheds (Grant et al., 2008). However, analyzing the frequency distribution of floods to account for collinearity in magnitude and frequency shows the largest flows becoming larger, and contemporary high flows becoming more frequent (Alila et al., 2009), contrary to the <10-year event limit cited above. This shift in western Oregon equates to a 40-year event becoming a 15-year event in a 25% patch cut, so this analysis suggests effects would be larger in more intense cuts in years immediately following harvest (Alila et al., 2009). In addition, floods vary strongly with precipitation, which can overwhelm treatment responses (Bowling et al., 2000). In some cases, inherent variability in flood response to harvest due to alternate processes shows a negative flood response (Andréassian, 2004; Bowling et al., 2000; Harr and McCorison, 1979). Last, because floods are relatively rare, our opportunity to detect them before vegetation starts to regrow is limited (Alila et al., 2009; Jones, 2000), and is why process modeling shows more consistent flood effects from forest cover than empirical studies (Seibert and McDonnell, 2010; Wayand et al., 2015). Such detection difficulties apply to roads as well as forest harvest.

Roads should theoretically increase flood intensity, but flood increases are not generally demonstrable because roads and forest harvest are rarely separate. In two locations in western Oregon, one forest had roads for four years prior to harvest (Jones and Grant, 1996) and another for one year prior to harvest (Harr et al., 1975). The first showed peak flows occurring 10-hr sooner in the roaded watershed and statistically insignificant increases in peak flows of ~20%. The second showed only winter peak flow increases in one watershed with 12% roaded area, and the effect of this was ~50% of the effect of cutting and roads combined. Both studies had ≤ 5 large flows to analyze. Road-related flood responses may be masked because interception of subsurface flows are small relative to precipitation, snowmelt, and soil recharge (Jones et al., 2000). Indeed, road effects on floods (but not peak flows) are often negligible in many field studies (Jones et al., 2000; King and Tennyson, 1984; Wright et al., 1990; Ziemer, 1981). Contrary to observations, modeling studies show roads increasing floods flows 2.9 to 27%

with increasing effects on larger events (LaMarche and Lettenmaier, 2001; Storck et al., 1998). Given these discrepancies a precautionary approach should assume roads can increase floods.

3.2 Low Flow and Forest Practices

Highlights

Key processes:

- Low flows are closely linked to soil moisture
- Summer soil moisture is increased with delayed snowmelt and reduced vegetation
- Non-forest ecosystems use the least water while mid-seral forests use the most
- Old forests with complex canopies use less water than young or mature forests
- Hardwood patches and gaps accumulate more snow than conifer forests
- Conifers intercept and use more water annually than hardwoods
- Conifers attain much larger stature and thus leaf area than hardwoods
- Fractured geology increases recharge and delays hydrograph recession

Management implications:

- 0.5-2 tree-height diameter gaps accumulate and shade snow to delay melt longest
- Create permanent meadows (~5% area), 30-100-year lasting early seral patches (1-30% area) from 30–50-year-old conifer plantations using VRH and by not planting or using herbicides
- Create old-growth structure (min 25% area) from 60-100+ year old mature stands using VRH
- Plant hardwood patches or minimize herbicides to encourage hardwoods
- Forest practices that increase recharge in fractured geology may have a greater impact on low flows

Guidelines

A fundamental principle gleaned from the literature review is that delaying snowmelt and reducing transpiration on hillslopes will increase soil moisture and low flows during flow recession (**Figure 2.3**). At least 20% of area needs to be harvested to illicit a low flow response. Snowmelt can be delayed for approximately 25 days, and this is altered by aspect in ways that vary seasonally and with elevation. Delaying snowmelt less than this will likely increase moisture during hydrograph recession but not baseflow (**Figure 2.4**). Harvest proximity to streams may matter, those closer to streams having more impact than those further away (covered more in riparian section). Harvest on north aspects likely delays snowmelt and soil moisture recession. Removing forest causes strong proportional, but short-lived increases in low flows as vegetation recovers. Transpiration is lowest for non-forest, highest for mid-seral forest, and intermediate for old forest (**Appendix 2**). Therefore, flows become deficits for long periods before returning to old forest baselines (**Figure 3.1** left). Current regeneration practices dramatically shorten non-forest conditions and inhibit hardwoods. Inhibiting hardwoods likely has long-term consequences for low flows because they have lower transpiration demand as they age than conifer forests.

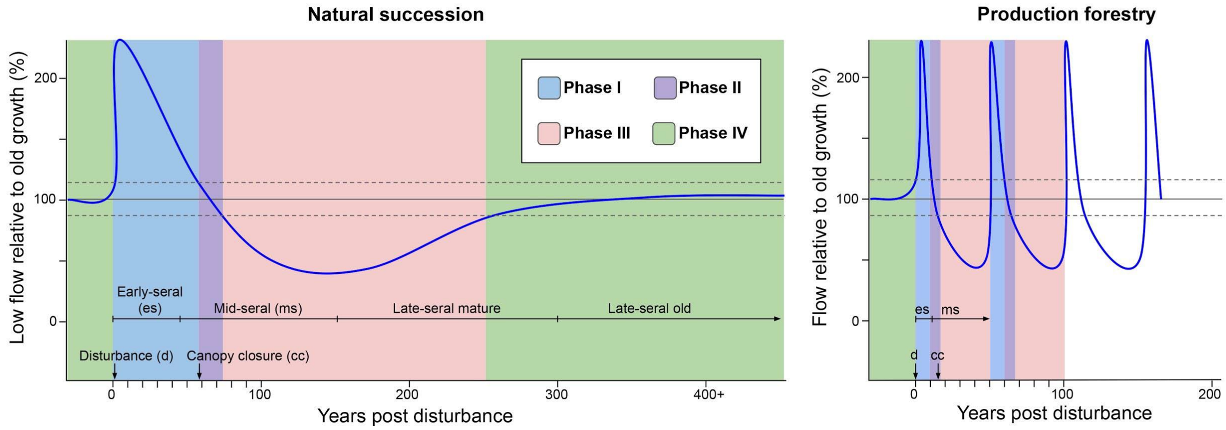

Figure 3.1: Conceptual model of low flow in relation to different forest stages shown in timeline at bottom of graphic. Colored background shows water phases of surplus and deficit relative to old growth forest: Phase I = surplus, Phase II and IV are neutral, and Phase III is a deficit. During natural disturbance and recovery low flow phases are stretched (left) relative to production forestry (right). In Production Forestry, the early-seral stage of surplus water is shortened and forest cut again before deficits can recover (right).

We suggest a four-part strategy to increase low flows (**Figure 3.2**). First, restore or even expand areas historically maintained by Native Americans in meadows and huckleberry fields and maintain them for long periods. Removing trees from these areas will cause immediate increases in soil moisture and provide cultural benefits. Second, create areas of lasting early-seral habitat. Historic estimates of this habitat range from 1 to 30% (currently < 0.1, Donato et al., 2020), and it naturally persists an average of 60 years before conifer canopy closure (Freund et al., 2014). Converting mid-seral plantation to early-seral forest using VRH that leaves close to 33% of trees in aggregates will be less contentious than converting mature forest. Refraining from planting and herbicides will delay conifer dominance by 30 to 80 years. Third, accelerate old-growth characteristics in mature forests, by including gaps that mimic natural systems using VDT. Old forests used to be 47 to 90% of forested area and are now closer to 7% in the Snohomish (**Table 1.2**). Mature forests already have large trees that can become large emergent trees and are beginning to experience processes that shape old-growth forests (e.g. mortality from fungus, advanced regeneration). There are objective methods for emulating old growth structure by applying reference conditions to LiDAR-based forest structure (Churchill et al., 2013; Jeronimo et al., 2018). The patterns of the largest trees are mimicked by focusing on individuals, clumps, and openings representative of a natural forest. This immediately reduces overstory leaf area and creates semi-shaded gaps that reduce transpiration of remaining understory trees. The effects of this type of treatment will likely last centuries as forests continue to become more complex. Fourth, incorporate more hardwoods. These trees intercept less precipitation and are smaller in stature at maturity, so use less water at old age than a conifer forest. They are also more resilient to disturbance and provide more habitat cavities (discussed in section 4).

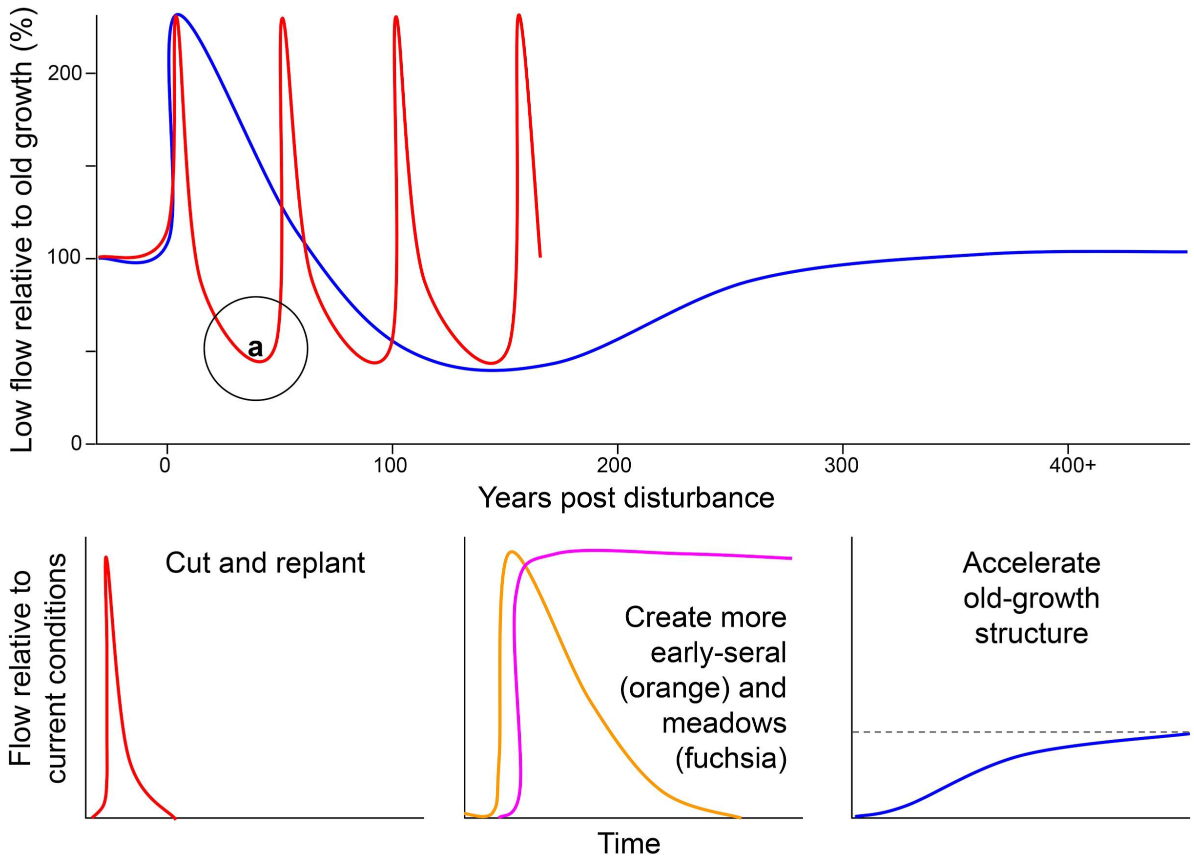

Figure 3.2: Low flow response to natural disturbance compared to 50-year rotation forestry (top). Highest transpiration demand and lowest flow (**a**) occur in mid-seral forest. Strategies to increase low flows (bottom) can include more area of current practices (left), creating lasting non-forest (middle), and accelerating old growth forest (right). Grey line shows asymptote for old-growth flows.

The probability of this strategy's success is dependent on how widespread and quickly we need low flows to increase, the proportion of land in each treatment class, and how feasible it is to achieve at scale. Because low flow gains recede within ~10 years, we cannot simply cut more using the same harvest practices (Harr, 1983). If we assume private owners are cutting as much as they can and are not likely to stop spraying herbicides and planting conifers, then gains from creating more early-seral habitat will have to come from public and tribal lands in mid-seral forest, which are ~40% of area in the Snohomish watershed (Table 4 of **Appendix 4**). Increasing proportion of land in old growth and hardwoods offers more flexibility than cutting mid-seral forest. At least 22% of area in the Snohomish basin are in riparian buffers (Table 6 of **Appendix 3**), all of which could be managed to include more hardwoods and old-growth structure. In addition, hillslope area on public and tribal lands could be used to accelerate old-growth characteristics. Preliminary analysis (Table 5 of **Appendix 3**) suggests a surplus of 28% area in mid-seral forest, and deficits of at least 24% old-growth and 1.8% of meadows. Moving 14% of mid-seral forest to early-seral or meadow and 14% to old-growth would likely attain appreciable flow increases (Appendix 4). **Figure 3.3** illustrates another example of what this strategy might look like in >50 years if 25% land area were converted to old growth, 10% were lasting early-seral, 1% sustained meadow, and the rest were managed as a regulated forest with production forestry.

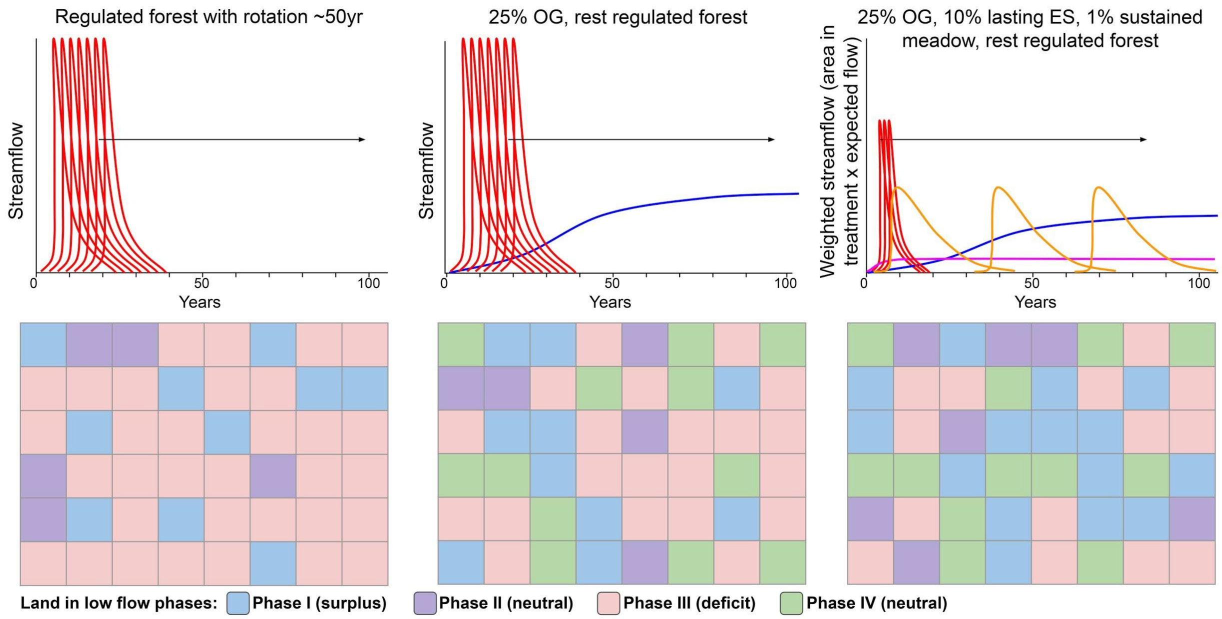

Figure 3.3: Conceptual strategies to increase low flows relative to old growth (OG, top) and forest area in hydrologic phases (see **Figure 3.1**) if strategy were applied perpetually (bottom). Production forestry (left), production forestry and accelerating old growth (center), and combination of production forestry, creating lasting early-seral (ES) and permanent meadows, and accelerating old growth (right). Red line is clear cut and replant, blue line is accelerating old growth structure, orange is lasting early-seral, and fuchsia is permanent meadow.

Management to increase low flows is complicated by the scale and timing of forest operations necessary to elicit a response (Appendix 4). Therefore, we may need to concentrate on critical regions. Low flow responses are highly variable ins response to proportion of area cut large watersheds (>1,000km^2), therefore, there is no guarantee cumulative effects in small drainages are additive in larger ones. If potential cumulative treatment area is not sufficient at large scale, forest practices will have to be concentrated in critical areas where low flow increases are the most important for Tulalip objectives.

Supporting Evidence

Many small gaps retain more snow than fewer large gaps, and dispersed thinning up to 33% of basal area does not increase snow accumulation (Dickerson-Lange et al., 2015). Gaps 0.5 to 2 tree-height in diameter are best for accumulating the most snow and retaining it longest (Broxton et al., 2015; Golding and Swanson, 1978; Lawler and Link, 2011; Sun et al., 2018). Snow can persist up to 13 weeks longer in gaps, but rarely persists longer than 25 days, and more typically is between 7 to 14 days (Dickerson-Lange et al., 2015; Harpold et al., 2015, 2014; Lundquist et al., 2013). Because hydrograph recession is curvilinear, only large changes in snow duration will affect low flows in late summer and fall (compare **Figures 2.4** and **2.6**). Some evidence shows that harvesting in snowy interior watersheds increases low flow (Gottfried, 1991; Van Haveren, 1988), it is unclear whether snow accumulations from gaps are directly responsible for increasing low flows in the in more coastal regions. Process modeling in colder interior climates, suggests small dispersed gaps increase summer low flows 14 to 40% (Sun et al., 2018).

Empirical data on duration of harvest effects in snow regions on stream flows is scarce, but some evidence suggests responses lasting 3 to 6 years (Pike and Scherer, 2003). Moisture differences due to harvesting on different aspects can vary between years and elevations. Snowmelt is delayed more on north than south aspects (see section 2.2). Because soil moisture is higher on north aspects (Geroy et al., 2011), concentrating harvests here may allow for more recharge than on south aspects. Alternatively, low flows may be more limited by timing of soil moisture deficit on south aspects than on north so may be more responsive to harvest. To our knowledge, the alternative mechanisms just mentioned between soil moisture deficits, hillslope aspects, and sensitivity to forest practices remain untested in the Pacific Northwest.

Cutting forests to reduce transpiration unequivocally increases soil moisture and low flows, but only for 5 to 10 years until vegetation recovers (Coble et al., 2020; Hicks et al., 1991; Keppeler, 1998; Perry and Jones, 2017; Surfleet and Skaugset, 2013). For example, soil moisture is 3 to 10% higher in summer following harvest of medium-sized gaps (Gray et al., 2002), but deficits are apparent 4-5 years post-harvest as vegetation cover exceeds ~30% (Adams et al., 1991). Of annual increased flow after harvest, ~20% is due to low summer flows (Rothacher, 1970). The largest effects of forest cover on summer flows in rain-dominant regions with dry summers are small in magnitude and large in proportion (Brown et al., 2005; Farley et al., 2005). Proportional responses can be ~60% greater in first-order streams than fourth order streams (Surfleet and Skaugset, 2013). Harvest closer to streams may increase the magnitude of low flow responses (Abdelnour et al., 2011; Bond et al., 2002; Stednick, 1996), likely because downslope forests use excess water before it reaches the stream. For example, a modeled harvest near a ridge has half the effect of a harvest near a stream (Abdelnour et al., 2011). Initial responses can easily exceed 150% (Keppeler, 1998; Perry and Jones, 2017), but can recede ~24% year^{-1} (Keppeler, 1998; Surfleet and Skaugset, 2013) due to forest regeneration.

Regeneration practices have profound implications for low stream flows. Most landowners plant seedlings 1-3 years after harvest and use herbicides to reduce competition (discussed below). Planting forests reduces streamflow relative to non-forest and accelerates the pace at which flows go into deficit by establishing vigorously growing trees quickly. For example, planting grass and shrubland with trees reduces annual water yield 23% in 5 years and 38-56% in ~20 years, with effects lasting at least 40 years (Bentley and Coomes, 2020; Farley et al., 2005). In large watersheds, the cumulative effects of harvest and planting can decrease summer flows by 43% and increase low flow days by 19 or more once harvesting reaches 50% over a period of only 20 years (Gronsdahl et al., 2019). However, large watershed responses are highly variable (see introduction to this section). For example, harvesting 30% of area can have negligible effects on low flow (Lin and Wei, 2008) owing to variability in harvests and forest ages across the watershed.

Spraying herbicides in conjunction with planting reduces the duration the early-seral successional stage by decades at a time when transpiration is lowest. Establishment of the overstory tree cohort varies from 30 to 100 years naturally (Franklin et al., 2002; Freund et al., 2014), while in plantations with herbicide use, establishment is reduced to between 2 and 20 years (Ulappa et al., 2020). Herbicides within the first 3 to 4 growing seasons is most effective, primarily working by reducing competition for water from shrubs and hardwood species (Harper et al., 2005). Herbicides reduce competing vegetation 14 to 80% and allow planted conifers to increase leaf area and stem volume by >350% compared to controls (Dinger and Rose, 2010). Herbicides also allow conifers to dominate within 3 years, covering 30 compared to 10% of ground area relative to non-herbicide controls (Dinger and Rose, 2010). Conifer stem volume gains from herbicides are still apparent after 12 years, and vary from 63 to 355% depending on the antecedent plant community (Rose et al., 2006). Once conifers are established, canopy closure and high transpiration are not far behind.

Most landowners grow plantations 40 to 80 years before harvest, and growth during this time strongly affects low flows (**Figure 3.1**). Clear cuts of native forests produce initial surpluses of 60 to >150% (e.g. Hicks et al., 1991) and gains are roughly proportional to area cut beyond 15 to 20% (Bosch and Hewlett, 1982; Sahin and Hall, 1996). Once established, young forests have more trees transpiring faster than older forests (Moore et al., 2004). These create low flow deficits within 7 to 15 years relative to native forest (Coble et al., 2020; Keppeler, 1998; Perry and Jones, 2017), and by the time plantation reach 35 to 45 years, deficits can be as high as 50 to 60% (Perry and Jones, 2017). This effect is not apparent with 40% dispersed retention or from 2 to 3 ha gap cuts (Perry and Jones, 2017). Harvesting only 13 to 26% of such plantations can increase streamflow 45 to 106% (Surfleet and Skaugset, 2013), but this is not enough to make up for deficits from cutting the original forests if immediately replanted. For example, harvesting plantations in western Oregon increased low flows 60 to 80% but only reduced the deficit relative to the pre-plantation forest to 21 and 36% after sequential ~50% harvests (Segura et al., 2020). Because planted trees after the first of these harvests were 5 to 10 years old and riparian buffers were used (discussed below), streamflow could not recover fully.

Although there are no studies documenting time for low flow deficits relative to old-native forest to disappear, (e.g. Coble et al., 2020 review studies up to deficit period but none to flow recovery), theoretically they could persist >100 years. Transpiration increases with LAI in homogeneous forest canopies (Moore et al., 2011a) so long as it is not limited by soil moisture (Moore et al., 2011b; Stoy et al., 2006). Thus far, studies have documented low flow deficits up to ~60 years in plantations with high leaf area concentrated in dominant trees (Perry and Jones, 2017; Segura et al., 2020). Leaf area in dominant trees can stay high for at least another century (**Table 2.2**), suggests continued high transpiration until leaf area diversifies to different canopy position. Canopy changes in vertical and horizontal leaf distribution typically occur only ager 150 to 200 years (Franklin et al., 2002). Thus, deficits created by establishing rapidly growing conifers that are now 40 to 60 years old likely increase or are at least maintained for another century before declining.

One last element of forests related low flows concerns the amount of hardwood species. Replacing conifers with hardwoods is less likely to increase low flows in the short term, and may even decrease them due to their rapid early growth and high summer water use compared to similar sized conifers (Moore et al., 2011a; Van Pelt et al., 2006). Yet, hardwoods have potential to increase flows over the long term because of their relatively small stature and leaf area at typical harvest ages. Sapflow per unit sapwood can be 1.4 times higher in hardwoods than conifers (Moore et al., 2004), so at aggregate, we might expect more water use. Even so, soil moisture under same-aged stands of red alder and Douglas-fir are similar to slightly higher on south aspects and 10 to 20% higher on north aspects, respectively (Moore et al., 2011). If rotations are allowed to go long enough, a conifer stand will have more leaf area than a hardwood stand (Franklin and Waring, 1980) because they can become so much larger and such volume production requires more leaf area. Using red alder and Douglas-fir as an example: Stand volumes for both species are ~320 m^3 ha^{-1} at 40 years. Alder stands reach maximum volume at 50 years between 300 and 400 m^3 ha^{-1}. At 50 years, Douglas-fir produce ~500 m^3 ha^{-1} and will increase this to 800 m^3 ha^{-1} by year 80 when most read alder is dead (Curtis, 1995; Peterson et al., 1996). This pattern is similar in other pairings between conifers and hardwoods (Peterson et al., 1996).

3.3 Water Quality and Forests Practices

Highlights

Key processes:

- Small stream temperature is closely related to sun exposure
- Maximum temperature increases with exposure while mean and minimum temperatures are less effected, increasing temperature range
- Temperature increases are not detectible in 1-tree-height- or in 15-30-m buffers
- Maximum temperatures cool 150-1400 m downstream of exposed reach if shaded
- Hyporheic exchange such as through permeable gravels and step pools buffer temperature
- Forests have less influence on wider and higher order stream temperature
- Temperature increases from harvest are short-lived
- Roads increase sediment by causing landslides and during road maintenance
- A minority of roads generate the majority of sediment
- Roads convey sediment long distances across hillslopes
- Riparian buffers are effective sediment filters

Key management implications:

- Buffers in clear cuts should be between 30 m and 1-tree-height wide and between 15 and 30 m wide if adjacent to less intense treatments (e.g. thinning)
- Riparian treatments should be separated by 200-1000 m or >3 to 5 years on small streams
- Logs should be placed in the stream to promote step pools
- Decommissioning particularly unstable roads can reduce most landslide problems
- Limiting traffic and thus maintenance on roads in sensitive reaches is a priority
- Decommissioning roads via ripping and mulching effectively reduces road runoff
- Disconnect road runoff before it reaches streams riparian areas

Guidelines

Forest practices guidelines for water temperature should be planned to mimic historic stream temperature variability. Reaches can become warmer or cooler with distance and this feature of stream temperature should be recognized in forest practices (Dent et al., 2008; Ebersole et al., 2015; Fullerton et al., 2017, 2015) so long as they respect critical thresholds. Stream temperatures from 20 to 23°C are lethal for fish and slightly lower temperatures are for amphibians, while healthy mean temperatures should remain below ~17°C (Jackson et al., 2001; Richter and Kolmes, 2005).

Buffer widths of 30 m mitigate most effects of clear-cutting adjacent slopes, while 15-m-buffers are mostly effective, but do carry some risk. If employing narrow buffers, or thinning within them, it is best to do so when adjacent to less intense harvest. Because stream temperatures can cool after warming within ~200 to 1000 m and riparian vegetation grows quickly to re-shade narrow streams, riparian thinning or harvest should be separated by enough space (>100m) or time (5 years) between adjacent/subsequent harvests to minimize cumulative temperature gain.

Context of geomorphology should be considered if designing riparian treatments because they change the sensitivity of stream temperature to sunlight. Areas with steeper gradients, step pools, and deep gravel or other means for increasing hyporheic exchange are less sensitive to changes in riparian buffers. Likewise, it is best to retain the densest buffers in areas of bedrock and low hyporheic exchange. Forestry increase hyporheic exchange by purposefully placing logs into streams to create stepped pools and decrease temperatures.

Roads are likely the primary source of sediment delivered to streams by initiating landslides and conveying sediment. Ditch maintenance and regrading are also strong factors. Because a minority of roads cause a majority of the problems, road planning and decommissioning must be specifically targeted. Paving busy roads, and ripping and mulching roads during abandonment are effective strategies.

Supporting Evidence

Water quality is defined primarily by temperature and turbidity (from sediment) because they correlate strongly to measures of ecological health. These indicators are particularly meaningful for fish populations that native and western cultures depend on. Riparian shade is strongly associated with stream temperature regime (Brown, 1969; Groom et al., 2011; Johnson and Jones, 2000; Moore and Wondzell, 2005; Roon et al., 2021), especially in the western Pacific Northwest (Chang and Psaris, 2013). Therefore, forest practices have the most effect on temperature when altering riparian zones around streams ranging from first to second order, 2-4m wide, and with low flow. Changes in maximum temperature are usually larger than changes in mean and minimum temperatures (e.g. Johnson, 2004; Roon et al., 2021). Contemporary riparian buffers at least one-tree-height wide are sufficient to offset harvest effects on stream temperature (Moore and Wondzell, 2005). Smaller buffers common in contemporary management (15 to 30 m) still mitigate most immediate problems (Bladon et al., 2016; Gomi et al., 2006; Groom et al., 2011; Reiter et al., 2020), but those 7-21m wide allow temperature to exceed policy thresholds (0.3°C) up to 40% of the time (Groom et al., 2011). There is evidence of increased temperature (7 day mean maximum temperature) from 1 to 3°C with buffers <15 m (e.g. McIntyre et al., 2018), while 30 m buffers appear adequate (Gomi et al., 2006).

Temperatures will increase after streams are exposed to more sunlight but decrease again as vegetation recovers. Initial increases in daily maximum temperature with 15 to 30-m buffers can be as high as 5.3°C (Cole and Newton, 2013), but they recede quickly. In productive ecosystems of the western Pacific Northwest, vegetation growth is rapid and can re-shade streams and reduce temperature increases to baselines in as little as a few years and up to 10 years after riparian areas are thinned or cut (Gomi et al., 2006; Moore et al., 2005; Roon et al., 2021). There is some evidence that cumulative upslope area harvested between 25 and 100% raises daily maximum temperature ~2.4°C, however, dominant controls were by geomorphology over harvest percent (Pollock et al., 2009).

Heat captured by streams can accumulate , however downstream heat transfer is rarely monotonic because of stream cooling and inherent temperature variability (Fullerton et al., 2015).

Streams flowing from sunny to shaded reaches are able to cool and this cooling creates spatial variability (Bladon et al., 2018; Moore and Wondzell, 2005; Roon et al., 2021). Generally, mean temperature increases downstream but temperature peaks do not (Cole and Newton, 2013), dampening to preheating levels within 100-1400m (Bladon et al., 2018; McIntyre et al., 2018; Roon et al., 2021). In large streams, temperature variability is high despite a warmer mean temperature because of small refuges of cool water from groundwater and exchange with groundwater (Ebersole et al., 2015).

Some temperature responses to contemporary buffers are variable because of factors other than reduced shade. Temperatures do not rise as much if a lot of logging slash is left over streams (Jackson et al., 2001; Kibler et al., 2013) or if streams flow intermittently above and below the surface (Janisch et al., 2012). Any underlying variables that increase exchange with groundwater also buffer temperature increases to reduced shade (Pollock et al., 2009; Story et al., 2011). This occurs on steeper slopes (Kasahara and Wondzell, 2003), with abrupt changes in flow slope as in stepped pools (Harvey and Bencala, 1993), with more wood jams (Dent et al., 2008), and when water passes through deep gravels (Johnson and Jones, 2000). For example, in western Oregon, upland and riparian harvesting in combination with heavy rains were responsible for a debris torrent that scoured the stream to bedrock. Bedrock reaches in full sun had higher maximum and lower minimum temperatures, while temperature was buffed to healthy levels as bedrock-warmed water flowed through downstream gravel (Johnson and Jones, 2000). Forest practices will have less influence on stream temperature in larger streams because they are too wide to shade and have more heat inertia with higher volume. Conversely, variables that increase source water temperature and reduce groundwater exchange lead to more intense heating with shade reduction. If source water is from shallow wetlands (Janisch et al., 2012) or flows over significant portions of bedrock (Brown, 1969; Dent et al., 2008; Johnson, 2004), streams are more likely to warm significantly. In short, modified riparian vegetation must be considered in the context of larger geomorphic processes to accurately diagnose how riparian treatments with effect stream temperature (Poole and Berman, 2001).

Chronic sediment input from cuts and logging roads, can reduce water quality. A few notable impacts of excess sediment are reduced visibility from more turbid water and infilling of gravel pores causing a reduction of suitable places for invertebrate habitat, fish to lay their eggs and restriction of hyporheic exchange. Restriction of hyporheic exchange with the alluvial aquifer increases water temperature (Packman and MacKay, 2003; Schälchli, 1992). Up to 4.6 times as much sediment can be mobilized in clear cuts compared to reference slopes (Rachels et al., 2020) and if this reaches road networks, it can be moved to streams. Poor engineering during installation can increase stream connectivity 40% and roads create slope instability that leads to 10 to 300 fold increases in landslide rates in wet climates (MacDonald and Coe, 2008; Wemple et al., 2001). Sediment from slides and surface erosion is then conveyed long distances along roads and delivered to streams with up to an order of magnitude higher amounts (Sidle et al., 2006; Wemple et al., 2001). Thus, road density can be proportional to sediment input if practices are not included to curtail it (Luce et al., 2001).

Although road density is proportional to sediment input (Luce et al., 2001), a minority of roads create the most problems (Al-Chokhachy et al., 2016; MacDonald and Coe, 2008). Heavily trafficked roads can produce 130 times as much sediment as an unused road (Reid and Dunne, 1984). A majority of road sediment comes from regrading and ditching, practices that increases with more traffic (Luce and Black, 2001; Rachels et al., 2020). Ripping and mulching unused roads effectively mitigates sediment runoff (Sosa-Pérez and MacDonald, 2017). Redirecting ditch water onto slopes (as mentioned for flood flows) so that it percolates or is filtered by vegetation before entering streams as is now required (WAC 222-24-020) is probably also effective. Landslides originating from road cuts can be reduced by leaving dispersed trees on steeper slopes to maintain root strength (Roering et al., 2011), especially above and below problem roads located with a tool like NetMap (Benda et al., 2007). Contemporary riparian buffers (15 to 30m) are a proven strategy for reducing sediment into streams so should be maintained (Hatten et al., 2018; Rachels et al., 2020). This does not mean buffers need to be dense conifers. Even relatively sparse forest buffers can filter sediment to healthy levels (Jackson et al., 2001), and there is little difference between forested versus herbaceous sediment filtration because it depends more on buffer width than composition (Yuan et al., 2009). Sediment spikes appear to be associated with upslope clear-cutting but are variable and also occur in uncut reference sites (McIntyre et al., 2018).

Section 3 References

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Section 4. An integrated strategy

Forestry can benefit flow regimes by targeting processes that dampen peak flows in winter and early spring, and processes that increase soil moisture in the summer and fall. When soil water is at or near saturation (winter and spring) forest practices that increase canopy interception (snow or water caught by leaves that sublimates or evaporates), slows snowmelt, improves infiltration, or decreases surface drainage networks will help reduce peak flows. As soil moisture percolates or dries during flow recession, forest practices that extend the snowmelt season or decrease plant water use (transpiration), especially near water sources, will help increase low flows. Likewise, forest practices can also improve water quality if roads are carefully designed, sited, and disconnected from streams, and by providing adequate riparian shade. Some of these strategies conflict with certain goals (e.g. decreasing riparian transpiration versus mitigating increasing stream temperature) so have to be incorporated into a broader strategy. There is likely a compromise where both can be maintained to maintain most ecological objective by focusing on pattern and timing of hillslope forest practices. In **Section 4.2** we focus on a cross-comparison of different recommendations from earlier sections and a synthesized set of guidelines.

Before synthesizing the guidelines, we must address riparian buffers more fully. While writing this report, it became apparent that riparian areas are a special case because of their importance on low stream flows, shade to regulate stream temperature, sediment filtration, and biodiversity. Riparian trees reduce water available for streamflow while providing shade to buffer temperatures, therefore create an apparent management conflict. This conflict is only relevant when viewing riparian buffers as a way to augment relatively few environmental variables (i.e. temperature measures) rather than as a unique ecosystem (Gregory et al., 1991). Riparian ecosystems have other important attributes including inputs of nutritious hardwood leaves and dead wood, diverse spatial structure, unique plant communities, and rich food webs (Nakano and Murakami, 2001; Vannote et al., 1980). In **Section 4.1**, we briefly review additional concerns related to the riparian ecosystem.

Last, we provide a brief evaluation of how the suggested guidelines above are likely to alter other ecosystem processes and traits in the Snohomish watershed, recognizing that this is an area needing more thorough review (**Section 4.3**).

4.1 A note on riparian areas

Riparian areas augment low flows primarily because of their landscape position. Connectivity between riparian areas and hillslopes are a primary control on magnitude and timing of base flows, and connectivity is higher when more upslope contributing area is concentrated above relatively small riparian zones (Jencso et al., 2010, 2009). Therefore, reductions of low flow due to riparian transpiration will be most pronounced where hillslope inputs are diffuse and riparian areas large. Beginning in early summer, transpiration creates diurnal fluctuations in flow and continues until riparian areas are disconnected from lateral soil moisture movement (Bond et al., 2002; Grayson et al., 1997; Moore et al., 2011b). The only near-surface connections to riparian areas will be from large adjacent hillslopes in late summer and fall (Jencso et al., 2010). When riparian vegetation is removed such diurnal fluctuations cease, suggesting fluctuations are independent of hillslope vegetation (Bren, 1997; Dunford and Fletcher, 1947). Such removal experiments only show annual flow increases from 0.8 to 4% (Salemi et al., 2012), but because low flows are such a small percentage of total flow, these are probably meaningful. They may help explain why clearcutting hillslope vegetation and leaving 15m-wide riparian buffers reduces, but does not eliminate, water deficits from the previous plantation (Segura et al., 2020).

Riparian vegetation also augments streamflow through its interaction with streams. Both the beaver dams and large wood in streams forces water onto the floodplain during high flows thus reducing peak runoff (Keys et al., 2018). At the same time impounding and slowing water helps recharge valley aquifers, which increases low flows later in the summer (Kasahara and Wondzell, 2003). Natural riparian areas have complex structure and composition including gaps, multi-layered canopies, and hardwoods (Nierenberg and Hibbs, 2000; Pabst and Spies, 1999, **Table 1.3**). Such conditions favor species like beaver that prefer hardwoods to conifers, and who's impoundments can decrease downstream temperatures 2.3℃, reduce flows by 20% and increase salmon habitat (Dittbrenner, 2019; Pollock et al., 2004). Many riparian areas have been converted to conifer plantations over the course of the last century and show little resemblance to previous systems.

Any serious attempts at altering stream flows with forest management practices should be done in tandem with river restoration and rehabilitation. The width of valley bottoms and how well hydrologically connected streams are to their floodplains impact low flows because these regulate how much water can be held within the alluvial aquifer. The literature is vast, but two promising trends to restore water tables in alluvial aquifers are zero stage restoration, which attempts to reconnect floodplains with stream flow (Cluer and Thorne, 2014), and re-introduction of beavers and implementation of beaver dam analogs (Dittbrenner, 2019; Pollock et al., 2014), which are used to raise water tables by increasing total ponded area. **Figure 2.7** shows a striking example of how a ponded section of stream from beaver activity resisted a fire that burned the rest of the landscape, including the entire valley bottom width of a downstream reach that did not have any ponding. Valley bottoms with high alluvial aquifer water tables buffer streams from drought, are resistant to fire and are refugia for animals and plants that can help reseed and restore surrounding lands.

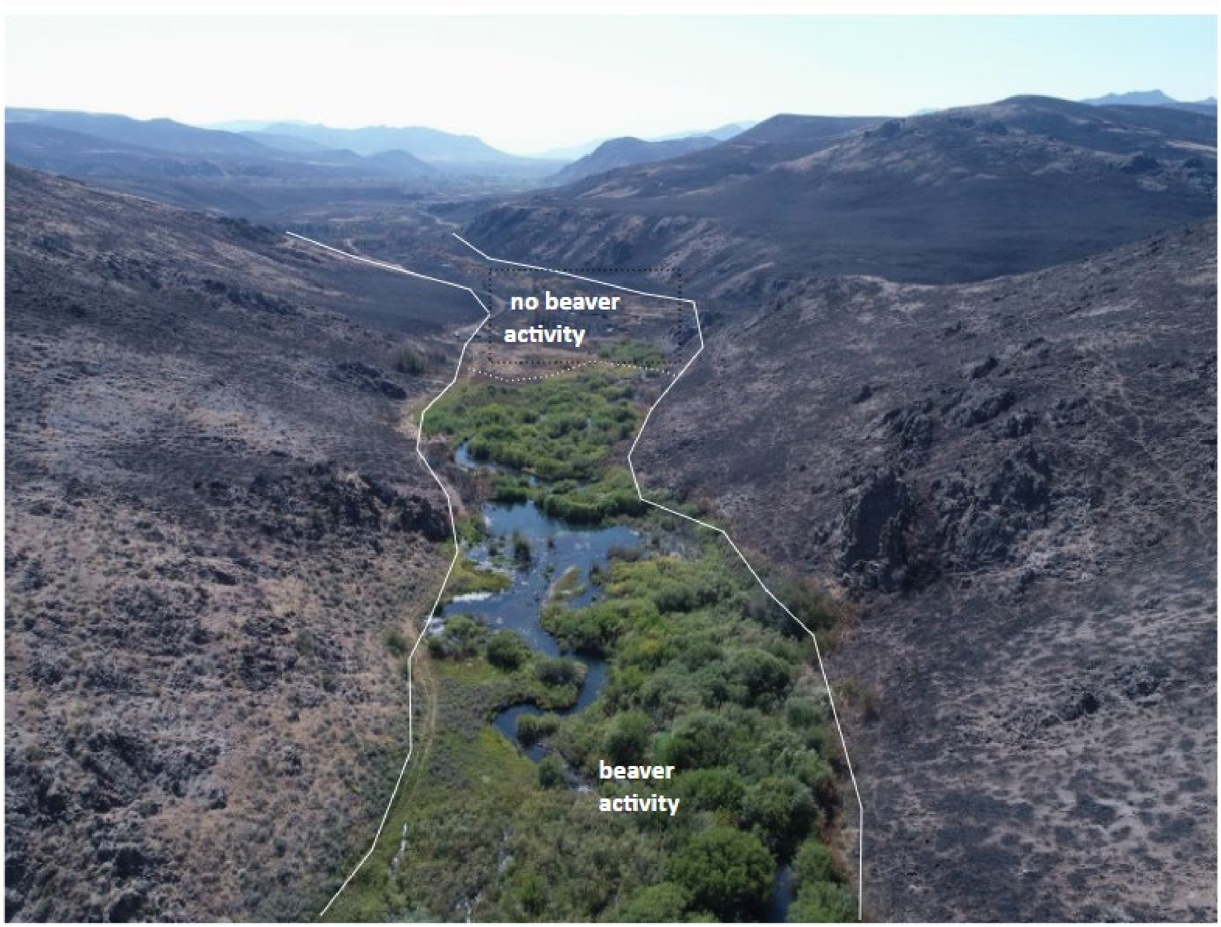

Figure 4.1: Photo beaver region of ponding after a fire in a dry landscape in Idaho. Photo by Joe Weaton.

Management conflicts in riparian areas arise when the focus is on one or a few indicators without considering multiple ecosystem processes. For example, cutting produces three biologically conflicting results: it can reduce transpiration, increase temperature, and reduce future large wood inputs (Benda et al., 2016; Kaylor et al., 2017; Roon et al., 2021). Conifers provide denser shade and lower water temperatures than hardwoods as well as more durable and large wood, so there is resistance to cutting them within buffers (Dugdale et al., 2018; Pollock and Beechie, 2014). Although stream temperature and wood input are important to fish, they may not always be limiting. For example, fish abundance and size can be larger near cuts because of increased food abundance and foraging efficiency (Bateman et al., 2018; Bilby and Bisson, 2011; Wilzbach et al., 1986) despite warmer temperature. Natural forests prior to harvest had more gaps (Pabst and Spies, 1999) and likely more variable stream temperatures than in streams bordered by conifer plantations. Peaks in temperature after riparian harvest along narrow streams are short-lived, maxing in 1 to 3 years and attenuating rapidly by 1 to 5 years as vegetation quickly closes over them (Arismendi and Groom, 2019; Gomi et al., 2002; Groom et al., 2017). On the other hand, reductions in transpiration can be long lasting if done by creating large enough spaces between tree crowns that they cannot rapidly close them. For example, in ponderosa pine stands, reducing tree density can reduce leaf area relative to controls for at least 25 years (Oren et al., 1987). Trees can be also be intentionally tipped into streams to provide immediate wood inputs during harvest (Reeves et al., 2016).

We argue that incorporating specific attributes of natural riparian areas into buffers rather than excluding or severely limiting harvest in them as is typically done, will have a longer lasting positive impact on flow, water quality, and other values (e.g. Moore and Richardson, 2012; Reeves et al., 2016; Sibley et al., 2012). First, selective overstory tree removal to reduce transpiration needs to be done so remaining trees still provide shade but also cannot quickly refill the canopy space, therefore will require creating gaps. Within riparian gaps, low lying vegetation can quickly shade small streams and reduce warming. Second, ancillary benefits to biodiversity and other resources should be considered as well as low flow, sediment, and temperature. Creating small gaps, snags and logs, and encouraging growth of different tree species diversifies understory food resources, wood and nutrient input, and habitat. More importantly, diversifying forest structure and composition in riparian monocultures will have impacts lasting centuries as these forests develop. Third, treatments that create patches of alder, poplar, and willow may encourage beaver, which increase aquatic productivity, water availability in the dry season and water quality.

Such a strategy will also need to include hardwoods for reasons other than attracting beavers. Without question, young hardwoods and conifers transpire more rapidly than older trees. However, conifers mature slower than hardwoods and become much older. Riparian vegetation with more shorter-lived hardwoods will develop structural complexity (gaps, understory trees, snags, and logs) sooner than Douglas-fir. In buffers designed to be perpetual, incorporating patches of hardwoods and other shorter-lived trees (e.g. Sitka spruce) will reduce future summer transpiration by accelerating forest structural diversity development. Dispersed thinning is not likely to accomplish this goal because overstory trees rapidly refill space. Rather, variable retention harvesting or thinning will create complex light environments and encourage development of multiple canopy layers and tree species.

Key takeaways are:

- Natural riparian areas are structurally complex and species-rich ecosystems
- Many forested riparian ecosystems are now dense conifers due to past management
- Dense conifers rapidly transpire and provide dense shade
- Shade recovers quickly after cutting in small streams
- Reducing riparian transpiration may be long lasting if creating multiple canopy layers
- Encouraging beavers with more hardwoods will likely increase low flows
- Riparian conditions can be improved by cutting ~30m gaps covering ≤25% of riparian area to reduce transpiration, encourage more diverse tree age classes and plant communities, and by putting logs in streams to emulate natural riparian systems (**Table 1.3**)

4.2 Integrating strategies

A successful strategy to create a landscape with well-regulated flows of high-quality water will need to incorporate guidelines for floods, low flows, and water quality at multiple scales. Reducing flooding must desynchronize runoff by creating heterogeneous canopy locally and broadly. Increasing low flows must decrease transpiration for extended periods and in a way that is unlikely to increase stream temperature or sediment. It may not be possible to accomplish both everywhere under current economic and forest structure constraints, however significant local responses to forest practices are certainly possible.

Tables 4.1 and **4.2** were compiled from the suggested guidelines for flooding, low flows, and water quality to identify where they align or conflict. The biggest potential conflicts between strategies are between forest practices to reduce floods and increase low flows, and between those to increase low flows and improve water quality. Tree interception can reduce flood potential, however so can desynchronizing runoff by creating varied canopies. Therefore, reducing transpiration by harvesting in complex spatial patterns at multiple scales has potential to both increase low flow and decrease floods (**Table 4.1**). Additionally, strategies to decrease transpiration need not compromise stream temperature and sediment regimes. If harvests are paired with compatible buffer treatments, areas of stream warming will be followed by stream cooling, creating patterns of temperature variability mimicking natural processes. For example, riparian buffers near clear cuts should be at least 30m wide and those adjacent to less intense harvest can safely be managed to reduce riparian transpiration. If warming is anticipated from a harvest then a stretch of ~200 to 1000m downstream should be managed to decrease stream for temperature by retaining shade and putting wood in the watercourse. Concentrating intense practices can localize sediment pulses if they are mobilized, while placing wood in stream channels can trap sediment.

Table 4.1: Management guidelines summarized for hillslope management.

	Hillslope forest				
Goal	Tree density	Harvest pattern	Landscape pattern	Successional classes	Composition
Floods	Vary density in concentrated harvest regions, leaving ≥ 1/3 mostly in aggregates to reduce soil compaction	Variable gap size and tree pattern, and % retention, but retain ≥ 1/3	Create regions of concentrated and dispersed harvests at catchment scale. Concentrated areas should have good infiltration and recharge	Avoid large blocks in stages with low structural variability to desynchronize melt and runoff. Old growth is naturally variable so is ok in large blocks	More conifers may reduce floods, unless snow and rain greatly exceed interception
Low flows	Reduce tree density enough to delay canopy re-closure, aggregated retention and heavy variable density thinning preferred to light dispersed thinning	Small gaps in snow zones and more intense VRH in areas of recharge and lower elevation. Space trees or clumps to delay canopy re-closure. Create spatial complexity, or create non-forest	Concentrate harvests in mid-seral forest and in critical recharge or habitat areas that need more flow	Increase proportion of non-forest and old forest classes by converting young and mature forest respectively	Shift to higher proportion of hardwood species. Where possible, create herb- and shrub-dominant communities

Water quality	Higher on unstable slopes	Dispersed retention on unstable slopes	Concentrate intense harvest in stable geology	More early-seral habitat and old growth near riparian buffers	Less critical

Table 4.2: Management guidelines for riparian areas, roads, and forest activities to achieve goals.

	Riparian areas			Roads	Forest activities
Goal	Buffer width	Structure	Composition	Extent/Connectivity	Various
Floods	Less critical	Less critical	Less critical	Minimize mid-slope roads and disconnect runoff from streams before riparian areas, decommission temporary roads	Tracked shovel logging and sky-high-lining to reduce compaction and channelization, VRH and VDT
Low flows	Narrower buffers	Older trees with complex spatial structure	Create more hardwood patches	Diverting runoff to hillslopes may increase hillslope soil moisture	Reduce herbicides and planting, employ variable VR
Water quality	Medium to wide buffers (15m to 1 tree-height)	Multiple layers and gaps and logs. Treatments separated by 200-1000 m or 3-5 years	Create hardwood patches in dense conifers. Hardwoods should be 20-60% cover	Decommission roads on unstable slopes close to riparian areas, trap or divert sediment to hillslopes, restrict traffic	Tipping trees into streams, tracked equipment with long arm to reach into riparian buffer without disrupting soil

Table 4.3: Integrated management guidelines integration suggestions from **Tables 4.1** and **4.2**.

Category	Subcategory	Integrated approach
Hillslope forest	Tree density	Low intensity thinning on steep slopes. Uplands: variable density harvest with wide tree spacing in dispersed retention, remove at least 1/3 of tree cover and no more than 3/4.
	Harvest pattern	Gaps to retain snow in higher elevations and larger to reduce transpiration rain zones, especially with geology conducive to aquifer recharge
	Landscape	Aggregate locally, especially if enough proportion of landscape cannot be

	pattern	treated to make a difference everywhere. In riparian areas space treatments ~200-1000 m or 3-5 years apart
	Successional classes	Target large contiguous areas of young and mature forest or historic meadows and huckleberry fields needing restoration. Push dense conifer forests to either complex early seral habitat or old growth
	Composition	Create early seral communities within historic ranges of variability, incorporate more hardwood species in forested areas
Riparian areas	Buffer width	Wider (>30m) when adjacent to intense cutting, narrower (~15 m) when adjacent to retention after harvest
	Structure	Riparian areas: Reduce canopy cover by 25% using ~30 m diameter gaps, encourage multiple vertical layers
	Composition	Ensure conifer-dominated areas have hardwood patches and hardwood-dominated areas have conifers. Hardwoods comprise 20-60% cover
Roads	Extent/ Connectivity	Reduce extent and connectivity where possible. Decommission problem or temporary roads, preferentially use ridge roads and cable systems to minimize road networks, divert water early and often
Forest activities	Various	Tracked equipment is preferred, reduce herbicides and planting where appropriate, use systems and timing to reduce soil disturbance such as harvesting on snow, using aggregated retention, and suspended cable logging systems.

The key forest practices to use in this strategy are VRH and VDT. Both practices conform to the principles of ecological forest management (Box 1) by retaining (~30% cover) varied structures even when dramatically reducing forest. Variability alters runoff processes in space and time, providing a regulated buffer of peak runoff at large scales. If such variability also includes non-forest and old-growth structure within natural ranges, it will likely also increase low flows. Lastly, variable retention practices increase the range of tree sizes, ages, and species, thus increasing options in the future as science evolves.

4.3 Evaluating other attributes

We will likely see more fires, invasive species, and insect outbreaks due to human activities (Halofsky et al., 2020; Hulme, 2009; Preisler et al., 2012), so the guidelines here must also account for these risks. Additionally, the Tulalip Tribes are concerned about cultural values such as persistence of camas meadows and huckleberry fields. Native Americans historically maintained forest openings by burning and there is good evidence they were burning frequently in Douglas-fir forests in near-coastal islands (Bakker et al., 2019; Boyd, 1999). Although not the focus of this report, some general ecological concepts can be applied to qualitatively evaluate the effect of these above guidelines on fire, invasive species, and insect outbreaks.

A forest's response to disturbance is often characterized in terms of resistance and resilience. Here we define resistance as the ability of an ecosystem to reduce the intensity of a disturbance. For example, a wet coastal forest that does not easily catch fire is resistant while an interior dry-forest that readily burns is not. Resilience is defined here as the ability of an ecosystem to return to its previous state after disturbance regardless of how extreme. Examples include west-side forests that take centuries to return to their previous state after severe fire as well as dry-forests with low fuels that return to their previous state within a few years following low intensity fires. We can use the concepts of resistance and resilience as measures of how forests may respond in the future. Two additional related terms are intensity and severity. Intensity is a measure of the pressure from a disturbance, for example, wind speed, fire heat, or insect pressure. Severity is a measure of how much damage (i.e. mortality) a disturbance causes, for example, tree mortality.

Fire in the Snohomish basin is strongly influenced by its position west of the Cascade mountains. These forests are wet relative to those on the east side. Because of their wetness they are normally resistant to fire. Native burning was common in meadows and coastal islands, but the extent of Indian burning in west side Cascade forests is uncertain because that knowledge was eroded due to many factors such as residential schools and policies favoring fire suppression. (Doug Deur personal communication, 2021). Evidence from burn scars and tree cohort data suggest in the majority of these forests west side forests burned infrequently with a fire return interval of centuries (e.g. Agee, 1993; Donato et al., 2020). Fuels grow quickly during wet periods, then have windows when they are burnable in late summer and fall. Because fuels are normally high and fuel moist, burns in these forests are usually weather- rather than fuel-limited. Fires during most years are relatively small (~500 ha) because fuel moisture is relatively high (Huff, 1995). However, when ignitions coincide with strong dry east winds (e.g. summer 2020), fires in these forests are regional and severe and are one reason we find similar aged tree cohorts across the western Pacific Northwest (Henderson et al., 1989).

This in contrast to east Cascade forests which are dry year-round and fuels grow slower than in west-side forests. Here, the weather window in which fires can spread is wide, therefore these forests are thought of as fuel- rather than weather- limited. There is strong evidence that these forests were maintained by Native Americans and burned at decadal frequencies (Whitlock and Knox, 2002).

We are expecting more opportunities for fire during moderate fire weather in the western Pacific Northwest as temperatures rise, but will likely also see the same pattern of dry east winds driving our largest fires. We summarize the rationale and expected outcomes in response to three overarching categories of our suggested guidelines on high and moderate intensity fires in **Table 4.4**. These categories are reducing the road network, increasing early-seral and old-growth structure, and shifting composition to more hardwoods. Not addressed directly in this report, but of relevance to resilience to future fire, is that planting more interior and drought-hardy conifer species such as western larch and western white pine will likely also strengthen resilience in addition to incorporating more hardwoods.

Table 4.4: Qualitative expectations of forest response to fire under the recommended guidelines.

Forest response to fire	Fewer roads	Creating more early seral and old growth structure	Shifting composition to more hardwood trees

Severity of largest fires (during dry east winds)	Minimal, possible decreased extent from fewer ignitions	Minimal, fires will still burn intensely	Minimal: But faster recovery because of resprouting ability of hardwoods
Resistance to fire during moderate fire weather	Moderate: may decrease because of fuel break loss	Lower in early-seral where humidity and fuel moisture are lower and windspeed higher. Higher in old growth relative to young and mature forest because of horizontal canopy gaps and higher moisture	Likely higher, hardwoods are chemically less flammable and fuel beds more compact
Resilience to more frequent fire during moderate fire weather	Minimal: can reduce ignitions	Decreased response time to current conditions: early seral responds quickly, old growth burns more variably than mid-seral forest leaving diverse biological legacies	Substantial decrease in response time: fuel bed burns less intensely, more soil water available, resprouting capability

Wind is another dominant disturbance in the western Pacific Northwest. Wind with enough force to blowdown significant trees recur sporadically roughly every 30 years as subtropical cyclones shift north (Mass and Dotson, 2010). Winds from these storms are focused and intense and can knockdown immense tracts of forest (https://climate.washington.edu/stormking). Unlike fires, winds kill overstory trees while leaving understory structure and species assemblage largely intact. Because of this, they favor shade tolerant advanced regeneration rather than the light-demanding herbs and shrubs that fire promotes. How a forest responds to wind largely depends on the understory structure and species before winds strike. We are expecting increasingly intense storms with climate warming, so wind events will likely also increase.

Other disturbances likely to change are increases in insect attack and invasive species. A central concept in ecology is that biodiversity provides insurance for ecosystem processes (Loreau et al., 2001; Yachi and Loreau, 1999). Each species has functions it performs optimally at different times. Systems with high biodiversity are more resistant to invasive species and resilient to pestilence, especially when damaging agents are species-specific as are many bark beetles. Thus, we evaluate biodiversity as an indicator of resistance to invasive species and disease.

Other indicators related to aquatic systems are dead wood inputs and landslides. Dead wood enhances habitat and hydrologic function by creating complex streambed and mid-water-column structure while also slowing water and sediment runoff as noted above. Landslides that mobilize sediment and wood into streams are a natural and necessary process (Nakamura et al., 2000). However, if too frequent, they can contribute harmful chronic sediment loads. **Table 4.5** shows the qualitative evaluation of effects of fewer roads, more early-seral and old growth forest structure, and more hardwoods on forest responses related to wind, biodiversity, presence of large wood, and landslides relative to current practices.

Table 4.5: Qualitative expectations of forest biodiversity, presence of large wood, and landslides to the proposed guidelines.

	Fewer roads	**Creating more early seral and old growth structure**	**Shifting composition to more hardwood trees**
Biodiversity	Fewer invasive species, enhanced aquatic migration and water quality	Higher: more sources of berries seeds, nuts, and nutritious foliage; in old-growth, more diverse layered canopy and old trees and dead wood	Higher: more nutritious foliage, epiphytes, and cavities
Large dead wood	Higher, less wood cutting near roads	Depends on legacies after treatment for early seral but more in old-growth and in streams	Lower, decay is much faster and trees smaller
Windthrow	Negligible response	Less if harvest boundaries are "softer" because of VDT and VRH and leaving strong dominants	Unknown
Landslides	Fewer	Neutral, especially if retention left on unstable slopes	Unknown

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Forest practices conclusions

Forest management in the Snohomish basin will likely have minor effects on the hydrologic regime unless efforts are coordinated across multiple watersheds. Increasing low flows by cutting more trees will likely also cause more rapid runoff and flooding unless the spatial pattern of cutting is carefully considered. This means using variable retention practices at stand scales, while also concentrating practices in some basins and not in others. The effect of using variability at multiple scales is to increase water available while desynchronizing its runoff in winter months when soils are wet. Such variability will also allow managers to target critical areas for increased response if broad-scale treatments at sufficient intensity or effect duration are not possible.

Forest management is nested within geologic constraints and precipitation regime (timing, form, and amount), therefore, streamflow responses can be variable with changes in forest cover. These constraints should be considered to the degree possible when planning where to place forest treatments. Focusing harvest in areas with faster recharge and better groundwater connectivity between high and low elevations should yield the best results.

Because the current forest conditions are a product of past management, including intensive silviculture to promote vigorous plantations, much of the landscape is now in low biodiversity, structurally homogenous, rapidly transpiring forest. Focusing efforts on these forests will yield many benefits. By turning some into permanent non-forest, we can restore Native American cultural values in meadows and huckleberry fields. By using VRH and not spraying herbicides and planting new trees, we can create biodiverse early-seral habitat, increasing biodiversity, and reducing transpiration demand for decades. If these areas are replanted, then the benefits of the initial harvest disappears within ~10 years. Likewise, mature forest leaf area can also be reduced in a meaningful way that preserves much of their function. VDT can be used to accelerate structural heterogeneity while still allowing remaining trees to provide shade, intercept fog, and stabilize slopes. Lastly, increasing biodiversity and increasing soil moisture can also be done by incorporating more hardwood species. Because hardwoods rebound quickly from fire and use less water, they are a useful and under-utilized tool.

Roads appear to be a major problem with no easy solution. Decommissioning roads is inevitably contentious. However, new guidelines that divert water before it reaches riparian areas is a step in the right direction and an area needing further research. There is a relatively new optimization tool allowing reduction of unneeded roads (Ross et al., 2018) and techniques such as skylining that allow foresters to avoid putting roads in at all.

Last, upslope forest management cannot ignore the riparian ecosystem and river restoration. Vegetation along rivers provides the last filter through which water passes before becoming streamflow. Both the structure of these streams (e.g. how connected to their floodplain), and the vegetation along it has strong implications for how low flows are expressed. Riparian buffers shade streams and filter sediment, however, buffers of dense conifers may also reduce biodiversity and low flows. Along narrow streams, vegetation rapidly re-shades streams, so here VDT in dense conifer buffers may be suitable. Such riparian treatments should be spaced in distance or time to reduce cumulative stream warming effects. Incorporating structural and compositional variability in such buffers will likely increase both biodiversity (including food for fish) and low flows.

Section 5. Modeling Support

This section summarizes the key models and other forest and watershed assessments in the Pacific Northwest that can be used to aid design and modeling of the forest treatments with the above-described guidelines. One component of this project is to locate natural areas to target for water recharge, which is the focus of **Section 5.1**. Another component is estimating the effects of hillslope forest practices on stream flow, which is the focus of **Section 5.2**. Section 5.1 focuses on wetland location and storage estimation models (**Section 5.1**), while Section 5.3 focuses on distributed hydrology models. Each briefly describe model inputs and lists key references. **Section 5.3** is a review of other forest and watershed assessments in the same region that provide information, indicators to assess model outcomes, datasets, and tools that may be useful for designing, training, and evaluating models.

5.1 Models for identifying wetlands & estimating water storage with LiDAR DEMs

Methods for identifying wetlands, potential wetlands, and locations with natural water storage potential are identified below. Commonalities between studies include the importance of high-resolution LiDAR-derived digital elevation models (DEMs); the use of topographically derived predictor variables such as topographic wetness index (TWI); inconsistent utility of depth to water table and other soil derived metrics; the use of Random Forest models to identify potential wetland locations; and the importance of local training datasets to improve model accuracy.

ESRI Arc Hydro: Wetland Identification Model (March 2020)* – This is a new Arc Hydro tool (v.2.5) with GIS functionality for predicting wetland locations using high-resolution **LiDAR DEM** and machine learning (*developed by Gina O'Neil et al., Univ of Virginia)

Key references:

O'Neil, G. L., Goodall, J. L., Watson, L. T. (2018). Evaluating the potential for site-specific modification of LiDAR DEM derivatives to improve environmental planning-scale wetland identification using random forest classification. *Journal of Hydrology*, 559:192-208. https://doi.org/10.1016/j.jhydrol.2018.02.009.

O'Neil, G. L., Saby, L., Band, L. E., Goodall, J. L. (2019). Effects of LiDAR DEM smoothing and conditioning techniques on a topography-based Wetland Identification Model. *Water Resources Research*, 55. https://doi.org/10.1029/2019WR024784.

O'Neil, G. L., Goodall, J. L., Behl, M., Saby, L. (2020). Deep learning using physically-informed input data for wetland identification. *Environmental Modelling and Software*. 104665. https://doi.org/10.1016/j.envsoft.2020.104665.

Other GIS tools for locating and estimating natural water storage capacity – These offer a rapid geospatial approach for locating and estimating capacity. Inputs: **slope**, **TWI**, **distance to streams** and **roads**. Uses available tools in ArcGIS and SAGA GIS. Jones et al., 2018 for estimating restorable wetland water storage at landscape scales.

Key references:

Uuemaa, E., Hughes, A. O., Tanner, C. C. (2018). Identifying feasible locations for wetland creation or restoration in catchments by suitability modelling using light detection and ranging (lidar) digital elevation model (DEM). *Water*, 10, 464. https://doi.org/10.3390/w10040464.

Jones, C.N., Evenson, G.R., McLaughlin, D.L., Vanderhoof, M.K., Lang, M.W., McCarty, G.W., Golden, H.E., Lane, C.R., Alexander, L.C., 2018. Estimating restorable wetland water storage at landscape scales. Hydrological Processes 32, 305–313. https://doi.org/10.1002/hyp.11405

Hydrologic Sensitivity Index (TWI + Soil water storage capacity) – The Hydrologic Sensitivity Index is defined as the difference between Topographic Wetness Index and soil water storage capacity. It was developed by Nannette Huber at WSU from what looks like unpublished data from a PhD student working with Anand Jayakaran & Joan Wu at WSU. Jayakaran's expertise is green stormwater infrastructure. Inputs: **LiDAR DEM, SSURGO soil data, and NAIP imagery.**

Key references

Rodak, C. M., Jayakaran, A. D., Moore, T. L., David, R., Rhodes, E. R., Vogel, J. R. (2020). Urban stormwater characterization, control, and treatment. *Water Environment Research*, 92. https://doi.org/10.1002/wer.1403.

Jayakaran, A. D., Moffett, K. B., Padowski, J. C., Townsend, P. A., Gaolach, B. (2020). Green infrastructure in Western Washington and Oregon: Perspectives from a regional summit. *Urban Forestry & Urban Greening*, 50. https://doi.org/10.1016/j.ufug.2020.126.

Natural storage potential of sites – This metric can be calculated using data from a LiDAR DEM, soil, land use/land cover (LULC), and long-term well data. This approach was designed for floodplains in Montana but may be flexible enough to be generalized.

Key reference

Holmes, D., McEvoy, J., Dixon, J. L., Payne, S. (2017). A geospatial approach for identifying and exploring potential natural water storage sites. *Water*, 9, 585. https://doi.org/10.3390/w9080585.

Soil water assessment tool (SWAT) improvements – Adds modules to the original SWAT tool for riparian and geographically isolated wetlands. The Soil & Water Assessment Tool is a small watershed to river basin-scale model used to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds. SWAT was developed initially to assess agricultural impacts. Inputs: topographic, soil, climatic, vegetation, management, and additional variables.

Lee, S., Yeo, I.-Y., Land, M. W., Sadeghi, A. M., McCarty, G. W., Moglen, G. E., Evenson, G. R. (2018). Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. Journal of Environmental Mgmt, 223. https://doi.org/10.1016/j.jenvman.208.06.006.

Simulating hydrologic connectivity to delineate watersheds – This approach uses graph theory to delineate watersheds and determine potential hydrologic connectivity. Inputs: **LiDAR DEM, National Agriculture imagery, National Wetland Inventory, National Hydrography Dataset**.

Key reference

Wu, Q., Lane, C. R. (2017). Delineating wetland catchments and modeling hydrologic connectivity using lidar data and aerial imagery. *Hydrol Earth Sys Sci*, 21, 7. https://doi.org/10.5194/hess-21-3579-2017.

Wetland Intrinsic Potential Mapping Tool – This is an ArcGIS tool that calculates the probability of wetland occurrence using known wetland locations, a set of input rasters, and the Random Forests algorithm. The tool calculates a number of topographic indices that have proven useful for wetland identification. It is capable of using any number of gridded inputs for classification. Inputs: **LiDAR DEM, other gridded datasets such as NDVI, soil depth, precipitation, etc.**

Key reference

Miller, Dan, and Meghan Halabisky. 2020. "Wetland Mapping ToolProjectPhase 2 Report." TerrainWorks.

On using beavers and beaver dam analogues to create wetlands – There is growing interest in reintroducing beavers and mimicking their actions to restore wetlands to create rather than locate wetlands.

Key references

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., Volk, C. (2014). Using beaver dams to restore incised stream ecosystems. *BioScience*, 64, 4. https://doi.org/10.1093/biosci/biu036.

Pilliod, D. S., Rohde, A. T., Charnley, S., Davee, R. R., Dunham, J. B., Gosnell, H., Grant, G. E., Hausner, M. B., Huntington, J. L., Nash, C. (2018). Survey of beaver-related restoration practices in rangeland streams of the western USA. *Environmental Management*, 61. https://doi.org/10.1007/s00267-017-0957-6.

Lautz, L., Kelleher, C., Vidon, P., Coffman, J., Rignios, C., Copeland, H. (2019). Restoring stream ecosystem function with beaver dam analogues: Let's not make the same mistake twice. *Hydrological Processes*, 33, 1. https://doi.org/10.1002/hyp.13333.

5.2 Distributed hydrology models

A number of distributed hydrology models appear capable of addressing how hillslope forest practices alter runoff processes. The models below have been used to estimate stream flow for large, forested, and snow-influenced watersheds. Each model includes algorithms representing numerous hydrological processes, including snow accumulation and melt, and groundwater-surface water interactions. **DHSVM** has been applied across the Pacific Northwest and **WEPP** has been applied to watersheds on the west slopes of the Cascade Mountains in Washington. **RHESSys** and **VELMA** have been applied in northern California and western Oregon. Model complexity ranges from high for process-based models (e.g., DHSVM), to low for statistical models (i.e., regression or correlation models of input and outputs variables, such as those using the unit hydrograph). Models of intermediate complexity are typically process-based but with simplifying assumptions. Selection of one or more final model may require discussions with experienced model users or prototyping candidate models.

Compared to forest growth models (such as the USDA Forest Vegetation Simulator), hydrology models simplify forest growth and management. Some inputs for hydrology models are directly available as outputs from forest growth models (such as tree height and canopy base height). Other inputs, such as leaf area index, can be estimated from forest growth model outputs.

DHSVM

The Distributed Hydrology Soil Vegetation Model (DHSVM, Wigmosta et al., 1994) (https://www.pnnl.gov/projects/distributed-hydrology-soil-vegetation-model) may be the most widely used fine scale hydrologic model for research in Pacific Northwest forested watersheds. Landscapes are represented using gridded (raster) input datasets where each raster cell has a model input value. The seven modules that represent the DHSVM coupled water and energy balance are: 1) evapotranspiration, 2) snow accumulation and melt, 3) canopy snow interception and release, 4) unsaturated moisture movement, 5) saturated subsurface flow, 6) surface overland flow, and 7) channel flow. Vegetation is represented by vegetation classes with associated parameters. The default time step value is 3 hours, and the model's spatial resolution typically ranges from 30 to150 meters.

DHSVM provides a detailed representation of the interaction between vegetation and hydrologic processes and therefore has been widely used to address hydrologic effects of timber harvest. For example, vegetation is represented using a two-layer canopy model. Snow intercepted over the plant canopy is also subject to multiple energy-driven melt processes and melt waterpathways from the canopy to the ground. A vegetation class is specified for each raster cell, and corresponding vegetation-specific biophysical parameters (e.g. seasonally varying leaf area index and albedo, stomatal resistance, hemispherical factional cover) are used to compute vegetation-influenced aspects of the water balance, such as evaporation and interception. A glacier module is available, and the model can also be coupled to the RBM stream-temperature model (Yearsley, 2012).

DHSVM has been used to evaluate rain-on-snow events and the effects of forest roads in western Washington watersheds (Storck et al. 1998); vegetation and stream flow timing in the Lake Tahoe region (Cristea et al. 2013); canopy gap creation and stream flow in the Cascade Mountains (east slopes) of Washington (Sun et al. 2018); and the effects of clearcut on snow melt and stream flow in south central British Columbia (Thyer et al. 2004). The relationship between elevation, clearcuts, and peak flow was also evaluated in a snow-dominated watershed in British Columbia (Whitaker et al. 2002). DHSVM has been parallelized to allow simulation of larger basins (Perkins et al. 2019).

Pros: Detailed representation of hydrologic processes: sophisticated representation of canopy interception and release of precipitation; most common fine-scale hydrological model used in PNW research; numerous studies conducted in PNW on wide range of hydrology related topics.

Cons: Complex to initialize; computationally intensive; detailed parameterization of vegetation but unclear how to implement forest growth and treatments over time, under current configuration the vegetation parameters are static. The roads implementation is in need of being modernized and is difficult to implement in its current form.

Key references

Cristea, N. C., Lundquist, J. D., Loheide, S. P., Lowry, C. S., & Moore, C. E. 2013. Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. Hydrological Processes.

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Wigmosta, M. S., Vail, L. W., & Lettenmaier, D. P. 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research, 30(6), 1665-1679.

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RHESSys

The Regional Hydro-Ecological Simulation System (RHESSys) (http://fiesta.bren.ucsb.edu/~rhessys/) is a spatially explicit modeling framework (Tague and Band 2004). RHESSys divides a landscape into hydrological units of arbitrary shape defined by similar vegetation, land use, soils, climate, and topography. Hydrologic processes are simplified compared to DHSVM. Hydrologic processes include snow accumulation and melt, and canopy interception. Explicit routing can optionally be used for saturated subsurface flow, overland flow, and channel flow.

Vegetation growth is simulated within the system and treatments and disturbances can be specified by the user during the simulation. The model runs on a daily time step.

The model has been used to simulate the effects of forest roads and forest harvest in several watersheds in Oregon (Tague and Band, 2001; Krezek et al., 2007) and in Yosemite National Park, CA (Christensen et al., 2008). The timing of peak snow melt in watersheds with varying subsurface draining rates were evaluated under climate change scenarios in the western Cascade Mountains in Oregon (Tague and Grant 2009). Tague et al. (2009) studied the relationship between the response of vegetation and hydrology to climate change and changes in transpiration rates.

Pros: Appears easier to initialize than DHSVM; vegetation growth and treatments are included in the simulation framework; arbitrarily sized hydrologic units and optional explicit routing may allow project to scale.

Cons: Some hydrologic processes are simplified compared to DHSVM; vegetation growth model will need to be parameterized to match FVS growth outputs; model has primarily been evaluated in Oregon and northern California.

Key references

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<u>WEPP (GeoWEPP)</u>

The Water Erosion Prediction Project (WEPP) model is a process-based, continuous simulation, distributed parameter, hydrologic and soil erosion prediction system (Renschler 2003). WEPP calculates key processes on an hourly time step. WEPP was recently updated to account for baseflow contributions and groundwater-surface water interactions to better match streamflow in large basins (Srivastava et al. 2017). Multiple versions of WEPP exist. GeoWEPP is an ArcGIS 10.x implementation to estimate water yield and sedimentation for a watershed using readily available datasets. GeoWEPP does not appear incorporate forest roads, while WEPP:Roads does not currently incorporate base flows. WEPP has been used to evaluate the effects of forest management on water yield in the Cedar River watershed, WA (Srivastava et al. 2017), in Idaho (Srivastava et al. 2020), and in Lake Tahoe, CA (Brooks et al. 2016).

Pros: Easier to initialize; includes a generalized hillslope method (limited to 2900 hillslopes, 1,000 channels, and 1 soil-cover per hillslope) and a site-specific flowpath method; it also has an ArcGIS interface.

Cons: Forest roads are not incorporated in GeoWEPP model; simple, only includes a static representation of forest vegetation; the model does not seem capable of modeling forest gap treatments

Key references

Brooks, Erin S., Mariana Dobre, William J. Elliot, Joan Q. Wu, and Jan Boll. 2016. “Watershed-Scale Evaluation of the Water Erosion Prediction Project (WEPP) Model in the Lake Tahoe Basin.” Journal of Hydrology 533 (February): 389–402. https://doi.org/10.1016/j.jhydrol.2015.12.004.

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Srivastava, A., E. S. Brooks, M. Dobre, W. J. Elliot, J. Q. Wu, D. C. Flanagan, J. A. Gravelle, and T. E. Link. 2020. “Modeling Forest Management Effects on Water and Sediment Yield from Nested, Paired Watersheds in the Interior Pacific Northwest, USA Using WEPP.” Science of The Total Environment 701 (January): 134877. https://doi.org/10.1016/j.scitotenv.2019.134877.

VELMA

The Visualizing Ecosystems for Land Management Assessments (VELMA) model is a spatially distributed ecohydrology model that links hydrological and biogeochemical processes within watersheds (Abdelnour et al. 2011). VELMA attempts to provide a model of intermediate complexity that is accessible to a broader range of practitioners and can scale to larger basins and longer timeframes.

Ground water flow follows a TOPMODEL framework (Bevens and Kirby 1979). TOPMODEL is a physically based, distributed watershed model that simulates hydrologic fluxes of water (infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing) through a watershed. The model simulates explicit groundwater/surface water interactions by predicting the movement of the water table, which determines where saturated land-surface areas develop and have the potential to produce saturation overland flow. Forest growth in VELMA is simulated using an evapotranspiration recovery curve (the S-shaped, asymptotic Chapman-Richards curve) following treatments (e.g. Zhao-gang and Feng-ri, 2003). VELMA has been used to evaluate forest harvest effects on streamflow in the H.J. Andrews long term ecological research (LTER) site in western Oregon and to model stream flow in a watershed in Humboldt County, VA (Luckens 2019).

Pros: Appears easier to initialize due to the availability of a graphical user interface (GUI); represents forest growth through time and can represent forest management and natural disturbance with variable frequency, location and types of changes to biomass scales to larger areas and longer timeframes;

Cons: Forest roads not incorporated; does not solve for the energy balance : evapotranspiration and snowmelt are linked to air temperature indices only; model does not represent canopy interception of precipitation or canopy shading and sheltering, and therefore likely overestimates precipitation inputs in forested areas and is unable to represent forest gap treatments; nopeer-reviewed literature on applications in Washington or snow-dominated watersheds.

Key references

Abdelnour, Alex, Marc Stieglitz, Feifei Pan, and Robert McKane. 2011. "Catchment Hydrological Responses to Forest Harvest Amount and Spatial Pattern." Water Resources Research 47 (9). https://doi.org/10.1029/2010WR010165.

Beven, K., and M. Kirkby (1979), A physically based, variable contributing area model of basin hydrology, Hydrol. Sci. Bull., 24(1), 43–69.

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Zhao-gang, L., Feng-ri, L., 2003. The generalized Chapman-Richards function and applications to tree and stand growth. Journal of Forestry Research 14, 19–26.

<u>Other Models</u>

WaSiM-ETH

The Water Flow and Balance Simulation Model (WaSiM-ETH;aka Wasserhaushalts-Simulations-Model) (http://www.wasim.ch/en/index.html) is a distributed hydrology model based on a gridded (raster) framework and a sub-daily time step (Schulla 2019). WaSim-ETH implements an intermediate level of complexity between fully process-based physical model and statistical models. A modular structure is used, allowing some modules to not be used in a simulation, and less data intensive methods to be used in some cases. WaSiM-ETH has been paired with a forest growth simulator in German forests (Sutmöller et al. 2011) and used to estimate future stream flows in the Columbia river headwaters under climate change scenarios (Bürger et al. 2011). WaSiM-ETH has been proposed as a potential model to evaluate forest restoration planning to increase snowpack, runoff, and streamflow in the Upper Columbia River by researchers at the University of Washington and TerrainWorks (Istanbulluoglu et al. 2014). It does not appear WaSiM-ETH has been applied in western Washington.

Key references

Bürger, G., J. Schulla, and A. T. Werner. 2011. "Estimates of Future Flow, Including Extremes, of the Columbia River Headwaters." Water Resources Research 47 (10). https://doi.org/10.1029/2010WR009716.

Istanbulluoglu E, L Benda, D Miller, M Bachmann, C Frans, K Andras, E Doyle. 2014. Developing a Distributed Hydrology Model for Use in Forest Restoration Planning to Increase Snowpack, Runoff and Streamflow in the Upper Columbia. Research Proposal.

Schulla, J. 2019. Model Description WaSiM-ETH. http://www.wasim.ch/downloads/doku/wasim/wasim_2019_en.pdf.

Sutmöller, J., S. Hentschel, J. Hansen, and H. Meesenburg. 2011. "Coupled Forest Growth-Hydrology Modelling as an Instrument for the Assessment of Effects of Forest Management on Hydrology in Forested Catchments." Advances in Geosciences 27 (March): 149–54. https://doi.org/10.5194/adgeo-27-149-2011.

Topnet

Topnet simulates hydrology over large basins using small watersheds as the individual analysis units (Bandaragoda et al. 2004). It is based on the TOPMODEL distributed hydrology model (Beven and Freer 2001). Spatial variability within a unit is represented by topographic wetness index and an area depletion curve. Topnet has been proposed as a potential model to evaluate forest restoration planning to increase snowpack, runoff and streamflow in the Upper Columbia River by researchers at the University of Washington and TerrainWorks (Istanbulluoglu et al. 2014). It does not appear Topnet has been applied in Western Washington.

Key references

Beven, Keith, and Jim Freer. 2001. "A Dynamic TOPMODEL." Hydrological Processes 15 (10): 1993–2011. https://doi.org/10.1002/hyp.252.

Bandaragoda, Christina, David G Tarboton, and Ross Woods. 2004. "Application of TOPNET in the Distributed Model Intercomparison Project." Journal of Hydrology, The Distributed Model Intercomparison Project (DMIP), 298 (1): 178–201. https://doi.org/10.1016/j.jhydrol.2004.03.038.

Istanbulluoglu E, L Benda, D Miller, M Bachmann, C Frans, K Andras, E Doyle. 2014. Developing a Distributed Hydrology Model for Use in Forest Restoration Planning to Increase Snowpack, Runoff and Streamflow in the Upper Columbia. Research Proposal.

5.3 Indicators, Datasets, and Tools

This section of the report reviews other assessments of forest and watershed conditions to identify relevant management and policy processes, assessment techniques, indicators, datasets, and tools. Appendix 4 tables 1 and 2 summarize these findings, with an additional emphasis on how indicators are combined and scored. An accompanying **Appendix 4** Powerpoint file contains graphics related to the assessment procedures and results for the Snohomish basin (where available). In the following section the Northwest Forest Plan is referred to as NWFP.

AQUATIC-FOCUSED ASSESSMENTS

Northwest Treaty Tribes' State of Our Watersheds (NTT-SOW)

Description

The Northwest Indian Fisheries Commission (NWI) has produced a State of Our Watersheds report every 4 years since 2012. These reports bring together data from the Tribes, the WA Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP), and other state and federal agencies to present a more complete set of indicators of habitat quality and quantity. The area covered is WRIAs 1-23 in western Washington that lie within tribal Usual and Accustomed fishing areas as defined by U.S. v. Washington (Boldt decision), but federal lands are excluded (no mention why). The reports track trends in 9 indicators for the Puget Sound region as a whole and also for each tribe's area of interest (the Snohomish basin for the Tulalip). Forest indicators include forest cover and riparian forest cover, based on NOAA C-CAP monitoring (from Landsat 30-m pixels). The reports do not track stream flows but do report groundwater withdrawals based on WADOE well permitting data.

URL

https://nwifc.org/publications/state-of-our-watersheds/

Indicators

- Forest Cover: from NOAA CCAP
- Riparian Forest Cover change: WDFW High Resolution Change Detection (HRCD) data for 2006 through 2017
- Groundwater withdrawals: from WADOE data

Datasets

- NOAA CCAP: https://coast.noaa.gov/digitalcoast/data/ccapregional.html
- Groundwater withdrawals: WAECY. (December 23, 2019). Water Well Logs Points. Olympia, WA: Washington State Department of Ecology.

Tools

- 2020 State of Our Watersheds Interactive Viewer
- Just seems to show the tribal boundaries but no indicator data.

Publications

- NWIFC 2020. 2020 State of Our Watersheds. Northwest Indian Fisheries Commission. https://nwifc.org/publications/state-of-our-watersheds/

NTA0970 Relevance

NOAA-CCAP forest indicator categories are much broader than the LEMMA data NTA0970 is planning on using, but their combination with NWI wetland data may be a useful approach and these data may be useful for historical context. NTA0970 forest practices scenarios could be reflected in the forest cover indicators to the extent gaps approaching 30m or greater are produced. Perhaps NTA0970 could suggest including some type of streamflow metric in future NTT-SOW assessments.

NW Forest Plan Aquatic & Riparian Effectiveness Monitoring Program (AREMP)

Description

AREMP looks at upslope and riparian influences to streams based on a GIS assessment of roads and vegetation conditions, and they assess in-channel conditions based on field measurement of indicators like temperature and large woody debris in a sample of ~250 sub-watersheds (HUC12) out of the ~2000 with >5% federal ownership in the NWFP area. Only federal lands are assessed because the NWFP only applies to federal lands (and key indicators used would be difficult to obtain for non-federal lands: limited access to private lands for field sampling and unavailability of forest road data for private lands). Reports are produced on a 5-year cycle. The last report and dataset were issued in 2017 (using 2012 data), and the next report is likely to be released in fall 2021.

URL

https://www.fs.fed.us/r6/reo/monitoring/watersheds.php

Indicators

Landslide risk

The AREMP shallow landslide risk indicator has changed over time. For the 15-year assessment it was simply a topographic risk based on the NetMap LSDEL indicator, which incorporates slope steepness, convergence (from a 10-m DEM) and distance to streams. For the 20-year assessment, a multiplier was developed with geology & soils staff to adjust for geology, landform, precipitation, and the potential for rain-on-snow events. Both of these assessments included multipliers for vegetation loss and roads. The 25-year assessment moved to a different but similar model (SINMAP), but only estimated road impacts (no vegetation component).

Vegetation

The AREMP vegetation indicators have also changed over time. For the 15-year assessment, a separate model was developed for each of 7 aquatic provinces, generally comparing average canopy cover and DBH metrics to expert-judgment-derived thresholds. The 20-year assessment also used canopy cover and DBH metrics but based their evaluation criteria on the empirical range found within each of 15 different vegetation type zones. The 25-year assessment is looking at canopy cover, an old-growth index of 80 years, and large trees per hectare (all only within the riparian zone). Average values by HUC12 are being reported with no further evaluation applied.

Drought

The report currently in production is incorporating the Standardized Precipitation Evapotranspiration Index (SPEI, Vicinte-Serrano et al. 2010), a widely used indicator of drought.

Streamflow

The report currently in production is incorporating trends in streamflow estimates based on the USGS National Hydrologic Model, which provides parameterizations for the Precipitation-Runoff Modeling System (PRMS) (Regan et al., 2018).

Datasets

- 20-year report results (from URL above) provide data and scores summarized to HUC12 sub-watersheds. Base data on vegetation are available from the LEMMA Lab (https://lemma.forestry.oregonstate.edu/data) and base data for landslide risk can be requested from the program. Drought and streamflow data may not be released until the current report is published.

Tools

- AREMP has not produced tools for external use, however, their methods for landslide risk and vegetation evaluation could be obtained from the author.
- Landslide risk methods have been based on two methods:
- NetMap: http://www.netmaptools.org/Pages/NetMapHelp/channel_2.htm
- SINMAP: https://hydrology.usu.edu/sinmap2/

Publications

Miller, S.A.; Gordon, S.N.; Eldred, P.; Beloin, R.M.; Wilcox, S.; Raggon, M.; Andersen, H.; Muldoon, A. 2017. Northwest Forest Plan—the first 20 years (1994-2013): watershed condition status and trend. Gen. Tech. Rep. PNW-GTR-932. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/pnw-gtr-932

Regan, R.S., Markstrom, S.L., Hay, L.E., Viger, R.J., Norton, P.A., Driscoll, J.M., LaFontaine, J.H., 2018, Description of the National Hydrologic Model for use with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, book 6, chap B9, 38 p., https://doi.org/10.3133/tm6B9

Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. 2010. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. Journal of Climate. 23(7): 1696–1718. https://doi.org/10.1175/2009jcli2909.1

NTA0970 Relevance

The USFS has a large influence over WRIA07, managing approximately 40% of the area, almost all forested. AREMP's upslope-riparian vegetation indicators use the latest LEMMA data (2017), which are more difficult to work than the 2012 version, since they are based on a multiple nearest neighbor approach to matching pixels to forest plots (they no longer match a single plot, and thus all its characteristics, to a pixel). However, comparisons of these two datasets might be worthwhile for key indicators. AREMP landslide risk methods and indicators can identify higher risk areas by topography and geology but links to vegetation characteristics are quite coarse for NTA0970 purposes. Neither accounts for varying wetness levels directly, although this might be possible through incorporation of more of the source SINMAP equation. AREMP has inchannel monitoring sites in 4 WRIA07 subwatersheds.

USDA Forest Service Watershed Condition Framework (USFS-WCF)

Description

The Watershed Condition Framework provides a planning framework for assessing and improving watershed conditions. The first step in the process is assessing the condition of watersheds using the Watershed Condition Classification specification, a hierarchical set of 12 indicators and 22 attributes/metrics indicators covering four broad process categories (aquatic physical/biological and terrestrial physical/biological). Subsequent steps are: Prioritize watersheds for restoration, Develop Watershed Restoration Action Plans, implement integrated suites of projects, Track restoration accomplishments, and Verify accomplishment of project activities.

The WCC was initiated in 2010 and is updated every five years. The 2020 assessment results may be completed locally by summer 2021, but are unlikely to be released publicly until some months later.

URL

https://www.fs.fed.us/naturalresources/watershed/condition_framework.shtml

Indicators

- The indicators are quite general, often providing only qualitative or broad quantitative targets, for example:
- Aquatic-Flow: The watershed lacks significant man-made reservoirs, dams, and diversion facilities.
- Aquatic-Riparian Vegetation: Native mid to late seral vegetation appropriate to the sites potential dominates the plant communities and is vigorous, healthy and diverse in age, structure, cover and composition on >80% of the riparian/wetland areas in the watershed.)
- Terrestrial-Forest Cover: Less than 5% of NFS land in the watershed contains cutover, denuded, or deforested forest land

Datasets

- Each national forest is responsible for assembling its own data and interpreting these in regard to the assessment guidelines. However, the regional office has assembled some national and regional level datasets in the past that can be used (Clean Water Act Section 303d water quality listings, riparian vegetation, road density, mass wasting, fire regime class, insect/disease risk).

Tools

- None

Publications

U.S. Department of Agriculture, Forest Service [USDA FS] 2010. Forest Service watershed condition classification technical guide. Washington, DC: U.S. Department of Agriculture, Forest Service. 41 p. http://www.fs.fed.us/publications/watershed/watershed_classification_guide.pdf

U.S. Department of Agriculture, Forest Service [USDA FS] 2011. Watershed condition framework. FS-977. Washington, DC. 24 p. http://www.fs.fed.us/publications/watershed/Watershed_Condition_Framework.pdf

NTA0970 Relevance

WCF indicators are quite broad and unlikely to be useful or affected by NTA0970 scenarios. However, while the WCF is less empirically-based (more expert judgment) than AREMP, it is more integrated into the USFS planning and restoration priority-setting processes. WRIA07 includes one priority watershed, the Upper South Fork Skykomish, which was designated for its anadromous fish habitat potential and has an associated restoration action plan.

Northwest Forest Plan Riparian Alternatives Study (NWFP-RA)

Description

The Aquatic Conservation Strategy (ACS) of the Northwest Forest Plan (NWFP) designated riparian reserves of two site-potential tree-heights on fish-bearing streams, and one site-potential tree-height on non-fish-bearing streams. These buffer widths were intended to be interim until more detailed analysis was done; however, such analysis has rarely occurred. This report examines two alternatives, where the buffer is split into two zones: an inner reserved zone and an outer zone where ecological forestry is permitted. Under alternative A, the inner zone is of one tree-height, and under alternative B, the inner zone is variable depending on four characteristics of each stream reach: susceptibility to surface erosion, debris flows, thermal loading, and habitat potential for target fish species. Reeves et al. (2018) provided further synthesis of the literature, arguing for a reduction of the standard NWFP riparian buffers from 2-to-1 tree height, based primarily on further research on riparian microclimates.

Indicators

- Surface erosion, debris flows, thermal loading, and intrinsic habitat potential for target fish species (all from the NetMap tool). Fish-bearing stream reaches with an intrinsic potential ≥0.5 or with an increase in thermal loading potential ≥10 percent or adjacent to areas of high erosion potential were placed in the “most ecologically sensitive” category, as were non-fish-bearing reaches with a high potential to deliver sediment and wood to fish-bearing streams.

Datasets

- NetMap data based on 10-m DEM are available for the Snohomish basin https://terrainworks.com/datasets

Tools

- NetMap from TerrainWorks: https://terrainworks.com/

Publications

Reeves, G.H.; Pickard, B.R.; Johnson, K.N. 2013. An initial evaluation of potential options for managing riparian reserves of the Aquatic Conservation Strategy of the Northwest Forest Plan. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://www.fs.usda.gov/treesearch/pubs/50788

Reeves, G.H.; Olson, D.H.; Wondzell, S.M.; Bisson, P.A.; Gordon, S.; Miller, S.A.; Long, J.W.; Furniss, M.J. 2018. Chapter 7: The aquatic conservation strategy of the northwest forest plan—A review of the relevant science after 23 years. In: Spies, T.A.; Stine, P.A.; Gravenmier, R.A.; Long, J.W.; Reilly, M.J., eds. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 461–624. https://www.fs.usda.gov/treesearch/pubs/56335 (August 10, 2018).

NTA0970 Relevance

If NTA0970 wishes to track vegetation conditions in the riparian zone, this project provides an alternative, more process-based approach to delineating riparian zones (as compared to the NWFP tree-heights approach). The NetMap tool provides a wide variety of calculated metrics relevant to stream conditions. NetMap provides a free download of their synthetic stream layers (produced from DEMs) with metrics for stream segment length, drainage area, elevation, distance to mouth, gradient, mean annual precipitation, mean annual flow, channel bankfull width, channel bankfull depth, Strahler stream order, azimuth and sinuosity. Further indicators and tools may require purchase.

Pacific Northwest Hydrologic Landscape Characterization (PNW-HLC)

Description

This assessment apportioned the landscape according to 5 characteristics which provide macro controls on the hydrology (primarily flow): climate (precipitation + evapotranspiration), seasonality, slope, aquifer permeability, and soil permeability. There are 10 hydrologic landscape classes represented in the Snohomish basin, with most of the uplands represented by the VsLMH class (very wet, maximum water surplus in spring, low aquifer permeability, mountainous, high soil permeability). In a recent paper, Jones (2020) link the HL landscape to climate scenarios to predict landscape vulnerabilities.

URL

https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=311666&Lab=NHEERL

Indicators

- Climate (precipitation + evapotranspiration), seasonality, slope, aquifer permeability, and soil permeability

Datasets

- Hydrologic Landscapes: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B7608F3FF-27E3-4A42-ADE7-F29C1CA1172F%7D
- Climate vulnerability: data for Jones (2020) will be released once final paper is accepted for publication.

Tools

- Climate vulnerability: code for Jones (2020) will be released once final paper is accepted for publication.

Publications

Leibowitz, S.G.; Comeleo, R.L.; Wigington, P.J.; Weber, M.H.; Sproles, E.A.; Sawicz, K.A. 2016. Hydrologic Landscape Characterization for the Pacific Northwest, USA. JAWRA Journal of the American Water Resources Association. 52(2): 473–493. https://doi.org/10.1111/1752-1688.12402

Jones, C.E.; Leibowitz, S.G.; Sawicz, K.A.; Comeleo, R.L.; Stratton, L.E.; Morefield, P.E.; Weaver, C.P. 2020. Using hydrologic landscape classification and climatic time series to assess hydrologic vulnerability of the Western U.S. to climate. Hydrology and Earth System Sciences Discussions. 2020: 1–49. https://doi.org/10.5194/hess-2019-638

NTA0970 Relevance

These hydrologic divisions could serve as broader groupings for the fine- level hydrologic work anticipated under NTA0970.

US Geological Survey Streamflow Conditions (USGS-Flow)

Organizations

US Geological Survey

URL

https://waterdata.usgs.gov/wa/nwis/rt

Description

The USGS collects data continuously at almost 400 streamflow, reservoir, water-quality, meteorological and groundwater sites in Washington State. Most of these data are transmitted via satellite and posted on-line in near real time. Approximately 20 sites are in the Snoqualmie/Snohomish River Basin.

Indicators

Main map displays current flow as percentile of 30-year average.

WaterWatch Toolkit: Duration Hydrograph, runoff duration, cumulative streamflow, summary of 7-day low flow, many others.

Datasets

A variety of flow metrics in tabular and map form available from WaterWatch Data Services.

Tools

WaterWatch Toolkit: A variety of flow-related metrics available as graphs and maps.

Publications

NTA0970 Relevance

Provides a variety of flow-related metrics. The WaterWatch Toolkit could provide ideas for how to summarize flow data.

WA State of Salmon in Watersheds (WA-SOSW)

Organizations

Governor's Salmon Recovery Office

Snohomish basin Salmon Recovery Forum

Snoqualmie Watershed Forum

URL

https://stateofsalmon.wa.gov

https://stateofsalmon.wa.gov/regions/puget-sound/

Description

[excepts from https://stateofsalmon.wa.gov]

In 1998, the Washington state legislature passed the State Salmon Recovery Act, which led to a Statewide Strategy to Recover Salmon in 1999, and a State of Salmon report and action plan in 2000 (then issued biennially from 2008).

Washington State established eight geographical salmon recovery regions to respond to the Endangered Species Act listings. Seven of those have regional organizations, which are governed by local boards and work with local watershed groups, salmon recovery partners, Indian tribes, state and federal agencies, and other community groups to reach consensus on how to recover salmon… All regional organizations have written recovery plans, which have been adopted by the federal government.

The Puget Sound Salmon Recovery Plan was developed in 2005 by regional experts and adopted by NOAA Fisheries in 2007. Subsequently, local experts in each watershed worked together to craft 16 individual chapters of the recovery plan to specify local recovery goals, priority recovery actions, and monitoring needs. In the Snohomish basin, local oversight and coordination of the Snohomish River Basin Salmon Conservation Plan is provided by the Snohomish basin Salmon Recovery Forum (Snohomish County) and the Snoqualmie Watershed Forum (King County).

Indicators

Salmon

- Adult spawners
- Adults harvested
- Juvenile out-migrants (smolts).

Watershed Health

- Land use and land cover
- Biological health in streams
- Stream physical habitat
- Riparian condition
- Water quality
- Water quantity (streamflow):
    - Summer Low Flow Trends (1975-2018)
    - 60-Day Summer Low Flow Trends

- Although stream flows have improved over the long-term, they have improved only slightly in the past several years.

Implementation Indicators

- Plan implementation progress
- Funding
- Barriers to fish passage
- Hatchery practices

Datasets

Salmon Data Hub: provides access to a wide variety of maps and datasets associated with the State of Salmon report.

Tools

Puget Sound Characterization Water Process Model (Stanley et al. 2016): GIS model combining 3 categories of information for each analysis unit (~7 mi2 in Snohomish basin)

1. Water delivery (precipitation, snow & rain on snow area) +
2. Surface storage (area of depressional wetlands and Lakes (WLS) in an analysis unit + the importance of the relative miles of different widths of the floodplains in an analysis unit (STS)) +
3. Recharge (relative area of higher and lower geologic permeability) + Discharge (relative miles of streams and rivers with different types of confinement that intersect deposits of higher permeability)

Publications

The Puget Sound Salmon Recovery Plan was developed in 2005 by regional experts and adopted by NOAA Fisheries in 2007. Subsequently, local experts in each watershed worked together to craft 16 individual chapters of the recovery plan to specify local recovery goals, priority recovery actions, and monitoring needs.

Hume, C., Wilhere, G., Stanley, S., Grigsby, S., and Slattery, K. 2015. Watershed Characterization for WRIA 7: Assessment and Recommendations for Protection of Water Flow Processes. Shorelands and Environmental Assistance Program, Washington Department of Ecology. Olympia, WA. Publication # 15-06-009. https://apps.ecology.wa.gov/publications/SummaryPages/1506009.html

Stanley, S., S. Grigsby, D. B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, George Wilhere. 2016. Puget Sound Characterization. Volume 1: The Water Resources Assessments (Water Flow and Water Quality). Washington State Department of Ecology. Publication #11-06-016. Olympia, WA. https://apps.ecology.wa.gov/publications/SummaryPages/1106016.html

NTA0970 Relevance

The State of Salmon in Watersheds report includes one flow indicator (Summer Low Flow Trends). It is only presented in a state-wide summary pie chart, but it likely that the data are the same as those used in the PSP-VS assessment presented next (only a few major river gauges). Hume et al. (2015) present a finer scale analysis of the importance of smaller landscape units for contributing to flow and salmonid habitat in the basin. While their GIS-based flow model is likely considerably simpler than the hydrologic models being considered by NTA0970, it may still provide a useful check and some of the underlying GIS layers may be directly applicable. Their overall prioritization approach (level of importance X level of degradation) could also provide ideas for prioritizing activities under NTA0970.

Puget Sound Partnership Vital Signs (PSP-VS)

Organizations

Puget Sound Partnership

URL

https://vitalsigns.pugetsoundinfo.wa.gov/VitalSignIndicator/ViewAll

Description

PSP is a state agency tasked with coordinating monitoring and restoration of the Puget Sound. They manage the Puget Sound Vital Signs program, which collects "…measures of ecosystem health that guide the assessment of progress toward Puget Sound recovery goals. Each of the six Puget Sound recovery goals are expressed with one or more Vital Signs. Vital Signs represent an important component of the ecosystem (e.g. marine water, economic vitality). Each component is, in turn, represented by one or more indicators. The indicators are specific measures of Puget Sound conditions, including human wellbeing, while ecosystem recovery targets are policy statements that express desired future conditions for human health and quality of life, species and food webs, habitats, water quantity, and water." (https://vitalsigns.pugetsoundinfo.wa.gov/About)

The two recovery goals most relevant to NTA0970 are abundant water quantity and healthy water quality. Abundant water quantity is assessed using an indicator of summer streamflows. Healthy water quality includes an indicator of freshwater quality based on the state's Water Quality Index.

Indicators

Summer Stream Flows: percentage change per year (1975-2019) in summer low flows, calculated by dividing the gain or loss of flow (cfs) per year by the average 30-day summer low flow over the 1975-2019 period. 12 large Puget Sound rivers are assessed; one is in WRIA7, the Snohomish river, gauged near Monroe, which shows a decline of -0.2 cfs/yr. An additional "non-focus" monitoring station on the Skykomish river near Goldbar shows a decline of -5.3 cfs/yr.

Freshwater Quality

- Freshwater impairments: water quality for waterbodies monitored under Section 303(d) of the Clean Water Act (number of listings)
- Benthic Index of Biotic Integrity
- Water Quality Index

WQI has not changed substantially since 1997 at the 31 river and stream monitoring stations across Puget Sound watersheds. However, WQI scores do demonstrate improvements in measures of fecal coliform bacteria and total nitrogen for major rivers in Puget Sound.

Datasets

Summer Stream Flows: U.S. Geological Survey Stream Gauging Network, compiled by the Streamflow Monitoring Program at the Washington Department of Ecology

Tools

Web Services: Funds, Progress Measure Reported Values, Intermediate Progress Measures, Ongoing Programs, Vital Sign Indicators

Publications

Puget Sound Partnership. 2019. 2019 State of the Sound report. https://stateofthesound.wa.gov/

NTA0970 Relevance

PSP-VS reports that summer streamflow in WRIA7's largest rivers (Snohomish, Skykomish) have declining trends, so NTA0970 could potentially help address this restoration goal. There do not appear to be any NTAs associated with this indicator, rather just a Regional Priority to Develop (or adapt) an Implementation Strategy for the Summer Stream Flows Vital Sign. WRIA15 does have a related NTA CHIN2: Establish and enforce water quantity and quality standards that conserve water resources for salmon.

WA DOE River and Stream Flow Monitoring (WADOE-Flow)

Organizations

Washington State Department of Ecology

URL

https://ecology.wa.gov/Research-Data/Monitoring-assessment/River-stream-monitoring/Flow-monitoring

Description

WADOE "…maintains a network of stream-gaging stations that report streamflow conditions in rivers and streams across the state. The information is used to monitor flow conditions for recreational activities, water supplies for migrating fish, and to develop strategies to respond to climate change. All of the data we collect are available to view and download." [source: homepage]

Indicators

The only specific indicator presented is in the Statewide Stream Summary Map, which shows current flow as percentile of 10-year average.

Datasets

Flow Monitoring Network: click on monitoring points to bring up more info; click on station name to go to page with more info, including historical data. Two monitoring stations are located in WRIA07, one on the Snohomish river and the other on the Skykomish, both near the town of Monroe, fairly low in the WRIA. Both are manual-stage-height stations, which means they only have a series of periodic gage readings instead of the continuous records maintained by telemetry sites. The PSP-VS entry has analyzed these stations for trends.

Tools

Flow Monitoring Network (also Geoservice): shows locations of gauges with links to data for each. WRIA07 gauges do not have data after 2016.

Freshwater Information Network: searchable database with map; lists >4000 metrics (mostly chemicals) but a few searches for flow information did not produce results:

- Search Criteria
  - Monitoring Program ID is RiverStream
  - Watershed (WRIA) is 07 - Snohomish
  - Result Parameter or its alias is in Stream/River Stage
  - Location Status is Active
- No matching records

Publications

Hume, C., Wilhere, G., Stanley, S., Grigsby, S., and Slattery, K. 2015. Watershed Characterization for WRIA 7: Assessment and Recommendations for Protection of Water Flow Processes. Shorelands and Environmental Assistance Program, Washington Department of Ecology. Olympia, WA. Publication # 15-06-009.

NTA0970 Relevance

Flow is an important indicator for NTA0970. This program shows the limited data collection in WRIA7, and it does not seem to provide much in the way of summaries or assessment of these data (however the PSP-VS has summarized trends).

WA DOE Assessment of State Waters (WADOE-ASW)

Organizations

Washington State Department of Ecology

URL

https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Assessment-of-state-waters-303d

Description

The federal Clean Water Act requires states to perform a water quality assessment every two years to track how clean the rivers, lakes, and marine water bodies are. Assessed water bodies are assigned to 5 categories that describe the quality of the water and status of any needed clean up and this complete list is referred to as the 305(b) list. Categories 4 and 5 are considered impaired/polluted. This list is referred to as the 303(d) list and these categories generally require a total maximum daily load (TMDL) or alternative remediation plan.

There are two TMDLs established in WRIA07: a Snoqualmie River Watershed Multiparameter TMDL to address DO and FC bacteria issues; and a Snoqualmie River Watershed Temperature TMDL.

Indicators

Streams & waterbodies by assessment category: based on updated Policy 1-11

Datasets

Current Water Quality Assessment database

Tools

Water Quality Atlas. The Water Quality Atlas is an interactive search and mapping tool that includes additional layers of information in an easy-to-use mapping application.

Publications

NTA0970 Relevance

Water quality assessment looks only at pollutants, not flow conditions, although flow can affect pollutant concentrations. If NTA0970 forest management options can increase summer low flows this could assist with the Snoqualmie River Watershed Temperature TMDL.

Snohomish County Stream Health Program (SC-SHP)

URL

https://www.snohomishcountywa.gov/4152/State-of-our-Waters

https://snohomishcountywa.gov/5365/Stream-Health

https://www.snohomishcountywa.gov/DocumentCenter/View/68193/State-of-our-Waters-Press-Release

Description

Each year we randomly select 30-50 sites to sample. The sites are selected to represent the four major land use types in the area: urban, rural, forested, and agricultural areas. Snohomish County looks at five key indicators to understand stream health. Three of the indicators, water quality, aquatic life, and habitat are summarized in the stream health report cards for each site. The other two indicators, land cover and hydrology provide context to understand changes in health over time. The site reports include a map tracing the watershed above the site and reporting the percent forested. Flow information is available through the separate Water Data Viewer map application.

Indicators

Water Quality Index (WQI): combination of 8 metrics developed by the WA State Department of Ecology

Benthic Index of Biotic Integrity (BIBI), is widely used to measure stream health and has specifically been adapted for the Puget Sound Region

Stream habitat (for salmon, steelhead and other aquatic life):

- Large woody material – number of large wood pieces
- Pool habitat frequency – number of pools
- Pool habitat area – total pool area out of the total wet area
- Streambank armoring – percent of the streambank with riprap or similar armoring materials
- Streambed fine sediment – percent of streambed material that is sand or silt (<6 mm)

Hydrology: daily/monthly yearly min/mean/max flows.

Land Use Changes: only general mention of percent forested in site reports.

Datasets

Individual stream health report cards (pdf) for each site available through the web map tool.

Water Data Viewer: flow and other data can be exported from the graph views.

Tools

Water Data Viewer (KISTERS): 476 sites; can filter by type of data collected (flow, quality, etc).

State of Our Waters Sample Sites Web Map: map with access to individual site reports (pdf).

Publications

No overview reports found, only site level reports.

NTA0970 Relevance

Quite a few more flow monitoring stations are available through the Water Data Viewer than are in the state-level monitoring program (WA DOE), with a few higher up in the WRIA.

King County Stream and River Monitoring Program (KC-RMP)

Organizations

King County Department of Natural Resources and Parks, Water and Land Resources Division

King County Water and Land Resource Division (WLRD) Hydrologic Monitoring Program

URL

https://green2.kingcounty.gov/streamsdata/

Description

The county appears to have 23 active streamflow monitoring sites in WRIA 7. A variety of graphing and download options are available. The water quality monitoring program includes 11 stations in WRIA 7. The data from the stream monitoring program are analyzed with the following objectives:

- Characterize the general water quality status of the stream
- Determine if applicable State and Federal water quality criteria are met
- Identify long-term water quality trends

Indicators

Water Quality Index (WQI): Puget Sound lowland stream version.

Flow: no specific flow indicators are promoted.

Datasets

Hydrologic Information Center: A variety of graphing and download options are available.

Tools

Station Map: can select gauges by data type, then download or view data and graphs.

Publications

King County. 2009. Identification of Streams Likely to Benefit from Additional Water Inputs. Prepared by Curtis DeGasperi and Jeff Burkey, Water and Land Resources Division. Seattle, Washington. https://your.kingcounty.gov/dnrp/library/2009/kcr2173.pdf

NTA0970 Relevance

As with the Snohomish County program, more monitoring stations are available.

TERRESTRIAL-FOCUSED ASSESSMENTS

USDA Forest Service Terrestrial Condition Assessment (USFS-TCA)

Description

The terrestrial condition assessment (TCA) is a national USDA Forest Service program which "evaluates effects of uncharacteristic stressors and disturbance agents on land-type associations (henceforth land types) to identify restoration opportunities on national forest system (NFS) lands" (Cleland et al. 2017). As with its predecessor, the Watershed Condition Framework, it was initiated relatively recently in response to government accountability office (GAO) reports criticizing the agency for not tracking its effectiveness (outcomes instead of inputs) consistently at the national level. The TCA is comprised of 13 indicators which are evaluated for each land type using the EMDS software's fuzzy logic system. Land types are based on patterns in surficial or bedrock geology, lithology, topography, soils and vegetation. They are similar to (or sometimes based on) the widely used Landfire program's biophysical settings (https://landfire.gov/bps.php).

Indicators

- Wildfire hazard potential (WHP): database produced by USFS Fire Modeling Institute http://www.firelab.org/project/wildfire-hazard-potential Raster data at the resolution of 270 m. It's built upon spatial datasets of wildfire likelihood and intensity generated for the conterminous U.S. with the Large Fire Simulator (FSim), as well as spatial fuels and vegetation data from LANDFIRE 2014 and point locations of past fire occurrence (ca. 1992 - 2015)
- National insect and disease risk map (NIDRM) produced by USFS forest health protection (FHP) http://www.fs.fed.us/foresthealth/technology/nidrm.shtml Raster data at the resolution of 270 m
- Vegetation departure index (VDEP) produced by LANDFIRE (http://www.landfire.gov). Raster data at the resolution of 30 m.

Datasets

- An ArcMap version of the output datasets (along with metadata) was released with the 2017 paper. The links in the paper are no longer valid but these data could likely be obtained from the authors. A version 2 assessment is in progress, but no updates have been released outside the USFS yet.

Tools

- Documentation of the NetWeaver logic model, which scores the input data was released with the 2017 paper. The links are no longer valid but these data could likely be obtained from the authors.

Publications

Cleland, D.; Reynolds, K.; Vaughan, R.; Schrader, B.; Li, H.; Laing, L. 2017. Terrestrial Condition Assessment for National Forests of the USDA Forest Service in the Continental US. Sustainability. 9(11): 2144. https://doi.org/10.3390/su9112144

NTA0970 Relevance

The version 1 TCA rates the Snohomish land type conditions overall as Good to Very Good, although increasing temperatures are rated as a Moderate stress to vegetation and a number of the riparian land types have Poor ratings for road densities. It would take further research to determine whether the NTA0970 scenarios might affect indicators for wildfire hazard, insects/disease, and vegetation departure.

NW Forest Plan Late-Successional/Old-Growth Monitoring Program (NWFP-LSOG)

Description

The LSOG program monitors the coverage of old-growth forests over time in the footprint of the Northwest Forest Plan (NWFP), including both public and private lands. LSOG is estimated separately based on Landsat imagery (using the LEMMA GNN classification approach) and using forest inventory and analysis (FIA) plot data. The program evaluates these indicators over time both in terms of absolute abundance as well as connectivity. Reports are produced on the 5-year cycle. The last report and dataset were issued in 2015 (using 2012 data) but the next report is likely to be released in summer 2021 (with yearly data 1986-2017).

URL

https://www.fs.fed.us/r6/reo/monitoring/older-forests.php

Indicators

- Old-growth Structure Index (OGSI): 0-100 rating indicating the degree to which a data point resembles old-growth characteristics (100–200-year-old stands, dependent on forest type) based on 4 metrics: (1) density of large live trees, (2) diversity of live-tree size classes, (3) density of large snags, and (4) percent cover of down woody material. Rating curves have been developed for 16 different forest types.

Datasets

- Old-growth Structure Index: 30-m raster with a 0-100 rating for each pixel. Binary (0/1) OGSI-80 and -200 layers are also available that indicate whether each pixel meets this age threshold or not. Covers all lands in the NWFP footprint.

Tools

- For habitat configuration and connectivity assessment, they used the software package GUIDOS (Graphical User Interface for the Description of image Objects and their Shapes) v2.2, to segment old-growth into 5 configurations relative to old-growth dependent species: core, core-edge, patch, finger, scatter.

Publications

Davis, Raymond J.; Ohmann, Janet L.; Kennedy, Robert E.; Cohen, Warren B.; Gregory, Matthew J.; Yang, Zhiqiang; Roberts, Heather M.; Gray, Andrew N.; Spies, Thomas A. 2015. Northwest Forest Plan–the first 20 years (1994-2013): status and trends of late-successional and old-growth forests. Gen. Tech. Rep. PNW-GTR-911. Portland, OR: U.S. Department of Agriculture, Forest

Service, Pacific Northwest Research Station. 112 p. https://www.fs.usda.gov/treesearch/pubs/50060

NTA0970 Relevance

The OGSI index may provide a useful indicator for NTA0970, and the report can provide some context on historical changes. NTA0970 scenarios are likely to affect the OGSI index through changes in the diversity of tree size-classes (and possibly through snags and down wood, if these are integrated into the modeling).

Integrated Landscape Assessment Project (ILAP)

Description

This project emerged out of the USFS PNW ecology program (see ecoshare link below), which primarily serves national forests in the region but also cooperates with other organizations (e.g. The Nature Conservancy). The ILAP project enhanced state-transition vegetation models (STM), which have been used in national forest planning since the late 1990s, and expanded their coverage to the entire states of WA/OR/AZ/NM. STM's model vegetation as a discrete set of successional classes linked together by transition probabilities (e.g. probability of fire vs. continued undisturbed growth). This relatively simple approach allows scenarios to be built rapidly based on expert judgments about class transitions. ILAP provided some empirical calibration of these models using the Forest Vegetation Simulator program (FVS) and also linked these STMs to new assessment modules for wildlife habitat, fuel treatment and community economics, above ground carbon pools, biomass, and wildfire hazard. Using these STMs, they projected landscape conditions into the future for forests (300 years) and arid lands (150 years). This study started in 2009 and ended in 2011.

URL

https://inr.oregonstate.edu/ilap

Indicators

- Fire Hazard: STMs integrated with a software application called the Fuel Characteristic Classification System (FCCS) to enable assessment of fuel properties and fire hazard with succession, disturbance, and management across landscapes over time.
- Timber production and biomass supply: STM results linked to models of timber production and biomass supply potential over time.
- Wildlife habitat: STM results linked to wildlife habitat models (mammals and birds).
- Rural community support: STM results linked to indicators of how much communities (census county subdivisions) are likely to benefit from increased wood supply based on community characteristics that may be of concern (indicators of socioeconomic well-being, business capacity, and effects of forest policies) and potential biomass supply.
- Climate-influenced vegetation change: STMs linked to the MC1 climate-vegetation model to project how vegetation might change over time under different climate scenarios.

Datasets

- https://oregonexplorer.info/node/38886
- Soils: Soils derived from NRCS SSURGO and STATSGO. Data is averaged across entire soil profile. Available water capacity; bulk density; texture percentages; depth to bedrock; pH; slope; geomorphic description; hydrologic group; taxonomic order, suborder, group, and great group.
- Potential Vegetation Type: Potential vegetation types used to correspond each veg model to an area of the landscape.
- Existing Vegetation (Forest): Year 2012 vegetation structure and cover classes modeled using the LEMMA Gradient Nearest Neighbor modeling method.
- Projected vegetation conditions: "Rollout" packages contain models and results used by the ILAP project for projecting landscape conditions for each model region for forests (300 years) and arid lands (150 years). The Path models provided have ILAP's spatially defined, modeling strata.

Tools

- STM models for modeling zones covering OR/WA: https://oregonexplorer.info/node/38886
- The STM software used has had a number of names/acronyms over time, including VDDT, Path, and now ST-Sim: https://apexrms.com/landscape-change/

Publications

Halofsky, Jessica E.; Creutzburg, Megan K.; Hemstrom, Miles A., eds. 2014. Integrating social, economic, and ecological values across large landscapes. Gen.Tech. Rep. PNW-GTR-896. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 206 p. https://www.fs.usda.gov/treesearch/pubs/47219

Related Info

- USFS PNW Ecology Program website
- https://ecoshare.info/ [Interagency Clearinghouse of Ecological Information]
- Most of the info here is old, but they are still posting annual reports from the USFS PNW Ecology Program.

NTA0970 Relevance

The STM models produced by this project could provide a more simple and expert-judgment-driven approach to vegetation modeling, if needed for some rapid scenario building where more detailed FVS modeling would be challenging. Potential Vegetation Type data may be useful for comparing current vegetation to a reference condition.

Glossary of technical terms

Surface Water Storage and Flow

Ablation: Loss of snow water equivalent by processes such as sublimation, evaporation, wind, and melt

Albedo: Proportion of radiative energy reflected by a surface

Baseflow: Portion of the streamflow that is sustained between precipitation events, fed to streams by delayed pathways. However, it should not be confused with groundwater flow- which is the portion of the stream flow that is comprised of groundwater.

Depression Storage- waterfilled depressions on hillslopes (also called vernal pools) due to low infiltration capacity. These depressions can become linked during high precipitation to contribute to higher runoff or slowly infiltrate and evaporate during the dry season.

Melt- Water melted from the snowpack

Run-off: Water "running off" the land surface

Surface Flow: Water running off on top of surfaces

Shortwave radiation: Energy from the sun. Shortwave radiation is strongly affected by sun angle (zenith) in the sky (e.g. low in winter and high in summer) and shading. Shortwave radiation is the dominant component of total radiation from other sources when sun angles are high.

Snow water equivalent (SWE)- Amount of water in snow and dependent on snow density. It is measured as the depth of water in mm that would result from instantly melting a given volume of snow over a known area

Stream discharge: The amount of water flowing in a stream at any particular point in time. Stream discharge is expressed as a rate of water volume per unit time.

Longwave radiation: Emitted radiation from trees and objects. Long wave radiation is less effected by shade and the dominant component of total radiation when solar angles are low. Humidity has a stronger effect on longwave than on shortwave radiation, (need more info on this last sentence if I include at all) My notes say LWR is more affected by shade when humidity is low than high but doesn't say in which direction, I assume shade = more longwave but not sure

Water Balance: Amount of annual precipitation in various storage compartments. Because inputs equal outputs, unknowns like subsurface storage can be calculated if other components are known.

Vegetative water gain and loss

Interception: Amount of precipitation as rain or snow that is captured on the surface of vegetation. Intercepted water can either renter the atmosphere, be absorbed by plant surfaces, or drip to the ground in varying proportions depending conditions such as humidity, wind, vapor pressure deficit, and water potential.

Sloughing: Snow that falls from the canopy to the ground

Sublimation: Moisture loss as snow converts to vapor, especially relevant in cold climates and snow intercepted in the canopy

Fog Drip: Moisture from fog that is intercepted and drips to the ground

Throughfall: Rain that passes through the canopy without being intercepted

Transpiration: Water that is drawn from the soil by plants and released to the atmosphere during photosynthesis

Leaf area index (LAI): One-sided silhouette surface area of all leaves above a given area of ground. This measurement is unitless because it is computed as leaf area/ground area.

Soil Moisture: The exchangeable water in soils above the water table that is available to plants.

Rock Moisture: The exchangeable water above the water table that is stored in the regolith and underlying bedrock available to plants.

Regolith: the layer of unconsolidated rocky material covering bedrock.

Radiative paradox: Conventional wisdom is that less forest cover equals more snow accumulation and faster melt because of low interception and high sun exposure. However, longwave radiation under increasing forest canopy can rise faster than corresponding decreases in shortwave radiation (sunlight) leading to faster melt in forests. This especially applies when sun angles are low and winters are often cloudy.

Subsurface Water Storage and Flow

Aquifer: an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt).

Alluvial Aquifer: an aquifer comprising unconsolidated material deposited by water such as river gravels, typically occurring adjacent to rivers and buried paleochannels.

Floodplain: an area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

Recharge: The primary method through which water enters an aquifer through deep drainage or deep percolation, where water moves downward from surface water to groundwater.

Groundwater: Water held underground in the soil or in pores and crevices in rock.

Groundwater flow: part of streamflow that has infiltrated the ground and has been (or is at a particular time) discharged into a stream channel or springs; and seepage water.

Hydrologic Connectivity: The condition by which disparate regions on the hillslope and valley bottoms are linked via subsurface water flow.

Hyporheic Exchange: The mixing of surface and shallow subsurface water through porous sediment surrounding a river and is driven by spatial and temporal variations in channel characteristics.

Hyporheic Zone: The region of sediment and porous space beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water.

Infiltration: Movement of water through the surface and into the soil.

Interflow: shallow subsurface flow moving over a layer impeding infiltration or percolation.

Percolation: Movement of water through the soil itself

Perched Groundwater: unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone. It occurs when subsurface water percolating downward is held by a bed or lens of low-permeability material.

Soil Piping: The progressive development of internal erosion within a soil horizon by seepage, appearing downstream as a hole discharging water

Seepage: Slow escape of water through porous material or small holes

Saturated Zone: Portion of the subsurface below the groundwater table. All interconnected openings and pores within the soil and rock are completely filled with water.

Unsaturated Zone: portion of the subsurface above the groundwater table. The soil and rock in this zone contains air as well as water in its pores.

Water Table: underground boundary below which groundwater saturates spaces between sediments and cracks in rock

Forest Ecology and Practices

Forest Structure: The configuration of plants, including the arrangement, number, age and size of trees.

Forest Composition: The relative quantities of which species are present within a forest

Forest Function: The “work” forests do, such as purify water, produce wood, and provide habitat

Ecosystem Integrity: An ecosystem with all its key parts and functions intact

Disturbance: Event that kills trees. Some disturbances kill smaller trees (e.g. low intensity fire), some kill overstory trees (e.g. wind), while others kill trees of all size classes (high intensity fire).

Resistance (to disturbance): Ability of an ecosystem to reduce the intensity of a disturbance. Examples include west-side forests that do not easily catch fire, but not dry-forests that readily and often burn.

Resilience (to disturbance): Ability of an ecosystem to return to its previous state after disturbance regardless of its intensity. Examples include west-side forests that take centuries to return to their previous state after intense fire as well as dry-forests with low fuels that return to their previous state within a few years following low intensity fires.

Biological legacies: Elements of the previous forest remaining after a disturbance, includes trees, snags, and biota that strongly affect subsequent forest succession.

Log: Dead wood on ground and a type of biological legacy

Snag: Dead and standing wood and a type of biological legacy

Regeneration: Established seedlings that will become the next forest

Advanced regeneration: Regeneration remaining after a disturbance that were present prior to the disturbance. Very common after windthrow events that topple overstory trees (also a biological legacy).

Natural regeneration: Seedlings established from trees (i.e. not planted)

Forest Canopy Closure: Time at which tree crowns begin to touch and exclude understory vegetation.

Silviculture: Cyclical system by which trees are harvested based on a criterion, regenerated, tended, grown, then harvested again.

Culmination of mean annual increment: Point on time vs basal area curve that rate of basal area change peaks. Used as a biological indicator of when to harvest for maximum wood production.

VDT: Variable density thinning is thinning of a tree plantation to non-uniform density, including canopy gaps, in which forest cover is maintained as the dominant vegetation cover

VRH: Variable retention harvest is harvest of trees in variable spatial patterns in which uncut trees remain in variable spatial patterns including aggregates and dispersed single trees. Unlink VDT, an objective in VRH is to initiate a new cohort of trees

Sustained yield: Yield of wood that could be removed indefinitely each year based on current forest production

Regulated forest: A forest designed with age classes such that the same amount is harvested each year in perpetuity (sustained yield)

Appendix 1: Forest Practices tables

Forest practices are generally defined as practices related to growing and harvesting timber, so include practices associated with planting, tending, and harvesting trees. This document describes relevant forest practices for reducing magnitude of flooding, increasing low summer stream flows, and reducing risks to ecosystem functions. Washington's forest practices are summarized and beautifully illustrated by the Washington DNR in their publication "Forest Practices Illustrated," (https://www.dnr.wa.gov/forest-practices-illustrated). This brief summary should give a reader enough understanding to see how they might be applied. The practices are organized around the broad themes of planning, harvest, site preparation and regeneration, and tending. Tables begin on the next page of this document.

Table 1a: Forest practices and significance to Tulalip Tribes in the following tables are presented by silvicultural steps in Figure 4. Table 1a shows those associated with planning. Excellent illustrations and descriptions of these practices can be found in the WA Department of Natural Resources publication “Forest Practices Illustrated” (https://www.dnr.wa.gov/forest-practices-illustrated).

Forest Practice	Description	Important effects
Step 1: Planning		
Element scale		
Cultural resources	Important spiritual and cultural sites (e.g. graves, spiritual centers, berry fields)	Preserves heritage and human connection to land
Snags and logs	Individual standing dead and downed logs, easy in aggregates, hard in dispersed retention, can also be created from live trees	Habitat, shade, seedling establishment (spruce and hemlock)
Leave trees	Trees remaining after harvest. These can be individual habitat trees, dispersed retention, or aggregates of trees. Forest practices rules set minimum levels of retention and pattern of retention within units (e.g. 4 trees per hectare at least 20m from edge).	Provides continuity between harvests, as habitat, by altering abiotic conditions, and a seed source.
Areas of biological importance	Rock outcrops, gaps with established shrubs with fruits and nuts, unique soil types with sensitive species	Unique habitat for under-represented plants and animals
Stand scale		
Riparian Buffers/Riparian Management Zones	Often one dominant tree-height wide on non-fish bearing streams and two tree heights on fish-bearing streams on Federal land. Smaller buffers vary on by state and private lands Depending on jurisdiction these can have core, inner, and outer zones with more harvest activity allowed moving from core to outer zones. Buffers are also created around other aquatic habitat like ponds, seeps, and springs.	Wood source to streams, bank stability, shade, runoff filtration, habitat
Retention	Elements retained in a harvest, rule of thumb in Ecological Forestry is to leave at least 1/3 of trees or area standing, done in aggregates or dispersed	Continuity of ecological functions between harvests
Landscape scale		
Harvest patterns	Patterns are either in patches (harvests) or networks (streams and roads). Spatial arrangement, shape, and size of patches change their properties so treatments should be designed with specific landscape functions in mind	Controls cumulative effects such as windthrow, humidity and fire, snow melt, stream temperature, sediment deliver, and suitable habitat
Road building Road maintenance	Locating, designing, and installing roads to reduce effects to right. Includes road slope and position, sediment basins, water diversion, erosion control, stream passage, closures, and decommissioning	Roads have permanent effects of hillslope hydrology, animal migration, invasive species, fire ignitions, landslides, and sediment delivery
Harvest triggers		
Culmination of mean annual increment	Point at which stand-level wood production reaches a maximum, used as biological indicator for cutting, often used on public land, dependent on site productivity	Maximizes wood production, creates rotations of 80+ years and larger trees
Net present value	Forest is cut when the net present value of harvesting the stand is within a predetermined return on the initial investment, usually from 5-7%, used in production forestry	Maximizes return on investment, creates rotations from 30-50 years, and small trees
Salvage	Logging after natural disturbance kills a stand to "recoup" losses, a famous example is logging dead trees after Mount St. Helen erupted	This is always an ecological tax unless as many dead trees remain as would have harvest had gone as planned with no disturbance
Ecological Forestry/Other	Based on economic goals tied to receipts (not return on investment), ecological goals and varies widely depending on goals	Does not maximize any single value, concept of rotation can break down depending on ages and sizes retention

Table 1b: Forest practices and significance to Tulalip tribes in the following tables are presented by silvicultural steps in Figure 4. Table 1b shows those associated with harvest. Excellent illustrations and descriptions of these practices can be found in the WA Department of Natural Resources publication "Forest Practices Illustrated" (https://www.dnr.wa.gov/forest-practices-illustrated)

Forest Practice	Description	Important effects
Step2: Harvest		
Harvest techniques		
Planking/barking trees	Historical native cultural practice of taking planks and bark from live cedar trees	Tree remains alive, entry point for decay
Shovel Logging	Tracked log loader moves piles of logs to loading site in successive swing locations	Less compaction and scarification
Tether Logging	Tracked feller lowered via winch down steep slopes	More control of logs and hazard on steep slopes
Skyline or high lead logging	High cable used to suspend (skylining) or drag (high lead) logs from downslope	Less scarification than yarding along ground, fewer roads
Ground Based	Methods such as hand falling, and cable yarding along the ground	More control of falling and transport, more compaction
Harvest type		
Regeneration harvest	Harvest with the goal of initiating a new cohort of trees	Resets succession at stand scale
Selection harvest	Goal of maintaining continuous canopy cover and trees of many ages	Does not reset succession at stand scale
Stand scale patterns		
Clear cut	All the trees except that required by law are cut, primarily used by industrial landowners	Rapid regeneration and growth, lowest cost, early seral habitat possible
Shelterwood/Seed tree	Shelterwoods leave 30 to 40 percent of the basal area after harvest, once new cohort is "free-to-grow" residual trees are cut.	Residual trees shelter regeneration from sun and frost and provide seed source. Sometimes second harvest was not cut so larger trees are component of new stand
Group selection	Harvest of unit in a few small blocks, often done with the objective of creating a regulated forest of even aged patches (even timber production through time using single age cohorts).	Slower regeneration and growth, increased cost, maintains some structural diversity
Aggregated	Harvesting in aggregates of trees that are not entered with equipment. Done post 1980.	Soil, logs, snags, and trees in aggregates are undisturbed. Better preservation of interior forest microclimates
Dispersed Retention	Trees are left evenly dispersed across unit, done extensively in	
Variable Retention Harvest (VRH)	Trees harvested in variable spatial patterns including aggregated and dispersed. Objective in VRH is to initiate a new cohort of trees while emulating natural disturbance. When riparian buffers are included, most variable retention treatment leave close to 1/3 of trees behind.	Allows flexibility to meet multiple objectives while preserving forest integrity
Commercial thinning, dispersed or variable density	A type of selection harvest where cut trees are merchantable but objective is not to create a new cohort. After the Northwest Forest Plan was implemented, most federal land managers moved towards thinning rather than regeneration harvesting.	Maintains forest cover and dispersed functions such as root strength but disturbs understory and wounds residual trees
Individuals, clusters, and openings (ICO)/other	Historic stand structure of distribution of individuals, clusters, and openings are reconstructed from field data and mimicked in prescriptions to create variability. Other approaches (e.g. Stoddard Neal) are similarly keyed to natural processes.	Insures structural heterogeneity is created in range of historic conditions
Landscape scale patterns		
Dispersed Patch Clearcutting	Harvesting done in dispersed ~15 ha patches across the landscape, often to establish a road network, distribute hydrologic effects, and distribute foraging for animals, generally done 1950-1970 .	Results in cumulative effects, especially with clear cuts of ~10 ha size
Other	Current practices are based on previous road networks and harvest schedules, with inclusion of public lands incorporating variable retention practices borders between harvests can become fuzzy and sizes more variable.	Various, but fewer cumulative effects than above

Table 1c: Forest practices and significance to Tulalip tribes are presented by silvicultural steps in Figure 4. Table 1c shows those associated with site preparation, regeneration, and tending. Excellent illustrations and descriptions of these practices can be found in the WA Department of Natural Resources publication “Forest Practices Illustrated” (https://www.dnr.wa.gov/forest-practices-illustrated)

Forest Practice	Description	Important effects
Step 3: Site preparation and regeneration		
Site preparation		
Clearing slash	Includes burning downed woody material and removing and reducing unwanted trees	Prepared mineral seedbed for desired species
Broadcast burning	This practice is not often practiced today in the Pacific Northwest, but is burning of slash as it lies when conditions permit	Same as above, can cause water repellency, can harm advanced regeneration, can activate dormant shrub seeds
Pile and burn	Slash is gathered into enormous piles and burned, sometimes piles are left as a component of the next stand	Can be important source of dead wood if left
Mastication	A special tool is used to shred unwanted shrubs and other vegetation or to break down slash	Remaining wood decays more rapidly so is less of a fire threat
Soil preparation	Not used in the Pacific Northwest, but in some regions, soil may be ripped	
Regeneration		
Herbicides	Aerial and ground application to reduce competition from unwanted hardwood trees, shrubs, and invasive species. Generally, the goal is to promote early dominance of conifers within less than a decade.	Changes composition of developing stand, greatly reduces competition with conifers, truncates pre-forest successional stage
Planting/Seeding	Planting 1-to-2-year-old bare-root seedlings by hand of genetically robust stock to ensure successful regeneration. Direct seeding has very low success rates used to include rodenticides and now are sometimes encapsulated in substrate capsules	Ensures next generation of trees is established, in combination with herbicides it speeds conifer dominance
Step 4: Forest tending		
Mechanical		
Pruning	Removing low branches	Reduce risk of surface fires entering canopy, reduces stem taper, and creates wood with fewer knots
Precommercial thinning	Thinning of a tree plantation to uniform density. Thinned trees are generally of no economic value.	Can increase growth of retained trees, can alter species composition
Commercial thinning	Thinning of plantation where thinned trees are merchantable.	Same as above. Also injures retained trees.
Chemical		
Fertilizing	Application of fertilizers after trees have established site dominance	Increases productivity of forest
Controlled burns	Intentional burns done in dry frequent fire forests (i.e. east side cascades)	Reduces fuel, large logs, kills smaller trees, and promotes regeneration. Can also change species composition

Table 1d: Forest practices and significance to Tulalip tribes are presented by silvicultural steps in Figure 4. Table 1d shows those associated with environmental mitigation. Excellent illustrations and descriptions of these practices can be found in the WA Department of Natural Resources publication "Forest Practices Illustrated" (https://www.dnr.wa.gov/forest-practices-illustrated)

Forest Practice	Description	Important effects
Environmental mitigation (steps 2-4)		
Sustaining wood production		
Reforestation	Policies require owners to ensure replanting success within a given time frame unless they can show a new proposed land use that is inconsistent	Shortens early seral stage
Annual allowable cut	Proportion of long term sustained yield allowed to be cut each year, sustained yield is amount of timber that can be theoretically extracted each year in perpetuity from a regulated forest	Can be used to justify increased harvest if forest practices increase productivity, and was used to justify converting old growth forest to productive plantations
Water quality/Roads		
Best management practices (BMPs)	States write BMPs to control non-point source pollution as part of the Clean Water Act, includes sediment from erosion, herbicides, and fertilizers	Policies and compliance vary by state, strong in some, weak in others
Roads	Decommissioning temporary roads and closing seldom used ones; ripping and mulching to increase infiltration; out-sloping, water bars, and culverts for water diversion; retention basins for sediment catchment; oversized culverts and bridges for aquatic species passage	Protects aquatic systems from increased flooding and chronic sediment
Unstable slopes	Steep or undercut slopes with unstable geology or hillslope morphology	Mobilizes sediment and wood to streams
Endangered species		
Habitat Conservation Plan	Long-term plan between either state or private owners and the federal government. Maintains habitat for endangered species on a broad scale so individual plans are not required on each unit. It is a permit to "take" individuals of an endangered species assuming the plan sustains healthy populations. Planning is expensive and subject to public scrutiny	Streamlines operations for large landowners with endangered species present
Safe harbor agreements	Agreement that if landowners attract an endangered species by creating habitat, they are still allowed to manage within that habitat.	Removes disincentives for creating habitat that attracts endangered species
Candidate conservation agreements with assurances	Agreement between agencies and landowners that if they improve habitat for species that might be listed, they will not have to change management should the species become listed	Removes regulatory uncertainty
Riparian areas		
Aquatic Conservation Strategy	Federal ownerships in western Washington use this strategy. Modification to riparian buffers has to have a watershed analysis before restoration	Framework for protecting aquatic resources
Other aquatic protections	Wetland management zones, riparian buffers	Reduced methods and harvesting
Fire		
Fuel reduction	Important on east side to reduce fuels especially near old large trees, fuels always high on west side of cascades	Reduces fire danger in dry climates, has little effect on fires in moist climates
Water tank on site	Water is always close by to put out fires caused by equipment	Stop fires before they get big
Restricted times	During dangerous fire weather, forest operations are suspended	Reduce probability of ignition

Appendix 2: Forest process value tables

Table 1: Values for some key processes from the literature. Most are drawn from Douglas-fir forests except references to conifers versus hardwoods. Absolute values are presented in mm of rain of snow water equivalent. More values can be found in the text.

Process	**Values**	**Citation**
Snow interception	≤100 mm annually <40 mm per storm 60-80% captured 30-40% loss (sublimation)	(Andreadis et al., 2009; Martin et al., 2013; Pomeroy et al., 1998; Storck et al., 2002)
Rain interception	Young Douglas-fir: 20-25% Old Douglas-fir: 23-25% ~80% occurs during large storms can intercept nearly all water during small storms	(Link et al., 2004; Pypker et al., 2005)
Throughfall	Young Douglas-fir: 12% Old Douglas-fir: 42%	(Pypker et al., 2005)
Infiltration	SW BC, Canada With root channels: 35cm hr^{-1} Without root channels: 12cm hr^{-1} Forest floor: 20cm hr^{-1} SW Oregon Clear cut and burn: 11cm hr^{-1} Snohomish area (Region 1 in Safeeq) Soil conductivity: 10.2 cm hr^{-1}	(Cheng, 1975; McNabb et al., 1989; Safeeq et al., 2015) Gridded soil datasets available: • http://www.cei.psu.edu (Miller and White, 1998) • https://www.epa.gov/national-aquatic-resource-surveys/streamcat-dataset-0 (Hill et al., 2016)
Transpiration	Riparian 1-6% of annual flow Conifer: 0.66-0.68 of precip. Hardwood: 0.49-0.54 of precip. 20-60 yo conifer: 1.8-3.9mm d^{-1} >240 yo conifer: 0.4-1.5mm d^{-1} Sap flow in 30cm-diameter trees nearly 2x that of >60cm diameter trees 80 yo stand may use 20% less than 30 yo stand of Douglas-fir	(Bond et al., 2002; Moore et al., 2004; Nippgen et al., 2016; Stubblefield et al., 2012)
Max recharge by zone	Snow: 10-20mm d^{-1} (Jun-Aug) Rain: 20-30mm d^{-1} (Mar-Apr)	(Safeeq et al., 2014)

Table 2: Attributes related to flow response to vegetation change from the literature. More values can be found in the text.

Attribute	Values	Citations
Annual change in discharge from cutting	Conifer: 2-4mm $\%cut^{-1}$ Hardwood: 1.7-2.5mm $\%cut^{-1}$ Shrubs: 0.9mm $\%cut^{-1}$ Shrub planting: -0.5mm $\%cut^{-1}$	(Bosch and Hewlett, 1982; Sahin and Hall, 1996)
Precipitation range for response for altered vegetation	Min: 450-500mm Max:1600-2500 mm	(Bentley and Coomes, 2020; Bosch and Hewlett, 1982; Zhang et al., 2001)
Threshold response	20 -25%	(Andréassian, 2004; Bosch and Hewlett, 1982; MacDonald and Stednick, 2003)
Low flow increase duration after cutting	5-10 years	(Coble et al., 2020; Hicks et al., 1991; Keppeler, 1998; Perry and Jones, 2017; Surfleet and Skaugset, 2013)
Annual flow reduction with afforestation	-23% after 5 years -38% after 25 years Pines can reduce runoff 40% Planting reduces flow for ≥40 years relative to grass (-44%) and shrubs (-31%) Relative changes larger (-27%) at drier sites than wetter sites (-62%)	(Bentley and Coomes, 2020; Farley et al., 2005)
Duration of peak flow response	10-year events for roughly 20 years, but hard to detect (see text)	(Bowling et al., 2000; Harr, 1983; Hicks et al., 1991; Jones, 2000).

Table 3: Reported ranges of leaf area index for Douglas-fir forests.

Vegetation type	**Site**	**LAI**	**Citations**
21-27-yo Douglas-fir 25-yo Douglas-fir plantation 450-yo Douglas-fir	HJ Andrews Wind River	10.7 10.2 9.6, not signif. diff.	(Pypker et al., 2005; Velazquez-Martinez et al., 1992)
Red Alder		<10	(Franklin and Waring, 1980)
Young (20-80) DF Mature (80-200) DF Old (>200) DF	HJ	~5-6 ~8-12 ~9-15	(Sillett et al., 2018; Thomas and Winner, 2000; Turner et al., 2000; Weiskittel and Maguire, 2007)

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Appendix 3: Proportion land area example for low flow change

Moving land area between vegetation types with forest practices may augment low flows. In this appendix, we make some simplifying assumptions to calculate a rough estimate of the amount of low flow expected under different management scenarios relative to land that is 100% old growth. Because of the simplicity of this analysis the relative responses are more important than the magnitude.

Proportion landscape example

To evaluate the feasibility for enhancing low flows by altering forest structure we can compare flows expected under the range of historic conditions, current conditions, and reasonable management scenarios. With some simplifying assumptions on how much runoff we expect from different seral forest stages we can evaluate if we are likely to fall within historic ranges. Below we perform this exercise using low flow expected from old growth forest as our reference. This metric means that if all land area were in old growth forest, runoff would equal 1, if in vegetation where runoff is higher, runoff would be >1 and vice versa. We break forest cover into broad categories present on both contemporary and historic landscapes for simpler interpretation and because we have credible estimates of these classes (Donato et al., 2020). These include: meadows with few trees, recently cut and regenerated plantations, early-seral ecosystems (shrubs), mid-seral forest, and late-seral forest.

Deriving estimates for expected low flow from different forest classes in the western Pacific northwest have to be subjectively interpreted because of the variety of reported results. Many studies report annual rather than low flow, or related metrics like transpiration. Low flows increase more proportionally and for longer duration than annual flows with decreases in vegetation cover (Brown et al., 2005; Scott and Smith, 1997). Thus, we use annual proportional change as a surrogate for low flow change when low flows were not reported as a conservative estimate. Additionally, on an annual scale, flow change within a precipitation regime is dictated by evapotranspiration (Zhang et al., 2001), therefore we also use relative transpiration changes to interpret low flow responses.

We broke the landscape into six vegetation classes with different runoff characteristics to estimate low flow. These were meadows, recent plantations, early-seral habitat, mid-seral forest, late-seral mature forest, and late-seral old forest (**Table 1**). Meadows were areas that could become forest but were dominated by herbs, forbs, and grasses. Meadows had the most runoff (**Table 1**). Recent plantations were areas not dominated by large trees, but had been planted with rapidly-growing conifers. Young plantations had less runoff than early-seral habitat and more than forested classes (**Table 1**). Early-seral habitats were generally shrub-dominated, so had less runoff than forested classes but less than meadows. Mid- to late-seral forest classes were dominated by trees of increasing size. Runoff was lowest for mid-seral forest and increased as forests developed spatial complexity with age (**Table 1**).

We interpreted relative low flows by first estimating runoff from meadows and mid-seral plantations, then estimating it for young plantations, early-seral shrub communities, and mature forest from these setpoints. Meadows and mid-seral flows were established by comparing old growth to immediate responses from cutting and forest regrowth after 30-50 years. Next, relative stream flow responses were deduced for early-seral and recent plantations based on literature citing changes to streamflow after planting trees or cutting mid-seral plantations. We assumed early-seral was the same as shrub communities and estimated based on relationships of planting or cutting shrubs to meadow-like conditions. Finally, late-seral mature forest was estimated based on simulated changes from mid-seral forest (**Table 1**).

Table 2. Rationale and expected low flow response relative to old growth forest.

Vegetation class	Rationale	Relative low flow	Citations
Meadows	Flow Increases after cutting old forest range 100 to >400%	2	(Farley et al., 2005; Perry and Jones, 2017)
Recent plantation	Flow increase from cutting lasts ~8 yr, within 2-8 yr flows can decrease exponentially from 10 to >80% relative to meadow and ~20% in 4 years	1.6	(Coble et al., 2020; Scott and Smith, 1997)
Early-seral	Shrub planting or clearing reduces flows ~6-15% relative to meadows and ~75% less than reducing mid-seral conifer	1.7	(Brown et al., 2005; Sahin and Hall, 1996)
Mid-seral	Transpiration in young stands can be >3x that in old stands, and low flows can decrease 40-60% relative to old forest	0.5	(Moore et al., 2004; Perry and Jones, 2017)
Late-seral mature	Transpiration reduced ~20% in mature forest relative to 30 yr forest, transpiration is related to growth and stand growth rate declines	0.75	(Curtis, 1992 Figure 5; Moore et al., 2011; Stubblefield et al., 2012)
Late-seral old	Reference defaults to 1	1	—

Historic range of variability of different land classes were reconstructed using published fire return intervals and forest developmental trajectories for Douglas-fir (Donato et al., 2020). We can augment estimates (Donato et al., 2020, **Table 3**) of landscape area in early-, mid-, and late-seral stages by splitting late-seral into mature and old forest. From Donato et al. (2020)'s Figure 4c we see late-seral forest (47-90%) comprises ~20 to 33% mature and ~67-80% old forest. Range of mature forest was therefore estimated as 47%*0.20 to 90%*0.33 and range of old growth as 47%*0.67 to 90%*0.80. To these, we can add proportions of non-forested land that would have been forest if they were not maintained by Native American tribes. These include at least 5% of area in mesic meadows supporting camas, beargrass, and other culturally important early-succession plants (Takaoka and Swanson, 2008), so we add a conservative range of 2 to 7% (**Table 3**).

Reconstructed low flows showed a range of 77 to 122% of that expected if all area was in old growth forest. Proportion area in vegetation classes were shifted to maximize low flows increases by increasing or decreasing area preferentially by their expected flows (**Table 3**). Low flows from historic forests were then compared to contemporary conditions and different management scenarios to better vegetation classes for management. Expected flow is simply a weighted average of % cover in each class and its expected flow relative to old growth (**Eq. 1**).

$$Eq.\ 1 \quad \boldsymbol{landscape\ flow = \sum_{i=1}^{\#\ classes} cover\ class_i * \ expected\ flow_i}$$

Table 3. Proportion of landscape with worst- and best-case scenarios for low flows based on minimizing or maximizing runoff within the natural range of variability in western Washington Cascades for each cover type. Ranges of cover variability modified from Table 3 and Figure 4c of Donato et al. 2019. Expected flow is weighted average of % cover and low flows from Table 1.

Cover	Historic range (% cover)	Worst runoff case (% cover)	Best runoff case (% cover)
Meadows	2-7	2	7
Early-seral	1-30	1	30
Mid-seral	8-36	36	8
Late-seral mature	9-30	30	9
Late-seral old	31-72	31	46
Expected flow relative to 100% old	–	77%	122%

Current compared to past conditions

We then compared historical estimates of low flow to current conditions and used the proportion area in these conditions to target land cover for improving low flows. Using forests structure interpreted from the (STRUCCOND, Ohmann and Gregory, 2011) USDA Forest Inventory and Analysis data (Bechtold and Patterson, 2005), we separated cover classes in the Snohomish watershed (WRIA7). These data cross-walked to pre-forest, young forest, mature forests, and old forests once we collapsed sparse and open into pre-forest, sapling and small into young forest, and retaining large and giant tree categories as mature and old forest respectively (**Table 4)**.

Table 4. FIA interpreted cover classes, percent cover, and simplification of classes for this analysis. Canopy cover estimate is based on trees > 2.5 cm diameter at 1.37 m above ground so excludes regeneration.

STRUCCOND	Cover	Description	This analysis
Open	6%	Canopy cover < 10%	Early-seral
Sparse	6%	Canopy cover 10-40%	Early-seral
Sapling/pole	22%	Canopy >40%, Quadratic mean diameter < 25 cm	Mid-seral
Small/medium	42%	Canopy >40%, Quadratic mean diameter < 25 – 50 cm	Mid-seral
Large tree	17%	Canopy >40%, Quadratic mean diameter < 50 – 75 cm	Late-seral mature
Large/giant tree	7%	Canopy >40%, Quadratic mean diameter > 75 cm	Late-seral old

We next estimated current forest cover in meadows and very young plantations and extracted them from the open cover class land area. We assumed 3% of area in the open class as a conservative estimate of current meadows. In modern forestry, many apparent early-seral conditions are actually young conifer plantations with higher evaporative demand than shrub-dominated communities. The remainder of row totals in Donato et al., 2020's Table 3 (last row of Table 1.1 in main text) represent these plantations and compose 17% of private land, 9% of state land, and an average of 3.3% of federal lands (area-weighted mean of USFS and National Park Service) in western Washington. We took these percentages out of the open class within each respective ownership category to arrive at estimates for land in recent plantations then added these to the totals for all other classes in the watershed (**Table 5**).

Table 5. Estimated percent of land area in the Snohomish watershed (WRIA7) excluding non-forest (river bars, rock) separated by land ownership and cover class

	% Cover				
	Federal	**County/State**	**Tribal**	**Private**	**Total**
Meadows	0.1	0.02	0.002	0.1	0.2
Recent plantation	0.1	0.1	0.01	0.4	0.5
Early seral	5.0	1.0	3.2	2.5	11.6
Mid-seral	22.6	16.8	0.9	23.9	64.1
Late-seral mature	10.4	3.0	0.2	2.9	16.5
Late-seral old	5.3	1.1	0.002	0.5	7.0
Total	43.5	22.0	4.3	30.2	100.0

Table 6. Estimated % area in each cover class and expected low flow relative to 100% old growth forest using a weighted average of multipliers in Table 1. Values outside of historic range are in bold.

Ecosystem type	Current conditions	Best historic runoff case	Worst historic runoff case	Historic range
Meadows	**0.2**	2	7	2-7
Recent plantation	**0.5**	0	0	0
Early seral	11.6*	1	30	1-30
Mid-seral	**64.1**	36	8	8-36
Late-seral mature	16.5	30	9	9-30
Late-seral old	**7.0**	31	46	31-72
Expected flow	72%	77%	122%	—

* All sparse cover (**Table 3**) was classified as early seral, but it could contain up to 40% canopy cover and some large trees; 60% included trees < 20 years old, 26% included trees 20-100 years old, and 14% included trees 100-250 years old.

The analysis of current conditions suggests we are 5% below the minimum historic expected low flows (**Table 6**). This estimate is conservative because 50% of area classified as early-seral was from the sparse class, so had young and mature trees ranging from 10 to 40% cover (**Table 3**). Above 20 % cover, annual flow decreases ~1.5% and 1.2% for each 10% increase in conifer and hardwood cover, respectively (Bosch and Hewlett, 1982; Brown et al., 2005). Additionally, Donato et al. (2020) estimate only ~9% of total area in recent plantations and early-seral conditions across Washington state, so current low flows are probably well below 72%.

To ensure a safe margin, it would be ideal to achieve low flows well within the natural range between 77 and 122%. The average is 99.5% and probably maintains an adequate margin of safety. Mid-seral forest is overrepresented while meadows and late-seral are underrepresented (**Table 5)**. Mid-seral forest is the most water demanding, so reducing it enough (≥28%) to be within historic ranges may achieve close to the expected flow we would have seen pre-colonization and under similar climate during the last 5,000 years (Whitlock et al., 2015).

Can we achieve our goals with current policy?

Mid-seral forest represent the dominant forest area in all lands (**Table 5**), and are especially prevalent in private and federal land. We can assume that under current policy, private owners will not move land out of active management creating this mid-seral surplus if they are not compelled to. Likewise, it is unrealistic to assume all mid-seral could or should be converted on non-private land. Thus, to move mid-seral forest to underrepresented classes, we will have to rely on Public and Tribal lands (40.2% of total area) that are not bound by the same economic constraints as private industry. In addition to mid-seral forest on Public and Tribal lands, we can target riparian buffers on all lands because harvest there is already limited. These can be allowed or encouraged to develop late-seral characteristics. The inner and core buffers provide the most protection and total 22.6% of total land area (**Table 5**).

Table 7. Percent land in Mid-seral condition and areas of riparian buffer across ownership categories. Last column is expected percent of each category in buffers if each category is randomly distributed across the landscape. Totals that do not add perfectly are due to rounding error.

Ownership	Mid-Seral (%)	Core, Inner, Wetland Buffers (%)	Percent in buffers
Federal	22.6	11.5	2.6
City and State	16.8	6.3	1.1
Tribal	0.9	0.3	0.0
Private	23.9	4.6	1.1
Total	**64.1**	**22.6**	**14.5**

It is useful to look at several plausible cases to examine such feasibility. **1)** Assume with enough time you can convert the 28% of forest in young trees above historic maxima to mature forest, and mature forest to old. This is a strategy inadvertently followed on federal lands where thinning is the primary harvest practice. **2)** Assume private lands are managed with no changes and all riparian buffers (22.6%) are encouraged to grow older, thus the proportion of buffer in early move to mid (2.6%), mid to mature (14.5%), and mature to old (3.7 %). On public and tribal lands, half of mature forest (13.6/2 =6.8%) moves to old. The remaining young forest above the historic range across all lands could then be moved first to meadows to attain the minimum 2% to meadows, then to early-seral forest. **3)** Move 14% of surplus young forest to early-seral or meadows, and move the other 14% to mature, and shift 14% of mature to old growth. All scenarios put us above the 77% historical minimum (**Table 7**), however, the latter two get much closer to the 99% target for maintaining a safe margin of error.

Table 8. Relative effects on shifting proportion of area in vegetation types according to three scenarios outlined in text on low flows relative to 100% of land in old growth (Expected flow). Totals that do not add perfectly are due to rounding error.

Vegetation type	Current	Scenario 1: Mid- to mature and mature to old	Scenario 2: Buffers age, half of mature to old, mid to non-forest	Scenario 3: Mid- to mature, mature to old, mid- to early
Meadows	0.2	0.2	2.0	0.2
Recent plantation	0.5	0.5	0.5	0.5
Early seral	11.6	11.6	23.5	25.7
Mid-seral	64.1	36.0	36.0	36.0
Late-seral mature	16.5	28.2	20.5	14.1
Late-seral old	7.0	23.5	17.5	23.5
Expected flow	**72%**	**84%**	**96%**	**97%**

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Appendix 5: Table of aquatic and terrestrial assessments

Table 1. Assessment names and websites

Abbreviation	**Assessment Name**	**Website**
AQUATIC-FOCUSED ASSESSMENTS		
NTT-SOW	Northwest Treaty Tribes' State of Our Watersheds	https://nwifc.org/publications/state-of-our-watersheds/
NWFP-AREMP	NW Forest Plan Aquatic & Riparian Effectiveness Monitoring Program	https://www.fs.fed.us/r6/reo/monitoring/watersheds.php
USFS-WCF	USFS Watershed Condition Framework	https://www.fs.fed.us/naturalresources/watershed/condition_framework.shtml
NWFP-RA	Northwest Forest Plan Riparian Alternatives Study	https://www.fs.usda.gov/treesearch/pubs/50788
PNW-HLC	PNW Hydrologic Landscape Characterization	https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=311666&Lab=NHEERL
TERRESTRIAL-FOCUSED ASSESSMENTS		
USFS-TCA	USDA Forest Service Terrestrial Condition Assessment	https://doi.org/10.3390/su9112144
NWFP-LSOG	NW Forest Plan Late-Successional/Old-Growth Monitoring Program	https://www.fs.fed.us/r6/reo/monitoring/older-forests.php
ILAP	Integrated Landscape Assessment Project	https://inr.oregonstate.edu/ilap

Table 2. Indicators and assessment methods

Program	Indicators	Indicator Integration	Evaluation criteria	Relevant Data / Tools
AQUATIC-FOCUSED ASSESSMENTS				
NTT-SOW	Forest cover, riparian forest cover	No aggregation of indicators, each is reported separately	Trend only	Historical forest cover
NWFP-AREMP	Old-growth index, canopy cover, landslide risk, drought, streamflow	Has varied over time: Full (all indicators) Separate (inchannel, upslope) None (current report)	Has varied over time: MCDA expert judgment Reference conditions None (current report)	forest vegetation: LEMMA riparian buffers: variable width landslide risk: Netmap, Sinmap drought: SPEI streamflow: NHD/PRMS
USFS-WCF	Aquatic-Flow Aquatic-Riparian Vegetation Terrestrial-Forest Cover	Attribute scores are aggregated by averaging within a 4-level hierarchical model (22 attributes > 12 indicators > 4 process categories > overall WCC score). Weighting only occurs at the process category level, with 3 indicators receiving 30% and one the remaining 10%.	Expert judgment "In this guide, we characterize a watershed in good condition as one that is functioning in a manner similar to natural wildland conditions." Some attributes make reference to natural distributions, while other rely on the level of threats identified. Overall score and each attribute rated: 1 = Functioning properly, 2 = Functioning at risk, 3 = Impaired function	Aquatic restoration priority-setting process
NWFP-RA	Surface erosion, debris flows, thermal loading, and intrinsic habitat potential	Indicators combined with logical OR.	Binary evaluation of each indicator.	Netmap tool generated the indicators.

Table 2. Continued

Program	Indicators	Indicator Integration	Evaluation criteria	Relevant Data / Tools
AQUATIC-FOCUSED ASSESSMENTS				
PNW-HLC	Hydrologic landscape classifications based on: Climate (precipitation + evapotranspiration), seasonality, slope, aquifer permeability, and soil permeability	Unique categorical combinations	None	hydrologic vulnerability to climate change
TERRESTRIAL-FOCUSED ASSESSMENTS				
USFS-TCA	Wildfire hazard potential Insect & disease risk Vegetation departure index	Fuzzy logic rules (EMDS)	Mostly percent of LTA affected	
NWFP-LSOG	Old-growth Structure Index: (1) density of large live trees, (2) diversity of live-tree size classes, (3) density of large snags, and (4) percent cover of down woody material	Average of element scores	Compared to characteristics of stands from 100-200 years old (depending on forest type)	Also looked at connectivity of old-growth habitat
ILAP	Vegetation cover-structure classes projected	None	Vegetation cover-structure classes cross walked for impacts on fire hazard, timber/biomass production, wildlife habitat, rural community support	Also looked at potential vegetation changes under climate change

Appendix 6: Selected Annotated Bibliography and Index

These are papers dealing with effect of forest practices on the categories below, most are review papers, but others are ones I thought were important.

Index

Forest composition and transpiration

(Jassal et al., 2009; Moore et al., 2004; Winkler et al., 2010)

Forest Practices and hydrology reviews

(Andréassian, 2004; Bosch and Hewlett, 1982; Brown et al., 2005; Coble et al., 2020; Goeking and Tarboton, 2020; Grant et al., 2008; Gribovszki et al., 2010; Lundquist et al., 2013; MacDonald and Stednick, 2003; Moore and Wondzell, 2005; Moore et al., 2005, 2005; Perry et al., 2016; Pike and Scherer, 2003; Salemi et al., 2012)

Hillslope Hydrology

(Klaus and Jackson, 2018; Rempe and Dietrich, 2018; Winkler et al., 2010)

Low Flows

(Coble et al., 2020; Gribovszki et al., 2010; Gronsdahl et al., 2019; Perry and Jones, 2017; Pike and Scherer, 2003; Segura et al., 2020; Winkler et al., 2010)

Peak flows

(Alila et al., 2009; Grant et al., 2008; Winkler et al., 2010)

Riparian

(Kaylor et al., 2017; Roon et al., 2021; Salemi et al., 2012)

Roads/Sediment

(Kaylor et al., 2017; MacDonald and Coe, 2008)

Stream temperature

(Beschta and Taylor, 1988; Brown and Krygier, 1970; Chang and Psaris, 2013; Johnson, 2004; Moore et al., 2005; Roon et al., 2021)

Water Storage and Recharge

(Klaus and Jackson, 2018; Rempe and Dietrich, 2018; Winkler et al., 2010)

Alphabetical Annotated Bibliography:

(Alila et al., 2009)

This paper offers an important counterpoint (with some bombast) to the idea that peak flows of >10-year return interval are now effected by forest harvest. They rest their argument on the fact that peak flow and frequency covary so cannot be analyzed separately as in previous analyses using ANOVA to compare the same rainfall event in different watersheds. They instead analyze the change in the frequency distribution of flows (i.e. comparing frequency of flows of similar magnitude but from different events) to show that all flows are larger and lager flows are more frequent.

This analysis “factored out” the effect of vegetation regrowth, which would dampen the effects over time. They also argue forcibly that roads are particularly problematic for increasing flood flows.

(Andréassian, 2004)

This review begins with an entertaining read of the history of debate about whether or not forest practices alter water flows and in what directions beginning before the middle ages and up to 2004. They then review 137 paired watershed studies after discussing their strengths (avoid climate and inter-basin variability) and weaknesses (assume stationarity of relationship between treatment and control watersheds).

The article discusses confounding problems with response variables for measuring discharge response to forest practices. For example, max variation in low rain year is less than max variation in a high rain year, so can make peak flow difference hard to detect.

General conclusions are:

- Fewer trees generally lead to more discharge but the effect is highly variable
- Deforestation generally increases flood peaks and volumes
- Annual discharge response less variable to vegetation change than floods, and floods can even show negative responses due to such high variability
- Effects of harvest are noticeable after 25% harvest for low flows
- Flow responses can diminish withing 5 years

(Beschta and Taylor, 1988)

Primary contribution was to show cumulative effects of harvesting are the most likely cause of rising stream temperatures during the warmest days of the year in a large drainage (325 km^2). Like other studies maximum temps rose more than minimum (6 vs 2 °C). Because air temperature slightly decreased over the same period this was attributed to increased solar exposure of streams.

Results are confounded by peak flows with also increase temperatures after they subside and changing forestry practices.

(Bosch and Hewlett, 1982)

This is a well-cited review of 94 global paired catchment studies.. Their goal was to draw some general conclusions about vegetation and annual water yield expressed as change in runoff for percent area harvested (mm $\%^{-1}$). One of their main conclusions is that conifers use more water than hardwoods and shrubs. This is another study showing that >20% needs to be harvested and that precipitation must be > ~450 and < ~1600mm to show a difference in water yield.

(Brown et al., 2005)

This global review examines four categories of vegetation change (afforestation, deforestation, regrowth, and forest conversion) with respect to time scale and seasonal patterns of flow changes.

They show that deforestation results in new equilibrium stream flows sooner that afforestation. They also show stronger proportional effects on low flows from vegetation change.

This paper provides some good graphs (Figure 2) compiled from multiple studies showing change in water yields expected with 100% cutting given different composition (Conifer, Hardwood, Eucalyptus, Scrub) given annual precipitation.

There is also a great graph (Figure 5) showing duration of water yield effects compiled from multiple studies as well as the breakdown of % flow reduction by annual and low flow for up to 25 years after treatment for conifers vs. eucalyptus (Figure 7).

The authors also try to generalize the effects across different contexts summarized in Table 1 and reproduced below.

Climate	Absolute response	Proportional response	References
Tropical/summer dominant rainfall	Larger changes in summer months, when rainfall is greater then monthly average	Two types of responses observed: (1) Similar changes in all months (2) larger changes in winter months, when rainfall is below monthly average	Blackie (1979), Blackie and Edwards (1979), Bruijnzeel (1988, 1990), Gafur et al. (2003), Sharda et al. (1988), Scott and Lesch, (1997) and Van Lill et al. (1980)
Snow affected catchment	Largest changes in months of snow melt	Larger change in summer growing season	Baker (1984), Troendle et al. (2001), Alexander et al. (1985), Troendle (1983), Schneider and Ayer (1961), Hornbeck et al. (1970) and Hornbeck (1975)
Winter dominant rainfall	Largest changes in winter months when rainfall in above monthly average	Largest change in summer months when rainfall is below monthly average	Bari et al. (1996), Bren and Papworth (1991), Burch et al. (1987), Caissie et al. (2002), Gallart et al. (2002), Keppeler and Ziemer (1990), Kirby et al. (1991), Lewis et al. (2000), Mein et al. (1988), Miller et al. (1988), Rogerson (1971), Rothacher (1970), Ruprecht et al. (1991) and Watson et al. (2001)
Uniform rainfall	Uniform change across all seasons	With deciduous vegetation there is a larger change during the spring months. Evergreen vegetation shows uniform change across all seasons	Hibbert (1969), Johnson and Kovner (1956), Lane and Mackay (2001), McLean (2001) and Swank et al. (2001)

Lastly, and appendix table in the document provides the complete list of reviewed watershed characterized by biophysical properties and arranged by region.

(Brown and Krygier, 1970)

Early paper showing dramatic increases in stream temperature after clear cut logging and attributing this to increased sun in the Oregon Coast range. Maximum temperatures went from 14 to 29°C and showed no change in a nearby stream with a buffer of brush and trees.

They also showed that a 25% patch cut with buffers did not have temperature increases with logging. The width of these buffers is not described.

This early study may have been the basis for some forest practices changes. Now riparian buffers are ubiquitous, so such dramatic changes are no longer attainable.

(Chang and Psaris, 2013)

This study of streams from the Pacific Coast, USA to Idaho and Montana demonstrates the relative importance of different variables for predicting temperature sensitivity (slope of temperature response) and maximum 7-day daily temperature at four scales and across space in the Columba basin.

Temperature sensitivity is largely driven by distance to coast (+), base flow relative to mean flow (-), and contributing area (+). Maximum temperature is driven by base flow relative to mean flow (-), % forest cover (-), and stream order (+).

They show that buffer-scale effects are more important than larger scales for determining stream temperature because these have the best predictability.

For temperature sensitivity, forest cover had a larger negative coefficient in western OR (no data in western, WA) and weaker negative coefficients in eastern OR and WA (Figure 10). Drainage area had less effect and base flow relative to mean flow had stronger effects on temperature sensitivity on west-side forests than more eastern forests.

(Coble et al., 2020)

This review emphasizes the long-term response of low flows to forest harvest.

The key aspect of this work is that they define hydrologic phase in response to cutting. Phase I: Increased low flow, Phase II: Neutral low flow, Phase III: Decreased low flow. This provided the bases for the four phases used in the current report by adding Phase IV: Recovery to old growth flows.

They show that within ~10 years forests have entered Phase II or III based on 25 catchments. They also provide limited evidence that the magnitude of responses attenuates due to increasing variability at large scale.

The review details three case studies 1) Casper Creek CA, 2) H.J. Andrews, OR, and 3) Mic Creek, ID. Essentially summarizing their results but not providing a cohesive synthesis between the three.

The following tables are worth reviewing:

Table 2 in this document summarizes many studies by catchment area, % forest removed, stand age, duration of low flow increase, neutral flows, and periods of decrease.

Table 3 provides dada on evapotranspiration rates using eddy-covariance measurements for Douglas-fir stands ranging from 7 – 450 years of age.

The main takeaways are the durations of the different phases: Phase I: 1-10 years, Phase II: ~6-20, Phase III: ~15 to >30 years.

(Goeking and Tarbaton, 2020)

This review of 78 studies focuses on the effects of stand-replacing and partial disturbances on streamflow. Their main metric was how many studies showed which direction of response. From their Table 2, most studies show increase in annual flow, peak flow, low flow, earlier snow melt, and more snow with loss of vegetation. In non-stand replacing disturbances, 15 studies showed increases, 10 showed no change, and 9 showed decreases in flow.

It is worth being careful interpreting their results which do not always give great context. For example, of the 9 showing a decrease in flows, all were due to recovery of vegetation after a period of time subsequent to disturbance (Table 5).

There is a heavy emphasis on LAI, which should be tempered when interpreting results because of canopy structural changes that can have the same LAI but different transpiration.

Their main conclusion is that partial disturbances have a more variable effect on stream flow than stand-replacing disturbances.

(Grant et al. 2008)

This is a thorough review of processes and history of the science behind peak flow responses to forest harvest. The review is laid out in terms of area in **rain-dominated**, **transient snow**, and **snow-dominated** drainages and the likely processes most influential responsible in each.

For example, the key factors they see in each zone in order of importance are as follows:
Rain: evapotranspiration, interception, condensation (fog), and snow accumulation and melt
Transient snow: snow accumulation and melt, evapotranspiration, interception, condensation
Snow: snow accumulation and melt, interception, evapotranspiration, condensation

Results from observational and modeling studies are covered within.

They also set up a good conceptual model (Figure 3) of different harvest intensity on peak flows where dispersed retention is on one end, variable retention in between, and clear cut on the other, with increasing effect on peak flows given the same proportion harvested.

Figure 4: This is a summary matrix of papers by % harvested in small and large watersheds and in the three precipitation zones, including location of study.

Tables 3 and 4 report peak flow changes and attributes of many studies (e.g. precipitation zone, percent harvested, location, cutting intensity, % peak flow response).

Many intermediate graphics summarize expected peak flow responses from harvest showing no peak flow response below ~20% harvest and % peak flow response at 100% harvest in rain (0 to ~40%), transient snow (~-8 to ~40%), and snow (0 to ~50%) zones, included modeled effects of roads (+~10%).

A key points they make is that heterogeneity in larger watershed will likely limit peak flow responses and that the magnitude of peak flows changed more during smaller storms than larger storms.

They develop the conceptual model copied below:

Likelihood of peak flow increase High ← → Low			Potential considerations
High	Moderate	Low	Road density
All or most	Some	Few or none	Road connectivity
Fast	Moderate	Slow	Drainage efficiency
Large	Small	Thinned	Patch size
Absent	Narrow	Wide	Riparian buffers

Lastly, they discuss the relative effects of peak flow increase on stream morphology as being confined to those of low gradient and with smaller streambed rock material (i.e. gravel).

(Gribovszki et al., 2010)

This paper is only included for completeness because it reviews diurnal fluctuations in streamflow with a section on riparian vegetation that may be useful if we decide to model and riparian treatments. In this section of the paper the review points to many other primary sources on the topic.

(Gronsdahl et al., 2019)

This paper offers one of the few looks at how large basin low flow may be impacted by cumulative harvest over time in a snow-dominated basin. After two decades of logging and once logging approached 50% harvest in the basin, daily low flow *reductions* were detectible (11 to 68%). Some caution should be exercised in interpreting the results because there are many confounding variables not controlled for.

The reductions in low flow were likely due to rapid regrowth of plantations following harvest.

(Jassal et al., 2009)

This study examined transpiration of Douglas-fir plantations for ~6 years using eddy covariance measurements until they were 7, 19, and 58 years old.

When comparing numbers in Table 1 across only years held in common, the transpiration/precipitation for the 51-58 year-old stand was 26.9%, for the 13-19 year old sand was 25.4%, and for the 1-7 year old stand was 18.3%.

The key finding is that transpiration rapidly increases to the rate of a dense plantation.

(Johnson, 2004)

This was a shading experiment done on a bedrock reach that then flowed into a gravely reach in the HJ Andrews. It showed that gravel acts as a thermal battery, moderating temperature swings.

The main point of the paper is that shade is more important for controlling stream temperatures in bedrock than in gravelly reaches. The only temperatures significantly effected were maximum temperatures in bedrock reaches. Mean and minimum temperatures were similar.

Importantly, the range of temperature in the gravelly reach was low (~1.6-2.1°C, mean ~16°C) while it was much higher in the in the bedrock reach (~7-8°C, mean ~16°C) and was almost solely due to increases in maximum temperature.

Johnson also discusses some controversial finding from the literature that are worth reviewing.

(Kaylor et al., 2017)

Light in mid-successional forests after harvest is less than that in old growth forests that once provided healthy stream flows.

This paper is important because it shows that an obsession with shade to provide lower stream temperatures likely does so at the expense of other ecosystem services in the riparian zone.

(Klaus and Jackson, 2018)

This is a metadata study that looks at travel distance of water down a hillslope as a perched saturated throughflow above an 'impermeable' layer. This paper argues that in contrary to standard thought in modelling, subsurface lateral flow is not continuously connected to the valley bottoms. Instead, most of this water percolates through the 'impermeable' layer prior to entering the stream. Travel distances ranged from 1 to several hundred meters from data gathered from 17 different hillslopes. They compile a nice table of data showing lateral travel distances of throughflow (Table 1).

This paper suggests that except during the wettest of storms where the ground is fully saturated, it should not be assumed that any shallow subsurface water makes it to the stream. Only the hillslopes closest to the valley bottom contribute water to the streams in this manner.

(Lundquist et al., 2013)

Very good synthesis of the dominant processes affecting snow accumulation and ablation in the western Pacific Northwest. This paper clearly shows that openings accumulate more snow than forest cover, melt rates are slower in forest, and on aggregate snow lasts longer in openings in our region.

(MacDonald and Coe 2008)

Similarly well-written account as the reference below but synthesizing the most important processes operating on roads. This paper includes many easily read diagrams and plain sense thinking.

Highlight include:

- Roads can create 10 to 300 fold increases in landslide rates
- Roads can increase sediment production by an order of magnitude
- Minority of roads cause the majority of problems
- Poor engineering is an avoidable connector of roads to streams, increasing connectivity by ~40%

(MacDonald and Stednick, 2003)

Although this review is focused on Colorado, many of the findings are relevant to this project. Stednick was a lead researcher on the Alsea watershed study in Western Oregon so his knowledge base is from the western Pacific Northwest. The writing is very clear and concepts presented simply.

Among the main points relevant to this project, are that:

- Low flow response is proportionally high but absolutely small and short lived.
- Vegetation is increasingly important as precipitation increases
- Most increases are in fall and early winter by increases antecedent soil moisture
- Timing of flow increase from snow is on front end of hydrograph

(Moore and Wondzell 2005)

Highly cited and fairly exhaustive review of the effects of forest harvest on hydrology in the Pacific Northwest. Covers essentially all topics and is a good go-to reference for general background information. This review covers all dominant physical processes (e.g. interception, snow melt, soil moisture), and has a heavy focus on the riparian zone.

Table 2 provides a list of studies in the Oregon Cascades showing attributes of each study (e.g. harvest type) and canges in annual, and peak flows in mm precipitation.

Table 3 and 4 summarize the same information for the Oregon Coast Range, Southern BC, and in small snow-dominated watershed.

(Moore et al., 2004)

This study compares transpiration of a 450 year old forest to a 40 year old plantation by scaling up sap flow measurements from 20 trees to stand-level measurements of forest structure.

They show that sapwood area is 21% higher in the young plantation, and young trees in this plantation had sapflow rates 1.5 times that of older Douglas-fir trees per unit sapwood. Likewise, old Douglas-fir trees had 1.5 time the sap flow rate per unit sapwood than western hemlocks. Young alder used the most water per unit sapwood at 1.4 times that of old Douglas-fir.

Because hemlocks are 59% of sapwood area in older forests and the remainder is largely from old Douglss-fir trees, the old forest was using 3.27 times less water than the plantation.

Transpiration rates in 40 to 60 year-old Douglas-fir were 1.8 to 3.9 mm day^{-1} and in trees >240 years old were 0.4 to 1.5 mm day^{-1}.

(Moore et al., 2005)

Reviews a large body of work on small (<1km^2 area and 2-3m wide channels) drainages in the Pacific Northwest in response to forest harvest with particular reference to riparian areas.

There is a basic review of hydrological processes to start, then review of forest management practices, followed by a section on monitoring and predicting stream temperature and its causes with models.

Temperature increases are dominated by increased sun, but also by channel erosion to wider and narrower channels after vegetation decreases. Hydrology can alter the effect of sun on the stream, however, in most cases, solar exposure is a dominant control in these small streams.

Important findings for our work are that maximum water temperatures rise more than minimum (±1-2°C) thus diurnal variability increases. Maximum temperature rise is higher in clear cuts than partial cuts and riparian buffers reduce effects of cutting if they are approximately 1-tree-height wide. Sparse buffers do not buffer stream temps (2.8-4.9°C rise) as much as dense buffers (0.5-2.6°C rise).

Temperature increases have cumulative effects downstream that are not additive due to hydrology, heating properties of water, and intermediate pooling of water.

Recovery of stream temperatures is dominated by solar radiation, takes approximately 10 years, and is not linear. Temps stay high until the canopy closes over the stream.

Table 1 provides a good overview of stream temperature responses to harvest but may not reflect contemporary harvest with more stringent buffer requirements.

(Perry and Jones, 2017)

This is an important paper for low flows in the western Pacific Northwest. They use long term datasets to show roughly 50% reductions in mid-summer low flow of very small streams due to rapid regrowth of 35 to 45 year-old plantation Douglas-fir. In dry years, they also show that duration of low flows can be up to 100 days longer in basins with plantations.

They over a comparison of several treatments over time including: Clear cut, patch cuts ranging from 25 to 50%, 40% retention shelterwood, and control.

Figure 6 is the meat of the paper, showing decline in low flow rapidly after harvest into deficits by years 10 through 15 and leveling at approximately -50% low flow response.

One criticism of this paper is they do not present absolute flows, and we know low flow responses are small in magnitude but large in percent change.

(Perry et al., 2016)

This 32-page report is an excellent review of hydrologic processes in the Pacific Northwest and how forest practices influence them in the Chehalis River basin. The Chehalis River basin is in Western Washington so much of the literature is relevant to this project.

The only substantive difference between the Snohomish and the Chehalis are that the Chehalis is generally lower in elevation, so is less changed by forest practices altering snowmelt.

They emphasize strong but transient (5-10 years) low flow responses as well as uncertainty in detecting post-harvest extreme flows with return periods > 10 years.

The report ends by recommending a spatially-distributed, physically-based hydrological approach for modeling effects of harvest on stream flows.

(Pike and Scherer, 2003)

It is hard to find many papers examining effects of forest harvest on low flows in snow-dominated basins. This review covers this topic. They comment on the extreme variability but consistent increases in low flows as well as the short-lived nature of low flow responses (3-6 years). This paper brings up more questions than answers.

(Rempe and Dietrich, 2018)

This paper makes the important point that water supply for transpiration is deeper than the depths of the soil layer. In this study in a densely forested hillslope in California, they found that up to 27% of annual rainfall is seasonally stored as soil rock moisture above the water table. It accumulates during the wet and mediates the initiation and magnitude of recharge and runoff. Over the dry season it is gradually depleted by trees for transpiration. During the summer months, when transpiration is high, groundwater levels decline slowly, runoff is small, and large changes in rock moisture storage occur. Dry-season rock moisture decline showed little year-to-year variability and no apparent sensitivity to the volume of precipitation that fell during the preceding wet season. Even in a drought year of less than half mean annual precipitation (2014 received 1027 mm of rain), the rock moisture storage capacity was reached, leading to the same pattern and magnitude of rock moisture depletion as years receiving more rainfall.

This is likely why clearcuts increase low flows since there is no more transpiration taking up this water. Forest Practices likely don't impact deeper groundwater pathways which is set by topography and geology as well as infiltration rates through types of rock.

(Roon et al., 2021)

This paper is a great study on effects of thinning riparian forest on stream temperatures in 10 small (2-4 m wide) streams in the redwood region 1-2 years post treatment. They examined maximum, mean, minimum, variability, and degree days of temperature effects above thinning, within 130-225m long thinned reaches, and in 150-200m reaches below thinning.

Thinning ~50% of basal area reduced shade by 20-30% while other thinning treatments only reduced shade by ~4%. All temperature measures of maximum and mean temperature increased in the more heavily thinned areas, while those in the lightly thinned saw not effect. Max temps rose 1.7°C in spring, 2.8°C in summer, and 1°C in fall. Mean temps only rose 0.5°C in spring and 0.9°C in summer.

Downstream effects were variable but most summer temps were within 1°C upstream temps within 600m of treatment.

This paper also has easy figures and tables to interpret as well as a good discussion of ecological reasons to alter riparian buffers in previously harvested stands. The discussion is also very clear and concise.

The author also provides stream temperature data summarized by different measures of stream temperature (e.g. # days > 16°C, mean weekly maximum temperature, etc) and by season.

(Salemi et al., 2012)

This review synthesizes papers examining the effect of riparian vegetation of water yield. This paper reports annual yield increases in absolute terms (e.g. mm yr^{-1}). They show similar but opposite effects of cutting riparian forest (483 ± 309 mm yr^{-1}) as planting forest along riparian areas (-456 ± 125 mm yr^{-1}).

Tables 1 and A1 show study results in detail and provide context for absolute yield increases by reporting annual precipitation and vegetation type.

Table 1 also reports findings in mm yr^{-1} %$harvested^{-1}$ similar to the reviews by Sahin and Hall,(1996) and Brown et al., (2005).

(Segura et al., 2020)

This is an important update to the Alsea watershed study and examines the effect of a second harvest on low flows using contemporary forest practices. Notably, one half a 40 to 60 year old plantation was clear cut leaving a riparian buffer, herbiciding, and replanting, followed by the same for the second half 5 years later.

The summer deficit relative to old growth forest was reduced from 50 to 21% after the first harvest, and only to 36% after the second. Most of the flow increases were in spring and fall.

The response may have been less than expected for cutting an old forest because of rapid regrowth of replanted trees and because the remaining riparian buffer was composed of young rapidly transpiring Douglas-fir from the previous plantation.

Although the authors highlight the relatively weak response relative to flows in old growth, it is still important to note that cutting plantations increased flow relative to the plantation by 40 to 80% during the summer months and more than 300 days showed an increase 40 to 50%.

(Ward et. al., 2020)

Very recent modelling paper done using data from HJ Andrews Lookout Basin where they connect the hillslope water balance to outputs measured at gauging stations. They have a nice conceptual figure on how they modelled the water flow. Article emphasizes the lessening of water availability during the driest months. There is 24.1% less flowing water days and 9.2% less stream length with flowing water from 2009-2018 when compared to data from 1953-1962. They emphasize that steeper and/or wider valleys are the most sensitive to drying from climate change.

This suggests that work done to increase stream-hillslope connections and increase groundwater storage should focus on steepest and/or widest valleys.

(Winkler et al., 2010)

This is a textbook chapter with an excellent complete picture view of hillslope hydrology and the link between forest cover and stream response. Covers percentage of precipitation intercepted, evaporated or transpired by trees as well as discusses hillslope runoff pathways. It is a good article for understanding the processes resulting in stream flow. They report a variety of stats on interception, stemflow, throughflow, snowmelt - but mainly based on forest composition in British Columbia.

(Sahin and Hall)

Table 1
Summary of results from the application of FLRA

Cover type	Yield change for 100% treatment (mm)	Yield change per 10% cover change (mm)	Membership width for 100% treatment; mm (%)
Conifer	330	23	131 (40)
Eucalyptus	178	6	102 (57)
Hardwood–conifer	201	22	26 (13)
Rainforest	213	10	153 (72)
Hardwood (MAP < 1500 mm)	201	19	128 (64)
Hardwood (MAP > 1500 mm)	169	17	157 (93)
Scrub (clearing)	92	9	60 (65)
Scrub (planting)	−220	−5	142 (65)

Important study sites

Casper Creek: Northern California paired watershed study

Alsea: Oregon Coast Range paired watershed study

HJ Andrews: Western Cascades paired watershed study

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