WATERSHED FUNCTION AND FOREST MANAGEMENT FOR SOUTH FORK NOOKSACK RIVER, WA

May 16, 2017

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Executive Summary

The amount, timing, and quality of streamflow in any river is the product of upland watershed processes: rainfall, runoff, soil infiltration, erosion, forest transpiration, and many more. As one avenue to address concerns over low streamflows and high water temperatures that regularly occur in the South Fork Nooksack River, we provide a synthesis of scientific research that addresses the role of forests and forest change in the uplands on watershed function, which contributes to downstream water quantity and quality. Based on the synthesis, we develop a conceptual plan for silvicultural and restoration actions that have potential to improve flows and lower temperatures.

Current watershed function is the result of both current land uses and legacy impacts that have altered the forests that historically covered the hillslopes of the watershed and the riparian zones of the tributary network. These forest changes affect the upland water cycle, sediment transport, and in-channel river processes. In particular, upland water storage has been generally reduced and the export of water from the watershed has been accelerated relative to natural conditions, leading to lower summer streamflows and warmer stream temperatures. Climate warming will exacerbate these conditions with less snowpack and earlier melt resulting in further reductions in summer streamflow and increases in stream temperature.

Scientific research demonstrates that upland forests and forest change have complex interactions with watershed processes, but several key impacts on downstream flows and temperatures have been identified in the western Pacific Northwest. In particular, the presence of dense forest stands generally reduces the amount and duration of snow stored on the landscape, except in locations that are exposed to high winds [1]. Dense, regenerating forests also use more water for transpiration and reduce water stored in the soil [2]. Forest road networks accelerate the export of upland water [3]. Where riparian forests and in-channel wood have been removed, stream channels have cut down into the sediment, leading to earlier depletion of water stored as shallow groundwater [4]. Additionally, removal of riparian forests also contributes to increased stream temperatures [5].

Several recommendations can be made to improve and maintain watershed function based on the best available science. However, these recommendations are conceptual in nature because they do not consider the local context of land ownership and regulations, nor do they include the spatial and meterological analysis that would be necessary for an implementation plan. Further analysis to identify locations and land ownership locations where such actions would be feasibile and have the largest impact on watershed function is recommended.

In the hillslopes, these recommendations center on silvicultural strategies to open up dense forest canopies via gap-cutting and thinning, to retain and protect forests in wind-exposed locations, and to implement uneven-aged forest management that protects some older stands from harvest. In the tributary riparian zones, these recommendations focus on actions to restore hydrolgic connectivity between the channel and alluvial valley in order to maximize shallow groundwater storage and improve water availability for the riparian forest community. Although there is likely to be substantial variability in effects based on year-to-year climate variability, forest heteorgeneity, topography, and geology, all of these actions are well-supported in the body of scientific research. Since forests strongly influence watershed processes, actions to improve watershed function through silvicultural and restoration actions has the potential to improve current in-stream conditions and dampen projected future impacts.

Background

The Nooksack Indian Tribe requested that Natural Systems Design prepare a synthesis on the role of forests and forest change in contributing the watershed function, and to make recommendations for application to the South Fork Nooksack River (SFNR) Watershed, Whatcom County, WA. Summer low flows and water temperature and their effects on aquatic habitat are key issues of concern on the SFNR. The primary purpose of this initial project is to develop a conceptual upland watershed management plan that addresses the role of land management in watershed function and hydrologic processes. In addition, the plan considers how land management may combine with forest disturbance and climate change to affect streamflow and water quality.

Since forest characteristics and forest change strongly influence watershed function, we review the best available science related to forest effects on upland hydrological processes. We then make recommendations for silvicultural practices that are most like to extend in-situ water storage and slow the export of water out of the watershed. The goal of these actions in the context of the SFNR is to maintain or increase summer soil water availability and streamflow magnitude, and to maintain or decrease water temperature and sediment loading. Upland hydrological processes also influence slope stability, but this synthesis is focused on watershed influence on streamflow quantity and temperature.

Best Available Science Review

Watershed Function Overview

Within the forested, mountainous watersheds of the western slopes of the Cascade range in Washington numerous watershed processes combine to influence the timing and magnitude of streamflow and water quality. Precipitation that falls in the watershed is stored, evaporated or sublimated back to the atmosphere, or transported to the stream network via overland or subsurface flow. Vegetation strongly influences the storage and movement of water in a watershed. Therefore, forest change from timber harvest, silvicultural management, fire, and insect outbreaks influences the timing, magnitude, and quality of streamflow. The effects of timber harvest [5–11] and natural disturbance [12–14] on hydrological quantities have been the subject of extensive research.

Climate warming is projected to affect both the timing and magnitude of streamflow in the SFNR [15–17]. The SFNR is historically characterized by streamflows driven by both rain and snow. High flows occur in the fall and early winter from rainfall, and in the spring from snowmelt. Climate change projects indicate that warming temperatures will raise the rain-snow transition elevation which will result in dimished seasonal snowpack, earlier snowmelt, and a shift in the timing of the spring streamflow peak (i.e., the freshet) to earlier in the year. Associated with these key hydrologic changes are numerous impacts to humans and ecosystems, which include increased flood magnitude, reduced summer water availability, and increased summer stream temperatures [15,16,18]. These projected changes highlight the important function of upland hydrologic processes to store water and sediment *in-situ* and to slowly release water to the stream network.

In addition to a warming climate, human-caused impacts such as forest harvest, road-building, fire, beaver trapping, and in-channel wood removal reduce the amount of water stored or accelerate the export of water from the watershed. Both current land use practices and legacy impacts affect current watershed function, and will combine to amplify or dimish the projected impacts of climate change. Thus, opportunties exist to adapt management practices and restore watershed function in order to buffer projected climate change impacts. For example, upland forest cover affects the amount and timing of snow and soil water storage, and forest management therefore has the potential to accelerate or delay the melting of snow and the depletion of soil moisture on the landscape [1,19–22]. Legacy impacts from widespread clearing of riparian forests and in-channel wood removal have contributed to down-cutting of river channels and accelerated export of surface and sub-surface water downstream [23,24]. Restoration of these river systems will increase sediment and water storage and slow the export of water from the network.

Forest Effects on Upland Water Storage

Water Inputs

Forests and forest change directly affect the upland water balance, including water inputs, outputs, and storage. Forest canopies intercept and store both rain and snow. Subsequently, 10-50% of the stored water returns to the atmosphere via evaporation or sublimation [25]. The amount of rain or snow that are intercepted depends on the density of leaves or needles and branches available to catch precipitation; thus, forest stands that have been thinned from silviculture or that have been defoliated from insects or fire intercept less precipitation [13,26,27]. However, since there is an upper limit to canopy water storage and since the interception rate also depends on atmospheric conditions [28–30] there is not a linear relationship between canopy density and rates of canopy interception and storage.

Within a forest, snow that reaches the surface by falling through or falling off the forest canopy then is stored as under-canopy snowpack. Rain or snowmelt that falls through or drips off the canopy then infilitrates the snowpack or soil at a rate determined by snow or soil grain size properties and antecedent liquid water storage. In western Washington forests, infiltration rates tend to be much larger than precipitation rates, resulting in relatively little ponding or overland surface flow of water [31].

Soil Moisture Storage

Forest influence soil moisture storage by modifying the magnitude of water inputs via canopy interception processes (discussed above), and by extracting soil moisture via tree roots for transpiration. Thus, numerous studies have documented that total annual water yield increases following forest removal because water input is increased (i.e., from the reduction in canopy interception) and water output is decreased (i.e., from the reduction/elimination of forest transpiration) [8,32,33]. Forest thinning also decreases total transpiration and increases soil moisture [34]. From a seasonal persepctive, immediately following forest removal both fall-winter peak flows and summer low flows increase [2,35]. However, as forests regenerate, and canopy interception and forest transpiration reduce water inputs and increase water outputs, the increases are lessened or eliminated.

The effect of forest removal and subsequent regneration on soil moisture storage and streamflow is complicated by transpiration rates that vary with forest species composition, leaf area, and with stand age [2,36,37]. After 2-4 decades of forest regrowth, summer streamflow from regenerating forests has been shown to be reduced relative to old-growth forest [35,38]. In regenerating forests on the western slopes of the Cascade range in Oregon, Perry and Jones (2016) demonstrated that average daily streamflow during July-September is 50% lower in regenerating Douglas Fir forests as compared to reference old-growth basins (i.e., 34- to 45-year-old stands versus 150- to 500-year-old stands).

Snow Storage

Forests affect both the magnitude of the seasonal snowpack and the timing and rate of snowmelt. Observational studies have demonstrated that canopy snow interception can capture 70-80% of falling snow in the Pacific Northwest, and that after interception the majority of snow stored in the forest canopy will melt [28,30]. Forests also attenuate wind, and the reduced windspeeds within and around forests can result in preferential snow deposition in forests [1,39] or redistribution of snow to forests or forest edges [40,41].

Forests also modify the under-canopy energy balance, which determines the rate of snowmelt. In particular, forests shade the snowpack from sunlight and shelter the snowpack from wind, both of which reduce the energy available for melt [42–47]. However, forests also contribute higher amounts of longwave radiation (i.e., thermal radiation) than the surrounding atmosphere, which can result in local effects like tree wells or stand-scale effects on snowmelt timing [19,48,49]. The black carbon deposition resulting from fire affects the reflectivity of snow and soil surfaces, which influences the energy balance and therefore rates of snowmelt and surface water evaporation [12]. Lastly, reduced wind speeds within forests also reduce melt rates during warm, windy rain-on-snow events driven by atmospheric rivers (i.e. "pineapple express" events) [43,50].

The net effect of forests and forest change on the magnitude and duration of snow storage on the landscape results from the combination of the numerous ways in which forests enhance or dimish snow accumulation and snowmelt. Thus, forests can either accelerate or delay snowmelt timing, and the overall impact of forest presence on snow storage duration varies with climate [19], topographic position [21], and forest type [27]. In a synthesis of observations from across the Pacific Northwest, Dickerson-Lange et al. (2017) demonstrated that the overall effect of forest presence on snow storage duration ranges from snow lasting several weeks longer in open areas as compared to within forests, to snow lasting several weeks longer within the forest. The range of forest effects on snow across the Pacific Northwest is attributed to the first-order influence of forest presence on snow accumulation: forest presence enhances snow deposition in windy locations and drastically dimishes snow deposition in sheltered areas.

Routing of Water Through the Stream Network

Timber harvest, splash damming, beaver trapping, and removal of in-stream wood during the 1800-1900s have resulted in widespread legacy impacts on river processes in the Pacific Northwest [51–53]. In response to overall reductions in channel complexity and hydraulic roughness from theses impacts, stream channels have cut down into the valley sediments and underlying bedrock. These channels become deeper, wider, and disconnected from their floodplains, which increases the amount of water and sediment conveyed downstream during floods, decreases streamflow during the summer low flow seasons, and decreases the elevation of shallow groundwater [4,23,24].

Forest change via timber harvest also indirectly affect the water balance in a watershed via the creation of forest roads, which can speed the routing of water out of the watershed [7,54]. Forest roads and related culverts essentially convert subsurface flow to surface flow, which dramatically increases the rate of transport to the stream network [55]. Erosion on forest roads also contributes fine sediments to the stream network [56].

Climate Change Impacts

Climate change is projected to reduce seasonal snowpack and summer streamflow in the Pacific Northwest, in general, and in the Nooksack watershed, specifically [15–17]. Modeled hydrologic projections for the SFNR indicate that the snow storage will decrease by over 50%, the timing of the spring streamflow peak will shift up to 8 weeks earlier in the year, and median summer streamflows will decrease by over 50% toward the end of the century (Figure 1; Murphy, 2016). These hydrological changes are primarily driven by increasing temperatures, which will result in an increasing proportion of winter precipitation falling as rain rather than snow and in higher snowmelt rates.

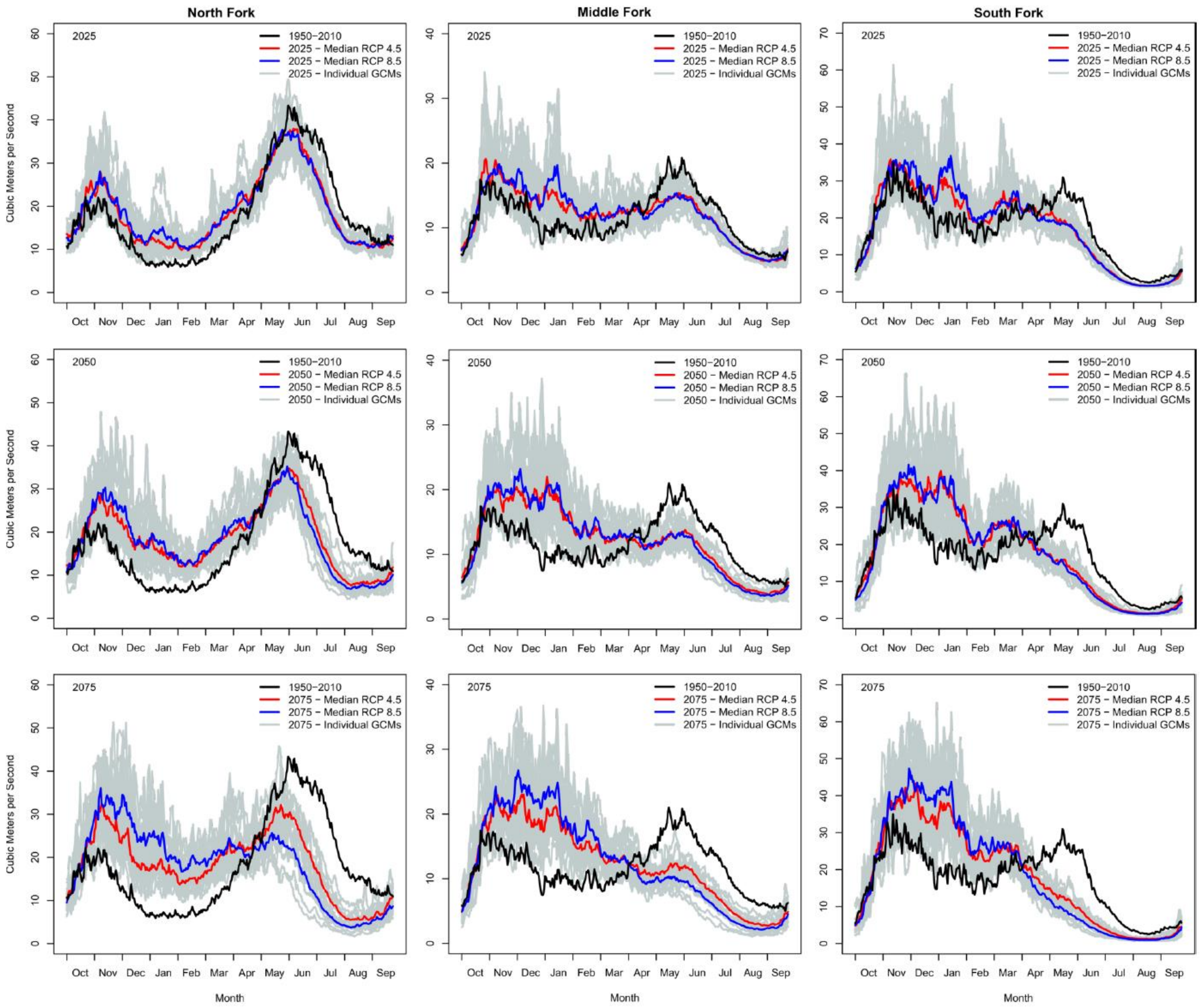

Figure 1. **Modeled future average daily streamflow in the North Fork Nooksack (column 1), Middle Fork Nooksack (column 2), and South Fork Nooksack (column 3) for 30-year periods centered on 2025 (row 1), 2050 (row 2), and 2075 (row 3). Black lines represent the historic simulation (1950-2010), and the blue and red lines represent average results for two future scenarios with different concentrations of greenhouse gases. Gray lines represent results from individual model runs, illustrating the range of results. Figure from [17].**

Results from global climate models also suggest that atmospheric river events are likely to become more frequent [57] and produce more intense precipitation [58] in California, Oregon, and Washington states. These extreme precipitation events are driven by narrow bands of warm, moist air from the tropical and subtropical Pacific Ocean making landfall on the western coast of the United States, and these events are the most common cause of flooding along the west coast [57,59]. Thus, more frequent or more intense atmorpheric rivers have the potential to increase the magnitude or frequency of peak flows and sediment transport.

Although the water balance linkage between snowpack magnitude and streamflow magnitude during the melt season is clear, there are many complex, interacting mechanisms that may amplify or dampen the projected reductions in summer low flows in a warming climate. Climate warming will continue to accelerate the melting of glaciers in Washington state, leading to a temporary increase in streamflow contribution from glacier meltwater and a decline in glacier mass [60]. However, the contribution of glacier meltwater to streamflow will ultimately decrease when the reduction in ice mass becomes large enough to overcome increased melt rates due to warming. Projections for the North Fork and Middle Fork Nooksack suggest that streamflow contributions from glacial meltwater will increase through the 2050s and subsequently decrease; the South Fork basin is unglaciated [17]. Since there are no glaciers in the SFNR watershed, and since glaciers occur above treeline, we do not consider glaciers when assessing climate and landcover impacts on upland hydrology in this synthesis.

Hydrological and Ecological Impacts of Watershed Function

Linkages To Downstream Water Quantity

Low Flows

The amount and timing of streamflow reflect the upland water balance: streamflow is the net result after accounting for precipitation (water input to the watershed), evaporation and transpiration (water outputs to the atmosphere), and soil moisture, snowpack, and groundwater storage. Upland water storage and the routing of water along the surface or through the subsurface influence the amount and timing of water entering the stream channel network.

The amount and duration of snow storage strongly influences numerous hydrological quantities in watersheds with a seasonal snowpack, such as the SFNR. The timing of snowmelt controls the timing of peak soil moisture [61] and the onset of soil moisture depletion due to transpiration [62], and the magnitude and timing of the spring freshet [15,17]. The timing of the spring freshet, in turn, sets the timing of the onset of baseflow during the dry low flow season.

Thus, projections for earlier and less snowmelt will result in lower baseflows and higher stream temperatures. However, the interplay between reduced snowpack, earlier snowmelt, and responses in evapotranspiration rates may also increase or decrease spring and summer streamflow magnitudes relative to the projected declines. Recent hydrologic modeling of historical evapotranspiration and streamflow demonstrate that decreasing snowmelt rates, which are expected as snowmelt timing moves earlier in the year, are associated with greater partitioning of soil moisture to evpotranspiration and therefore less partitioning to streamflow [63,64]. These results raise the possibility that future summer streamflows will be even lower than projected.

In addition to the broad influence of snow storage on streamflow, forest effects on soil moisture storage also influence the magnitude of baseflow. Forest removal generally increases soil moisture storage, but transpiration rates during forest regeneration vary with species and age [2,36]. Thus, summer streamflow following forest removal due to harvest or fire is likely to increase relative to an undisturbed stand for several years when transpiration in the cleared forest is low. In the subseqent decades, transpiration in the regenerating forest will surpass the undisturbed forest, resulting in a decrease in streamflow relative to the undisturbed stand.

Lastly, legacy impacts on channel morphology and streamflow routing also affect the magnitude of baseflow. Where channels are incised, the increased hydraulic gradient between the shallow groundwater elevation and the in-channel water surface elevation results in a lowering of the shallow groundwater elevation, less water available to riparian vegetation, and early dewatering of the stream [4,23,65]. Empirical studies and modeling have demonstrated that re-aggradation of incised channels through restoration actions increases shallow groundwater elevation and baseflow; however, increased riparian water availability may also result in incresed transpiration losses that diminish gains in summer streamflow, while contributing to more robust vegetation [24].

In summary, complex interplays between snow, soil moisture, vegetation transpiration rates, and streamflow exist, but the primary realtionship between watershed function and downstream streamflow magnitude is well-established. More water stored in the uplands later in the spring and summer translates to more summer streamflow. Conversely, less water stored in the uplands later in the spring and summer translates to less summer streamflow. Restoration of hydrologic processes that increase the amount and magnitude of upland water storage and that reduce the rate of transport therefore have potential benefits on increasing the contributions to streamflow later in the dry low-flow season.

Peak Flows

Forest removal also impacts the magnitude and frequency of moderate floods that have a recurrance interval of 1-6 years. Increases in flood magnitude of up to 39% for rain-dominated watersheds and up to 47% for mixed rain-snow watersheds have been reported for up to 15-20 years after timber harvest [3,66]. Research on the effects of forest removal on more extreme floods (e.g., the 50-year or 100-year flood) is complicated by disagreements over statistical detection methods [10]. The underlying process explanation for increased peak flows is that water input from snow increases (i.e., reduced canopy interception) and water output from transpiration decreases so runoff generation increases. In addition, snowmelt during rain-on-snow events is higher where forest has been removed due to exposure to wind [43]. However, it is not well understood how these modifications scale with increasingly extreme precipitation events.

In addition to the effects on runoff generation during peak flow events, forest removal or change also increases the magnitude or frequency of moderate floods that generally increase channel erosion and can initiate down-cutting [67]. The resulting incised channel conveys more water downstream without spilling overbank during floods, and can therefore increase the flood magnitude at downstream locations [68]

Linkages To Downstream Water Quality

Water Temperature

Both riparian and upland processes affect water temperature. Riparian forest removal directly affects water quality by increasing direct sunlight and therefore water temperature [5,11]. In a review of studies regarding the effective size of riparian buffers to meet water quality goals, Broadmeadow & Nisbet (2004) report effective buffer widths that range from approximately 45 – 220 feet to meet temperature moderation goals. Recent modeling in Northeast Oregon demonstrates that restoration of riparian forests in combination with stream channel narrowing can offset project climate change impacts by reducing stream temperature by 1.8 to 3.5˚C [70]. Consideration of the water quality effects of restoration actions to narrow stream channels is important because projected increases in the frequency and size of peak flows are expected to result in an enlargement of stream channels, and therefore more direct sunlight on the stream, regardless of riparian buffers (Figure 2).

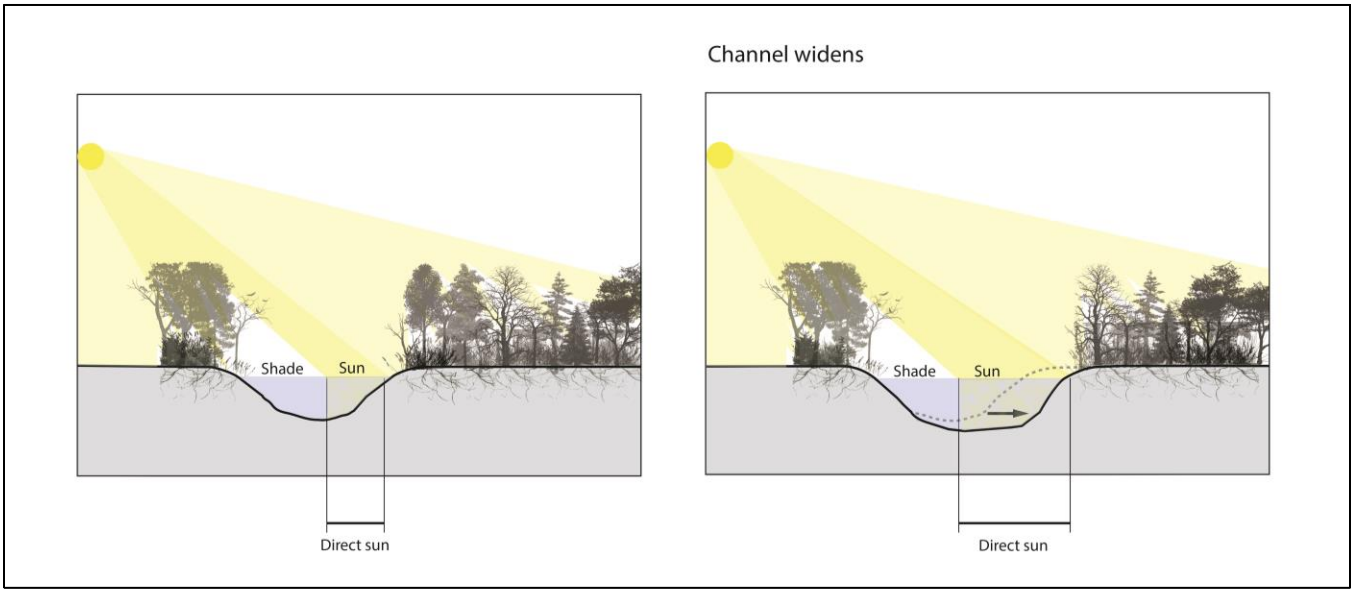

Figure 2. Conceptual drawing of the effect of channel widening, which is expected along with increasing peak flows, on the amount of direct sunlight on a stream (Graphic by K. Patrick, Natural Systems Design).

In addition to riparian shading, the extent of hyporheic exchange in complex channel forms affects water temperature [71]. The presence of beaver dams and ponds increases thermal heterogeneity [72]. Furthermore, the amount and timing of upland snow storage affects water temperature both through the advection of cooler water into the stream network, and through controlling the volume of streamflow [73]. Empirical analysis of snowmelt timing and maximum annual stream temperature in the SFNR suggest that summer stream temperature is higher when the snow melt out date is earlier (Figure 3). Thus, water temperature is linked to both upland water storage and in-channel processes.

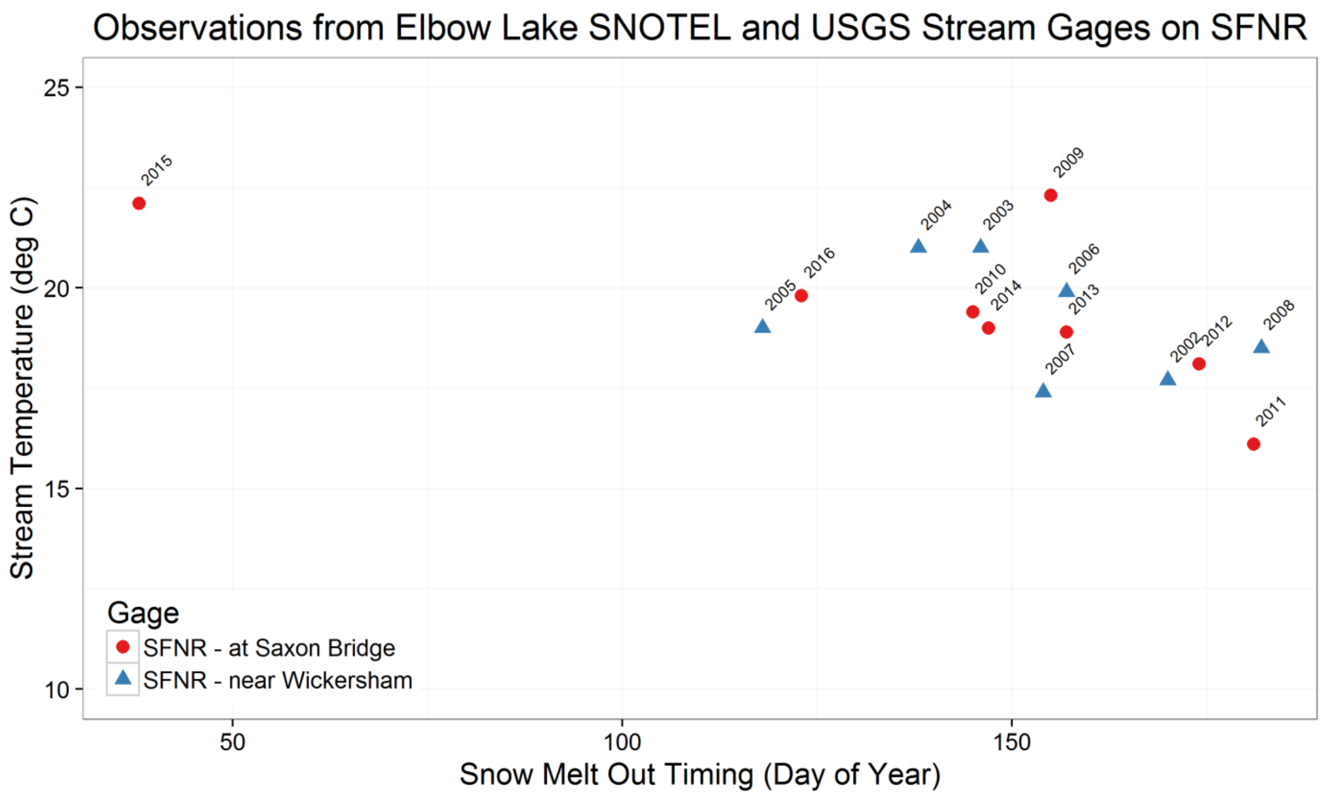

Figure 3. Maximum annual stream temperature (° C) versus snow melt out timing (day of year, where 1 = January 1) in the SFNR watershed. Stream temperature observations are from two USGS gages on the SFNR (indicated by symbol shape and color) due to change in gage location in water year 2009. Snow melt out timing is the first day with no snow at Elbow Lake SNOw TELemetry station (elevation 3040 feet). Water years for each data point are indicated in black next to each symbol.

Sediment

Upland forest hydrology processes also influence water quality through the generation and storage of sediment. Forest removal via harvest or fire increases hillslope erosion [74] and the frequency of landsliding [75], which increases sediment loads. The forest road network associated with timber harvest additionally increases both erosion and landsliding [55].

Linkages to Ecosystem Benefits

Upland watershed function affects the health of both terrestrial and aquatic ecosystems. The seasonal snowpack protects plants from diurnal temperature extremes, influences the length of the growing season, and contributes to soil moisture availability [76–78]. Local water storage in the uplands and the riparian corridor affects forest health, including resiliance to drought, wildfire, insect infestation, and disease [79].

The influence of watershed function has important downstream consequences for aquatic habitat. Water stored in the uplands and in the riparian zone contributes to critical in-stream flows for fish [80]. In addition, upland watershed function ultimately affects water quality and the complexity of in-stream habitat [18,72].

Conceptual Watershed Management Plan for SFNR

Application of Best Available Science

Based on the synthesis of the best available science, and the location of the SFNR in the western Pacific Northwest region, we propose a conceptual plan for silivcultural practices and restoration actions to improve and sustain watershed function. Although the contribution of some actions to watershed function is well-established, others are subjects of active research and we have made efforts to disclose areas of uncertainty. Futhermore, explicit consideration of topographic (elevation, slope, and aspect), meteorologic (snowpack characteristics, wind speeds, cloud cover), and landcover (forest) characteristics are recommended to refine any management plan before implementation (See Appendix 1). Additionally, we emphasize that the plan was developed based on the best available hydrological science without regard to feasibility of implementation, land ownership, or exisiting regulatory framework. Development of an implementation plan would require additional analysis of where and how to integrate the conceptual plan into forest management and stream restoration actions.

In order to buffer current low flows and water quality impairments and projected climate change impacts, this watershed management plan for the SFNR is focused on maintaining and improving watershed function. In particular, silvicultural management and restoration actions that increase the amount and duration of *in situ* water storage, and that slow the transport of water and sediment from the uplands and out of the watershed are recommended. The broad goals of this conceptual plan include:

1. Maximize snowpack retention through spatially-variable forest thinning or retention
2. Maximize soil water storage through forest thinning and uneven-age forest management
3. Slow the export of water through reduction in road networks
4. Increase alluvial water storage and slow the export of water through stream restoration

Note that any silvicultural actions to decrease canopy density and optimize snow or soil moisture storage must also be balanced with the role of in-tact forest to retain sediment and slow erosion rates. Therefore, gap-cutting and thinning, rather than clear-cutting, are the recommended silvicultural actions. Furthermore, analysis of stand ages and densities could help target locations for silivicultural actions that would additionally improve forest health and ecosystem complexity.

Maximize Snowpack Retention

Recommendations for snowpack retention are based on a hierarchy of forest-snow interactions that drive snowpack retention in the Pacific Northwest (Figure 4)[1]. First, retain forests in locations with high wind speeds (e.g., ridges, windward-facing slopes) because in these locations the forest serves as a site of preferential snow deposition and the forest reduces snowmelt rates (i.e., Case A in Figure 4).

Next, open the forest canopy through gap-cutting or thinning. Analyses of the net effects of forests on snow storage duration on the western slopes fo the Cascade Range demonstrate that in areas of low wind, the reduction of snowpack via canopy interception far outweighs the role of the forest in shading the snowpack and slowing snowmelt rates. Thus, reducing canopy cover via gap-cutting or thinning will increase both the magnitude and duration of snow storage (i.e., Case E in Figure 4).

However, either shelterwood thinning (spatially heterogeneous) or a high proportion of uniform thinning is likely required to see a benefit to snow storage. Results of an investigation in the Cedar River watershed showed that uniform thinning to achieve a 20-25% reduction in canopy cover had no significant effect on snow storage duration, and subsequent analysis suggested that a minimum of 50-60% reduction is requried to increase snow storage duration [20,81].

The optimal gap size would be small enough to attenuate wind, but there are high uncertainties with quanitfying wind dynamics through forest gaps; limited research suggests gap sizes of less than 5 tree heights [82]. An additional consideration for gap size is the potential for shading the snowpack and reducing melt rates based on solar geometry [45]; however, since generally cloudy conditions prevail in the SFNR during the melt season, this is a less important consideration [1].

Lastly, silvicultural actions to increase snowpack retention should consider the current and future elevation of the rain-snow transition line. Gap-cutting and thinning higher in the watershed where more precipitation falls as snow may have a larger effect on watershed function currently, and will be more robust in a warming climate.

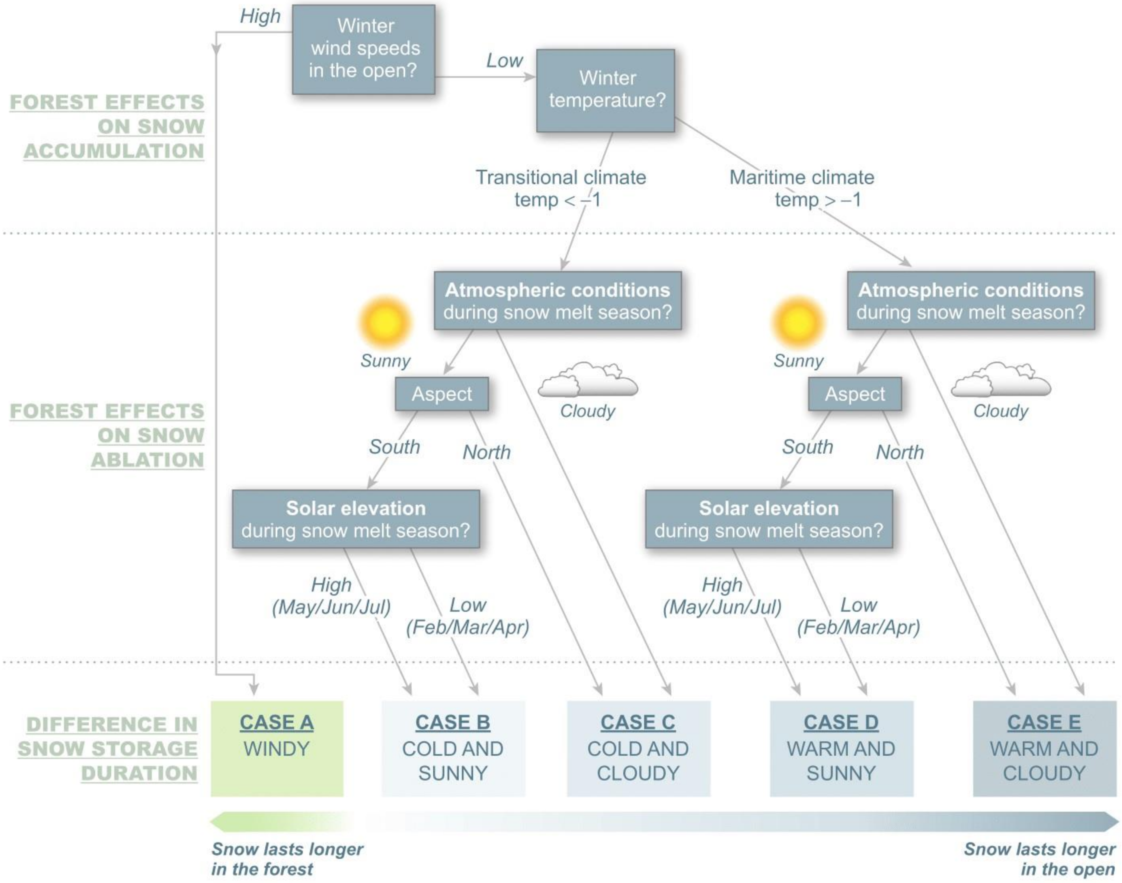

Figure 4. Decision tree model to identify dominant forest-snow interactions and the net effect of forest on snow storage duration for a location in the Pacific Northwest, USA. Based on findings from Dickerson-Lange et al. (2017).

Maximize Soil Water Storage

To optimize soil moisture storage we recommend silvicultural gap-cutting or thinning, combined with protection of selected stands to allow for maturation. Thinning strategies will reduce stand-scale transpiration and increase soil moisture storage in the short-term [34]. Uneven-age management and preservation of some stands to allow full maturation will reduce transpiration rates and increase soil moisture storage in the long-term [2,35]. Invesitgations of the difference in transpiration rates between regenerating (decades old) and old growth (centuries old) forests demonstrate that old growth forests transpire less, but additional research is needed on a more complete forest age spectrum [2,83].

Slow the Export of Water

Two strategies to slow the export of water are recommended: assessment and reduction of the road network and restoration of incised channels in the tributary stream network. Forest roads can serve as surface flow pathways, and also convert slow subsurface flow to rapid surface flow where they intersect with hillslopes [7,54,55]. Reduction in the length of the network and the disconnection of the network from the stream network both reduce the speed of water export from the uplands.

Within the stream network, incised channels accerate the export of water due to increased conveyence capacity to transmit flood flows downstream and due to draining of the shallow groundwater during the summer that results from the steep hydraulic gradient between groundwater and the lowered channel bed [23,24]. Thus, restoration actions that re-aggrade the incised channel have a dual effect to slow the export of water during the summer season and also increase local shallow groundwater storage, both of which contribute to increased baseflows and lowered stream temperatures.

Benefits of Improving Hydrologic Function

Together, these recommendations are likely to improve watershed function, with hydrologic benefits that include increased soil moisture availability, increased baseflows, and decreased peak flows. In turn, these hydrologic effects also contribute to lowered stream temperature by increasing summer streamflow and decreasing peak flows that will cause channel widening (and increases in stream temperature). Lastly, all of the recommended actions have additional ecological benefits for forest health and aquatic and terrestrial habitat.

Recommended Actions

In summary, based on the review of the best available science and conceptual application to the SFNR, management and restoration actions that are likely to benefit overall watershed function include:

- Silvicultural actions to optimize snow storage duration
    - Gap cutting (1-5 tree heights in diameter)
    - Uniform thinning (reduce canopy cover more than 25%, probably most effective at greater than 50-60% reduction)
    - Shelterwood thinning (uneven thinning similar to gap cutting, create small openings in canopy)
    - Retain and protect forests in wind-exposed areas (e.g., ridges)
    - Focus efforts higher in the watershed to provide resilience to increasing temperatures and subsequent shifts from snow to rain
- Silvicultural actions to maximize soil moisture availability
    - Gap cutting (1-5 tree heights in diameter)
    - Thinning of overly-dense stands
    - Forest preservation to allow maturation of selected stands
- Reduce length of road network and disconnect road network from stream network
- Reduce impervious areas
- In-channel restoration to re-aggrade incised channels, increase alluvial water storage, and slow the export of shallow groundwater

- Floodplain and wetland restoration and reconnection
- Focus efforts higher in the valley network to provide downstream benefits to baseflow quantities

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Appendix 1. Recommended Future Analyses for SFNR Watershed

The following analyses are recommended in order to refine the conceptual plan and to develop an implementation plan specific to the SFNR watershed:

- Analysis of spatial characteristics to categorize the watershed by elevation band, aspect, and potential for topographic shading.
- Analysis of long-term average cloud cover during different seasons in concert with analysis of snowmelt timing for average and more extreme conditions (i.e., 5th percentile) to determine the relative importance of forest shading on snowmelt rates. To assess the climatology of cloud cover, we recommend using some combination of empirical and modeling approaches, possibly include station data from the Western Regional Climate Center, the Bristow-Campell empirical method [84] to estimate atmospheric transmissivity from meteorology, analysis of cloud cover based on remote sensing products such as MODIS and Landsat.
- Analysis of local and gridded wind data to map locations subject to high winds.
- Coupled eco-hydrological modeling of hydrological and carbon fluxes, with time-varying traspiration rates to test effect of stand age and forest mangement strategy on streamflow (e.g., VELMA model).
- Collection and analysis of observational snow data in 1-3 paired open/forest locations to validate conceptual model based on Dickerson-Lange, *et al.* (2017).
- Silvicultural analysis of forest stand age, density, and condition to target multi-benefit silvicultural actions.
- Quantification of length and density of road network and assessment of hydrologic connectivity to channel network.
- Field survey of geomorphic conditions and frequency of in-channel large wood in alluvial valleys of the tribuary network to estimate potential for increasing alluvial water storage through stream restoration.