Can wood placement in degraded channel networks result in large-scale water retention?

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Introduction

In forested channel networks wood can be the dominant control on grade and shear stress partitioning. In these systems a loss of wood triggers channel incision that results in a lowering of alluvial groundwater tables and loss of water storage within a watershed. It also speeds up the routing of water out of channel network. Alluvial channels consist of two distinct channels conveying water: i) a surficial channel of open channel flow and ii) a subsurface hyporheic groundwater "channel" of flow moving through a porous medium of alluvial sediment. The velocity of water moving through these two pathways varies by up to five orders of magnitude. Thus, the subsurface flow volume can have a significant role in water retention within basin as well as supplementing baseflows. Channel incision leads to a substantial reduction or even complete loss of subsurface water capacity by lowering water tables and evacuating alluvial sediment. Shields et al (2009) report that 60-90% of sediments leaving many watersheds are due to channel incision. There are several major causal mechanisms triggering channel incision (e.g., Schumm et al. 1984). Dams cut off sediment supply which will drive downstream incision without a major reduction in peak flows (e.g., Galay 1983, Williams and Wolman 1984, Ligon et al 1995, James 1997, Kondolf 1997). Another mechanism of channel incision is changes in flow regimes that increase the magnitude and frequency of peak flows such as urbanization (e.g., Hamer 1972, Booth 1990). Large scale forest clearing can increase channel drainage networks and the frequency of bankfull or bed mobilizing peak flows which can result in channel incision (e.g., Wemple et al. 1996, Prosser and Moufi 1998, Marden et al. 2005, Perry et al. 2016). Channelization and shortening the length of channels also contributes to incision by increasing hydraulic gradients and sediment transport capacity (e.g., Simon 1989, Simon and Rinaldi 2006). In North America, the historic removal of beaver contributed to channel incision through the loss of in-stream wood dams beavers created (e.g., Pollock et al. 2007, 2012, 2014). We believe the most wide-spread cause of channel incision involves the forest clearing and the loss of in-stream wood either by direct removal or clearing (e.g. Prosser and Soufi 1998, Collins et al. 2002, Brooks et al. 2003, Marden et al. 2005, Stock et al. 2005, Brummer et al. 2006, Montgomery and Abbe 2006, Sear et al 2010, Phelps 2011, Abbe et al. 2016). By definition, this has led to an extensive loss of the natural alluvial and surface water storage that once existed. Figure 1 illustrates a recent example of rapid incision and gully formation after industrial logging. The ecologic benefits of wood placement are well established and are being used around the world (e.g., Abbe and Brooks 2011, USBR and ERDC 2016, Bridges et al. 2018). They can also help to attenuate flood peaks (Anderson 2006, Nisbet 2012, Abbe et al. 2016, Bridges et al. 2018) and reduce organic contaminants (Peter et al. 2019). The focus of this paper is highlight the potential role wood placements can have on raising water tables and substantially increasing the water storage within a channel network.

The Role of Wood in Storing Alluvium and Water

Wood has two important hydrologic influences, it can slow downstream routing resulting in "spreading out a hydrograph" (Anderson 2006) and store large volumes of alluvium within stream valleys, enlarging subsurface channels (e.g., Abbe 2000, Abbe and Montgomery 2003; Montgomery and Abbe 2006). The role of wood on stream channel grade has been well established. Veatch (1906), Guardia (1933) and Harvey et al. (1988) documented 5 meters (15 ft) of channel incision in the Red River of Louisiana after logjam removal. Hartopo (1991) showed that a major expansion of Lower Colorado River delta in Matagorda Bay occurred after logjams were removed from the Little Colorado River in the Texas coastal plain, corresponding to deposition of approximately 14,000,000 cubic meters of sediment in a 29 year period after logjam removal (Abbe 2000). Removal of logjams in the Ozette River (1951-52) lowered Lake Ozette 4.5 ft (Brummer et al. 2006). This resulted in 30,000 ac-ft of lost storage in the lake. Logjam clearing contributed to simplification in the Upper Cowlitz River in the West Cascade mountains of Washington where the number of forested islands per km in the river reduced from over 5 to 2 (Abbe et al. 1997). Brooks et al. (2003) demonstrate how riparian forest clearing in southeast Australia resulted in a 240% increase in channel slope, 360% increase in depth and 700% increase in channel capacity, evacuating alluvium that had been stored for 27,000 years. Brooks and Brierley (2002) describe a "mediated equilibrium" of river morphology dependent on wood and vegetation. In the Olympic and Cascade mountains we have both observational evidence and detailed documentation of channel incision following the removal of in-stream wood. Brummer et al (2006) describe the role of wood in the vertical stability of channels and how wood removal can lead to two meters or more of incision followed by lateral channel migration that evacuates alluvium that had been in long-term storage. Abbe et al. (2013, 2015) documented up to 3 meters (9 ft) of incision in the South Fork Nooksack River draining the western Cascades in northern Washington State. The upper basin has no dams, urbanization, or channelization. Landuse within the basin is primarily industrial timber harvest which tends to increase peak flows and sediment supply and decrease in-stream loading of functional wood. Despite increases in sediment supply, the South Fork Nooksack has experienced significant incision. We believe the causal mechanism has been removal of in-stream wood and a subsequent increase in the effective basal bed shear stress. Katz et al. (2019) document over a meter (3 ft) of incision in the South Fork Newaukum River, another system with extensive industrial timber land and no dams or urbanization. Stock et al. (2005) attributed two meters (6 ft) of incision in the West Fork Teanaway River in the eastern Cascades of central Washington over the last century entirely due to wood removal. This incision not only included evacuation of all the alluvium once stored in the streambed, but a meter of erosion into the underlying bedrock. Over the last decade there has been considerable work on the role of beaver on water storage and reversing channel incision (e.g., Pollock et al. 2007, Beechie et al. 2008, Fouty 2013, Pollock et al. 2012, 2014). It is important to remember that beaver dams account for just one subset of the types of wood accumulations that occur from a variety of physical processes such as bank erosion, landslides, and windthrow (e.g., Abbe and Montgomery 2003).

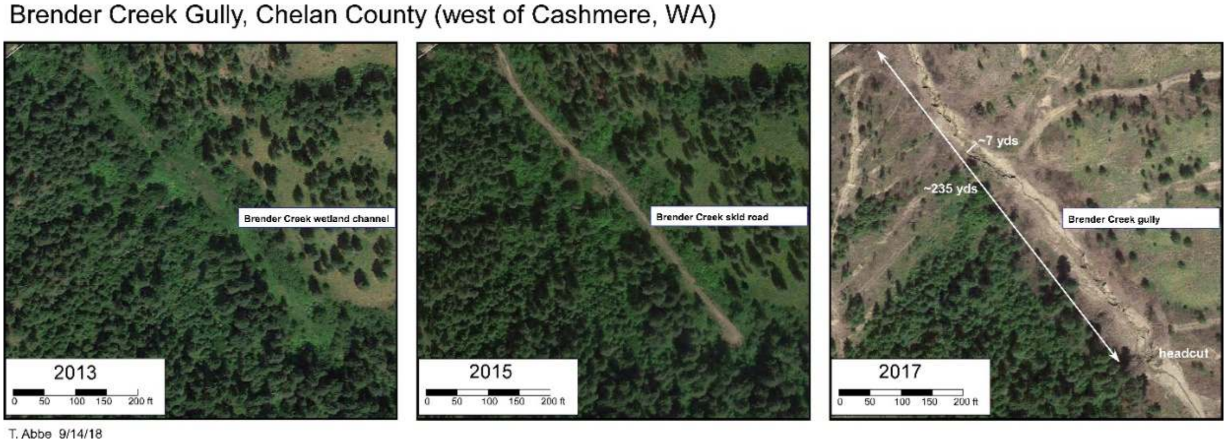

Figure 1a: Example of timber harvest disturbance to second order subsurface alluvial channel, Brender Creek south of the Wenatchee River, Chelan County. Timber skid road was routed up a second order alluvial valley with subsurface runoff (no open water channel). Shortly after logging, a gully formed and evacuate more than 25,000 m^3 of alluvium, converting the channel from subsurface to overland flow.

Figure 1b. Close up showing gully incision in Brender Creek (previous figure), 2017. Up to 7 m (21 ft) of downcutting happened in 2017, shortly after the site was logged (Figure 1a). Photo courtesy of Washington Department of Fish and Wildlife and Chelan County Natural Resources.

Our primary hypothesis is that restoring channel spanning wood accumulations increases water retention within a channel network. When extrapolated to the scale of human landscape disturbance, we believe channel networks once naturally retained much more water than present day conditions that rivaled or exceeded the water retention of large dams. Our secondary hypothesis is that by storing alluvium that would otherwise not be retained, wood is essential in creating and sustaining large subsurface alluvial channels which slow water export (movement out of basin), supplement downstream flows, improve water quality, and enhance riparian forest health. Conversely, channel incision leads to loss of water storage and rapid water export from the basin.

The images in Figure 1 convey an important message regarding the impact of incision on the routing of flow through a channel network. The original surface water channel was shallow and wide (evident by the skid road within the channel). Prior to logging channel was heavily vegetated (first panel of Figure 1a). After the gully formed the channel deepened, widened and became smoother. Surface water flow through the gully moved about eight times faster than the pre-existing vegetated channel. The gully also destroyed a large sub-surface groundwater channel conveying flow through the alluvium. Flow through porous media move much slower, by 4-5 orders of magnitude, than flow through a surface channel. Flow in surface channels is commonly expressed by the Manning's equation

$$(1) \qquad U = \frac{(R^{2/3}\, S^{1/2})}{n}$$

U = flow velocity, m/s
R = hydraulic radius, m
S = hydraulic gradient
n = Manning's roughness coefficient (0.035 for smooth channel, 0.09 for very rough channel)

Flow through a porous medium is commonly expressed by Darcy's equation:

$$(2) \qquad U = \frac{K}{p}\,\frac{\Delta h}{\Delta L}$$

K = hydraulic conductivity of material, m/s. This varies by orders of magnitude
p = porosity of the material
$\Delta h/\Delta L$ = hydraulic gradient (S)
Δh = hydraulic head (vertical change in water elevation over distance □L), m
ΔL = horizontal distance of flow path

Subsurface flow not only reduces the rate at which water is exported from a basin, but it plays a major role in cooling and cleaning the water. This can be a critical role for the ecology of salmon streams.

Table 1 illustrates the difference in routing times of flow through a stream valley 10 km in length with a valley gradient of 0.03 and filled with a well-graded alluvium of silt, sand and gravel. The presence of alluvium creates subsurface groundwater channels that have a significant effect on the rate water is exported out of a basin and thus potential contributions to recessional dry season stream flows. Natural variations in bedrock valley constrictions can be a factor in forcing subsurface flow back to the surface.

Table 1 – Routing times within a 10 km alluvial stream with a 3% gradient.

Flow Condition	Routing time (3% grade over 10 km)	
	hours	days
Surface water through incised channel	0.4	0.01
Surface water through natural channel	3.2	0.13
Subsurface water through alluvium*	14,854	619

*subsurface flow diminishes substantially for incised channel due to lower water table and evacuation of alluvium from the valley. Subsurface flow can be effectively eliminated when incision reaches bedrock. Subsurface flow assumes no significant macropores or preferential flow paths.

Research on the hydraulic effects of wood has demonstrated the importance of wood not only in storing sediment, but in reducing sediment transport capacity by shear stress partitioning that reduces the effective shear stress available for grain mobilization (Shields and Gippell 1995, Buffington and Montgomery 1999, Manga and Kirchner 2000). Relatively small accumulations of wood within a streambed can have a substantial influence on reducing the shear stress available for grain mobility (sediment transport). This reduces the stream's capacity to move larger grains and sediment volumes, resulting in a finer streambed (lower median grain size) and bed aggradation. This is consistent with fact that many streams with high wood loading have multiple shallow channels with large volumes of floodplain sediment deposition (Abbe et al. 1996, Abbe and Montgomery 2003, Montgomery and Abbe 2006, Sear et al. 2010). Wood can store sediment in channel with gradients over 15% (Abbe 2000, Abbe and Montgomery 2003).

$$\tau_0 = \tau_{GS} + \tau_{LWD} \qquad (3)$$

τ_0 = total bed shear stress = ρgRS

τ_{GS} = grain stress that is effective shear stress available to sediment transport

τ_{LWD} = shear stress acting on wood

ρ = water density

g = gravity

R = hydraulic radius

S = slope of energy grade line

Channel and floodplain deposition enlarges the subsurface channel where water is moving much slower. The fact that groundwater flow is moving so much slower means that increased groundwater storage and flow has a net effect of slowing the export of water from the watershed. The headwaters of a channel network typically start with convergent topography ("channels") filled with colluvium where flow is entirely subsurface. Wood and vegetation increase the length of subsurface flow in a channel network which slows the rate that water is exported from the watershed, supplementing flows in dry periods. Incision not only increases water velocities in the stream and speeds the export of water out of the basin, but it can cut down to underlying bedrock and entirely eliminate the alluvial subsurface channel (e.g. Schanz et al. 2019). The lower invert of the incised channel lowers the adjacent groundwater table which drains a substantial portion of water stored in the alluvium. Prior to incision, channel connectivity to the floodplain was reflected in a relatively flat-water surface gradient across the valley. The principal gradient would have been down the valley. After incision the groundwater gradient rotates toward the channel (i.e., perpendicular to the valley) and increases. Water quickly drains from the alluvial aquifer into the incised channel where it is rapidly routed downstream (Table 1). Prior to incision flow moved much slower down valley, retaining water within the watershed. This same process explains how subsurface tributary channels can maintain flows in downstream channels well into dry seasons and why gullies dry up so quickly. Basic definitions of the surface and subsurface channel and incision are illustrated in Figure 2.

Restoration within about 2 km of Poison Creek, a tributary to Mission Creek in north central Washington, resulted in this exact scenario. After wood placement , the channel aggraded, filling with sand and fine sediment. Water levels also increased, extending across large portions of the valley bottom in places. Portions of the channel and floodplain remained wetted through the summer and into the winter. Several restoration projects focused on in-stream wood placement illustrate this (Figures 3-4). Similar post-project conditions were observed in Toppenish Creek, a snow-dominated, moderate gradient tributary to the Yakima River in Yakima County, Washington (Figure 3) and the South Fork Nooksack, a rain-dominated river southwest of Mount Baker in northwest Washington (Figure 4). Another important influence of wood and vegetation goes back to the discussion of sediment transport capacity. The finer the sediment being deposited, the lower the hydraulic conductivity and rate of subsurface water flow. To illustrate the importance of grain size and how the grain size of a porous medium influences the flow of water down through surface area resistance, consider that gravel has a surface area of 15 cm^2/cm^3. Sand is 150 cm^2/cm^3, silt is 1500 cm^2/cm^3 and clay is 8,000,000 cm^2/cm^3. In summary, in streams dominated by a large subsurface alluvial channel, water moves much slower, thereby raising water tables and increasing water storage. The slower moving alluvial groundwater can supplement flow in downstream portions of the channel network, sustaining higher base flows.

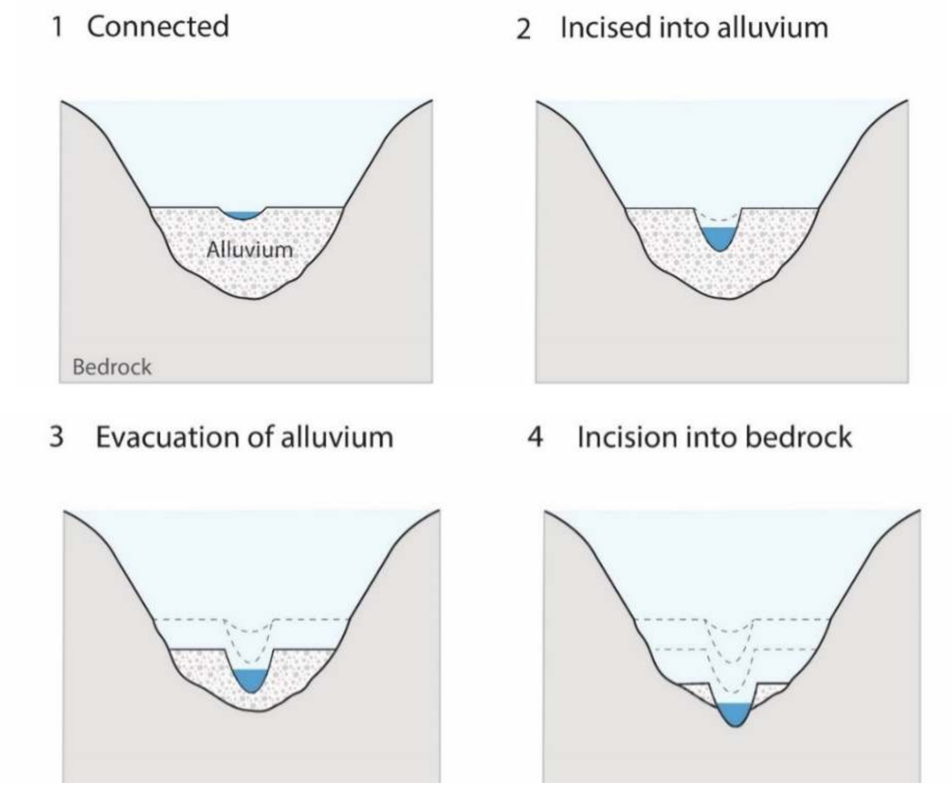

Figure 2. Illustration of depicting an alluvial channel consisting of a surface water channel and subsurface alluvial groundwater channel (1). Channel incision (2-4) has three key impacts: 1) lowering the water table, 2) enlargement and smoothing of the surface water channel, and 2) reduction of the alluvial subsurface channel and export of alluvium that may have taken thousands of years to accumulate. Water storage is lost by lowering the water level of the alluvial reservoir and routing it more quickly out of valley.

Flow Augmentation

Summer baseflows are currently too low and too warm in many streams across the Columbia River basin, resulting in a range of water scarcity problems, from water rights curtailment of irrigators to fish mortality from high stream temperatures (Ecology and U.S. Department of the Interior, 2012; Malloch and Garrity, 2012; Schneider and Anderson, 2007). Baseflows are projected to decrease further in many tributaries as climate warms and snowpack and soil moisture water storage are reduced (Elsner *et al.*, 2010). For example, average unregulated August streamflow in the Wenatchee River (modeled at Monitor, WA) is projected to decrease by 50-65% by the end of the century (Hamlet *et al.*, 2013). Current and future water scarcity are motivating proposals for new water storage projects, such as dams, that introduce new risks and impacts to aquatic ecosystems (Ecology and U.S. Department of the Interior, 2012). Restoration actions offer a viable alternative to increase water storage and dampen climate change impacts on the baseflow hydrograph, while simultaneously providing many ecosystem benefits.

As channel incision proceeds, overbank flow becomes less frequent, which reduces water storage in adjacent wetlands and floodplains. In addition to reduced groundwater recharge via overbank flow, the shallow groundwater is essentially drawn down by the lowered stream channel. This in-turn reduces the down-valley flow of groundwater that existed prior to incision. In gaining reaches, the hydraulic gradient between the subsurface groundwater stored in the floodplain and the surface water stored in the channel increases with the vertical distance between the two water surfaces. A steeper gradient drives flow from the groundwater to the channel, leading to faster and earlier seasonal lowering of the local groundwater table (Schilling *et al.*, 2004). Reduced surface and subsurface water storage within the river network subsequently results in lower baseflows, and mortality of shallow rooted riparian vegetation (Beechie *et al.*, 2008; Loheide and Gorelick, 2005; Wilcox, 2005).

Extensive restoration of incised streams has the potential to increase storage of alluvial sediment and water, and to augment low flows during the dry season. Restoration also has a suite of ecological benefits that have been widely recognized and supported as part of salmon recovery efforts in the Columbia River basin (Honea *et al.*, 2009; Katz *et al.*, 2007). Less recognized, however, are the critical benefits of the increased water storage and baseflow contributions that river restoration provides to water resources, aquatic habitat, and forest health. Although the idea has been intermittently proposed across the western United States (Van Haveren, 2004; Ponce and Lindquist, 1990) and assessed in California (Emmons, 2013; Loheide and Gorelick, 2006; Tague *et al.*, 2008; Wilcox, 2005), work to consider and quantify the effects of restoration on water resources in the Pacific Northwest is sparse (Fouty, 2013).

Figure 3. Toppenish Creek in Yakima River basin of central Washington in June 2015 prior to restoration (a). Same location in Toppenish Creek on October 4th, 2017 after restoration using channel spanning wood placements (b). Photo was taken at end of summer during period of

minimum flows yet channel is largely full of water. The estimated increase in water storage following restoration is 20 acre-ft over a 500 m reach and 240 m wide valley (76 ac-ft/mile).

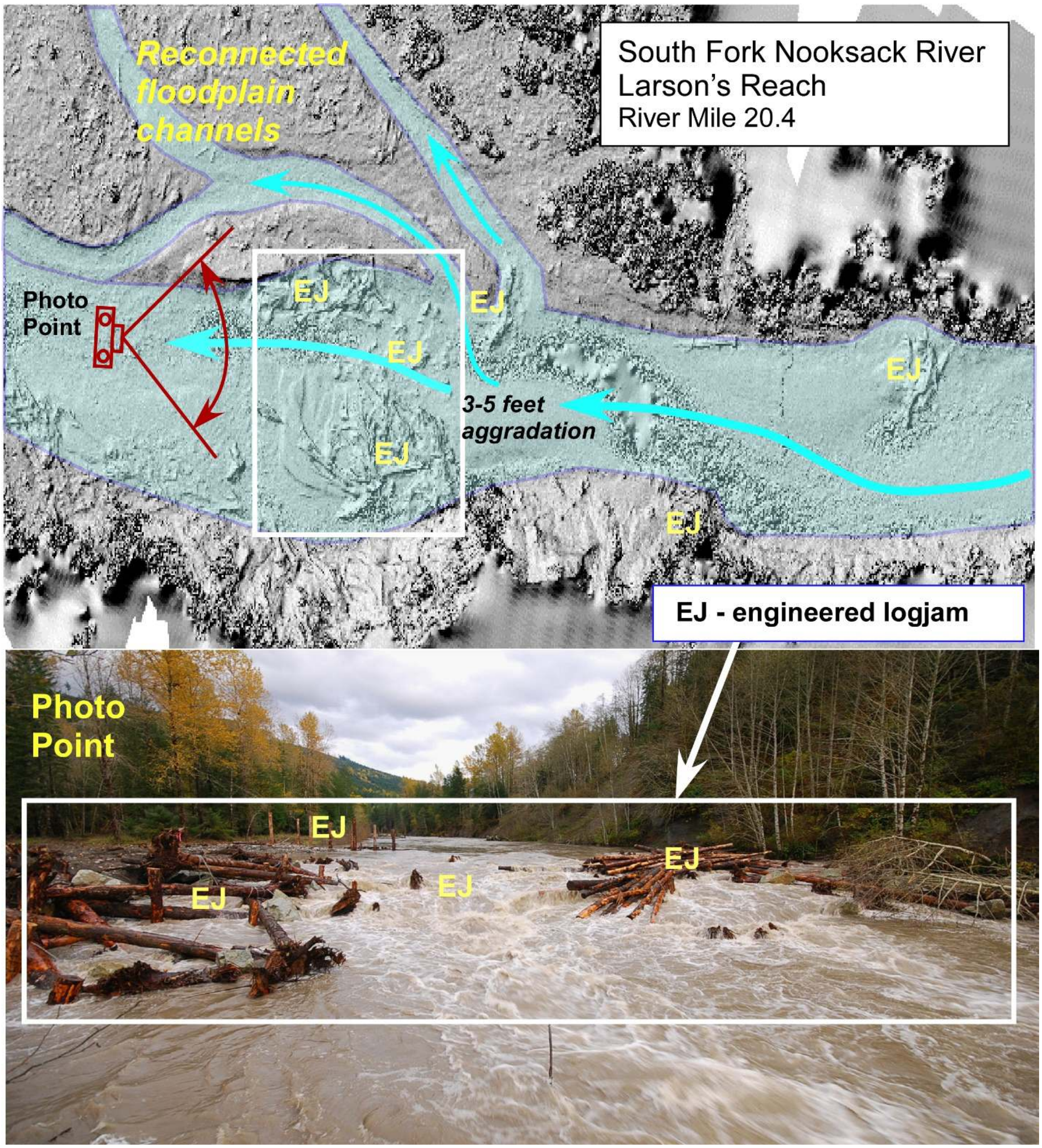

Figure 4. The South Fork Nooksack River, a large montane river draining the west Cascades in Skagit and Whatcom Counties. Prior to restoration wood placement, this reach of the river had experienced three meters of incision (Abbe et al. 2015). Channel spanning engineered wood placements in 2016 raised water levels about 1.5 meters, reconnecting 25 acres of floodplain, forming one km of new side channels within a 0.6 km segment of the valley. The instream structure corresponds to the white water in the photo (looking upstream). Restoration within the treatment area created 30 ac-ft (102 ac-ft/mile) of additional water storage.

Restoration approaches to store water and sediment

Restoration actions that implement channel-spanning structures or barriers constructed from natural materials are designed to re-aggrade the channel bed through the trapping of sediments and improve hydrologic connectivity between the channel and the surrounding floodplain (Figure 3). Approaches range from installing engineered log jams (Abbe *et al.* 2003, 2015; Abbe and Brooks 2011) to beaver dam analogs (Pollock *et al.*, 2012) to creation of small earthen dams (i.e. 'pond and plug') (Wilcox, 2005), but the underlying concept is similar: partially block the channel to increase hydraulic roughness, slow and impound streamflow, and capture and store sediment.

Backwatered areas created by the stream impoundments act as surface water storage, which raise the local surface water elevation and, consequently, the surrounding groundwater elevation (Figure 2). The lower flow velocities initiate deposition of sediment, which raises the elevation of the channel bed and reduces local stream gradient (Abbe and Montgomery, 2003; Abbe and Brooks, 2011; Brummer *et al.*, 2006). Backwater pools formed by channel-spanning structures are therefore temporary in any one location, because channel aggradation is the primary geomorphic goal when restoring incised streams. However, the channel aggradation drives a long-term increase in local groundwater storage (Hammersmark *et al.*, 2008; Schilling *et al.*, 2004; Tague *et al.*, 2008) and improved geomorphic function, which includes natural wood recruitment processes that create new backwatered areas (Collins *et al.*, 2012). Thus, a restored stream will sustain increased surface and subsurface water storage even though locations of backwater pools will shift through time.

Re-aggradation of the incised channel raises the in-channel water surface elevation, which results in a newly saturated wedge of subsurface floodplain sediments in a gaining stream (Figure 2). Local groundwater-surface water interaction vary longitudinally with position in the watershed, and locally with subsurface characteristics (Payn *et al.*, 2012); however, reaches above the mountain-to-valley transition (i.e., mountain front recharge zone) tend to be net gaining with baseflow contributions from groundwater (Covino and McGlynn, 2007). Thus, widespread restoration throughout the upper watershed has the potential to increase surface and subsurface water storage. The approach has been considered in California, where Emmons (2013) estimated 97,000 acre-feet of "restorable" groundwater storage if all impaired reaches were re-aggraded in the montane meadows of the Sierra Nevada. Within the Columbia River basin, Fouty (2013) estimated an increase in surface and subsurface water storage of 40-53 acre-feet/mile from restoration actions on Camp Creek, an incised stream in the Wallowa-Whitman National Forest in Oregon. The analysis was based on analysis of channel and valley morphology and soil types along a 0.75-mile reach.

Restoration of in situ water storage has been shown to increase instream water quantity and improve water quality. Both observational and modeling studies have demonstrated at the reach-scale that re-aggradation of incised streams can result in a 10-20% increase in baseflow early in the dry season (Ohara *et al.*, 2014; Tague *et al.*, 2008). The additional contribution is a result of the raised water surface elevation in the re-aggraded channel. The hydraulic gradient between the shallow groundwater elevation and the in-channel water surface elevation is reduced, which slows the drainage of the shallow groundwater reservoir (Fouty, 2013; Loheide and Gorelick, 2006). The reduced rate of groundwater inflow subsequently extends the duration of the baseflow contribution of these inflows, which contributes to more and colder water later in the season. Loheide and Gorelick (2006) combined stream temperature measurements with coupled groundwater-surface water modeling to demonstrate elevated groundwater inflow through a restored reach in a Sierra Nevada meadow. In the restored reach streamflow persisted several weeks after adjoining reaches were dry and stream temperatures were more than 3 °C lower than in adjoining, untreated reaches. Wondzell and Swanson (1999) show how breaching of wood jams led to incision of a 200 m long study reach, transforming a multi-channel morphology to a simple single channel. This reduced hyporheic exchange lowered groundwater oxygen and dissolved organic carbon.

There is consensus in the literature that stream restoration addressing incision increases local groundwater storage. Some studies have demonstrated increased baseflow contributions, but others have suggested that gains in baseflow may be partially or fully offset by increased water use from riparian vegetation. The lowering of the groundwater table from channel incision has been observed to cause vegetation mortality or a conversion from a wetter ecosystem to a drier one (Loheide et al., 2009). Therefore, the increased amount and longer duration of water storage in the shallow groundwater likely improves the health of the riparian vegetation (e.g., Fouty, 2013; Loheide and Gorelick, 2006). For example, Tague et al. (2008) analyzed streamflow measurements above and below a restored reach and found that baseflow was increased downstream of the restored reach early in the summer season, but increases in baseflow were diminished by late summer. The authors suggested that the change was due to increased evapotranspiration from restored riparian vegetation. Another study in a northern California meadow utilized hydrologic modeling to assess restoration effects and found that although groundwater storage increased, local in-meadow baseflow decreased due to increased evapotranspiration while downstream baseflow increased and altered groundwater flow paths (Hammersmark et al., 2008). In contrast, Essaid and Hill (2014) found that modeled baseflow decreased both in-meadow and below the restored meadow, which they attribute to increased evapotranspiration. Despite local variations in hydrological fluxes, all studies demonstrate additional groundwater storage and most demonstrate groundwater input to the stream, which suggests that, at a minimum, restoration actions will result in healthier riparian vegetation and lower summer stream temperatures (Bogan et al., 2003; Baird et al., 2005; Loheide et al., 2009). It is noteworthy that restored stream segments are likely to retain more organic matter which can increase water holding capacity of alluvial material (Hudson 1994, Libohova et al. 2018). Hudson (1994) shows that when organic matter content increased from 0.5 to 3% the available water content of the alluvium more than doubled for three different grain sizes of soil (sand, silt-loam and silty clay loam).

In addition to variable recharge and transpiration rates, the volume of restorable water storage and related benefits to water resources depends on the extent of channel incision and/or valley lowering that has occurred. Incision on the order of one to several feet has been widely observed across the Washington State (Abbe et al. 2009, 2013, 2015, ; Beechie *et al.*, 2008; Fouty, 2013; Pollock *et al.*, 2014). However, the almost complete loss of alluvial sediments and subsequent valley down-cutting has also been documented in the Teanaway River, in central Washington (Stock et al. 2005, Schanz et al. 2019). Successful restoration of incised river channels has been widely documented, and the restoration of lowered river systems is also theoretically possible. For example, Pollock *et al.* (2014) present a conceptual model of how beaver dams (or analogous structures) raise both the channel and valley elevation, and the amount of alluvial sediment and water stored. River restoration has been shown to aggrade channels where there is sufficient sediment supply from upstream or adjacent hillslopes (e.g., Abbe et al. 2013).

Methods

We present a framework for evaluating potential water storage using simple geometric computations of valley alluvium and water content, estimates of channel incision and assumptions of alluvium characteristics using field observations. Our analysis includes a GIS based analysis of digital elevation models (DEMs), aerial imagery, and analysis of field data that includes topography, water levels, sediment, vegetation, and how these attributes change over time.

We began with a reach-scale geomorphic assessment of stream incision and utilized field-derived and spatial data to estimate watershed-scale water storage potential through restoration in Mission Creek, which flows into the Wenatchee River near Cashmere, Washington (Figure 5). The 240 km^2 Mission Creek watershed is located relatively low on the eastern slopes of the Cascade Range, with snowmelt-fed spring streamflow and dry conditions in late spring and summer. The watershed is steep with a mean slope of 44% and relief of 1843 m with elevations from 241 to 2085 m. Summer water quantity and quality impact the availability of irrigation water to orchards along the mainstem as well as the health of the Endangered Species Act-listed spring Chinook salmon and summer steelhead runs. Both Mission Creek and the Wenatchee River are on the Clean Water Act 303(d) list of impaired water bodies for water temperature exceedances. Field inspections of Poison Creek, a second order channel draining into Mission Creek revealed incised channel segments lacking wood and segments where wood still maintains stream grade and creates wetlands, as well as incised segments (Figure 6).

As part of the work we developed a semi-automated GIS analysis to provide initial predictions of incision and potential water storage using DEMs and segmented stream networks with drainage area attributes (Figure 6). The GIS analysis computed stream gradient, delineated valley bottoms and widths, and estimated incision (with a high resolution one meter DEM). Using valley width, reach length, extent of incision and stream gradient, we then compute the restorable sub-surface water volume, flow contribution per reach length, surface water storage and minimum treatment density. This assessment of water storage through river restoration in Mission Creek represents a pilot project led by Chelan County Natural Resources Department to evaluate the feasibility of a multi-benefit strategy to address current and future water quantity and quality. In contrast to the suite of new dams and reservoirs that are currently proposed in Washington and across the west to buffer projected climate impacts (Ecology, 2016; Ecology and U.S. Department of the Interior, 2012), a water storage strategy based in re-initiation of natural processes includes additional benefits, rather than impacts, to aquatic and terrestrial ecosystems. To support a robust comparison of water storage strategies, we developed and applied methodology for estimating potential reach and watershed scale water storage from the restoration of incised channels.

To estimate water storage potential from restoration in Mission Creek, we completed a geomorphic assessment in three study reaches, from which we estimated water storage potential at the reach-scale. We subsequently extrapolated the reach-scale estimates to the watershed-scale in order to estimate the potential for water storage and baseflow contribution from extensive restoration. We conceptualized the restorable subsurface volume as a wedge of sediments (Emmons 2013) that would become saturated when the channel bed elevation was raised, extended along the length of the alluvial valley (Figure 7). The shape of this wedge depends on the water surface elevation in the channel, which we approximated as the channel bed elevation during baseflow and on the groundwater surface elevation at the edge of the floodplain, which we approximated as the surface elevation at the hillslope-valley transition.

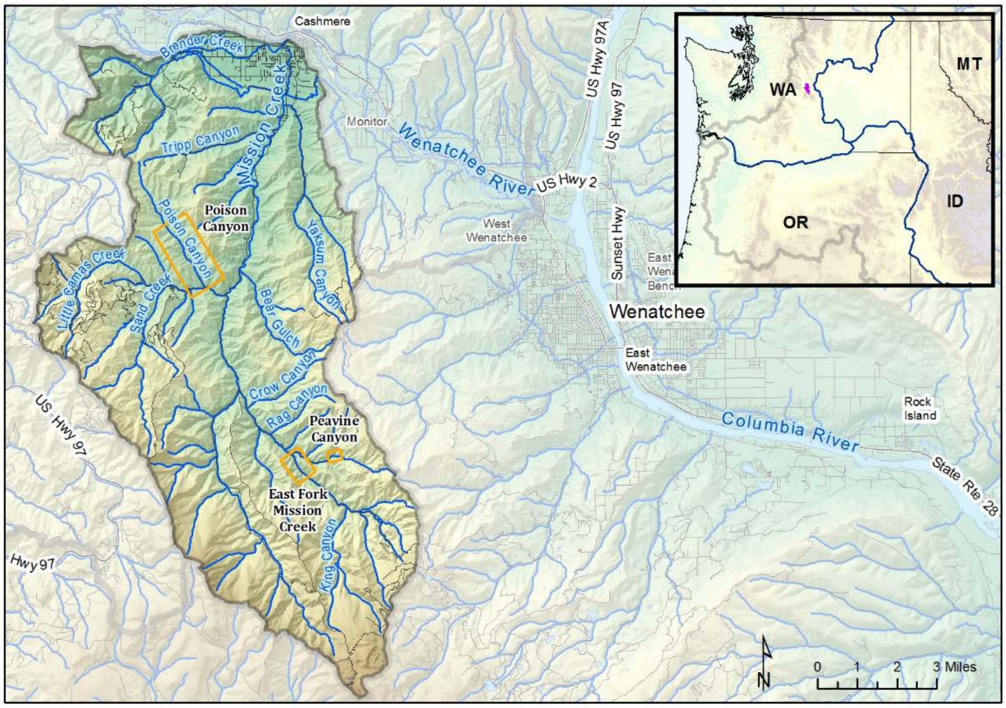

Figure 5. Map of the Mission Creek Watershed, with the three study areas indicated in gold rectangles. Inset map shows location in the Pacific Northwest, the Columbia and Snake Rivers indicated as blue lines and the boundary of the Columbia River basin indicated as a gray line.

To estimate surface water storage from backwatered areas triggered by in-channel wood structures, we computed the ideal density of structures along the reach and estimated a water storage volume per structure. Similar to an artificial impoundment, surface water storage volume from in-channel wood structures is positively correlated to valley width and structure spacing (i.e., area of potential storage) and negatively correlated with valley slope. Thus, low-relief reaches with wider valley bottoms will have greater surface water storage potential per in-channel wood structure versus steeper channels with naturally confined valleys where storage potential is low. We therefore estimated additional surface water storage based on the average reach gradient and a target aggradation height to estimate the backwater influence of each structure and the maximum treatment density.

We averaged the reach-scale results for restorable water storage (i.e., combined volume of surface and subsurface water storage per length of stream restored) to the watershed-scale in order to estimate the potential to restore water storage if restoration actions were implemented across incremental fractions of the stream network. The analysis assumes that the incised conditions observed in the study reaches are representative of conditions across the watershed and neglects spatial variability in channel and valley morphology. We utilized existing channel location data from the National Hydrography Dataset, and excluded reaches in agricultural valleys and reaches with a stream gradient higher than 10%.

Figure 6 - 4-panel figure – a) Photos of wetland reaches in Poison Canyon showing wood as the downstream hydraulic control (a) and shallow height (0.5-1') from water surface to bank (b). Photos of severely incised reaches in Poison Canyon. (c and d)

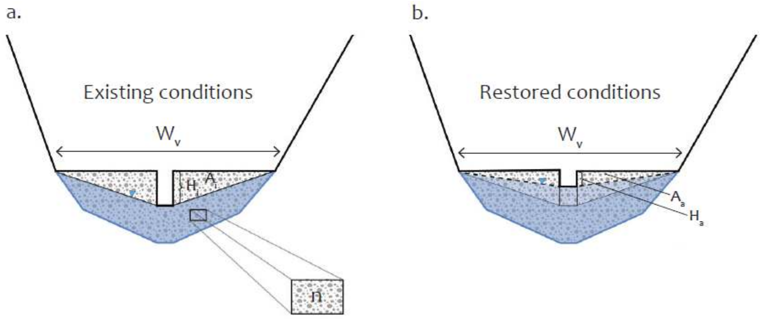

Figure 7a, b. Graphical definitions of influence of incision on alluvial water storage.

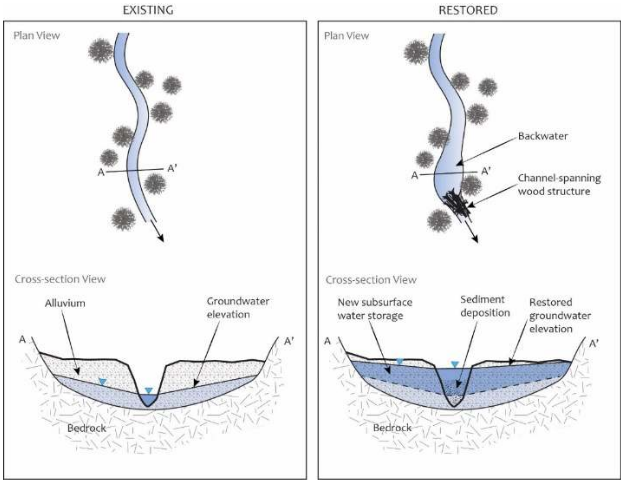

Figure 7c. Illustration of restoring alluvial water storage.

Estimates of water storage (m^3/km or acre-feet/mile of stream restored) were converted to a baseflow contribution by computing the flux of water from the shallow groundwater to the channel. The baseflow contribution is based on assumptions of homogeneous sediments with a uniform saturated hydraulic conductivity, and a constant hydraulic gradient. Flux was computed through the wetted area of the channel wall (assuming a baseflow water depth of 0.15 m) to represent groundwater inflows only, and therefore neglects upwelling and downwelling hyporheic exchange through the stream bed.

Preliminary Results

We have applied the GIS model to several small watersheds draining to the Wenatchee River in Chelan County totaling 791 km^2 and 596 km of stream. Our preliminary estimate of potential water storage for this area came to approximately 13.6 million m^3 (11,000 acre-ft). An example of results for the 240 km^2 Mission Creek watershed are presented in Figure 8. Given these results are for low-order montane streams with relatively narrow valley bottoms, we believe the results are conservative (low) with regards to extrapolating to larger areas.

The geomorphic assessment of three study reaches yielded observations of substantial upland sediment sources, widespread channel incision, and in-channel large wood contributing to local sediment storage. Historical photos from Mission Creek indicate that hillslope and channel erosion was widespread around the 1930s-1950s, and was likely due to grazing and logging activities combined with friability of the underlying sandstone bedrock. In response, the Civilian Conservation Corps (CCC) constructed terraces and wooden check dam structures to slow erosion; Peavine Canyon is thought to be the location of some of these historical structures (Matt Karrer, USFS, personal communication).

Channel and floodplain sediments are dominated by sand and gravel. Channel bed sediments consist of 10-40% sand, 10-90% gravel, and 5-40% cobbles. We observed sandstone bedrock in the channel in one location in both East Fork Mission Creek and Poison Canyon. Floodplain sediments characterized by test pits consist primarily of sand from 0 to 0.61 m (0-2 ft) depth. Based on the field assessment and geologic context of the watershed, we applied a constant value of 0.35 for the porosity (i.e., interstitial space) of the floodplain sediments (sand). This simplification is based on published values for sand and gravel (Morris and Johnson, 1967), the location of the field site within two similar geologic formations (i.e., the Chumstick and Swauk Formations), and observations of homogeneous floodplain sediments.

Estimate for potential surface water storage in Poison Canyon and East Fork Mission Creek from backwatered areas are 3,065 and 12,260 m^3/km (4 and 16 acre-feet/mile), respectively. The differences between the two reaches reflect differences in channel gradient, valley width, and longitudinal extent of incision. We estimated the volume of surface water behind each structure at 160 to 345 m^3 (0.13 to 0.28

acre-feet) per channel-spanning structure based on the geometry of a stream gradient, a 1.2 m impoundment height, and a ponded width equal to half of the valley width (9 and 20 m, respectively). Based on the channel morphology and gradient, the maximum treatment density is 35 structures per km.

Reach-average subsurface alluvial water storage from channel restoration is estimated at 1,456 and 8,274 m^3/km (1.9 and 10.8 acre-feet/mile) in Poison Canyon and East Fork Mission Creek, respectively. The restorable reach-average alluvial water storage is an order of magnitude higher in East Fork Mission Creek due to the larger valley width and the longitudinally continuous incised condition. The estimate for Poison Canyon is based on the observation and delineation of three geomorphic conditions in Poison Canyon, ranging from no incision (i.e., the wetland complexes) to severe incision. Thus, the amount of restorable groundwater storage from channel aggradation was highest in the most severely incised reaches, but we computed a reach-average value that includes all three conditions. In contrast, we observed longitudinally continuous incision in East Fork Mission Creek, and estimated restorable water storage for the reach based on reach-average values of incision. Whereas channel restoration in Poison Canyon and East Fork Mission Creek represent a range of low scenarios for restorable water storage in Mission Creek, we additionally estimated high scenarios from hypothetical valley restoration, for which the entire alluvial is raised. Since restoration of alluvial across the valley substantially raises the vertical dimension of the subsurface wedge of saturated sediments, the restorable subsurface alluvial water storage is higher. Estimated combined values for channel and valley aggradation are 8,660 and 22,140 m^3 (11.3 and 28.9 acre-feet/mile) for Poison Canyon and East Fork Mission Creek, respectively. When looking at incised channels in larger alluvial valleys, the potential storage goes up substantially. For example in Toppenish Creek (Figure 3), wood placement rose the water table an average of 2.8 ft, resulting in 76 acre-ft/mile of additional water storage. For the South Fork Nooksack example (Figure 4), the water table was raised 4.9 ft, resulting in 180 ac-ft/mile of water storage. The work in Misson, Toppenish and South Fork Nooksack only involved wood placement. Work by the US Forest Service in Staler Creek, Willamette National Forest (Powers et al. 2018) had even more incision (>9 ft) and took an aggressive restoration approach that filled the incised channel, the estimated increase in water storage (using same Mission Creek methodology) is 350 acre-ft/mile. These estimates make a strong case for restoring incised channels simply based on the potential water retention.

We applied the estimated combined surface and subsurface water storage values for Poison Canyon and East Fork Mission Creek under the channel and valley restoration scenarios to extrapolate to watershed-scale restoration. Poison Canyon and East Fork Mission Creek represent a range of geomorphic conditions and morphology, and therefore water storage potential. Thus, the range of the two estimates applied to the stream network is intended to reflect some of the spatial variability in restorable water volumes. In the Mission Creek watershed we estimate that there are 8 km (5 miles) of stream network that have a stream gradient less than 5% and are not adjacent to a road, and 40 km of stream network that have a stream gradient less than 10% and are not adjacent to a road. Based on extrapolating the mean volume per length of restoration values derived in the reach-scale estimates to the length of treatable stream network, we estimate the total potential surface and subsurface water storage of treating all 8 km with an average stream gradient less than 5% to be 370,000-789,400 m^3 (300-640 acre-feet) in the low and high restoration scenarios, respectively. In the context of this linear extrapolation, water storage scales with length treated, so restoration applied to 10% of the feasible stream network would result in 10% of the water storage. The magnitude the streamflow flux provided by additional alluvial water storage scales with the length of the treated stream network. The additional streamflow contributions following the restoration actions range from $5.7\text{x}10^{-4}$ - $4.8\text{x}10^{-2}$ cms (0.02 to 1.7 cfs). Additional flow can be supplied to the stream (above base flow) for three or more months depending on the extent of the restoration.

Feasibility of restoration approach in Mission Creek

Geomorphic assessment of the two study reaches in conjunction with widespread effects from historic impacts suggest that incision and channel disconnection from the floodplain is common in the Mission Creek watershed. Under these impaired conditions, Mission Creek is likely transporting more water and sediment out of the channel network earlier in the season as compared to reference (historic) conditions. Therefore, historic and on-going channel incision contribute to downstream impacts including decreased baseflows, higher stream temperatures, and increased sediment loads.

Identification of wetland complexes in Poison Canyon demonstrates that placement of in-channel large wood is likely to initiate channel bed aggradation and the storage of both alluvial sediment and water. The average stream gradient of 4.1% the Poison Canyon study reach would be considered relatively high for some restoration approaches. However, the existence of two wetland complexes provides local examples of the role of wood for providing hydraulic control and storing alluvial sediment in this watershed at these gradients. Beavers typically build dams in perennial stream channels with slopes of less than 6%. The buried check dam structures in Peavine Canyon illustrate sediment storage potential in steeper (gradient = 6.8%) ephemeral reaches and suggest that the total amount of stream network that could be treated is closer to 24.8 miles (40 km) with gradient < 10%, opposed to 8 miles (13 km) with gradient < 5% in Mission Creek.

Observations of two locations with in-channel bedrock exposure combined with a large hillslope sediment source further suggest that valley-lowering may have occurred, and that there is high potential to capture and store sediment. In this case, the higher estimates may be more accurate reflections of the long-term water storage benefit. Restoration of a lowered valley would require repeated restoration actions through time combined with riparian forest restoration and the re-initiation of large wood recruitment processes.

Comparison with Built Infrastructure

The analysis presented herein indicates that widespread restoration may be a feasible approach to improve water storage and increase baseflow, and comparison with previous cost estimates for traditional dam structures demonstrate that the approach may also be cost-effective. Previous assessments of potential for water storage and low flow augmentation from surface water impoundment identified three project locations within Mission Creek (Montgomery Water Group, 2006). In particular, two sites for off-channel reservoirs and one site for an instream reservoir were identified. The potential reservoirs would provide 51, 95, and 926 acre-feet of storage for an estimated construction cost of $25,000, $58,000 and $8,000/acre-foot, respectively. The estimated instream flow benefit ranges from 0.5 cfs to 12.9 cfs for 30 days for during the summer (Montgomery Water Group, 2006).

For comparison, we estimate a cost of $4700/acre-foot of additional surface and subsurface water storage from restoration. This estimate is based on an estimated cost of $1000/in-channel structure and an implementation density of 53 structures/mile, along with estimated mean surface and subsurface water storage of 11.4 acre-feet/mile. Note that costs associated with operations and maintenance (O&M), potential negative habitat impacts, and increased downstream risks are not included in either estimate, but are likely to be much higher for a traditional engineering approach than a restoration approach.

Accounting for Evaporative Losses

The estimates of water storage for Mission Creek neglect uncertainties related to how evapotranspiration rates and timing may change with an increase in the elevation of the shallow groundwater (Tague et al., 2008). Although more water will theoretically be available, the additional water storage will be partitioned between baseflow augmentation and transpiration by riparian vegetation. Further study is needed to understand how transpiration rates, in the short-term, and plant communities, in the long-term, may shift with increased shallow groundwater availability in this watershed.

Although more transpiration represents a loss to baseflow from a water budgeting perspective, more robust riparian vegetation and forests are more resilient to drought, fire, and insect outbreaks (Allen, 2009; Grant et al., 2013; Polvi and Wohl 2013, Millar and Stephenson, 2015). Healthy riparian forests additionally provide a source for abundant in-channel wood that repeatedly creates backwater effects and prevents incision (Collins et al., 2012). In contrast to evaporation off the water surface of a reservoir, the water that is consumed by the transpiration process contributes to the health of riparian vegetation and river function. Wetted valley bottoms and healthy trees increases fire resilience. Riparian vegetation and hyporheic flow also have a significant role in lowering stream temperatures (e.g., Johnson 2004, Seixas et al. 2018) and improving water quality (e.g., Peter et al. 2019).

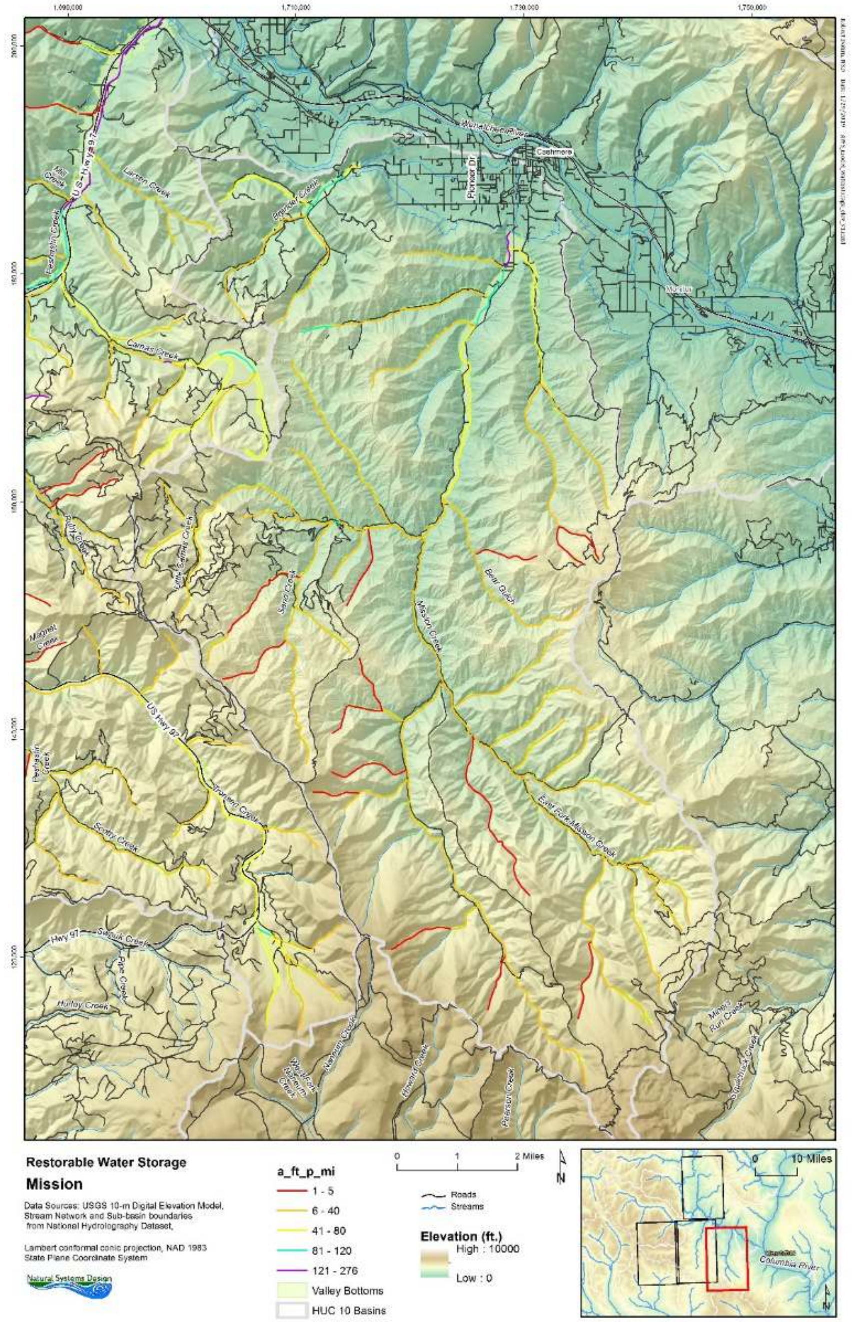

Figure 8 Water storage potential estimates based on 10m digital elevation model of 209 km^2 Mission Creek basin in Chelan County on eastside of Cascade mountains, north central Washington.

Implications for water storage in the Western U.S.

The assessment of water storage potential in Mission Creek represents a replicable approach that could have substantial benefits to baseflow quantity and water quality in the context of the Wenatchee River watershed or even the Columbia River basin. The Mission Creek watershed constitutes a relatively small portion of the Wenatchee River watershed, but the analysis presented herein suggests that the water resources benefits from extensive restoration are on par with the estimated benefits of more traditional approaches. As stated in our preliminary results, we show a range of 11 to 29 acre-ft/mile for small alluvial valleys and 76 to 350 ac-ft/mile for intermediate sized alluvial valleys. Washington State has about 74,000 miles of perennial channels and more than twice that of ephemeral channels. Assuming a range of 20 to 250 ac-ft/mile and just using perennial channel length, there could be 1.5 to 18 million ac-ft of potential water storage. Including Oregon these numbers more than double. Applying same methods to California alone yields 12 to 150 million ac-ft. Given that this approach is also applicable to ephemeral channels (e.g. Fouty 2013) and that they account for twice the length of perennial channels, we believe our estimates for potential water storage are conservative. We acknowledge there is a great deal of uncertainty but believe these estimates further support the value of stream restoration and stress the importance of additional research into restoring incised channels and channel spanning wood placement. Restoring natural water storage processes represent a sustainable, multi-benefit strategy to address water scarcity, with benefits to salmon recovery and forest resilience. The volume and baseflow contributions of stream restoration are more difficult to quantify than built infrastructure such as reservoirs, but the numerous ecosystem benefits and virtual absence of negative impacts of restoration make restoration for water storage a compelling approach. This analysis provides a quantitative estimate of the water storage and baseflow augmentation benefits of stream restoration in Mission Creek together with supporting example of other regions that serves as a starting point for thorough consideration of innovative water resource solutions in the Western United States.

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