To: Pete Cruickshank and Mike Kaputa; Chelan County Natural Resources

From: Susan Dickerson-Lange, PhD, Tim Abbe, PhD, PG, and John Soden, MS, PWS;
Natural Systems Design

Date: April 3, 2017

Re: Mission Creek, Phase I Assessment: Water Conservation Through Stream Restoration

BACKGROUND

Introduction

Mission Creek, in Chelan County, Washington, flows into the Wenatchee River near Cashmere, Washington. The lower 6 miles of Mission Creek flow through an agricultural valley, with surface withdrawals from the creek utilized for orchard irrigation. The upper portion of the basin includes federally and state-managed lands in addition to private timber land and residences. Dry season streamflow in Mission Creek is over-allocated, resulting in water shortages. Key issues of concern are dry season water quantity and quality, which impact the health of the spring Chinook and summer steelhead runs and availability of irrigation water.

The Chelan County Natural Resource Department (CCNRD) requested that Natural Systems Design (NSD) conduct a restoration and water conservation assessment for the upper portion of Mission Creek. The primary purpose of this project is to estimate the historic loss of water storage from channel incision and valley erosion in Mission Creek, and, conversely, to quantify the potential for water conservation and storage through restoration. The assessment focuses on the river valley upstream of the main agricultural valley, from approximately the confluence of the main stem Mission Creek with Sand Creek (RM 7).

This analysis is the initial phase of a larger vision for assessment, implementation, and monitoring to utilize geomorphic restoration as a strategy for water augmentation during the low flow season. Broadly, we envision the following phases:

> Phase 1. Pilot assessment in Mission Creek (described in this memorandum)
>
> Phase 2. Pilot engineering design and implementation in 1-2 reaches of Mission Creek, followed by monitoring and additional implementation depending on observed aggradation rates
>
> Phase 3. Design and implementation in more extensive network of Mission Creek tributaries

The basis for this assessment is that the valley bottom serves as a critical reservoir for both alluvial sediment and water. Land use changes and disturbances that result in the erosion of large quantities of sediment out of the valley network or the loss of natural surface storage such as wetlands effectively result in a loss of *in-situ* water storage. Reduced surface and subsurface water storage within the river network subsequently results in lower streamflow during the dry season. Extensive stream restoration therefore has the potential to increase storage of alluvial sediment and water, and therefore augment low flows during the dry season. Increased in-situ storage of sediment and water simultaneously provides aquatic and terrestrial ecosystem benefits, including improved water quality, riparian water availability, forest health, and fire resilience.

Upland water storage

Numerous upland hydrologic processes contribute to the critical watershed function to store and transport water to the stream network. Components of upland water storage include snowpack, soil moisture, groundwater, and surface water (natural and built). Each of these reservoirs contributes water to streamflow, and the amount and timing of available water depends on the rate of water export from the watershed, both from evapotranspiration (i.e., loss to the atmosphere as water vapor) and from the routing of water to and through the channel network.

Historic and current land use impacts such as timber harvest, road-building, beaver trapping, and in-channel wood removal have generally resulted in channel incision (i.e., down-cutting) throughout the Pacific Northwest (Collins *et al.*, 2002; Phelps, 2011; Pollock *et al.*, 2014; Abbe *et al.*, 2015, 2016). The result is increased erosion and downstream sediment transport and a deeper channel network that is laterally disconnected from its floodplain. Consequently, during periods of high flow, large volumes of water are rapidly conveyed out of the watershed without spilling over-bank and recharging shallow groundwater. During the dry season, the lower elevation of the incised channel relative to the shallow groundwater elevation sets up a hydraulic gradient that drives flow from alluvial groundwater storage into the channel (Beechie *et al.*, 2008). Thus, incised channels typically reduce shallow groundwater storage in the riparian zone.

Therefore, the overarching goals of a restoration strategy to conserve water are to:

(1) Maximize in-situ water storage, and

(2) increase summer baseflow.

Restoration of natural geomorphic processes that store and retain water and sediment have multiple hydrological and ecological benefits, including addressing current issues with overallocation of surface water, improving riparian ecosystem health and resilience to drought and fire by increasing shallow groundwater availability, improving aquatic ecosystem health by increasing instream flows and decreasing water temperature and sediment loads, and increasing aquatic habitat complexity.

Projected climate change impacts will reduce upland water storage in the form of snowpack and soil moisture, and speed the transport of water to the channel network (Elsner *et al.*, 2010). This depletion and early release of natural water storage is projected to result in decreased baseflow (i.e., low flow) during the dry season. 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). However, restoration actions that initiate increased storage of alluvial sediments and water have the potential to dampen climate change impacts on the baseflow hydrograph.

Relevant Previous Work

Water Storage Estimates

Previous assessments of flow conditions and water storage potential have been completed in the Wenatchee basin. Low flows and dewatering (i.e., no flow) and high stream temperatures are reported as issues of concern (Montgomery Water Group, 2006; Schneider and Anderson, 2007). In a preliminary assessment of potential for water storage and low flow augmentation from surface water impoundment by Montgomery Water Group (2006), three project locations within Mission Creek were identified.

Two sites for off-channel reservoirs were identified, including one within the East Fork Mission Creek basin and one near the existing Mission Creek Lake (Montgomery Water Group, 2006). The East Fork Mission Creek off-channel reservoir would provide 95 acre-feet of storage for an estimated construction cost of $58,000/acre-foot and an instream flow benefit of 1.2 cfs for 30 days during the late summer. The Mission Creek Lake reservoir would provide 51 acre-feet of storage for $25,000/acre-foot with an instream flow benefit of 0.5 cfs for 30 days during the summer.

One site for an instream reservoir was proposed at Little Camas Creek for 926 acre-feet of storage at an estimated cost of $8,000 per acre-foot with a flow benefit of 12.9 cfs for 30 days (Montgomery Water Group, 2006). This project received the third highest ranking in the cost-benefit assessment. However, potential impacts from reductions in downstream flow due to the large size of the reservoir relative to annual flow volume were noted. Stream channel restoration on Peavine Canyon, Poison Canyon, and Sand Creek were considered and the potential volume of water storage was stated to be very small, but no supporting analysis was provided. A follow-up study assessed potential costs and benefits of the identified projects, but the Mission Creek reservoirs were excluded from this analysis (Anchor QEA, 2011).

Legacy Impacts and Restoration Potential

Across the Pacific Northwest, the history of extensive timber harvest, splash-damming, instream wood removal, beaver trapping, and floodplain grazing has resulted in widespread loss of beaver ponds and floodplain water bodies, incision of stream channels, and a loss of instream channel and habitat complexity (Collins *et al.*, 2002; Phelps, 2011). The legacy of these historical impacts is reduced surface water storage, increased sediment transport and related effects on water quality, disconnection from floodplains and the associated functions to store sediment and water, and degradation of aquatic habitat (Abbe and Montgomery, 2003).

Two general categories of incision, and the related lowering of the shallow groundwater, have been identified: channel incision and valley incision. Where the channel bed has incised relative to the floodplain, in-channel sediment storage is reduced and a hydraulic gradient is set up between the shallow groundwater and the in-channel water elevation. The gradient drives increased flow from the alluvial sediments and into the channel, where the water is rapidly exported from the watershed. The result is early de-watering of the floodplain, resulting in lower baseflows, and mortality of riparian vegetation with shallow roots (Beechie *et al.*, 2008). By implementing restoration actions which raise the bed elevation, the hydraulic gradient is diminished and water is stored in alluvial sediments later into the dry season, which, in turn, makes shallow water available to riparian vegetation and contributes more water to instream baseflows (Tague *et al.*, 2008).

Where channel incision is not slowed or reversed by restoration actions, the morphology of the stream follows a cycle in which channel incision is followed by valley widening and the development of an inset floodplain (Figure 1, after Schumm, Harvey, & Watson (1984)). Alternatively, continuing channel incision can also reach the bedrock, resulting in almost complete loss of alluvial sediments combined with down-cutting of the bedrock (Stock *et al.*, 2005). Widespread erosion due to logging and grazing was identified in the Mission Creek basin and strategies to increase sediment storage in the channel network were implemented in the mid-1900s (Figure 1). Although bedrock incision has not been widely noted in the Mission Creek basin, the Stock *et al.* (2005) investigation suggests that valley-scale lowering has likely occurred over much of the region. Additionally, we observed one location with in-channel bedrock exposure during our field assessment of East Fork Mission Creek, suggesting the evacuation of alluvial sediments (see below).

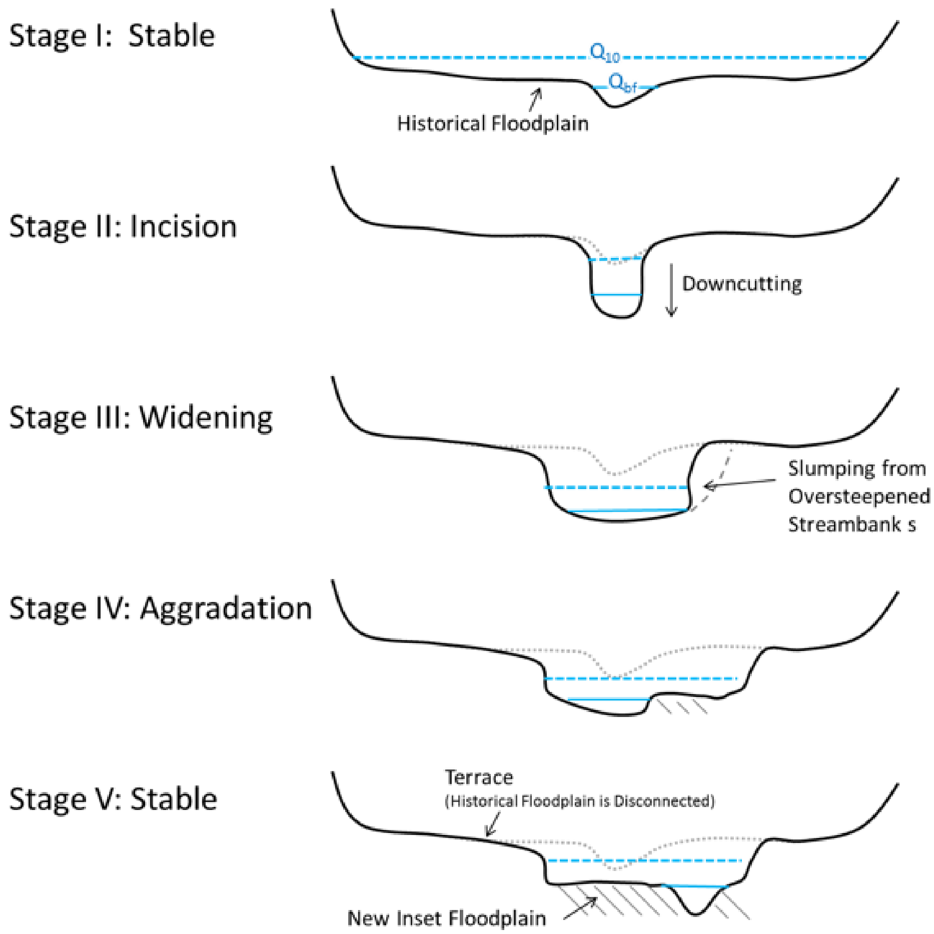


Figure 1. Illustration of the channel evolution model (Schumm et al., 1984) in which channel incision (stage II) is followed by widening and the development of an inset floodplain, which effectively represents a net lowering of the alluvial base of the valley.

Previous Erosion Control Efforts

Historic photos of Peavine Canyon show the presence of terraces and wooden check dam structures which were built by the Civilian Conservation Corps (CCC) to slow erosion around the 1930s-1950s (Figure 2). In August 2016, NSD and the CCNRD visited Peavine Canyon, which is thought to be the site documented in the historic photographs (Matt Karrer, USFS, personal communication). No check dam structures were visible, but slope breaks along the first-order, ephemeral channel were evident. We infer that the check dam structures lie underneath the sediments that have accumulated in the last several decades. The comparison between historical and current conditions, along with numerous exposed tree roots on the hillslopes (Figure 3) suggest that sandstones from the surrounding Chumstick Formation is contributing large amounts of sediment to the channel network. In summary, these observations indicate the presence of a large hillslope sediment source and support the feasibility of restoration actions to initiate extensive bed and valley aggregation.

Figure 2. Historical photos from the mid-1900s (a, b, c), compared to photo taken at nearby location in August 2016 (d): US Forest Service sign explaining soil erosion issues and rehabilitation efforts of the 1930s-1950s (a), rock-terrace structure intended to slow hillslope erosion (b), wooden check dam structure intended to store sediment in ephemeral channel (c), inferred location of wooden check dam structures in Peavine Canyon, which are presumed to be complete buried where there are regularly spaced topographic steps along the channel (d).

Figure 3. Photographs of exposed tree roots on hillslopes (a, b), which provide evidence of at least 6 inches of hillslope erosion of the underlying Chumstick Formation sandstone.

Water Storage Potential of Restoration Actions

The result of both channel and valley down-cutting is the net export of alluvial sediments out of the watershed, which is effectively a loss of alluvial water storage. In addition, the scarcity of in-channel wood and beaver complexes is effectively a loss of surface water storage. The extent to which alluvial sediment and water storage can be restored depends on the extent of restoration. Wood accumulations in Olympic Peninsula rivers have been shown to affect the channel and floodplain by up to 35 feet (Abbe, 2000). By increasing hydraulic roughness (i.e., resistance to flow), in-channel wood accumulations increase local sedimentation rates and raise the elevation of the water surface (Abbe and Montgomery, 2003; Pollock *et al.*, 2014). Thus, restoration actions such as the implementation of channel-spanning wood structures, re-introduction of beavers, or construction of beaver dam analogs ultimately increase storage of both alluvial sediment and water (Figure 4, from Hafen and Macfarlane (2016)).

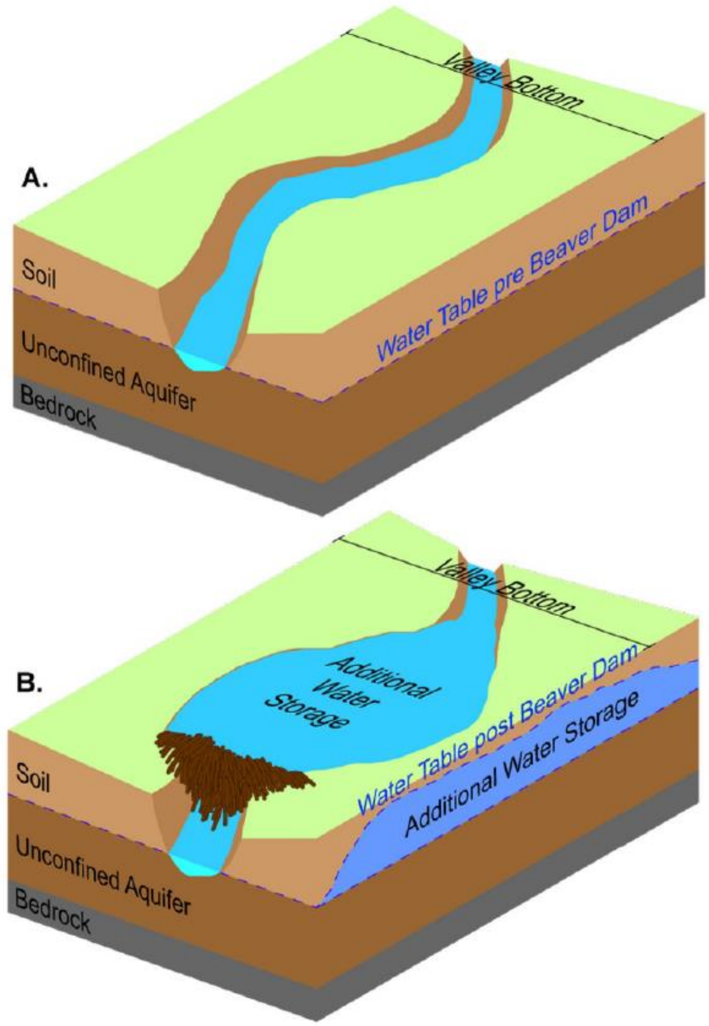


Figure 4. Illustration of the effect of adding beaver dam analogs to a channel: (A) Before restoration the elevation of the shallow groundwater is controlled by the water surface elevation in the incised channel, and (B) after restoration the water surface in the channel is elevated along with the elevation of the local groundwater, representing an increase in both surface and subsurface alluvial water storage. Figure from Hafen & Macfarlane (2016).

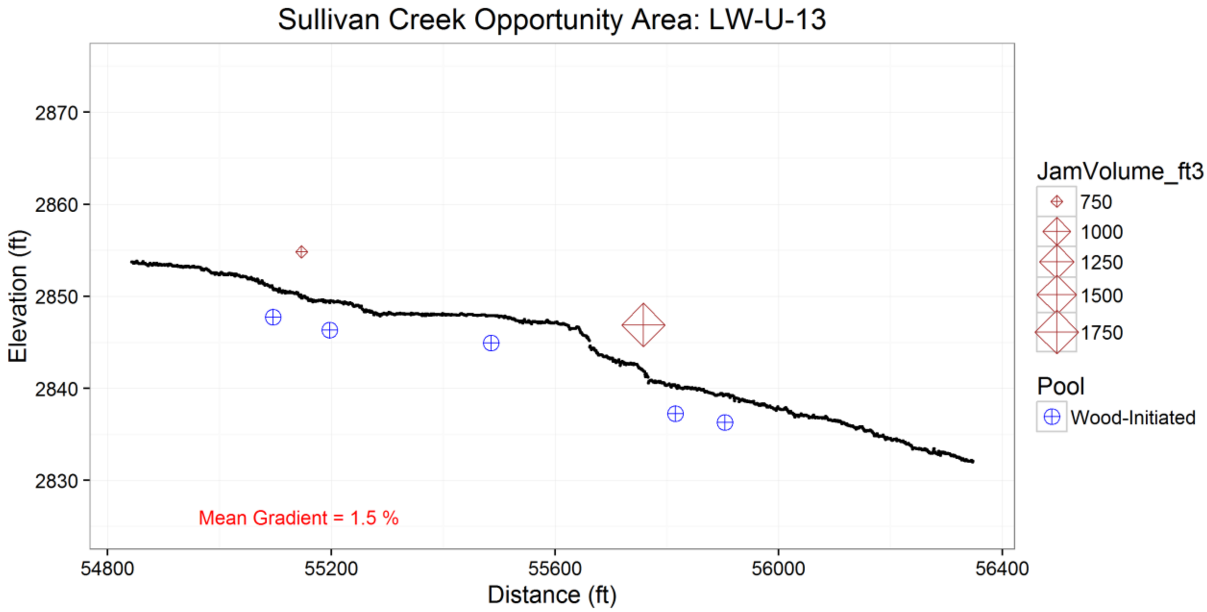


Figure 5. Topographic profile (black line) along a reach at Sullivan Creek, a tributary to the Pend Oreille River, Washington. Brown diamonds show locations of large wood jams and blue circles show locations of wood-initiated pools. Note that the large wood jam in the middle of the profile is holding approximately 7 feet of aggraded sediments.

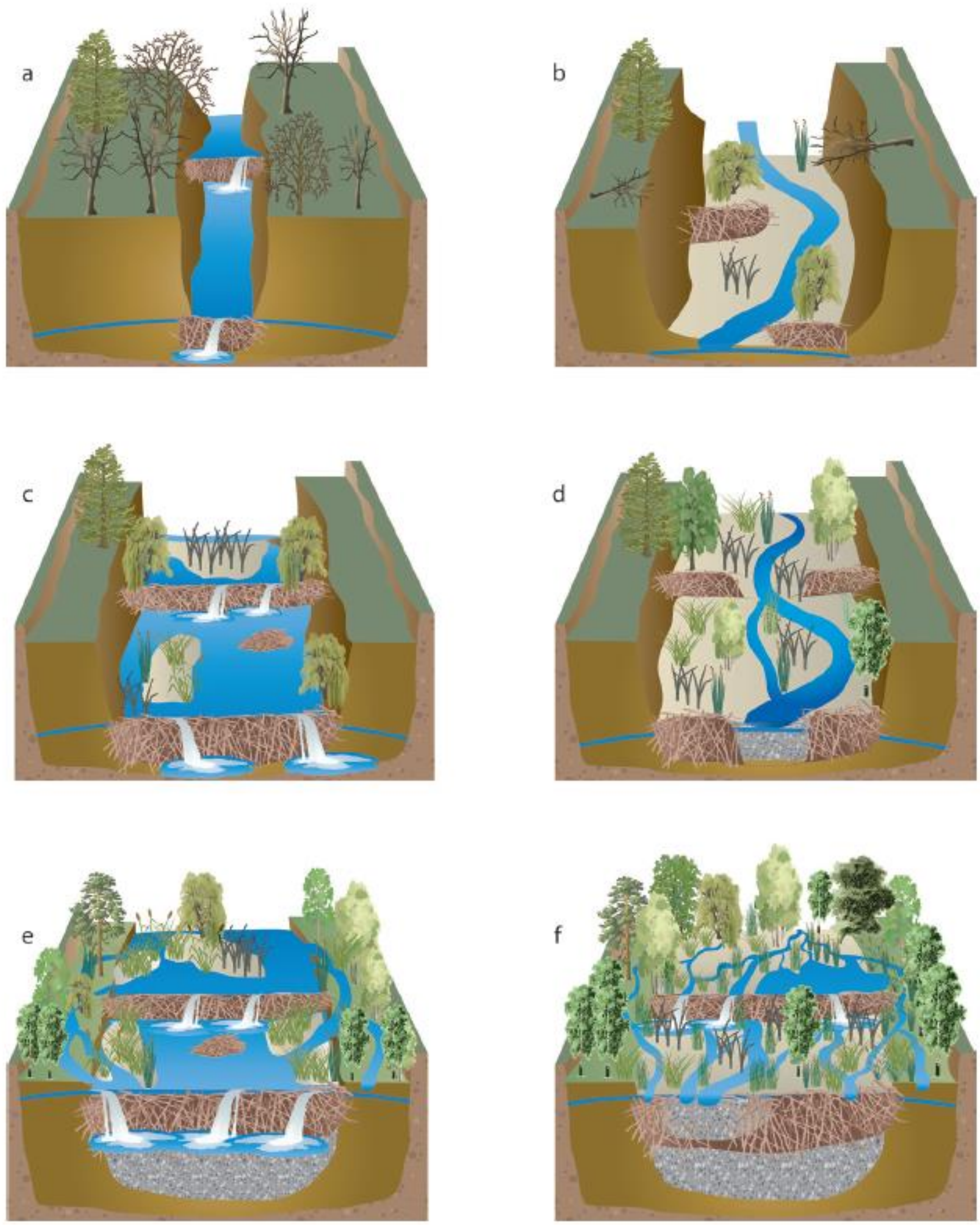


Figure 6. Illustration of the sequence of effects from beaver dams on channel and valley agraddation and local groundwater elevations from Pollock et al. (2014)**. Beaver dams raise water surface and groundwater elevation in incised channels (a), but high stream power ultimately leads to widening and development of an inset floodplain (b). Beaver dams in this lower stream power regime again raise water surface and groundwater elevation (c). The result is channel and valley aggraddation (d), which ultimately leads to reconnection with floodplain (e), development of floodplain side channels (f), and sustained increased storage in alluvial sediments and groundwater.**

The crux of the idea of using restoration actions to increase alluvial water storage is to use in-channel wood structures to create local areas of backwater where both water and sediment are stored. Backwatered areas such as beaver ponds act as surface water storage, which raise the local surface water elevation and, consequently, the surrounding groundwater elevation (Figure 4, note annotations for "Additional Water Storage" and "Water table post Beaver Dam"). The lower flow velocities also allow for deposition of sediment, which raises the elevation of the channel bed and reduces local stream gradient (Abbe and Montgomery, 2003; Abbe and Brooks, 2013) (Figure 5). Re-aggradation of the incised channel reduces the hydraulic gradient between the shallow groundwater elevation and the in-channel water surface elevation, and slows the drainage of the shallow groundwater reservoir (Beechie *et al.*, 2012; Fouty, 2013). Both observational and modeling studies have demonstrated that re-aggradation of incised reaches can results in a 10-20% increase in baseflow early in the dry season (Tague *et al.*, 2008; Ohara *et al.*, 2014). Widespread restoration has been considered as a strategy to increase water storage in incised streams. Emmons (2011) estimated 97,000 acre-feet of "restorable" groundwater storage if all impaired reaches were re-aggraded in the meadows of the Sierra Nevada, California. 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.

Each channel-spanning structure implemented as part of restoration actions will also form a backwater pool, which increases surface water storage, raises the water surface elevation, and slows the drainage of the shallow groundwater (Figure 4). Previous studies quantifying the volume of water stored behind beaver dams in southeast Alaska and Russia found average winter (i.e., maximum) values of 0.28 to 1.01 acre-feet per pond, depending on the height of the dam and the length of the backwater area (Beedle, 1991; Klimenko and Eponchintseva, 2015; Hafen and Macfarlane, 2016). Backwater pools are temporary, however, because where streamflow is impounded velocity decreases and sediment is deposited, which results in channel aggradation. This is the primary geomorphic goal of restoration. These geomorphic changes subsequently raise shallow groundwater and therefore improve the health of the riparian vegetation. In turn, healthy riparian forests provide a source for abundant in-channel wood that repeatedly creates backwater effects and prevents incision (Collins *et al.*, 2012). Thus, in the fully restored state, additional water storage includes both surface water bodies created from in-channel wood and alluvial (subsurface) water storage.

In addition to reintroducing local backwatered areas and re-aggrading incised reaches, the restoration of valley elevation is also theoretically possible where the entire valley has been lowered from channel incision followed by widening. For example, the almost complete loss of alluvial sediments and subsequent valley down-cutting has been documented in the Teanaway River watershed in Kittitas County, WA (Stock *et al.*, 2005). In order to address restoration of these drastically impacted systems, Pollock et al., (2014) proposed a conceptual model for the use of beaver dams or beaver dam analogs to raise both the channel and valley elevation, and the amount of alluvial sediment and water stored (Figure 5). A large-scale re-aggradation and restoration of a lowered valley network following evacuation of the alluvium would require substantial hillslope sediment input, which is clearly present in the Mission Creek watershed.

Previous investigations are clear that restoration increases local groundwater storage. However, the extent to which gains in baseflow may be diminished from restored riparian vegetation remains a key uncertainty. With increased availability of shallow groundwater, the plant community and/or transpiration rates may shift. Studies have demonstrated mixed results and suggest that the effects of restoration on baseflow may depend strongly on local hydrologic conditions. For example, Tague *et al.* (2008) observed increased baseflow early in the summer season, but found that by late summer the increases in baseflow were offset by increased evapotranspiration losses 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 while downstream baseflow increased (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 groundwater recharge that is driven by contributions from upslope groundwater and hillslope runoff mechanisms rather than overbank flow, as in the Hammersmark *et al.* (2008) and Ohara *et al.* (2014) investigations. Despite local variations in dominant hydrological processes, all studies demonstrate additional groundwater storage and groundwater input to the stream, which suggests healthier riparian vegetation and lower summer stream temperatures (Bogan *et al.*, 2003; Baird *et al.*, 2005; Loheide *et al.*, 2009).

Approach

To estimate water conservation potential from restoration in Mission Creek, Phase 1 included a field assessment in two study reaches, estimation of water storage potential from field data in the two study reaches, and extrapolation of reach-scale estimates to the watershed-scale. Phase 2 is proposed to include engineering design and implementation for restoration actions in 1-2 pilot locations, and phase 3 would include implementation in a larger portion of the stream network.

Field Assessment and Findings

Field Assessment of Geomorphic Conditions

This assessment included a reconnaissance-level field investigation of geomorphic conditions in two study reaches: Poison Canyon and East Fork Mission Creek (Map 1). Both reaches were selected in consultation with CCNRD staff because previous observations of incised conditions and high feasibility for restoration without adjacent roads. The field assessment included estimates of the vertical extent of stream incision, measurements of stream and floodplain morphology, characterization of sediment grain sizes, and qualitative assessment of relevant geomorphic features such as floodplain connectivity. NSD and CCRND staff visited the two field sites on 9 November 2017. Subsequently, we analyzed field observations in conjunction with spatial datasets to extend the geomorphic assessment and make quantitative estimations of water storage potential along the length of the study reaches. The availability of a lidar-derived digital elevation model (3-feet (ft) resolution) of Poison Canyon allows for more sophisticated geomorphic analysis than in East Fork Mission Creek, where topographic data is based on USGS 40-ft data.

In both study reaches, floodplain sediments were characterized via test pits, observations of cut bank stratigraphy, and estimates of grain size distributions of the channel bed. Sand is dominant with some gravels, cobbles, and organic materials. Observations of sand as the main component of the alluvial sediments are congruent with the location of the study reaches within the Chumstick and Swauk Formations. These geologic layers consist of Eocene (~45 million years old) aged sedimentary rocks, with extensive sandstone that is known to be highly erodible (Gresens *et al.*, 1981).

Poison Canyon

Three geomorphic conditions along an 8500-ft section of Poison Canyon were identified from field observations and cross-sectional analysis of the topography: (1) Wetland complexes, (2) moderately incised reaches, and (3) severely incised reaches (Map 2, Figure 7).

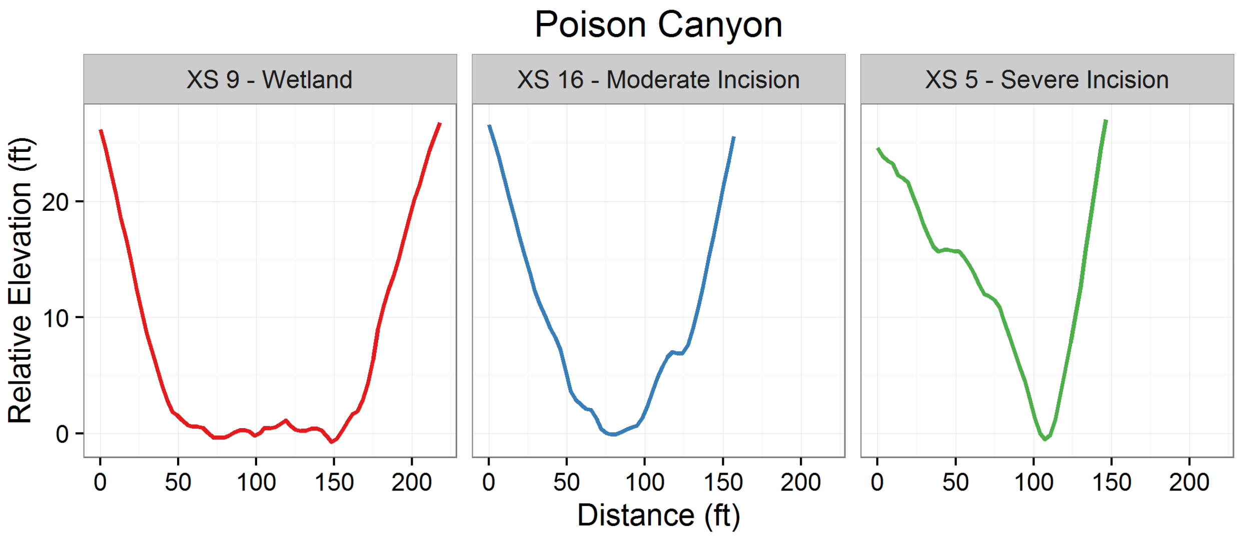


Figure 7. Topographic profiles from Poison Canyon showing elevation relative to local water surface (feet) from left bank to right bank (i.e., looking downstream) across three representative cross sections in a wetland reach, a moderately incised reach and a severely incised reach. See locations on Map 2.

Figure 8. Photos of wetland reaches in Poison Canyon showing wood as the downstream hydraulic control (left) and shallow height (0.5-1') from water surface to bank (right).

Figure 9. Photos of severely incised reaches in Poison Canyon.

Two 1000 to 2000-ft long wetland complexes were identified from observations and spatial data. These complexes represent 36% of the total channel length included in the field investigation, and are characterized by low gradient, multiple shallow channels, and flat valley bottom topography (Figure 6). Within the wetland complexes, average valley width is 100 feet, based on the digital elevation model at the delineated reaches. Field investigation identified the hydraulic control as instream large wood at the downstream end, in addition to numerous locations throughout these wetland complexes (Figure 8). These reaches provide a local demonstration for the potential effect of restoration on alluvial sediment and water storage. Observations of suggest that wood currently acts as a hydraulic control and placement of in-channel wood pieces and structures in incised reaches will initiate sediment storage and alter the channel-floodplain morphology of the reach.

Moderately incised reaches were observed to have a 2-3 ft elevation difference between the channel bed and the closest floodplain terrace (Figure 7). In these reaches, average valley width is 60 feet. Moderately incised reaches account for approximately 21% of the channel length investigated.

Severely incised reaches were observed to have a 4-5 ft or larger elevation gradient between the channel bed and floodplain, and were associated with cutting through large deposits of sediments from alluvial fans or landslide deposits (Figure 7 and Figure 9). In these reaches, average valley width is 50 feet. Severely incised reaches extend over approximately 43% of the channel length investigated.

East Fork Mission Creek

Moderately incised conditions were observed along a 3300-ft long reach of East Fork Mission Creek, starting at the crossing with USFS Road 7100, which has been decommissioned (Map 3). Channel morphology and sediment distributions were estimated at four locations, and depths from the top of bank to the channel bottom range from 2.2 to 6.1 feet. An inset floodplain was observed at one location (XS 3, Map 3), and the inset floodplain surface was located 3.9 feet lower than the relict floodplain. Average depth from the top of the bank to the channel bottom is estimated to be 4.9 feet. Average valley width in the East Fork Mission Creek study reach is approximately 130 feet, based on the digital elevation model (Figure 10).

Channel and floodplain sediments are dominated by sand and gravel (Figure 11). Channel bed sediments consist of 10-40% sand, 10-90% gravel, and 5-40% cobbles. Boulders were present in the channel at the highest location in the reach (XS 4, Map 3). Floodplain sediments consist primarily of sand from 0-2-feet depth. We observed sandstone bedrock in the channel in one location near XS 3 (Figure 12, Map 3).

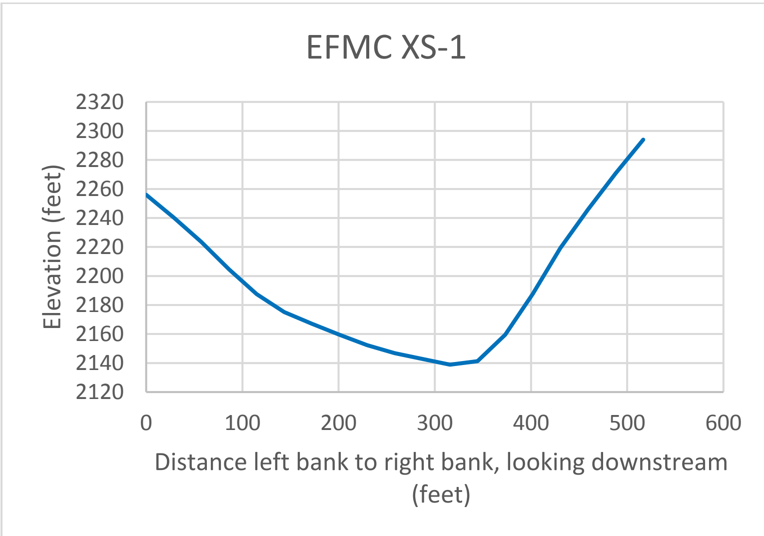


Figure 10. Example topographic profile across East Fork Mission Creek, based on 40-ft USGS digital elevation model.

Figure 11. Photos of channel and floodplain sediments along East Fork Mission Creek.

Figure 12. Photo of bedrock in the channel of East Fork Mission Creek.

Preliminary Restoration Assessment for Mission Creek

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. Potential downstream impacts of increased and earlier water and sediment transport include decreased baseflows, higher stream temperatures, increased sediment load, and increased flood peaks.

Restoration actions such as placement of in-channel wood pieces, implementation of beaver dam analogs, or construction of engineered log jams are likely to initiate channel bed aggradation and the storage of both alluvial sediment and water. Field evidence provides examples of the role of wood in this watershed for providing hydraulic control, reducing the local stream gradient, and storing alluvial sediment.

The identification of geomorphically distinct reaches in Poison Canyon additionally provides a framework for restoration options (Figure 7, Map 2). Where the stream is severely incised, restoration actions would halt incision and re-aggrade the channel bed. There is less opportunity in these reaches to increase alluvial sediment and water storage because aggradation will occur only in the narrow corridor of the channel until lateral connectivity is restored. However, these reaches are acting as sediment source, and restoration actions are needed to maintain current alluvial sediment and water storage rather than contributing to a net export of stored sediments. Moderately-incised reaches present high opportunity to both aggrade the channel bed, and to ultimately store additional sediment in the floodplain. This channel and floodplain aggradation together represents a higher volume increase for additional sediment and water storage. Lastly, wide wetland complexes where the channel is not incised represent high potential for valley aggradation, with larger increases in sediment and water storage than channel aggradation alone.

Restoration actions will re-initiate fluvial processes to store alluvial sediment and water, to reconnect the channel to its floodplain, and to recruit large wood into the channel (Beechie et al., 2008; Tague et al., 2008; Collins et al., 2012; Pollock et al., 2014). In addition to the estimated contribution to streamflow presented below, increasing alluvial sediment and water storage will have benefits to water quality, aquatic habitat complexity, and riparian water availability.

Quantitative Estimation of Water Storage Potential

Reach-scale estimates

We used the field data and published values to estimate potential for water storage and low flow augmentation in Mission Creek. In particular, we included current conditions and estimated low and high bounds on how much subsurface water could be stored *in situ* in the two study reaches under low and high scenarios of aggradation from restored conditions. The low estimate consists of re-aggradation of incised channels only, whereas the high estimate consists of re-aggradation of both channel and valley. Both the low and high estimates include the same approximate volume of new surface water storage that would be introduced as a result of implementing channel spanning wood structures that create backwatered areas. These reach-scale estimated volumes were then spatially extrapolated to the watershed-scale based on stream gradient.

Methods

Subsurface Alluvial Water Storage

The potential change in subsurface alluvial storage was estimated based on simplified valley geometry, after Emmons (2013). In cross-sectional area, the current zone of **unsaturated** sediments is approximated as two triangles, which extend horizontally from the valley edges to the channel edge, and vertically from the channel edge to the depth of the incised channel (Figure 13a). The construction of these unsaturated triangle assumes that the elevation of the incised channel is approximately the same as the water surface elevation in the channel. By implementing restoration actions that raise the channel bed elevation and the water surface elevation in the channel, the vertical dimension of the unsaturated triangle is shortened (Figure 13b).

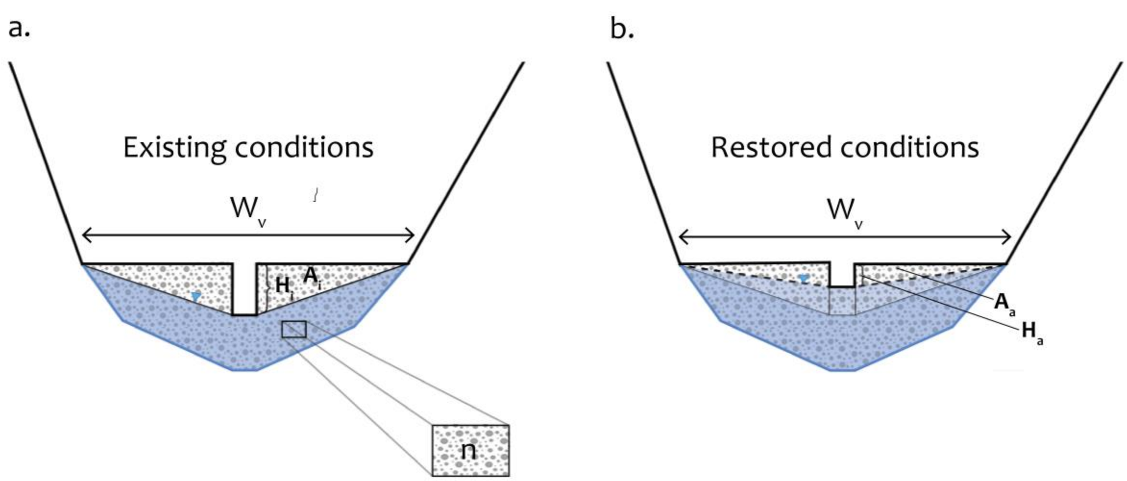


Figure 13. Conceptual diagram of valley cross-section under existing (a) and restored (b) conditions. See text for symbol definitions.

Under both existing and restored conditions, the simplified groundwater surface (i.e., the groundwater flow line) is sloped from the valley edges, where local groundwater elevation is influenced primarily by hillslope water inputs (surface and subsurface), and the channel, where the local groundwater elevation is influenced primarily by the water surface elevation in the channel. Thus, the slope of this surface becomes less steep between existing and restored conditions because the water elevation at the channel is controlled by the channel bed elevation and water surface elevation, both of which shift upward with aggradation and backwatering. When calculating the increased subsurface water storage from re-aggradation of the channel bed, we ignore the water surface elevation of the water in the channel and use the channel bed elevation as the water surface elevation (e.g., Figure 13). These estimates are therefore conservative, and reflect additional storage during the low flow season. Added in-channel surface water storage is considered separately from added subsurface storage (see *Reach-Scale Estimates for Surface Water Storage*).

The change in subsurface alluvial water storage is approximated from the geometry of the cross-sectional area of the alluvial valley. The areal difference between the two unsaturated triangles on either side of the channel (i.e., one rectangle for computations) under existing conditions and under restored conditions represents a newly saturated area under restored conditions. The newly saturated subsurface area is effectively an increase in alluvial groundwater storage (Figure 13).

The following equations were therefore used to compute the change in water storage from restoration in a single reach.

The area of half of the unsaturated zone (i.e., one triangle) under existing, incised conditions, A_i (Figure 14a), is given as half of the product of the height from bed elevation to floodplain elevation, H_i, and half of the valley width, $W_v/2$:

$$A_i = \frac{H_i \times \frac{W_v}{2}}{2}$$

The area of half of the unsaturated zone (i.e., one triangle) in aggraded conditions, A_a (Figure 14b), is given as half of the product of the height from aggraded bed elevation to floodplain elevation, H_a, and half of the valley width, $W_v/2$:

$$A_a = \frac{H_a \times \frac{W_v}{2}}{2}$$

The area of newly saturated triangle, A_s (Figure 14c), is the difference between the two unsaturated triangles:

$$A_s = A_i - A_a$$

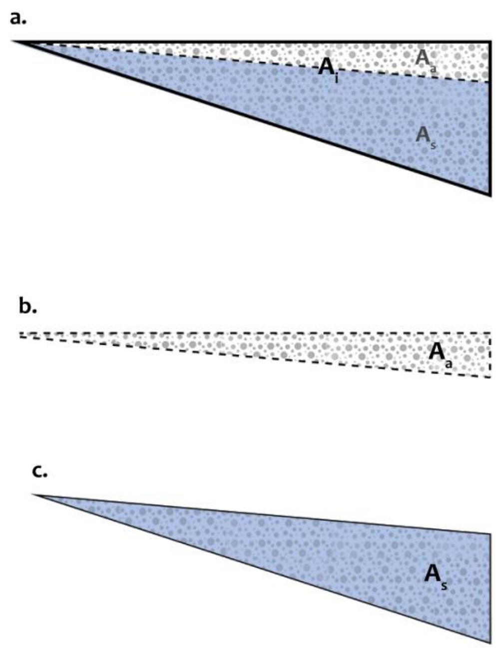


Figure 14. Conceptual diagram of the three triangles for which area is calculated.

The volume of water storage in the newly saturated wedge of alluvial sediments, V_s (Figure 15), is computed as the cross-sectional area of the valley (i.e., two triangles, or $2A_s$), multiplied by the porosity (n) of the sediments (i.e., the interstitial space between the sediment grains which fills with water under saturated conditions, and is a function of grain size, shape, and sorting), multiplied by the reach length (L_r):

$$V_s = 2A_s \times n \times L_r$$

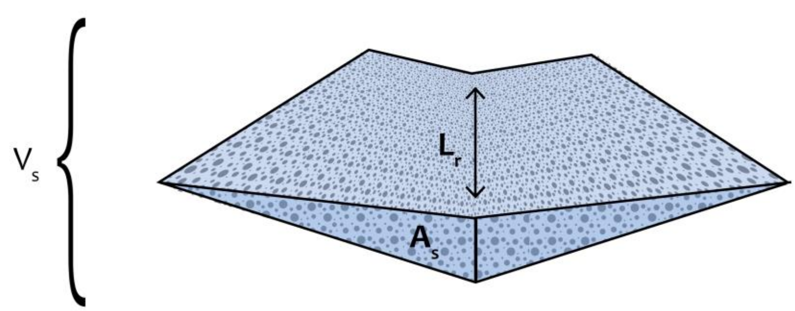


Figure 15. Conceptual diagram of the volume of water storage restored from channel aggradation.

Although the porosity of sediments is naturally variable, we used 35% porosity (i.e., n=0.35) for all of the calculations. 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 field observations of fairly homogeneous floodplain sediments.

We bracketed the calculations via low and high values for aggradation potential. The low scenario estimates channel bed aggradation only. The potential amount of channel aggradation under restored conditions is based on average channel depths observed in the field and from spatial analysis, minus a restored bank height of 1 ft. The high scenario estimates the additional aggradation of the valley floor, resulting from additional sediment storage triggered by restored lateral connectivity between the channel and floodplain.

We estimate the additional water storage from the valley aggradation as a rectangular volume added to the wedge estimated from channel aggradation (Figure 16).

The volume of the additional rectangular volume from valley aggradation, V_v, is the product of the height of valley aggradation (H_v), the valley width (W_v), the porosity (n), and the reach length (L_r), where:

$$V_v = H_v \times W_v \times n \times L_r$$

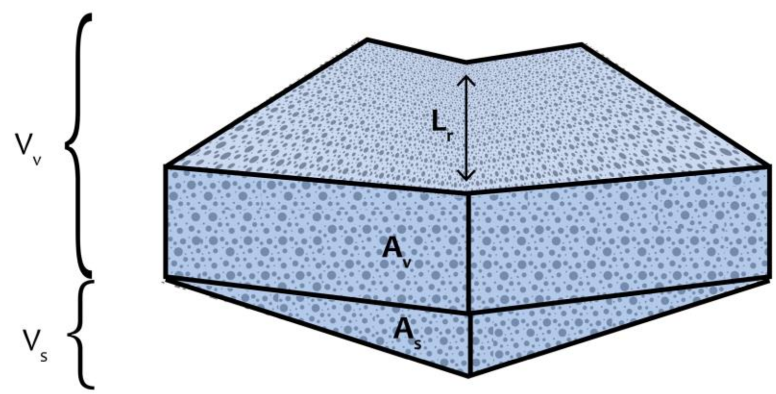


Figure 16. Conceptual diagram of the volume of water storage restored from channel aggradation and additional valley aggradation.

Thus, total volume of restored water storage for a channel and valley aggradation scenario is computed as:

$$V_{total} = V_v + V_s$$

Reach-Scale Estimates for Subsurface Alluvial Storage

Based on partial availability of high-resolution (3-ft) topographic data, we used two approaches: 1) a lumped approach in East Fork Mission Creek, and 2) a geomorphically explicit approach in Poison Canyon. We then applied results from the two reaches to extrapolate to the watershed.

The East Fork Mission Creek analysis relied on 40-ft topographic data. Thus, we used field observations from four cross-sections (Map 3) to determine an average height from bed elevation to floodplain (H_i) and valley width (V_w). We then used these average values to estimate the additional storage from restoration along the entire reach.

In Poison Canyon, high-resolution lidar data are available. Thus, we tested a refined approach in which we mapped geomorphic units (described above, Map 2) and used valley width and reach length from the mapped units along with field observations of average depth of incision by geomorphic unit in our estimation of additional storage from restoration.

Estimation of Streamflow Contribution from Subsurface Alluvial Storage

We estimated the magnitude and duration of the streamflow contribution by additional subsurface alluvial storage in each study reach. Robust quantification of groundwater-surface water interactions requires a sophisticated numerical model to account for time-varying flow rates and multi-dimensional subsurface flow paths. We made major simplifying assumptions to approximate the streamflow benefit from the restored water volume, including: (1) perpendicular lateral flow from shallow groundwater into the channel (rather than oblique to the channel), (2) a single saturated hydraulic conductivity (k_{sat}) of 100 meters/day for coarse sand or gravel (Heath, 1982), (3) a constant gradient based on the slope of the shallow groundwater table from hillslope to restored surface water elevation, and (4) groundwater flux through channel sidewalls only, neglecting upwelling from the channel bottom. Thus, the flux of water from the shallow groundwater to the channel (Q) is approximated as:

$$Q = k_{sat} \times \Delta z \times Area_{channel\ walls}$$

The lateral gradient, Δz, and the wetted area of the channel walls ($Area_{channel\ walls}$) depend on the depth to the restored surface water elevation. The restored surface water depth is approximated as 20% of the bank height under restored conditions. Thus, Δz is the ratio between 80% of the bank height (i.e., the hydraulic drop from the valley side to the channel) and half of the valley width ($W_v/2$). The area of the channel walls is the wetted surface area through which the additional storage flows laterally to reach the channel. This surface is approximated as the product of 80% of the restored bank height (H_a), the reach length (L_r), and porosity (n), all multiplied by 2 to include both sides of the channel:

$$Area_{channel\ walls} = 0.8H_a \times L_r \times n \times 2$$

In this way, both the flux (Q) and the duration of additional streamflow (V_s/Q or V_{total}/Q, for the low and high restoration scenarios, respectively) from lateral drainage of shallow groundwater can be estimated. The duration of flow augmentation is approximated as the total volume divided by the constant flux (given as a volume per time), but the flux would actually vary through time.

Including Additional Surface Water Storage at the Reach-Scale

To estimate the additional surface water storage from backwatered areas triggered by in-channel wood structures (e.g., Figure 4b), 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 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 of 3 ft to estimate the backwater influence of each structure and the ideal treatment density.

Results

In East Fork Mission Creek, we computed alluvial water storage potential of 7 and 18 acre-feet along the 3300 ft study reach for the channel aggradation (i.e., low) and valley aggradation (i.e., high) scenario, respectively (Table 1). The computations are based on a low scenario of 3 ft of channel aggradation to a high scenario of 3 feet of channel aggradation and an additional 3 ft of valley aggradation. In the 8540 ft study reach in Poison Canyon, we computed alluvial water storage potential of 3 and 11 acre-feet for the low and high scenario, respectively.

In both reaches, we normalized the results to determine water storage potential as a volume per length of restored reach, in acre-feet per mile. The lumped approach in East Fork Mission Creek provided a larger water storage estimate on a per-length basis, due to the larger valley width. Thus, we applied the mean of the two reaches for the low and high scenarios, 6.4 acre-feet/mile and 20.1 acre-feet/mile, to bracket the range of water storage potential via extrapolation to the watershed-scale. Spatially variable valley width is not explicitly considered in the extrapolation, but, by using the mean value from East Fork Mission Creek and Poison Canyon, the estimate accounts for a range of valley widths.

Table 1. Potential subsurface alluvial water storage estimated for two study reaches.

Study Reach	Study Reach Length (ft)	Study Reach Average Width (ft)	Study Reach Average Gradient (%)	Average Incised Depth (ft)	Average Valley Aggradation (ft)	Channel: Total Acre-feet	Channel: Estimated Flux	Channel: Total Acre-feet/mi	Channel + Valley: Total Acre-feet	Channel + Valley: Total Acre-feet/mi	Channel + Valley: Estimated Flux
Poison Canyon	8540	60	4.1	Varies from 1 to 4.5	3.3	3.1	0.12 cfs for 13 days	1.9	18.3	11.3	0.12 cfs for 80 days
East Fork Mission Creek	3300	130	4.3	4.4	3.3	6.7	0.02 cfs for 160 days	10.8	18.1	28.9	0.02 cfs year-round
Mean of two reaches								6.4		20.1	

Table 2. Potential surface water storage from backwatered areas.

Average Stream Gradient (fraction)	Aggradation Height (ft)	Upstream Influence of Structure (ft)	Maximum Density of Structures per Mile	Estimated Width of Backwater Pond (ft)	Estimated Surface Water Storage per Structure (acre-feet)	Estimated surface water storage per mile (acre-feet/mi)
0.01	3	300	18	40	0.41	7
0.03	3	100	53	30	0.10	5
0.05	3	60	88	20	0.04	4

Based a channel gradient of 1-5% and target aggradation height of 3 ft, we estimate a backwater influence and a fully implemented treatment density (Table 2). For example, at an average stream gradient of 3%, a fully implemented treatment density would consist of ~50 structures per mile. We estimate the volume of surface water behind each structure at 0.1 acre-feet per structure based on the geometry of a 3% stream gradient, a 3-ft aggradation height, and a ponded width of 30 ft. This estimate is lower than previously published values for beaver ponds of 0.28-1.01 acre-feet/pond (Beedle, 1991). The increased surface water volume from 50 structures per mile at a volume of 0.1 acre-feet per structure equates to 5 acre-feet/mile of additional surface water storage.

We apply this estimate of 5 acre-feet/mile of surface water storage to extrapolate to the watershed-scale.

Extrapolation to watershed-scale

Methods

The purpose of watershed-scale extrapolation of these computations is to estimate the upper-bound for the potential to restore water storage if restoration actions were implemented across some percentage of all feasible reaches. This 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. To extrapolate to the watershed-scale we utilized existing channel location data from the National Hydrography Dataset, and excluded reaches in agricultural valleys. We then flagged the presence or absence of a road adjacent to the channel in order to account for constraints on restoration actions where a road might be impacted.

We computed the gradient of each section of the channel network, and excluded channels with a gradient higher than 10% from analysis. The average gradient along the East Fork Mission Creek study reach is approximately 4.3%, and the average gradient along Poison Canyon is 4.1%. Poison Canyon is somewhat steeper in places, but the presence of wide, alluvial wetlands where hydraulic grade is controlled by the presence of in-channel wood (discussed above) suggest that restoration actions are feasible for reducing gradient and storing alluvial sediment. Current research indicates that beavers typically build dams in perennial stream channels with slopes of less than 6%, and that beaver dam analogs can be constructed on reaches with higher stream power to initiate similar responses, including backwatering and aggradation (Pollock *et al.*, 2014). Furthermore, the inferred storage of sediment trigged by CCC structures in the ephemeral first-order channel in Peavine Canyon (gradient = 6.8%) supports the feasibility of restoration actions in higher gradient reaches (Figure 2). However, these higher gradient reaches may have less impact on alluvial water storage than on alluvial sediment storage. As such, we computed watershed-scale potential for restored water volumes based on application of restoration actions to all upland reaches in two gradient bins: below 5% and below 10% (Map 4).

Although valley width and morphology will vary with gradient, we used the simplifying assumption that the volume per distance estimates for potential water storage based on analysis in the two study reaches are applicable to the rest of the channel network. Extrapolation to the watershed-scale includes estimates of additional sub-surface and surface water storage.

Results

Estimates for potential increases in alluvial water storage from restoration range widely based on restoration scenario and the length of the stream network that was included in each estimate. The lowest potential water storage results from a low restoration scenario (i.e., channel aggradation only), applied to a small fraction of the lowest gradient reaches in the stream network (Figure 17, red lines on left-hand plot). The highest values were estimated for valley restoration applied to a large fraction of all reaches with a gradient under 10%.

Based on the premise that the most feasible restoration strategy will include implementation in lower gradient reaches, reaches without roads, and only a fraction of the possible reaches, in Table 3 we present estimated water storage values for a subset of the results shown in Figure 17. Table 4 presents the same results, but for alluvial subsurface storage only, in order to separate out subsurface versus surface storage.

The magnitude the streamflow flux provided by additional alluvial water storage scales with the length of the treated stream network (Figure 18). The additional streamflow contributions range from 0.02 to 1.7 cfs. In these estimates, the duration of streamflow contribution depends only on the restoration scenario (Figure 18). This result is an artifact of the simple estimation methods: both the subsurface volume and the streamflow flux scale linearly with length, so length of stream network treated essentially cancels out.

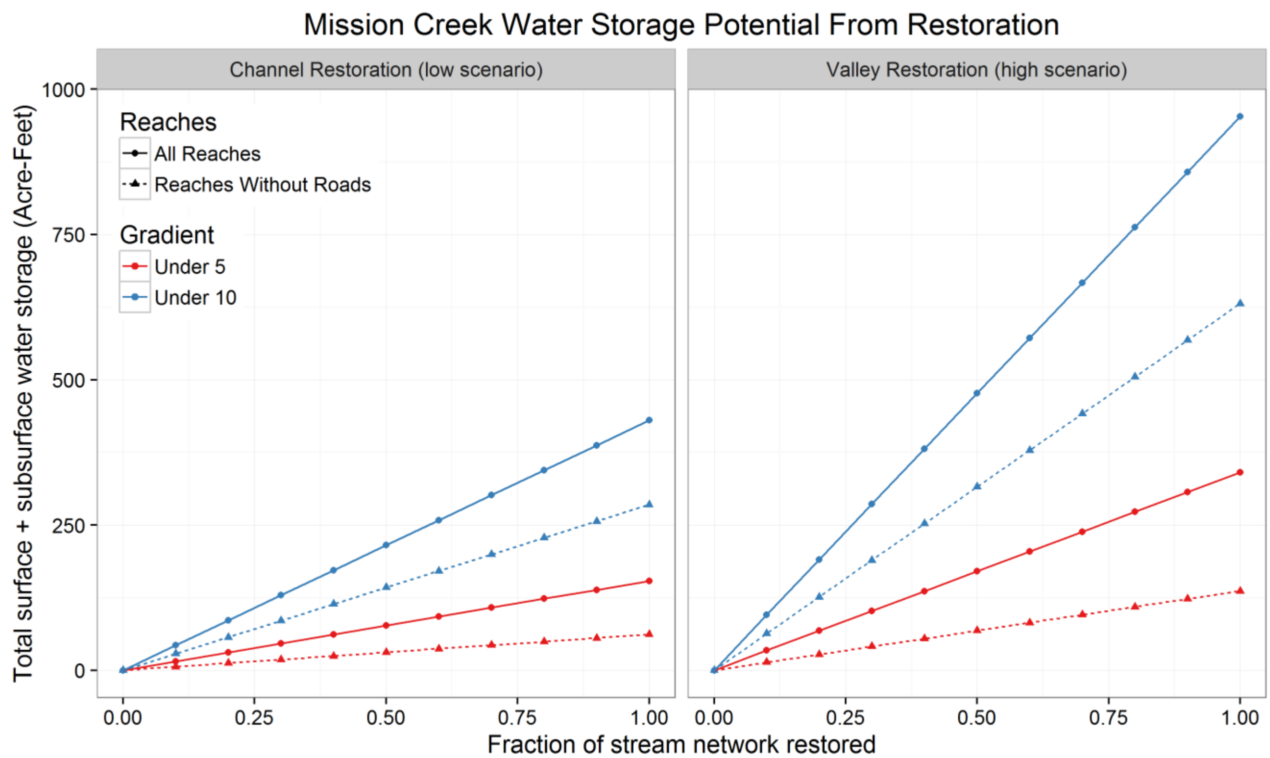


Figure 17. Potential alluvial water storage the low and high restoration scenarios, as a function of the fraction (0 to 1) of the treatable channel network to which restoration actions are applied. Colors indicate the maximum stream gradient of reaches included in the estimate (<5% and <10%), and symbols and line types further indicate the inclusion of all reaches under that gradient threshold, or only reaches that are not adjacent to roads.

Table 3. Potential total additional water storage (acre-feet), including subsurface alluvial storage and surface storage from backwatered areas, for the low and high restoration scenarios, to a percentage (10-50%) of the treatable channel network, which is based on a threshold for average gradient (<5% or <10%) and which excludes all reaches that are adjacent to roads.

Restoration Scenario	Gradient Threshold for Restoration Potential (%)	Total Length of Treatable Stream Network (i.e., below gradient threshold and not adjacent to a road) (mi)	Subsurface storage (acre-feet) from treating 10% of Stream Network	Subsurface storage (acre-feet) from treating 20% of Stream Network	Subsurface storage (acre-feet) from treating 30% of Stream Network	Subsurface storage (acre-feet) from treating 40% of Stream Network	Subsurface storage (acre-feet) from treating 50% of Stream Network
Channel Restoration (low scenario)	< 5	5	6	12	18	25	31
Channel Restoration (low scenario)	< 10	25	29	57	86	114	143
Valley Restoration (high scenario)	< 5	5	14	27	41	55	68
Valley Restoration (high scenario)	< 10	25	63	126	189	252	316

Table 4. Potential subsurface alluvial water storage (acre-feet) only (i.e., excluding additional surface water storage from backwatered areas) for the low and high restoration scenarios, applied to a percentage (10-50%) of the treatable channel network, which is based on a threshold for average gradient (<5% or <10%) and which excludes all reaches that are adjacent to roads.

Restoration Scenario	Gradient Threshold for Restoration Potential (%)	Total Length of Treatable Stream Network (i.e., below gradient threshold and not adjacent to a road) (mi)	Subsurface storage (acre-feet) from treating 10% of Stream Network	Subsurface storage (acre-feet) from treating 20% of Stream Network	Subsurface storage (acre-feet) from treating 30% of Stream Network	Subsurface storage (acre-feet) from treating 40% of Stream Network	Subsurface storage (acre-feet) from treating 50% of Stream Network
Channel Restoration (low scenario)	< 5	5	3	7	10	14	17
Channel Restoration (low scenario)	< 10	25	16	32	48	64	80
Valley Restoration (high scenario)	< 5	5	11	22	33	44	55
Valley Restoration (high scenario)	< 10	25	51	101	152	202	253

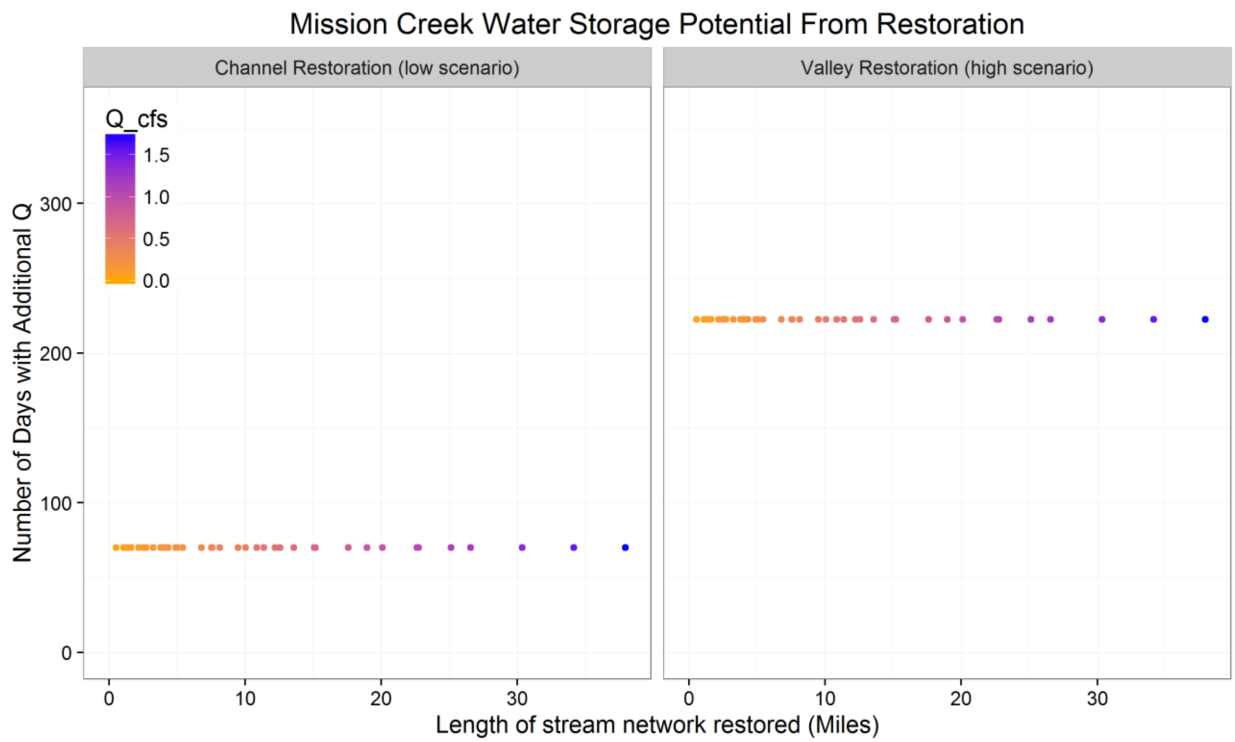


Figure 18. Potential contribution to streamflow (Q, in cfs) from subsurface alluvial water storage in the low (left) and high (right) restoration scenarios. The streamflow contribution (symbolized by color) varies as a function of the length of the stream network restored (x-axis, miles). The number of days (y-axis) of that given streamflow contribution is constant in each scenario because both the additional storage and the additional Q scale linearly with length of the stream network restored.

Discussion

Uncertainties

This approach neglects uncertainties related to how evapotranspiration rates and timing may change with an increase in the elevation of the shallow groundwater (Tague *et al.*, 2008). Therefore, this analysis demonstrates that more water will theoretically be available, and that the additional water storage will be partitioned between baseflow augmentation and transpiration by riparian vegetation. Additional water availability for riparian vegetation is likely to increase the resilience of the riparian forest to fire and insect outbreaks (Grant *et al.*, 2013), but will also reduce the baseflow effect by an unknown amount. In addition, previous work has suggested a positive feedback as it relates to water storage and restoration: water holding capacity of alluvial material increases as a function of the proportion of organic matter in the floodplain (Hudson, 1994). Thus, restoration that raises shallow groundwater levels and contributes to healthier or more productive riparian vegetation may also increase the contribution of organic matter to the floodplain sediments and therefore increase the amount of water stored and to decrease the rate of release.

This analysis makes numerous simplifying assumptions: homogenous floodplain sediments, constant valley width and depth of incision, and lateral groundwater flow at a constant rate. Thus, these estimates are simply a first-order estimate for watershed-scale water storage potential, and the local effects of restoration actions will vary substantially with channel and valley morphology. The true additional alluvial water storage and contribution to baseflow would be a complex function of riparian transpiration, timing of the onset of baseflow (i.e., when the water surface elevation in the channel drops below the elevation of the shallow groundwater), spatial heterogeneity in sediments, time-varying sub-surface flow rate, and the routing of water through the channel network. A thorough assessment would require numerical modeling of sub-surface flows.

Comparing Infrastructure Versus Restoration

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 a median implementation density of 53 structures/mile (Table 2), along with estimated surface and subsurface water storage of 11.4 acre-feet/mile (Table 1 and Table 2). For comparison estimates for the implementation costs of additional storage for previously considered infrastructure projects in the Mission Creek watershed range from $8000-58000/acre-foot. 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 an infrastructure approach than a restoration approach.

Preliminary Restoration Concepts

Recommendations for Next Steps

We recommend design, implementation, and monitoring of a pilot project in Poison Canyon. With three geomorphically-distinct reach types, there is opportunity to both initiate sediment storage and aggradation processes and to reverse the loss of sediment, and therefore alluvial water, storage in severely incised reaches.

In particular, we recommend design and implementation of channel-spanning wood structures, along with pre-and post-implementation quantification of the elevation of local groundwater, channel bed elevation, and water surface elevation. Monitoring of downstream streamflow. Before and after project implementation would also support future efforts to quantify the hydrologic effect of restoration

In-Channel Structures

Due to access constraints in Poison Canyon and the relatively small width of the channel and valley, implementation via hand tools is likely to be feasible in this reach.

Beaver Dam Analog – Wood Bundles

The construction of simulated beaver dams would involve the installation of bundled woody material that has been harvested locally. Thinned material could be bundled to a diameter of 2-4 ft using biodegradable (manila) rope at two to three locations along the bundle length (Figure 19). Typical bundle lengths would be based on channel widths and potential to secure the bundles to adjacent riparian trees. Single bundles or bundles placed end to end can be installed within the channel, anchored to existing riparian vegetation (Figure 19) or using simple, small diameter batter (angled) posts.

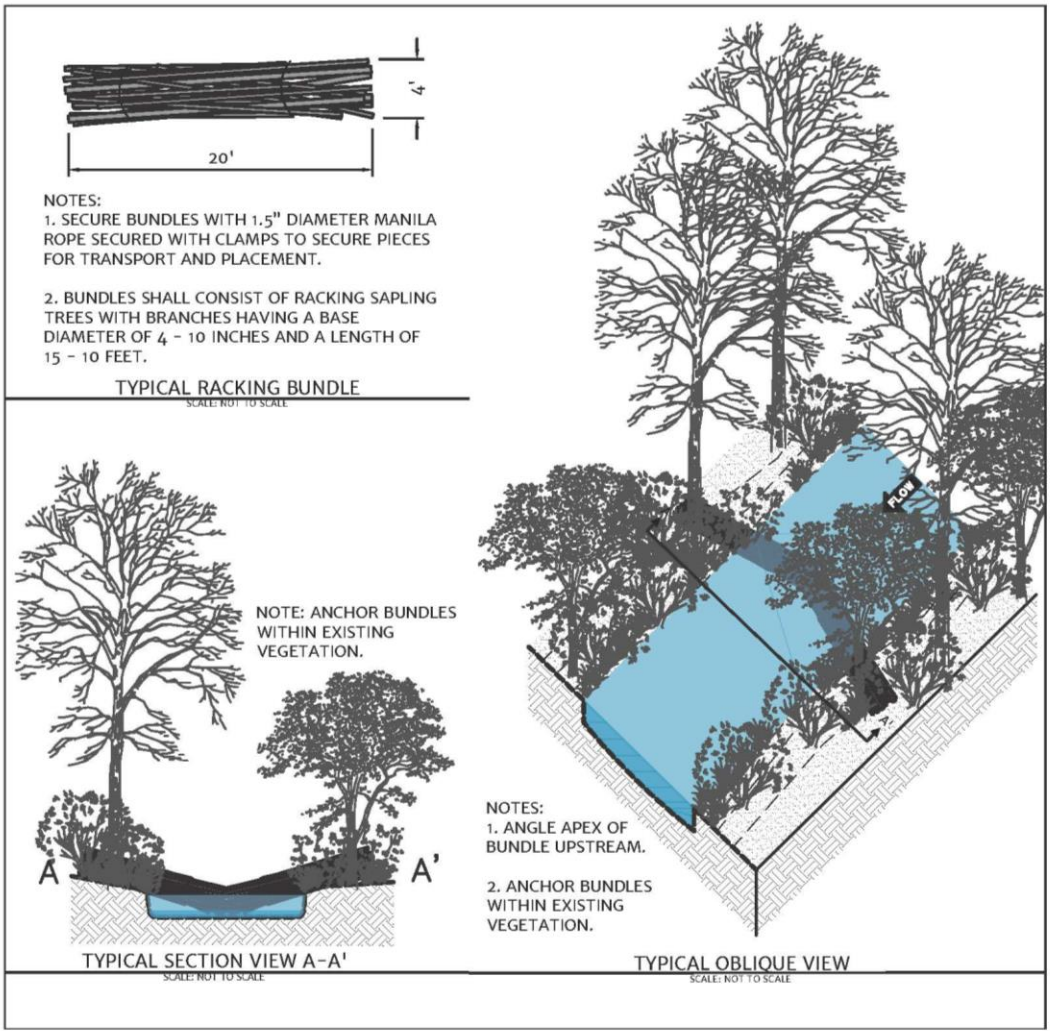


Figure 19. Example of typical racking bundle comprised of 10 - 20 ft poles <10-inch diameter. Bundles are bound to a diameter of 4 ft using 1.5-inch manila rope and clamps at two locations. Shown is a typical installation of two wood bundles placed end to end and anchored within existing vegetation to create a low-lying beaver dam analog.

Beaver Dam Analog – Post Lines

Lines of posts, or pickets, driven into the channel provide a stable platform in which to rack large wood or weave smaller branches and racking material (Figure 20). These structures have been implemented as beaver dam analogs to initiate aggradation, particularly where the availability of riparian trees to provide anchoring is lacking (Pollock *et al.*, 2012). These structures also provide potential sites for future beaver dam complexes, which would substantially increase the footprint and the benefit of the project.

Figure 20. Example of beaver dam analog using a post line and weaving (Photograph from Pollock et al. (2012)).

Large Riparian Wood Placement

Where sufficiently large riparian trees are present, mechanical pulling ("tree tipping") or felling into the channel is another option for adding channel-spanning wood structures (Benda et al., 2016). The required length and diameter of riparian trees, along with the number and placement ("racking") will all scale with channel morphology and hydraulics. This method can be combined with either the post lines or wood bundle methods to increase materials racking and aggradation.

Recommended Next Steps

Recommended next steps for pilot implementation in Poison Canyon include:

- Collection of field data, including:
    - Topographic survey
    - Identification of location and type of structures for placement
        - Based on minimum spacing, availability of materials, and construction feasibility.
    - Assess morphology to inform sizing of structure
- Assess local hydrology and hydraulics
- Complete conceptual treatment typical designs based on field data and stability calculations
- Complete proposed conditions analysis and a design report
- Begin permitting process with relevant agencies

List of Maps

References

Abbe T, Brooks A. 2013. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration.419–451. DOI: 10.1029/2010GM001004

Abbe T, Bilby B, Shields D. 2016. Geomorphology and Hydrology Considerations. In *National Large Wood Manual. Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure*Bureau of Reclamation and US Army Engineer Research and Development Center.

Abbe TB. 2000. Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System.University of Washington.

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* **51** (1-3): 81–107 DOI: 10.1016/S0169-555X(02)00326-4

Abbe TB, Ericsson M, Embertson L. 2015. Channel incision and floodplain abandonment due to historic wood removal in Washington State, USA. In *Wood in World Rivers 3rd International Conference July 6-10 2015*Padova, Italy. Available at: http://intra.tesaf.unipd.it/cms/wwr3/

Anchor QEA. 2011. Water Storage Report - Wenatchee River Basin. Kirkland, Washington.

Baird KJ, Stromberg JC, Maddock T. 2005. Linking Riparian Dynamics and Groundwater: An Ecohydrologic Approach to Modeling Groundwater and Riparian Vegetation. *Environmental Management* **36** (4): 551–564 DOI: 10.1007/s00267-004-0181-z

Beechie TJ, Imaki H, Greene J, Wade A, Wu H, Pess G, Roni P, Kimball J, Stanford J, Kiffney P, et al. 2012. RESTORING SALMON HABITAT FOR A CHANGING CLIMATE. *River Research and Applications* **22** (July 2011): n/a–n/a DOI: 10.1002/rra.2590

Beechie TJ, Pollock MM, Baker S. 2008. Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA. *Earth Surface Processes and Landforms* **33** (5): 784–800 DOI: 10.1002/esp.1578

Beedle D. 1991. Physical Dimensions and Hydrological Effects of Beaver Ponds on Kuiu Island in Southeast Alaska.Oregon State University.

Benda LE, Litschert SE, Reeves G, Pabst R. 2016. Thinning and in-stream wood recruitment in riparian second growth forests in coastal Oregon and the use of buffers and tree tipping as mitigation. *Journal of Forestry Research* **27** (4): 821–836 DOI: 10.1007/s11676-015-0173-2

Bogan T, Mohseni O, Stefan HG. 2003. Stream temperature-equilibrium temperature relationship. *Water Resources Research* **39** (9): n/a–n/a DOI: 10.1029/2003WR002034

Collins BD, Montgomery DR, Fetherston KL, Abbe TB. 2012. The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology* **139-140**: 460–470 DOI: 10.1016/j.geomorph.2011.11.011

Collins BD, Montgomery DR, Haas AD. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences* **59** (1): 66–76 DOI: 10.1139/f01-199

Elsner MM, Cuo L, Voisin N, Deems JS, Hamlet AF, Vano JA, Mickelson KEB, Lee S-Y, Lettenmaier DP. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* **102** (1-2): 225–260 DOI: 10.1007/s10584-010-9855-0

Emmons JD. 2013. Quantifying the restorable water volume of Sierran meadows.University of California, Davis.

Essaid HI, Hill BR. 2014. Watershed-scale modeling of streamflow change in incised montane meadows. *Water Resources Research* **50** (3): 2657–2678 DOI: 10.1002/2013WR014420

Fouty S. 2013. A strategic response to climate change: Restoring water storage capability to stream ecosystems on public lands with the help of beavers, wolves, and fire

Grant GE, Tague CL, Allen CD. 2013. Watering the forest for the trees: An emerging priority for managing water in forest landscapes. *Frontiers in Ecology and the Environment* **11** (6): 314–321 DOI: 10.1890/120209

Gresens RL, Naeser CW, Whetten J w. 1981. Stratigraphy and Age of the Chumstick and Wenatchee Formations: Tertiary Fluvial and Lacustrine Rocks, Chiwaukum Graben, Washington. *Geological Society of America Bulletin* **92** (5_Part_II): 841–876 DOI: 10.1130/GSAB-P2-92-841

Hafen K, Macfarlane WW. 2016. Can Beaver Dams Mitigate Water Scarcity Caused by Climate Change and Population Growth? *StreamNotes: The Technical Newletter of the National Stream and Aquatic Ecology Center, USDA* Available at: https://www.fs.fed.us/biology/nsaec/assets/streamnotes2016-11.pdf

Hamlet AF, Elsner MM, Mauger GS, Lee S-Y, Tohver I, Norheim RA. 2013. An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. *Atmosphere-Ocean* **51** (4): 392–415 DOI: 10.1080/07055900.2013.819555

Hammersmark CT, Rains MC, Mount JF. 2008. Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. *River Research and Applications* **24** (6): 735–753 DOI: 10.1002/rra.1077

Heath RH. 1982. Basic Ground-Water Hydrology. Reston, Virginia.

Hudson BD. 1994. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* **49** (2): 189–194

Klimenko DE, Eponchintseva DN. 2015. Experimental hydrological studies of processes of failure of beaver dams and pond draining. *Biology Bulletin* **42** (10): 882–890 DOI: 10.1134/S1062359015100064

Loheide SP, Deitchman RS, Cooper DJ, Wolf EC, Hammersmark CT, Lundquist JD. 2009. A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA. *Hydrogeology Journal* **17** (1): 229–246 DOI: 10.1007/s10040-008-0380-4

Montgomery Water Group. 2006. Multi-Purpose Water Storage Assessment in the Wenatchee River Watershed. Kirkland, Washington.

Morris DA, Johnson AI. 1967. Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the US Geological Survey, 1948-60. Washington, DC.

Ohara N, Kavvas ML, Chen ZQ, Liang L, Anderson M, Wilcox J, Mink L. 2014. Modelling atmospheric and hydrologic processes for assessment of meadow restoration impact on flow and sediment in a sparsely gauged California watershed. *Hydrological Processes* **28** (7): 3053–3066 DOI: 10.1002/hyp.9821

Phelps JD. 2011. The Geomorphic Legacy of Splash Dams in the Southern Oregon Coast Range.University of Oregon.

Pollock MM, Beechie TJ, Wheaton JM, Jordan CE, Bouwes N, Weber N, Volk C. 2014. Using Beaver Dams to Restore Incised Stream Ecosystems. *BioScience* **64** (4): 279–290 DOI: 10.1093/biosci/biu036

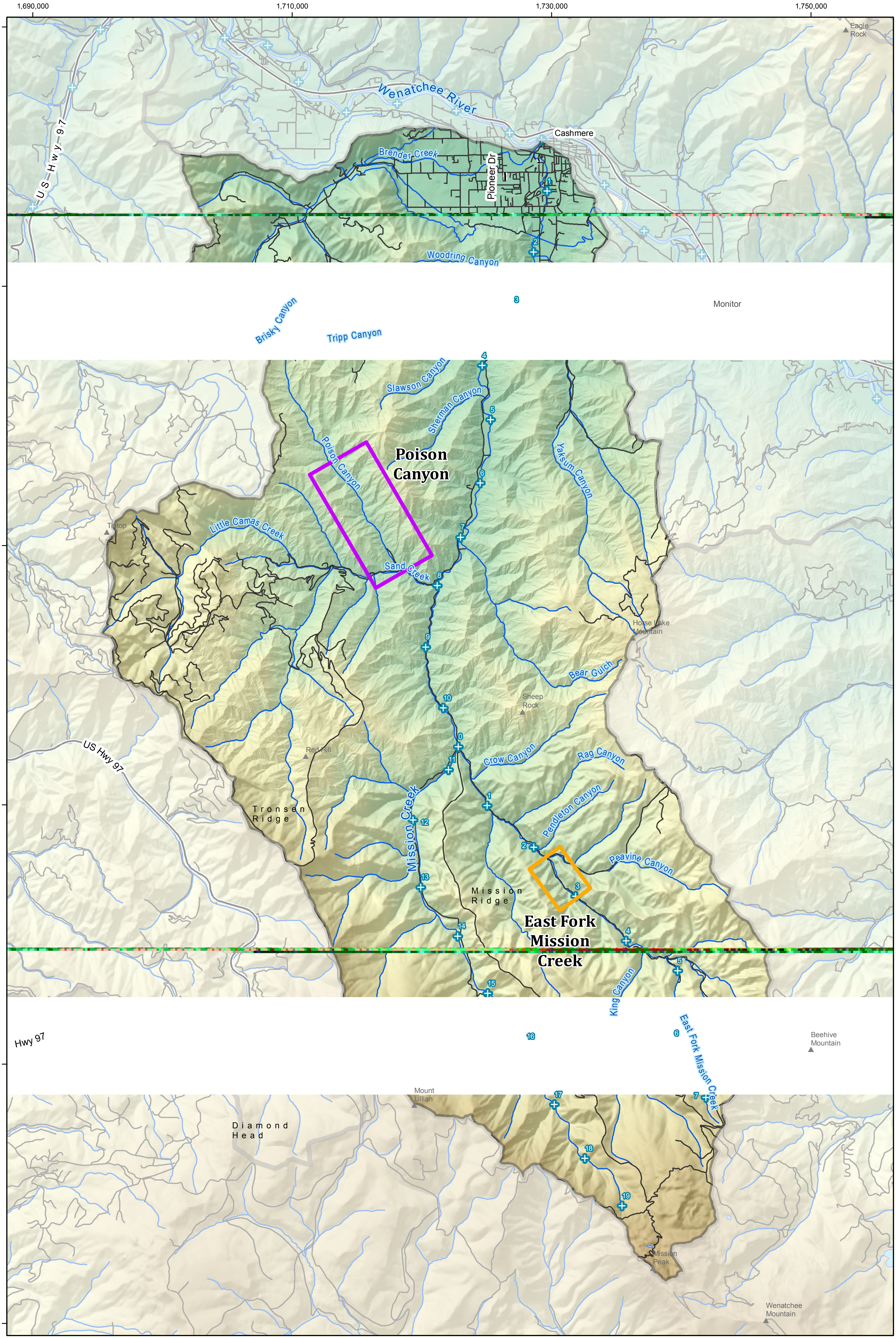
Pollock MM, Wheaton JM, Bouwes N, Volk C, Weber N, Jordan CE. 2012. Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed Design Rationale and Hypotheses. Seattle, WA.

Schneider D, Anderson R. 2007. Wenatchee River Watershed Temperature Total Maximum Daily Load-Water Quality Report. Olympia, WA. Available at: https://fortress.wa.gov/ecy/publications/documents/0710045.pdf

Schumm SA, Harvey MD, Watson CC. 1984. Incised channels: morphology, dynamics, and control. *Water Resources Publications*

Stock JD, Montgomery DR, Collins BD, Dietrich WE, Sklar L. 2005. Field measurements of incision rates following bedrock exposure: Implications for process controls on the long profiles of valleys cut by rivers and debris flows. *Geological Society of America Bulletin* **117** (1): 174 DOI: 10.1130/B25560.1

Tague C, Valentine S, Kotchen M. 2008. Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed. *Water Resources Research* **44** (10): n/a–n/a DOI: 10.1029/2007WR006418



Map 1. Overview of watershed and study reach locations

Mission Creek, Chelan County, Washington

Data Sources: USGS 10-m Digital Elevation Model, Stream Network and Sub-basin boundaries from National Hydrology Dataset,

Lambert conformal conic projection, NAD 1983
State Plane Coordinate System

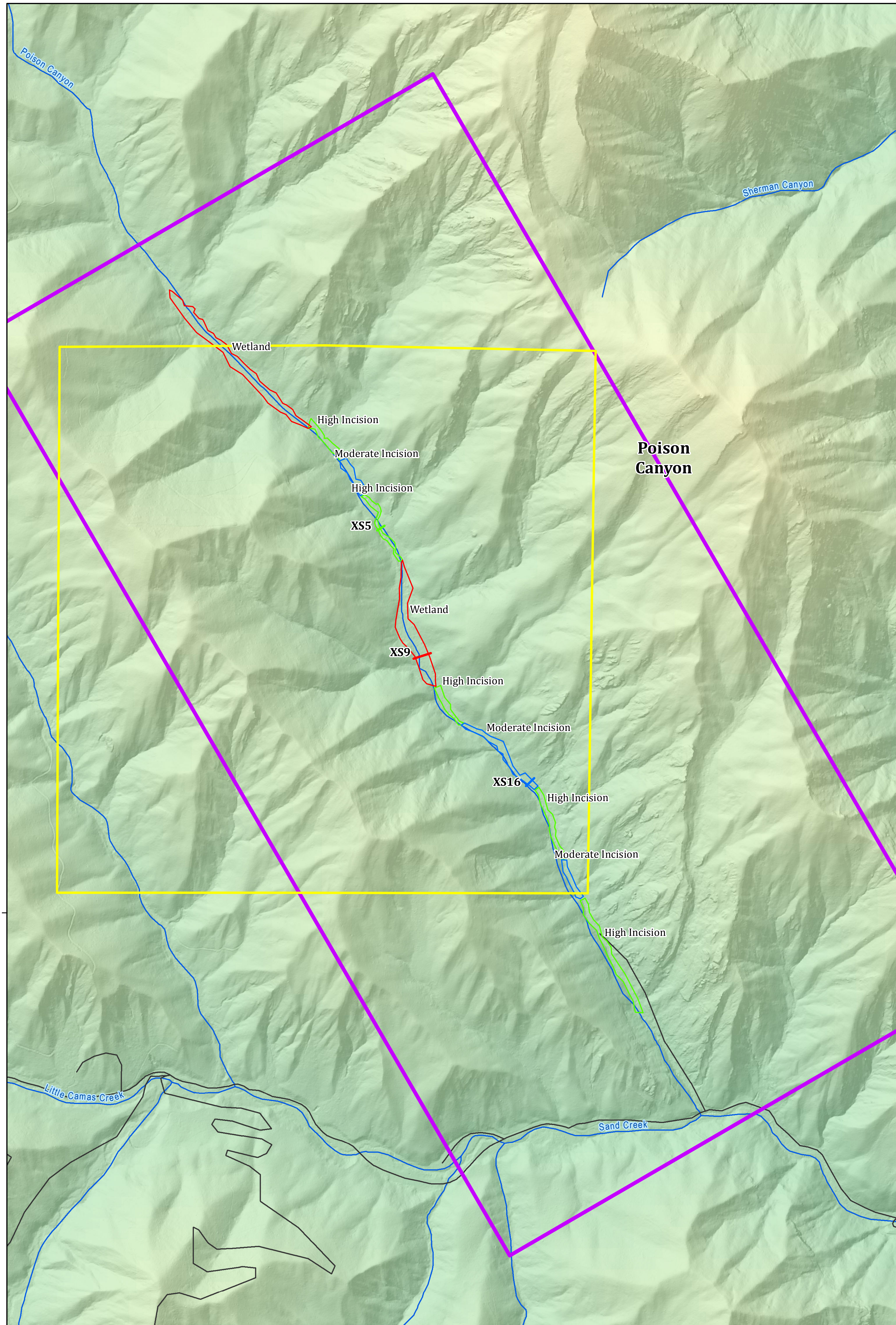
N

0 1 2 3 Miles

Natural Systems Design

- ▲ Mountain Summit
- Roads
- Streams
- River Mile Marker
- Poison Canyon Study Reach
- EF Mission Creek Study Reach

Susan Dickerson-Lange and Shawn Higgins, NSD Date: 4/3/2017 1_Mission_Overview.mxd



Susan Dickerson-Lange and Shawn Higgins, NSD Date: 4/3/2017 2_Mission_Poison.mxd

Map 2. Poison Canyon Study Reach

Mission Creek, Chelan County, Washington

Data Sources: USGS 10-m Digital Elevation Model, Stream Network and Sub-basin boundaries from National Hydrography Dataset, Local hillshade from 1-m lidar Digital Elevation Model (Chelan County)

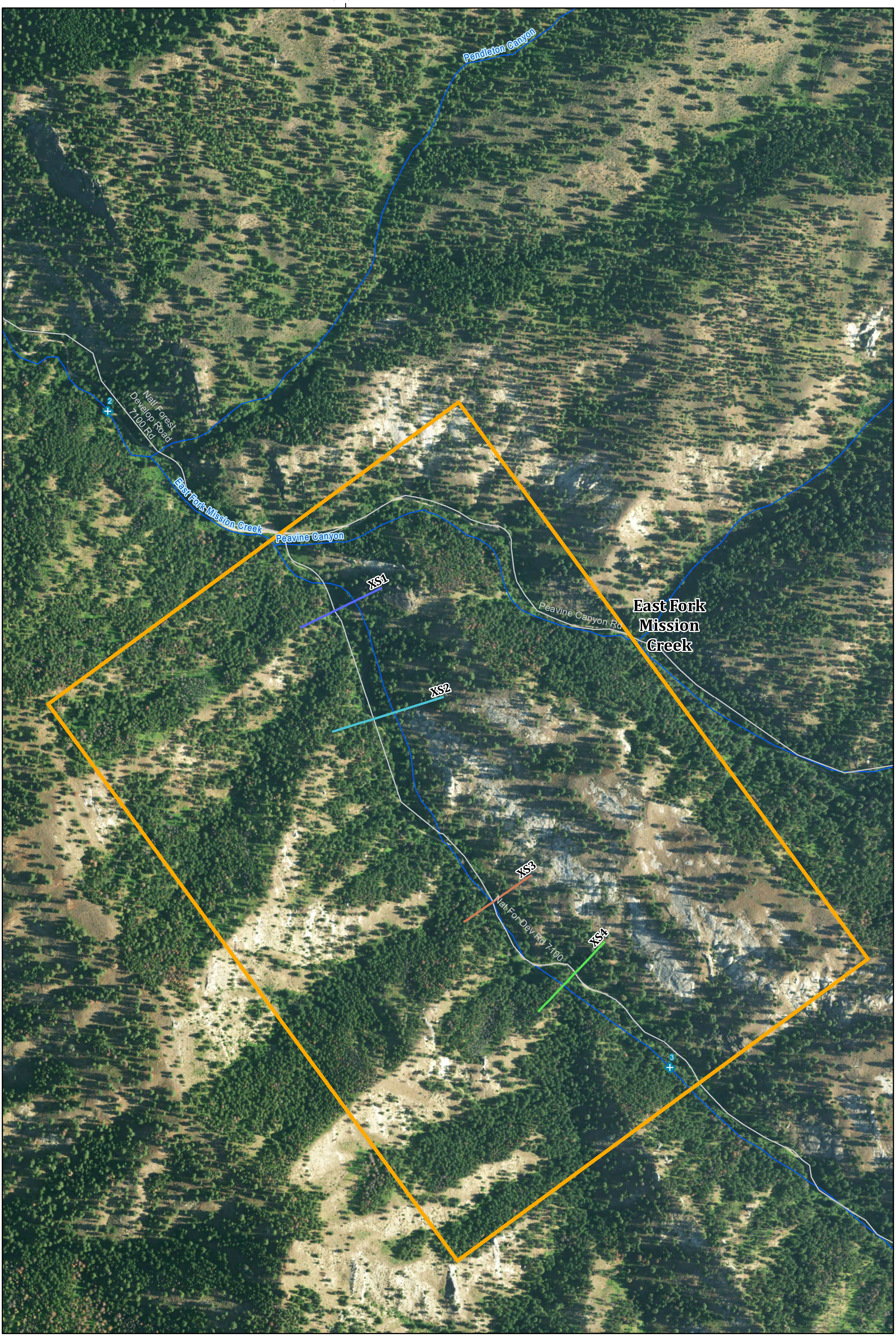
Lambert conformal conic projection, NAD 1983
State Plane Coordinate System

N

0 500 1,000 1,500 Feet

Natural Systems Design

- Mountain Summit
- Roads
- Streams
- River Mile Marker
- Study Reach
- WDNR Parcel



Susan Dickerson-Lange and Shawn Higgins, NSD Date: 4/3/2017 3_Mission_EFMC.mxd

Map 3. East Fork Mission Creek Study Reach

Mission Creek, Chelan County, Washington

Data Sources: USGS 10-m Digital Elevation Model, Stream Network and Sub-basin boundaries from National Hydrography Dataset, USDA NAIP Imagery

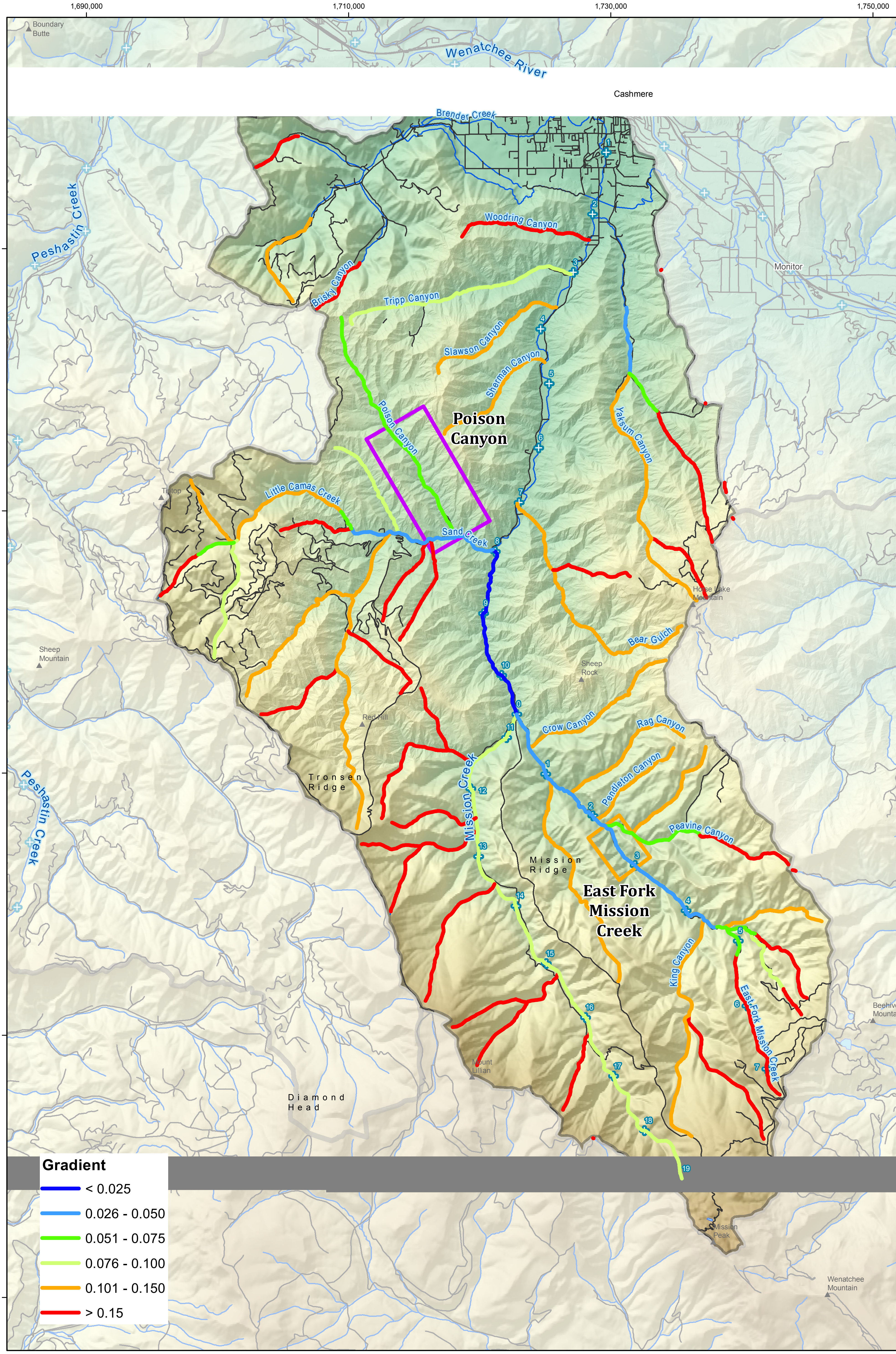
Lambert conformal conic projection, NAD 1983
State Plane Coordinate System

N

0 300 600 900 Feet

▲ Mountain Summit
River Mile Marker
Roads
Streams

Natural Systems Design



Map 4. Average stream gradient by reach

Mission Creek, Chelan County, Washington

Data Sources: USGS 10-m Digital Elevation Model, Stream Network and Sub-basin boundaries from National Hydrography Dataset,

Lambert conformal conic projection, NAD 1983
State Plane Coordinate System

N

0 0.5 1 1.5 2 2.5 Miles

Mountain Summit
Roads
Streams

Natural Systems Design

Susan Dickerson-Lange and Shawn Higgins, NSD Date: 2/14/2017 4_Mission_Stream_Gradients.mxd