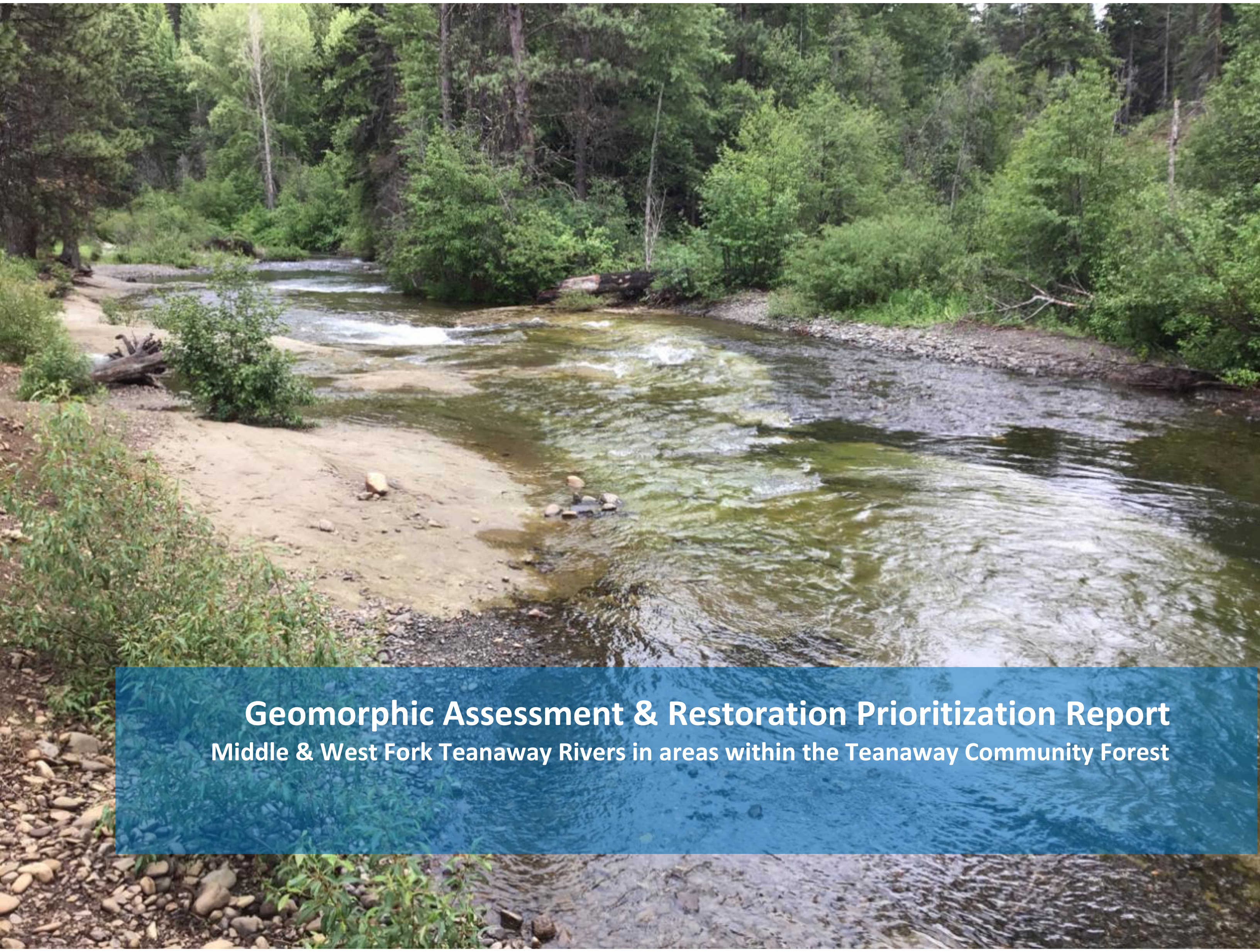

Geomorphic Assessment & Restoration Prioritization Report

Middle & West Fork Teanaway Rivers in areas within the Teanaway Community Forest

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF MAPS

LIST OF APPENDICES

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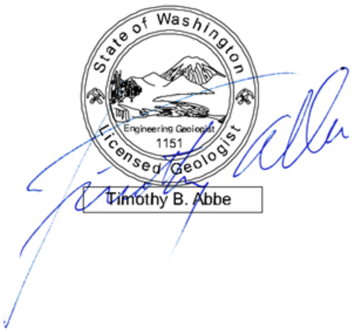

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1. INTRODUCTION

Channel downcutting or incision impacts many western watersheds and has significant impacts on aquatic and riparian habitat. Incision not only lowers the channel bed and in-stream water elevations, but lowers the adjacent groundwater table. These changes disconnect floodplains, drain wetlands, rapidly route water out of the basin and simplify in-stream habitat. Incised channels experience a substantial increase in unit stream power due to narrower, deeper cross-sections with greater sediment transport capacity that triggers more incision and conversion of channels from alluvial to bedrock. These physical changes within a watershed can decrease cold water fish productivity. Higher unit stream power can result in deeper bed scour that can result in higher mortality of salmonid eggs and conversion to bedrock can eliminate spawning completely. Given the severe consequences of incision, halting and reversing channel incision is the single most important stream restoration action for impacted systems. In the West and Middle Forks of the Teanaway River there have been three historic human actions that contributed to incision of 6-10 feet over the last century: splash damming, in-stream wood removal, and channelization (Stock et al., 2005; Collins et al., 2016; Schanz et al., 2019).

The Teanaway River (Teanaway) watershed supports populations of threatened Mid-Columbia steelhead, in addition to spring Chinook salmon, westslope cutthroat trout, rainbow trout, mountain whitefish, and sculpin and dace species (WDFW, 2015). Reports suggest that the Teanaway supported healthy salmon runs prior to 1904, when industrial logging activity rapidly expanded, and salmon runs were nearly non-existent in the West and Middle Fork Teanaway by 1916 (Bryant & Parkhurst, 1950). The watershed historically supported threatened bull trout, but no bull trout have been observed in the Teanaway since 2005 (WDFW, 2015).

Habitat for fish and other wildlife in the Teanaway has been impacted by human land use activities beginning in the late 19th century, with widespread industrial logging, mining, heavy grazing, an increase in road density, and floodplain farming and residential development. Over time, these cumulative legacy watershed scale impacts have made the Teanaway watershed and in-stream habitat less resilient to disturbances such as fire, insect outbreaks, and flooding. Climate projections for the upper Yakima River basin (including the Teanaway) indicate hotter, drier summers and wetter winters, conditions which are expected to exacerbate winter flooding and impair late summer baseflow and thermal conditions for fish.

More than 50,000 acres of land was acquired by the State of Washington in 2013 to become the Teanaway Community Forest (TCF), which is managed by the Washington State departments of Natural Resources (WADNR) and Fish and Wildlife (WDFW) to include a mix of working lands (grazing, timber), recreational opportunities, and fish and wildlife habitat (WDFW, 2015). WDFW was granted a “Deed of Habitat Restoration and Working Lands” or conservation easement over the TCF lands, and is charged with restoring the Teanaway (WDFW-WDNR 2013). TCF management must also comply with management objectives of the Yakima Basin Integrated Plan (YBIP), which includes water supply, watershed protection, and community partnerships. Legislation for the TCF and the YBIP explicitly identifies the need for restoring watershed health through the protection, enhancement, and creation of wetlands (WDFW, 2015). The Teanaway is a stunning watershed with substantial potential to meet these management objectives, but restoration actions are needed to recover aquatic habitat from more than a century of human impacts.

WDFW, Yakama Nation (YN), US Fish and Wildlife Service (USFWS) and NOAA Fisheries Biologists developed an Aquatic Restoration Strategy that identified priority streams for protection and restoration in the Teanaway watershed, which include the mainstem forks (North, Middle, and West) and their fish-bearing tributaries. The Mid-Columbia Fisheries Enhancement Group (MCFEG) and YN have worked with state agencies and local and regional stakeholders to restore aquatic habitat in these priority streams throughout the Teanaway. The North Fork (NF) Teanaway sub-basin was prioritized based on greater fish-bearing stream length and basin area, and higher production potential for Chinook salmon, steelhead, bull trout, and resident fish; as well as stream flow and stream temperature. Assessment work and restoration actions in the NF were conducted between 2015-2021, and restoration and monitoring efforts are ongoing. Restoration activities by MCFEG, WDFW, and YN are now expanding to include the West Fork (WF) and Middle Fork (MF) Teanaway rivers and fish-bearing priority streams in these forks such as Carlson Creek (tributary to WF).

MCFEG contracted Natural Systems Design, Inc. (NSD) to complete a geomorphic assessment and wetlands inventory and to identify restoration opportunities for the WF and MF Teanaway rivers (Figure 1). This work is a partnership between MCFEG, YN, and WDFW; and restoration objectives for this effort include:

- Increasing and improving available fish habitat for focal species (Spring Chinook, steelhead, bull trout) by increasing perennial channel length, pool frequency, gravel retention and cover.
- Enhancing natural water storage (slowing surface water runoff and increasing alluvial groundwater storage) to augment summer baseflows
- Improving and/or increasing wetland habitat
- Increasing floodplain connectivity and frequency of engagement
- Increasing hyporheic flow pathways to improve stream temperature
- Improving stream habitat suitability for beaver

NSD completed a geomorphic assessment and wetlands inventory for the Middle and West Fork Teanaway rivers and identified and evaluated restoration opportunities with MCFEG, YN, and WDFW in 2021. This report documents NSD's geomorphic assessment work and restoration opportunities prioritization for the WF and MF Teanaway. NSD has prepared a separate wetlands inventory report to support the prioritization of restoration opportunities and ultimately the completion of project permit applications.

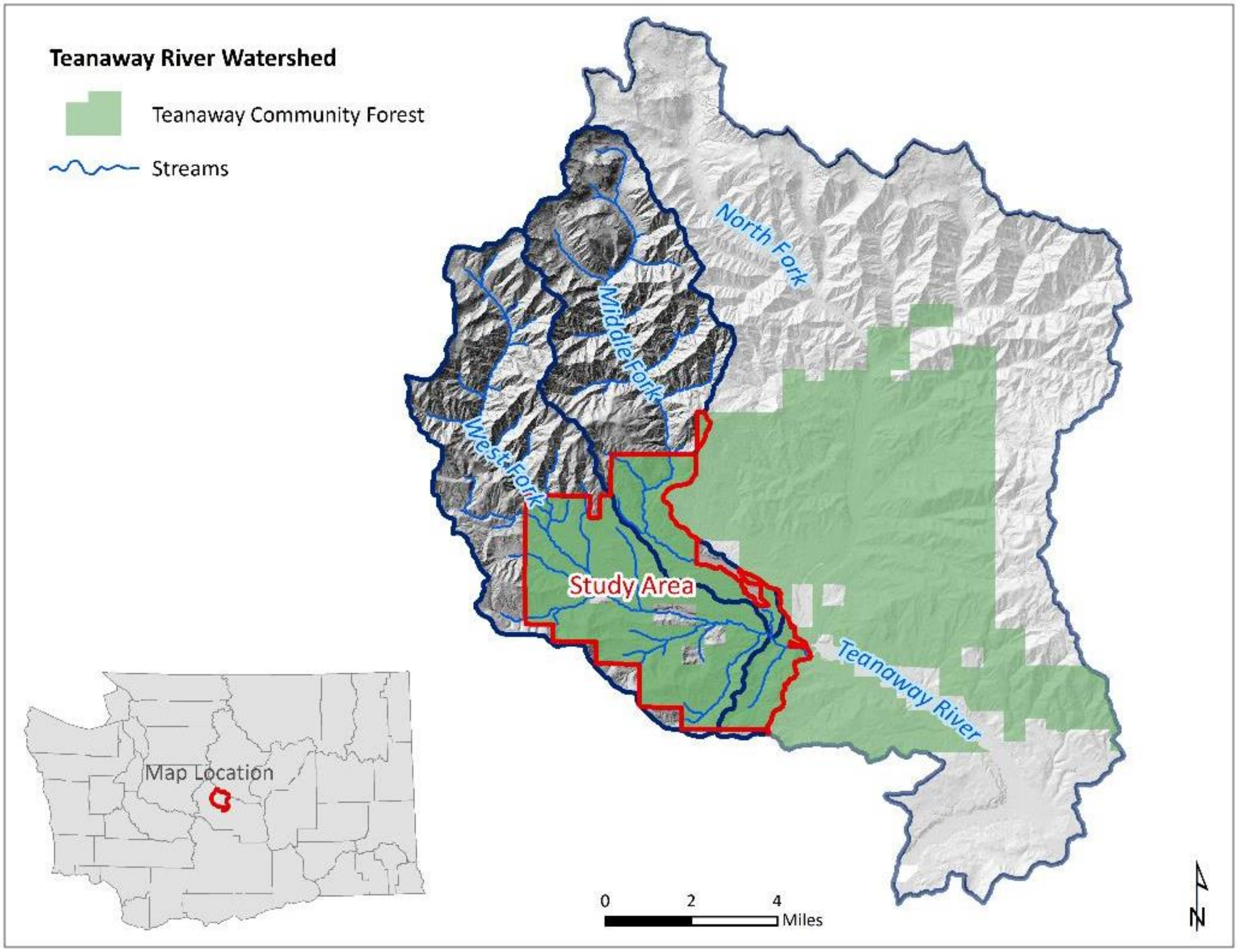

Figure 1. Middle and West Fork Teanaway study area (red outline) within the Teanaway Community Forest (green shaded area)

The Lower Teanaway valley is largely private ownership, and upper basin is in Okanogan-Wenatchee National Forest.

2. WATERSHED SETTING & HISTORIC CONDITIONS

The Teanaway watershed is on the east slope of the Cascade Mountains in central Washington State (Map 1). The WF and MF Teanaway within the TCF are the primary focus for this assessment, and flow generally east and southeast from the Cascades to their confluence with the NF Teanaway, which then becomes the Teanaway River before flowing into the Yakima River near Cle Elum. The Teanaway watershed covers 206 mi^2, roughly 95 mi^2 of which is in the NF drainage, with the WF and MF spanning 39 and 30 mi^2, respectively (Table 1). Between the MF and WF, the WF has lower relief and mean watershed slope, with less of the watershed having slopes greater than 30%. Lower gradient areas largely correspond with the broad alluvial valleys of the mainstem forks, and with the smaller alluvial valleys of several named tributaries (Corral, Sandstone, Dingbat, and Carlson creeks) that drain the southern portion of the study area. Tributaries to the MF are mostly higher gradient, confined valleys. Both the MF and WF valleys are low gradient within the study area, with high potential for restoring alluvial water storage and in-stream habitat. Low gradient tributaries to the WF also have high potential for restoring water storage.

Table 1. Watershed characteristics for the Teanaway River forks

WATERSHED METRIC	WEST FORK TEANAWAY	MIDDLE FORK TEANAWAY	NORTH FORK TEANAWAY	TEANAWAY AT YAKIMA RIVER CONFLUENCE
Basin Area (mi^2)	39	30	95	206
Minimum Elevation (ft)	2250	2250	2200	1810
Maximum Elevation (ft)	6400	6440	7360	7360
Mean Elevation (ft)	3500	4150	3970	3640
Relief (ft)	4150	4190	5160	5540
Mean Slope (%)	35	46	41	37
Watershed with Slopes > 30% (%)	55	80	71	60

2.1 Watershed Geology

The Teanaway watershed has been shaped by volcanic, tectonic, and glacial activity, and surface geology in the MF and WF watersheds is broadly divided into three geologic regions that shape erosional processes and the composition of sediment sources in the MF and WF (Map 2). The northern-most portion of the basin (North of Hex Creek in the WF and Malcolm Creek in the MF) is mostly underlain by highly erodible Tertiary sedimentary rocks (Swauk Formation sandstone), with small areas of Jurassic sedimentary rocks in the vicinity of Medra Creek (Tabor et al., 1982, 2000). The middle portion of the watershed (from Hex Creek to Corral Creek in the WF and roughly from Malcolm Creek to RM 5 in the MF) is underlain by older, erosion resistant basalt rocks within the Teanaway formation (Tabor et al., 1982). The lower portion of the WF and MF watershed is underlain by more erodible Roslyn formation sandstones, with some interbedded siltstones and shales. The broad river valleys of the MF and WF were carved by glaciers, creating glacial moraines and kame terraces in some locations, with glacial drift deposits in the mainstem MF and WF valleys and lowlands (Tabor et al., 1982). The most prominent of these drift deposits in the study area is side stream alluvium of the Swauk Prairie subdrift, which forms terraces approximately 100 ft above the modern alluvial valley bottom (Tabor et al., 1982). These terraces are composed of sand, gravelly sand, and sandy gravel and are prone to mass wasting, which is evident along the valley margins throughout the MF and WF. Quaternary alluvium spans much of the valley bottom in wider (800 – 1500 ft) alluvial portions of the Teanaway forks. Sandstone bedrock under these Quaternary deposits is exposed in numerous places in the mainstem MF and WF where the channel has incised or eroded laterally into bedrock.

Bedload sediments in the study area originate predominantly from the Teanaway basalts and Swauk formation sandstones of the upper watershed, as Roslyn formation sandstone rapidly erodes to sand-sized particles (Schanz et al., 2019). Tributaries to much of the study area (below RM 4.8 on the MF and 7.4 on the WF) drain only Roslyn sandstones and thus contribute little to no bedload material to the Teanaway mainstems (Schanz et al., 2019). These highly erodible bedrock materials are currently not retained within the alluvial valley bottoms of the MF and WF due to an overall lack of channel roughness and limited hydraulic complexity, thereby increasing channel incision and degradation of water storage and in-stream habitat.

2.1.1 Ecological Setting & Historic Conditions

The Teanaway River, within the TCF is predominantly low relief, gentle terrain, with broad historic floodplain valley bottoms, at low- to mid-elevations with a dry climate. The TCF encompasses the watershed's transition from steeper, wetter mountainous headwaters of the Teanaway to broader alluvial river valleys with riverine and meadow wetlands and diverse plant assemblages, and this gradient or ecotone corresponds with high fish and wildlife biodiversity (Winford & Meyer, 2017).

Plant communities not altered by human activities would consist of stands dominated by Ponderosa pine, lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), and/or Douglas fir (*Pseudotsuga menziesii*). Shrub communities would be diverse and vary with elevation, aspect, canopy cover, and duration of soil saturation and seasonal inundation. Dry upland communities would typically support redstem ceanothus and snowbrush (*Ceanothus sanguineus; C. velutinus*), serviceberry (*Amelanchier alnifolia*), blue elderberry (*Sambucus cerulea*), red elderberry (*Sambucus racemosa*), and birch-leaved spirea (*Spiraea betulifolia*) (Franklin and Dyrness 1988).

More than half of the WF and MF watersheds are forested, predominantly with Douglas fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*), with some subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) in the upper basin. Grand fir (*Abies grandis*), Engelmann spruce (*Pinus engelmannii*), and western white pine (*Pinus monticola*) are generally less common tree species, however grand fir has expanded over the past century due to fire suppression (Amec, 2013; Bommarito, 2019). The riparian community is commonly dominated by a mixture of disturbance and moist soil adapted deciduous species, including various species of willow (*Salix* spp.), black cottonwood (*Populus trichocarp*a), Sitka alder (*Alnus viridus spp. sinuata*), Douglas maple (*Acer glabrum var. douglasii*), and vine maple (*Acer circinatum*), with widely scattered conifers (e.g., western red cedar [*Thuja plicata*], Sitka spruce [*Picea sitchensis*] and/or Engelmann spruce, grand fir, and Douglas fir); open areas, including scrub-shrub and emergent wetlands contain a typically diverse assemblage of deciduous shrubs, interspersed with grasses, sedges, rushes, and forbs.

The species and size of riparian vegetation directly influences the impact it has on river system functions. Often only coniferous species such as spruce, cedar, pine, and Douglas fir, as well as some black cottonwoods, can grow large enough to resist the forces of the river and remain stable enough to hold banks and form logjams. These trees become key pieces that are stable within the stream channel during flood flows. Smaller species such as alder and young trees, are typically not large enough to provide these functions. Thus, it is important for trees to be able to grow large enough to function properly as structural components within the riparian forest ecosystem. Pastured lands provide almost no structural or habitat functions to river systems as grass roots are not deep enough to stabilize banks, they provide no shade, and cannot act as a source of large wood to the stream. Pastured areas do at least allow for groundwater recharge and dissipation of flood energy, and are preferable to floodplain encroachment by roads and residential development, which are widespread in privately owned lands in the MF valley.

The Teanaway watershed historically had a dry, open Ponderosa pine forest with a high frequency, low severity fire regime that maintained open areas below the tree canopy and reduced ground and ladder fuels (Bommarito, 2019). Trees with diameter greater than 4-5 ft were not uncommon in the surrounding forest (Figure 2, Henderson, 1990). Low gradient streams, wet meadows and wetlands were abundant due to sizable beaver populations and accumulations of in-stream large wood (GLO, 1900; Bryant & Parkhurst, 1950). Geologist and geographer Israel Cook Russel's journal notes from c. 1892 in the Teanaway note that the river was completely diverted by a logjam, "with drift-wood to a depth of twenty feet for a distance of some three hundred yards" (Russell 1989, p. 243). These channel-spanning "valley logjams" (Abbe and Montgomery 2003) would have been a dominant mechanism influencing valley morphology within the Teanaway watershed. Buried logjams on terraces in both the MF and WF also provide evidence that abundant large wood accumulations were present prior to Euro-American contact, trapping sediment and redirecting the river to form multiple channels (Schanz et al., 2019).

The Teanaway (named after Chief Ten-a-weisn, or 'place of fish and berries') has been used by the Kittitas Band of the Yakama people for food gathering, hunting, and fishing for millennia (KCCC, 1989). Permanent Native settlements in Kittitas County are documented back to at least 4600 B.C.E., and legends describe the upper Yakima River basin as being carved by the thrashing of a battle between Wishpoosh (a giant beaver god) and Coyote, highlighting the importance of beaver to the region and its Native peoples (Deichl et al., 2011). The Yakama bands using the upper Yakima region were considered semi-nomadic, utilizing cyclical vegetation zones for food gathering, hunting, and fishing at different times throughout the year (Deichl et al., 2011). Historical reports described healthy salmon runs in the Teanaway prior to widespread industrial logging beginning in the early 20th century (Bryant & Parkhurst, 1950). The area continues to be important in the seasonal round of resource gathering for Native people.

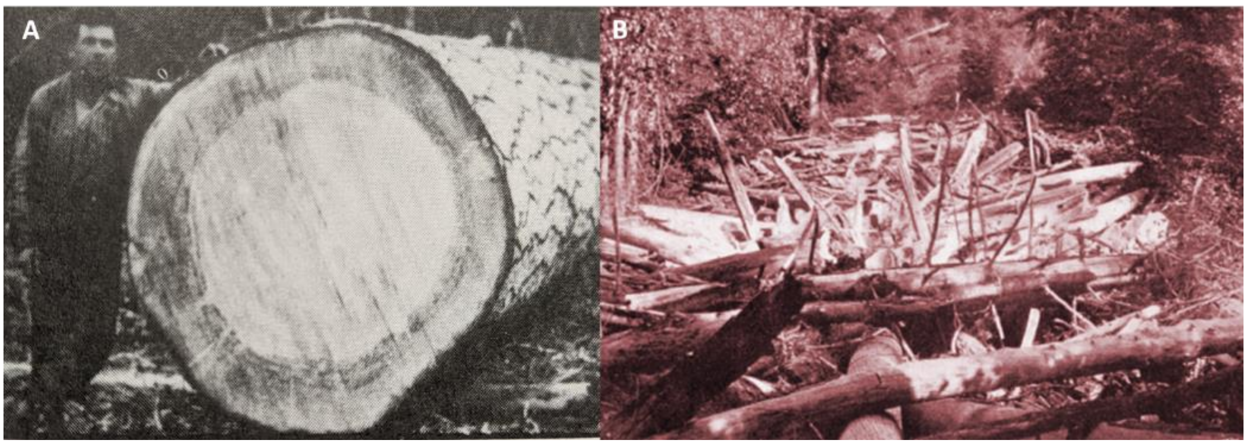

Figure 2. (A) 5.5 Ft Diameter Ponderosa Pine in the Nearby Swauk Creek Basin in 1931

Figure 2. (B) valley[1] Logjam in the MF Teanaway, circa 1892

Natural logjams retained alluvial sediments and spread water out over adjacent floodplains. Russell, I. C. 1909. Plate XII. p.239. Historic logging cleared almost all of the large trees from the valley bottoms.

3. HUMAN DISTURBANCES

3.1 Current Land Use

The MF and WF Teanaway watershed is split roughly evenly between the TCF and Okanogan- Wenatchee National Forest (OWNF), with private land ownership mostly limited to parcels in the lower mainstem forks. Roughly 50% of the watershed is forested, but large swaths of the lower WF and MF valley bottoms have been cleared for hay farming and residential development. Some areas previously cleared by logging or fire disturbance have been maintained as open grassland meadows for grazing. Portions of the watershed are still actively grazed and harvested for timber. In many places along the mainstem forks, the Teanaway has been confined to a small portion of its historic floodplain by push-up dikes, roads, historic railway grades, and artificial drainages (KCSMP, 2013). These impacts have limited the rivers' natural ability to create and sustain habitat through floodplain engagement, large wood recruitment, and the formation of floodplain wetlands.

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[1] "valley logjams" are channel-spanning accumulations of stable wood that aggrade river beds and can re-direct channels, influencing the topography of an entire valley bottom (Abbe and Montgomery 2003).

3.2 Logging & Forest Management

Intensive logging of the Teanaway watershed began in the 1880s, and Cascade Lumber purchased a large block of forested land in 1903 (Henderson, 1990; Amec, 2013). Through 1915, much of the logging was concentrated in the upper watershed, with logs transported to the MF and WF and then floated down to the Teanaway to mills along the Yakima River. Earthen and wooden splash dams were used to rapidly transport logs downstream, scouring the river channel with a torrent of logs and water (Figure 3). Remnants of these earthen splash dams are visible in lidar data such as near RM 4 in the WF (Figure 4). Natural logjams and in-stream large woody material (LWM) were typically removed to expedite downstream transport (Mayo et al., 2009), exacerbating the impacts of reduced large wood supply on in-stream wood loading. Splash damming contributed to more than 6 ft of incision into bedrock in the MF and WF, creating floodplain terraces perched 10-20 ft above the channel and reducing the active channel corridors of the MF and WF by 20 and 53%, respectively (Schanz et al., 2019). In the lower WF, the channel has incised more than 20 ft through Roslyn formation sandstone bedrock (Collins et al., 2016). Estimates of bedrock incision driven by splash damming are as high as 0.9 inches per year in the MF and WF, which is roughly 20 times higher than erosion rates during the late Holocene (Schanz et al., 2019). Splash damming and timber harvest greatly reduced in-stream wood loading and alluvial sediments, creating a positive feedback for high energy, sediment mobilizing runoff and ongoing incision wherein bedload and large wood material are easily evacuated from the river corridor (Collins et al., 2016).

With construction of dams in the upper Yakima River and the expansion of railroad, rail transport of logs replaced log drives and splash damming by 1915 (Henderson, 1990). From 1915 to 1930, railways were constructed up the valleys of nearly every major tributary to the Teanaway and used to transport logs to Cascade Lumber Company mills in Yakima (Figure 5; Henderson, 1990). The Casland railyard and associated structures extended over much of the valley bottom near the confluence of the MF and WF with the NF Teanaway (Figure 5). The largest trees (Ponderosa and tamarack) were selectively harvested in the early 20th century, and the Cascade Lumber Company returned to previously logged stands in the 1940s to harvest more timber (Henderson, 1990; Bommarito, 2019). By this time, logging trucks had replaced railcars for transporting logs to the mill, and logging roads traversed much of the Teanaway watershed. Aerial imagery from 1954 shows the widespread extent of timber harvest and logging roads in what is now the TCF (Figure 6). Many of these logging roads are still in use within the WONF and TCF. Boise Cascade Company and later American Forest Holdings repeatedly harvested large tracts of forest prior to the establishment of the TCF in 2013. Active and remnant railroad and road alignments constrain the MF and WF channels to straightened flowpaths in many locations, thereby increasing channel gradient and exacerbating channel incision.

Repeated logging of the largest timbers in the Teanaway removed almost all of the original large Ponderosa pines and tamarack in the watershed, which naturally grow in more open, park-like stands typical of the eastern slopes of the Cascades. Subsequent replanting and regeneration of a higher stem density Douglas Fir forest has further altered forest structure and composition in the MF and WF watersheds, benefiting more shade tolerant species. Within privately owned forest lands and the OWNF, decades of fire suppression also increased stem density and changed species composition from fire-tolerant Ponderosa to a more shade tolerant fir-dominant forest (Bommarito, 2019). The combination of logging impacts and fire suppression has made forested areas of the Teanaway more vulnerable to disturbances from fire and insect outbreaks and dwarf mistletoe. Spruce budworm has impacted 61% of the Teanaway basin, affecting 11.4 mi^2 of the WF and 10.8 mi^2 of the MF (Amec, 2013 and references therein). Increases in fire severity from greater understory fuel loading and a higher stem density have also resulted in large fires in the Teanaway, including the Jolly Mountain fire of 2017, which burned a total area of 58 mi^2 and roughly 32 mi^2 within the WF and MF watersheds. The combined effects of tree kill from fire and insects has potential to dramatically increase loading of smaller (< 8 in diameter) LWM to impacted streams in the watershed (Amec, 2013). Sources of stable, large wood available for recruitment to the channel are currently limited, and smaller diameter logs are unlikely to form stable logjams in the high velocity bedrock reaches of the MF and WF.

Figure 3. Log Drive in the Teanaway River

Sawed logs staged in the channel and then sent downstream through splash damming which created an artificial flood peak laden with logs. To enable wood transport natural wood accumulations in the rivers were removed. These events severely eroded channels where they occurred. Photo from CWU Library.

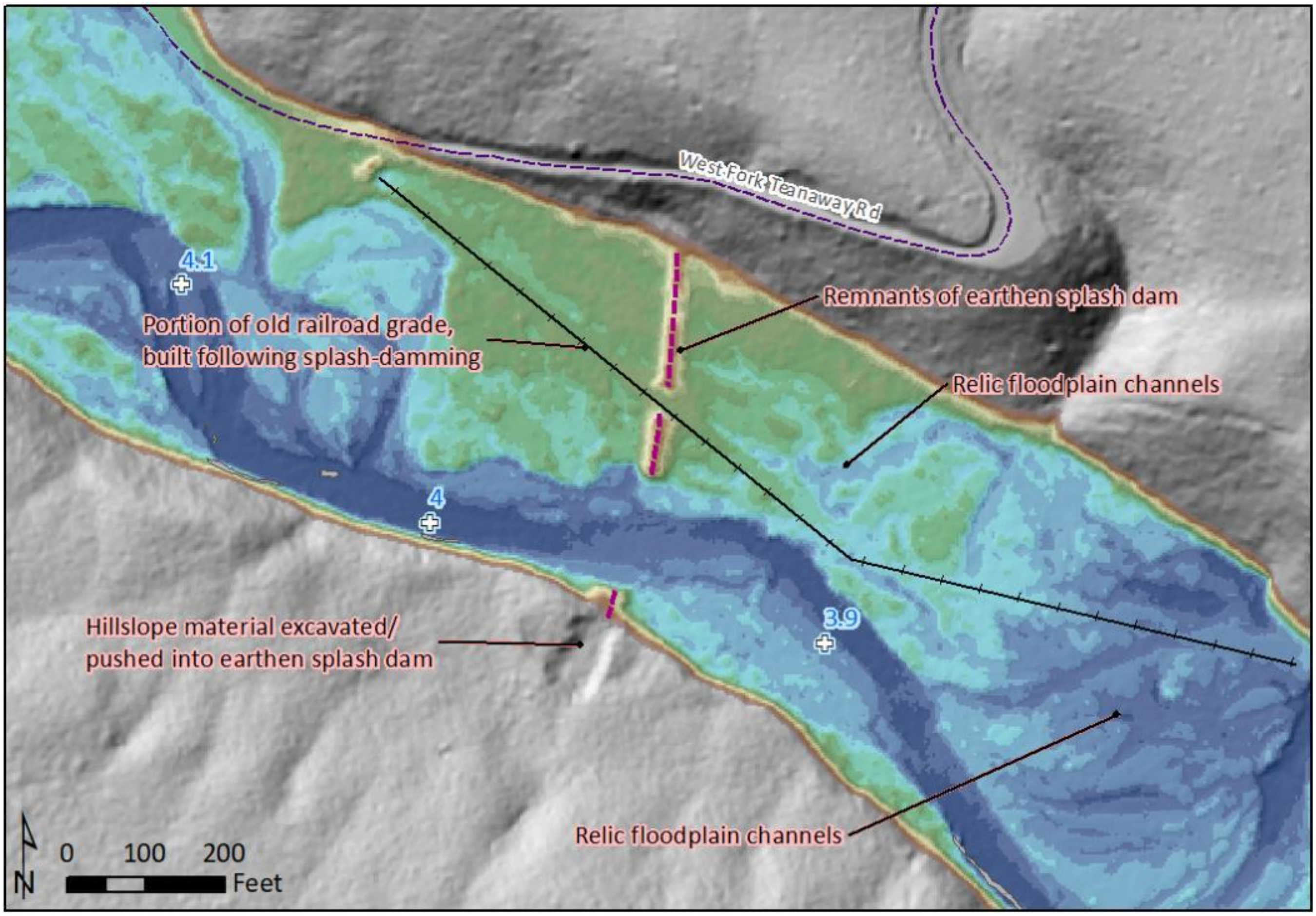

Figure 4. Remnants of Old Earthen Splash Dam and Later Remnants of Railroad Grade Used for Logging in the West Fork Teanaway

The lack of any evidence of a road grade on the south side of the valley and historic accounts of splash damming support interpretation. Trees growing on the dam are about 80-100 years old. Relic channel meanders in valley bottom upstream and downstream of dam indicate entire valley bottom was once engaged by the river. Constraining the river along the south margin of the valley reduced its length and further contributed to channel incision.

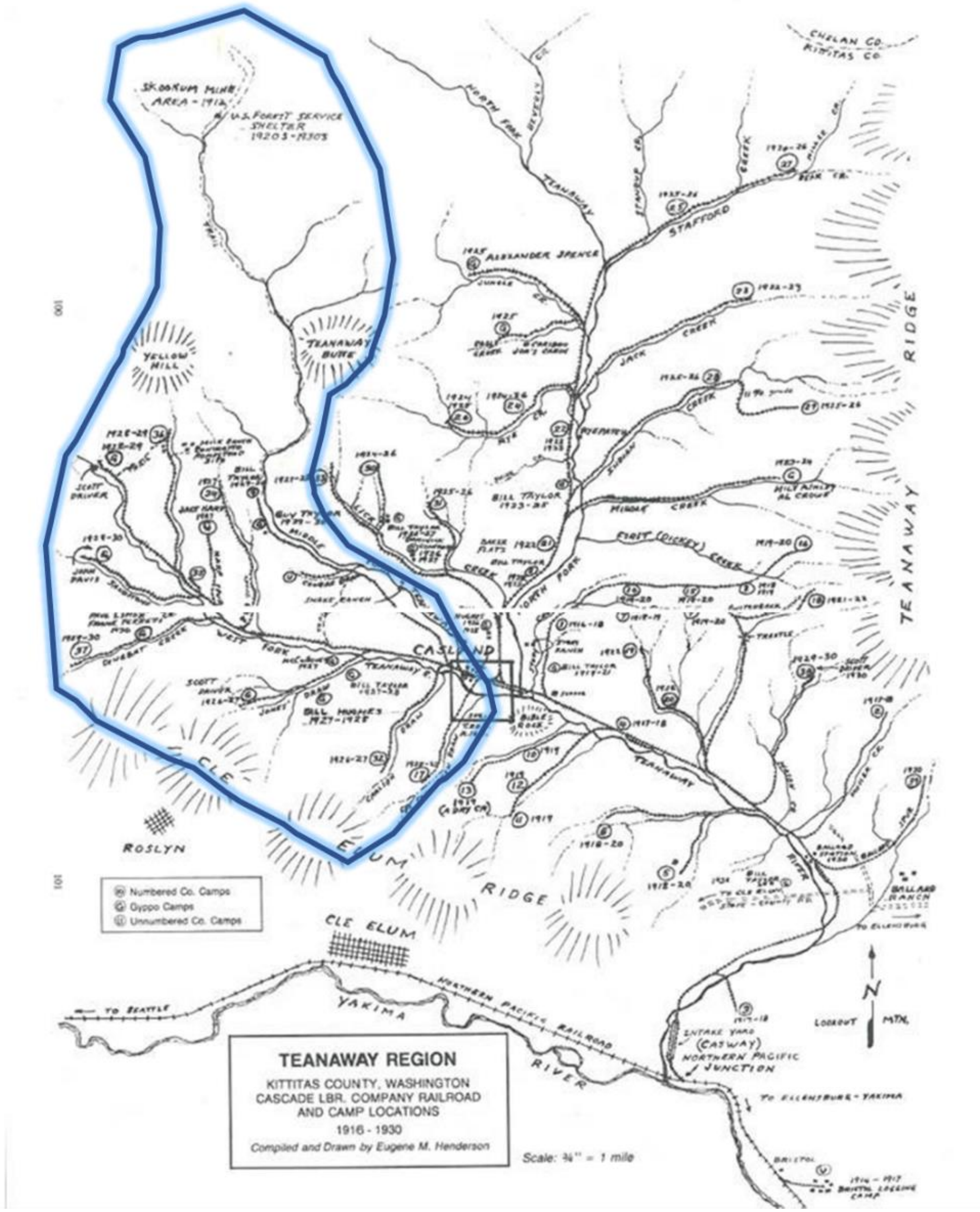

Figure 5. Map of Railroads, Logging, and Mining Camps

Approximate extent of MF and WF watersheds outlined in blue. Historic logging was done from ridge to stream, so very few old growth trees remain in these watersheds. Compiled and drawn by E. Henderson (1990)

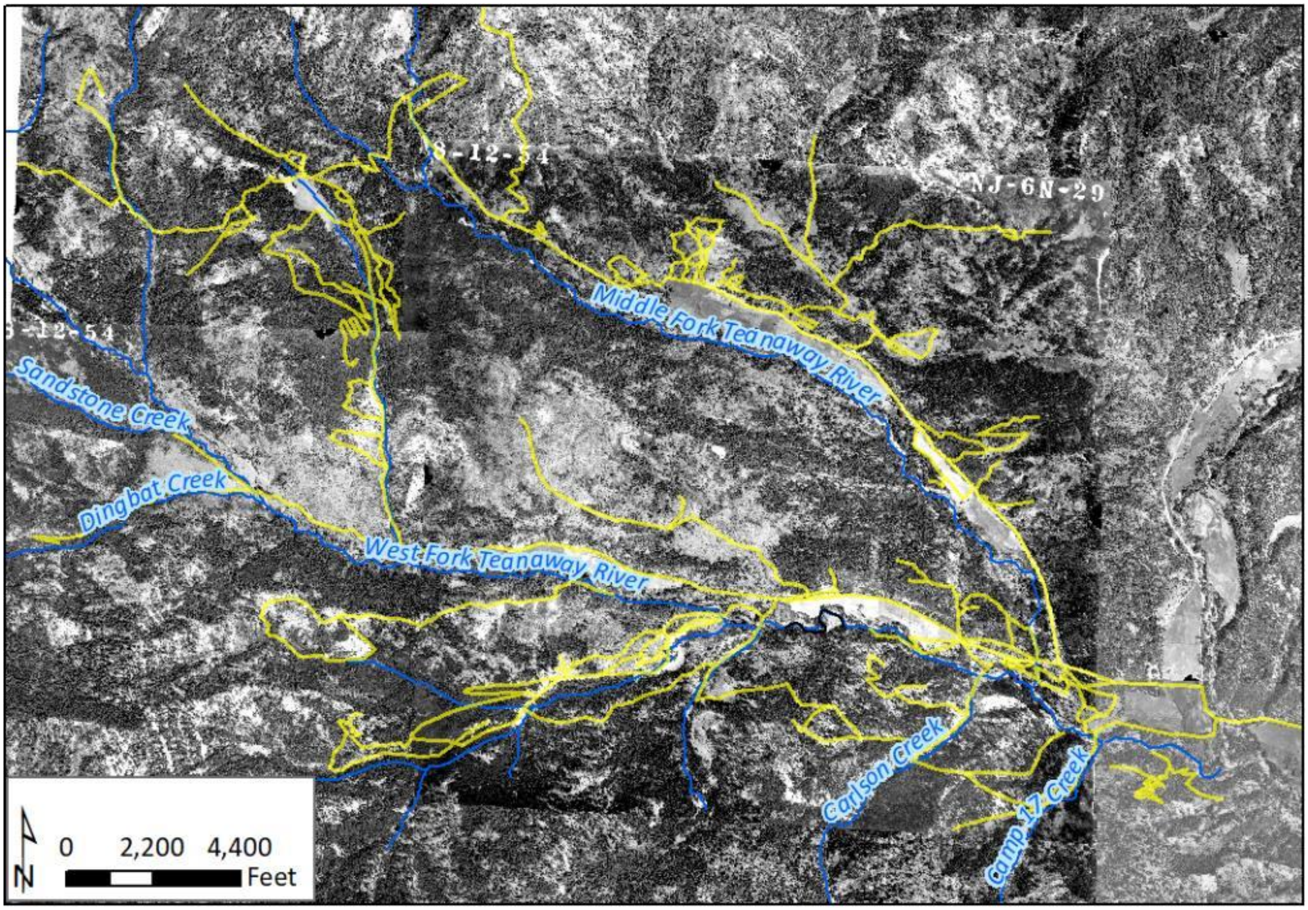

Figure 6. 1954 Aerial Imagery of the MF and WF Teanaway

Large blocks of the watershed were cleared by timber harvest, with valley bottoms mostly denuded of trees and actively used for agriculture. Logging roads (highlighted in yellow) are prevalent throughout much of the watershed by 1954. Photos from CWU Libraries.

3.3 Grazing

The majority of accessible land within the Teanaway has been grazed by sheep and cattle, beginning in the early 20th century (Amec, 2013). At one time, as many as 15,000 sheep grazed in the Teanaway in the early 20th century (Bommarito, 2019). Heavy grazing has had two main effects on the Teanaway ecosystem: reducing low ground fuels that promote expansive low severity, high frequency fires (Bommarito, 2019), and by impacting bank stability and riparian vegetation establishment where livestock access stream channels. Grazing induced fire exclusion has ultimately led to higher stem density and ladder fuel loading in historically fire-prone areas, increasing the risk of high severity fires. Grazing is still active throughout the Teanaway, including in portions of the TCF. Efforts by YN, MCFEG, and WDFW to reduce cattle impacts to riparian areas include exclusion fencing and replanting.

Valley bottom lands, including floodplains, were cleared for farming, primarily hay and grazing. In many of these areas the river channel was straightened and constrained along valley margins, and floodplains were ditched in areas to transform wet floodplain areas to agriculture (evidence in Indian Creek (Section 16)). These areas lack in-stream structure and have minimal riparian forest areas for shading the stream channel.

3.4 Trapping

Beaver trapping throughout the western U.S. in the latter 19th century and early 20th century nearly extirpated beaver from many watersheds and dramatically altered the storage and movement of water on the landscape (Pollock et al., 2015). Fur trapping in the upper Yakima basin began in roughly 1833, with fur traded by both Euro-American trappers and the Kittitas and Klickitat peoples at Fort Nisqually (Deichl et al., 2011). Beaver were functionally extirpated from the region by 1850, and unregulated trapping of beaver continued well into the 20th century. Reductions in beaver populations in the upper Yakima have been identified as one driver of declines in Middle Columbia River steelhead and the loss of wet meadows and wetlands in the Teanaway (KCSMP, 2013). WDFW and MCFEG relocated beaver to the Teanaway between 2011 and 2016 (Babik & Meyer, 2015). Beaver act as ecological engineers, slowing and raising the water surface, creating floodplain wetlands, and maintaining wetted forest openings. These habitat features can benefit fish, aquatic invertebrates and other food sources for fish and wildlife, and stream water quality.

3.5 Mining

Mining within the Teanaway began in the early 1900s (Henderson, 1990). The Skookum Mine in the upper MF was extensive and is included in mapping by Henderson (Figure 5; 1990). The Skookum site operated through 1916, with copper, gold, and silver material processed at a nearby mill. A US Forest Service station was later built at the mill site and used in the 1920s-1930s (Henderson, 1990). The Kangley and Gallagher mines were both located in drainages to the NF Teanaway, with gold and chrome mined through the latter half of the 20th century (Amec, 2013). Mounds of side cast material, tailings, small railways, and old mining equipment are still present in portions of the upper MF and NF watersheds. In some locations, these remnant features constrain stream channels and the impact of tailings on water quality in the Teanaway is not known.

3.6 Roads

Logging roads throughout the watershed expanded rapidly in the first half of the 20th century. In some places, road grades coincided with abandoned railroad alignments, occupying elevated berms across the floodplain in both the MF and WF and in several larger tributaries. In other locations, new road grades were created adjacent to the railway prisms, further disconnecting floodplain areas. There are numerous places in both the MF and WF where modern day road alignments cut off old meander channels or low-lying floodplain wetland areas. In some reaches, the road is aligned against the valley margins along the toe of the slope. In these locations, the road intercepts surface and groundwater flowing downslope and into the valley, generally concentrating surface runoff into roadside ditches and through culverts. Upland logging roads and roads managed by WADNR or the USFS traverse most hillsides in the Teanaway basin, and in some locations these roads increase soil erosion and landslide activity (e.g. MF Teanaway Road between the WF and MF). There are over 138 miles of active roads within the TCF in the MF and WF watersheds, which span both mainstem valleys and nearly every tributary in the basin.

Human disturbance is credited with the loss of alluvial sediment and bedrock incision within the West and Middle Forks of the Teanaway. The principal impacts were splash damming, wood removal and channelization. One positive factor is the lack of dams within the watersheds that cut off sediment supply. The rivers have bed material but the simplified bedrock channels simply have too much sediment transport capacity to retain it. Restoration actions such as channel-spanning wood accumulations will provide the roughness necessary to reduce transport capacity and trap sediment. Aggrading the channel will also disperse and reduce the depth (and shear stress) of high flows that continue to scour the river bed.

4. HYDROLOGY

4.1 Watershed Climate

The Teanaway watershed has hot (81 °F), dry summers and cold (25°F), snowy winters, with mean annual precipitation ranging from 20 in yr^{-1} in the lower basin to 90 in yr^{-1} in the upper watershed, 80% of which falls as snow between October and March (Amec, 2013; PRISM, 2021). The WF receives an average of 51 in yr^{-1} and the MF receives an average of 56 in yr^{-1} (PRISM, 2021). Temperatures are lowest in December through January and highest in August, with the greatest precipitation falling in November, December, and January (Figure 7).

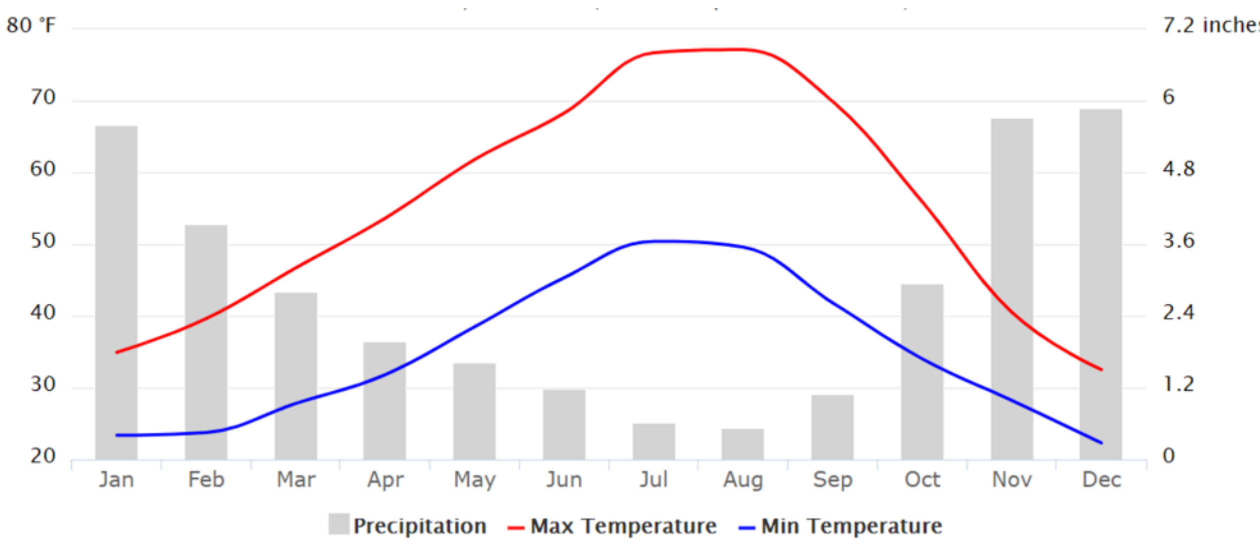

Figure 7. Temperature and Precipitation (1981-2010 Normals) at the Confluence of the MF and WF Teanaway

Data & plot from Hegewisch & Abatzaglou.

4.2 Streamflow

Streamflow information for the Teanaway has been measured at multiple locations for varying periods of time (

Table 2). The U.S. Bureau of Reclamation gage (TNAW) downstream of the Teanaway forks has the most complete flow record and was used for the bulk of the hydrologic analyses (e.g., flow exceedance, annual hydrograph, flow statistics), however all data were compared in terms of runoff timing and magnitude to identify errors or patterns associated with diversions or withdrawals between gage locations.

Gage data for the mainstem Teanaway was scaled to the MF, WF, and NF based on contributing drainage area. Based on field measurements during low flow (August 8-9, 2011) conditions, there is evidence that the relationship between basin area and streamflow is non-linear, at least for low flow periods (Figure 8). This is likely driven by higher elevation and snowpack retention in the NF when compared to the WF where field measurements were taken (Figure 9). No flow measurements were collected in the MF during that period. Additional field measurements in the three forks would improve flow scaling from the mainstem gage site. Each of the Teanaway watersheds have unique hypsometric curves showing the cumulative percentage of land as a function of elevation (Figure 9). This is important in understanding percentage of the basins that are likely to receive precipitation as snow or rain.

Table 2. Streamflow Gage Data for the Teanaway River used in Hydrologic Analysis.

SITE	AGENCY	LOCATION	WATER YEARS	DRAINAGE AREA (MI^2)	NOTES
TNAW	USBR	At forks	1909-1915, 1948-1950,1966-Present	172	Most complete record, some winter gaps
12480000	USGS	Below forks	1967-1973	172	
TEAW	USBR	Lambert Road	1998-Present	192	Missing large periods of winter data
39D110	WA ECY	Red Bridge Road	2015-Present	192	Seasonal gage, monitored April - October
12480500	USGS	Below Hwy 970	1909-1914, 1946-1952	200	

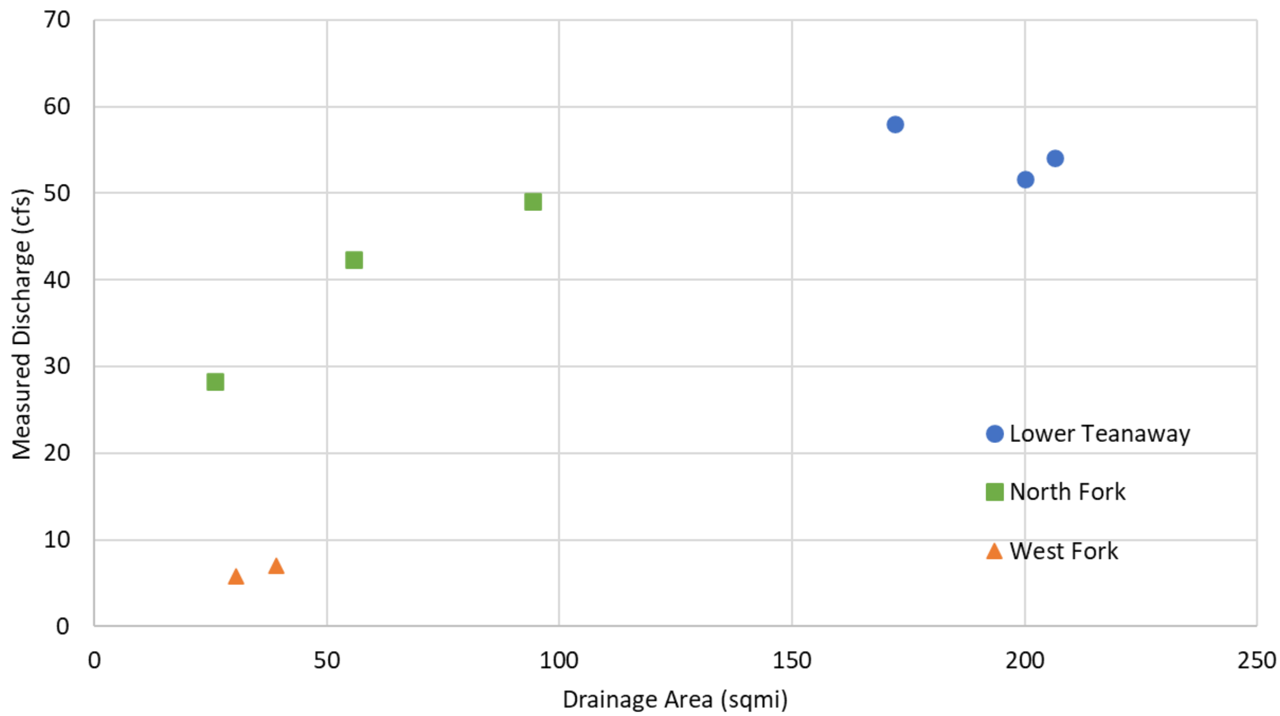

Figure 8. Measured Discharge (August 2011) versus Drainage Area for the Mainstem, NF, and WF Teanaway

Note that WF discharge is much lower than the NF for measurement locations with similar drainage areas, suggesting greater area-weighted flow contribution from the NF during low flow periods.

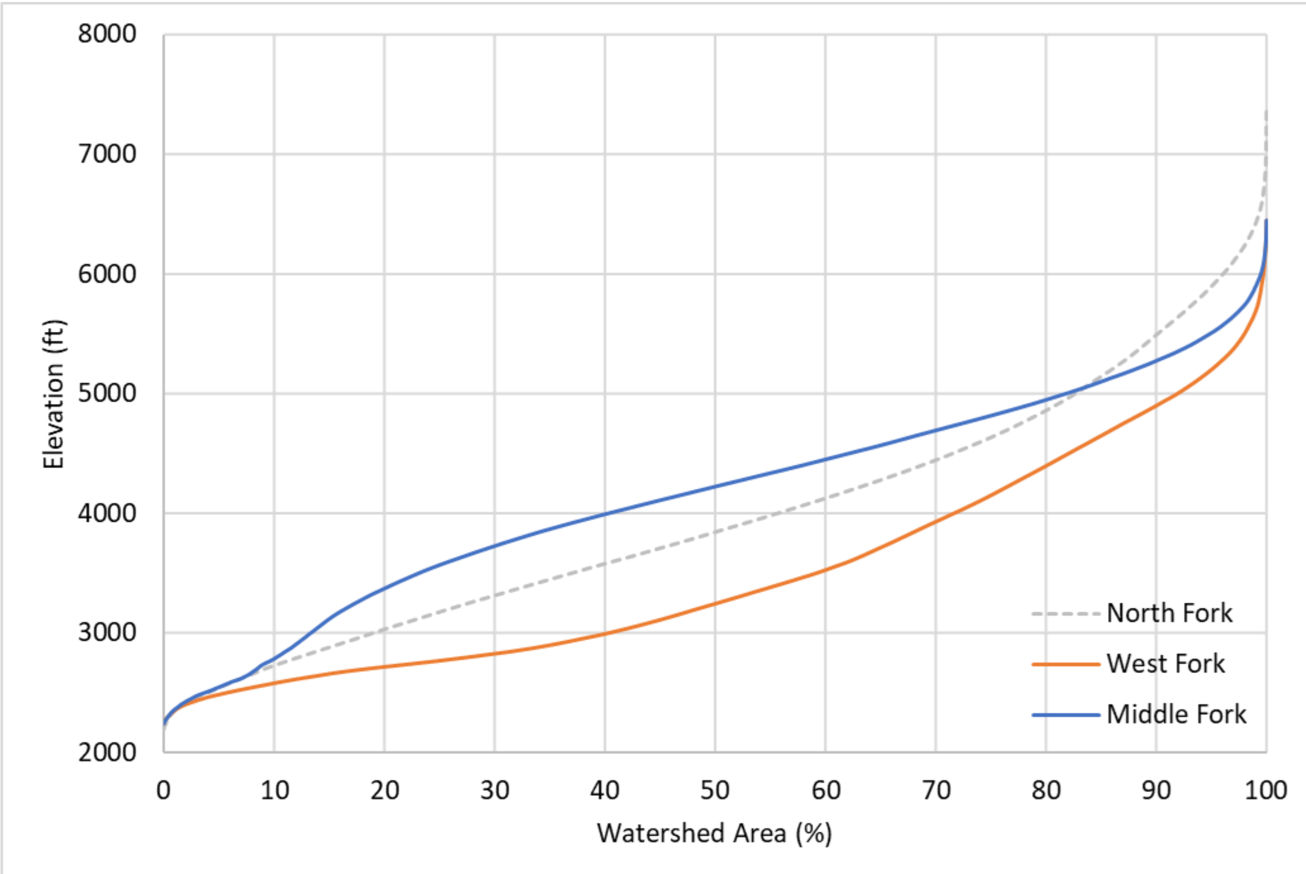

Figure 9. Hypsometric Curves for the NF, WF, and MF Teanaway Watersheds

These curves illustrate potential sensitivity of each watershed to snow versus rainfall precipitation and runoff. Under the historic climate regime each of the basins has been dominated by snow melt. The lower elevations of the West Fork basin make it the most susceptible to rain on snow and rainfall events.

The water year in the Teanaway begins with low flows in October, increasing with fall and winter rains and rain-on-snow events, and then peaking in April through June with snowmelt runoff (Figure 10). Flow exceedance probabilities for the MF and WF were estimated from scaled daily streamflow at the TNAW gage. Flow exceedance indicates the percentage of time (or number of days) a given flow is exceeded in a given water year. Higher exceedance probabilities indicate that a given flow occurs more days during the year, and the 90% exceedance flow is often used to represent summer baseflow. Estimated exceedance flow probabilities for the MF and WF are shown in Figure 11 and summarized in Table 3. Summer low flows are partially reduced by stream diversions for pump and pipeline irrigation systems in the mainstem forks, also impacting thermal conditions (KCSMP, 2013).

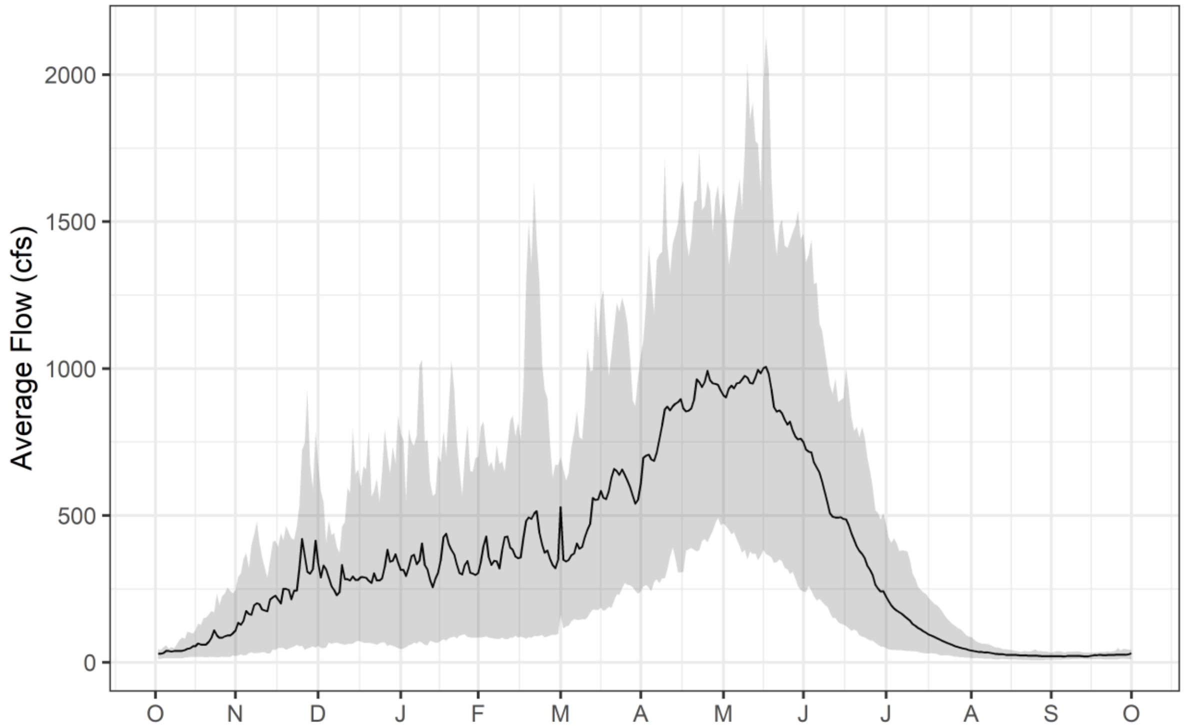

Figure 10. Mean Annual Hydrograph for the Teanaway River at the Forks (USBR TNAW Gage)

Gray bands span 10-90th percentiles.

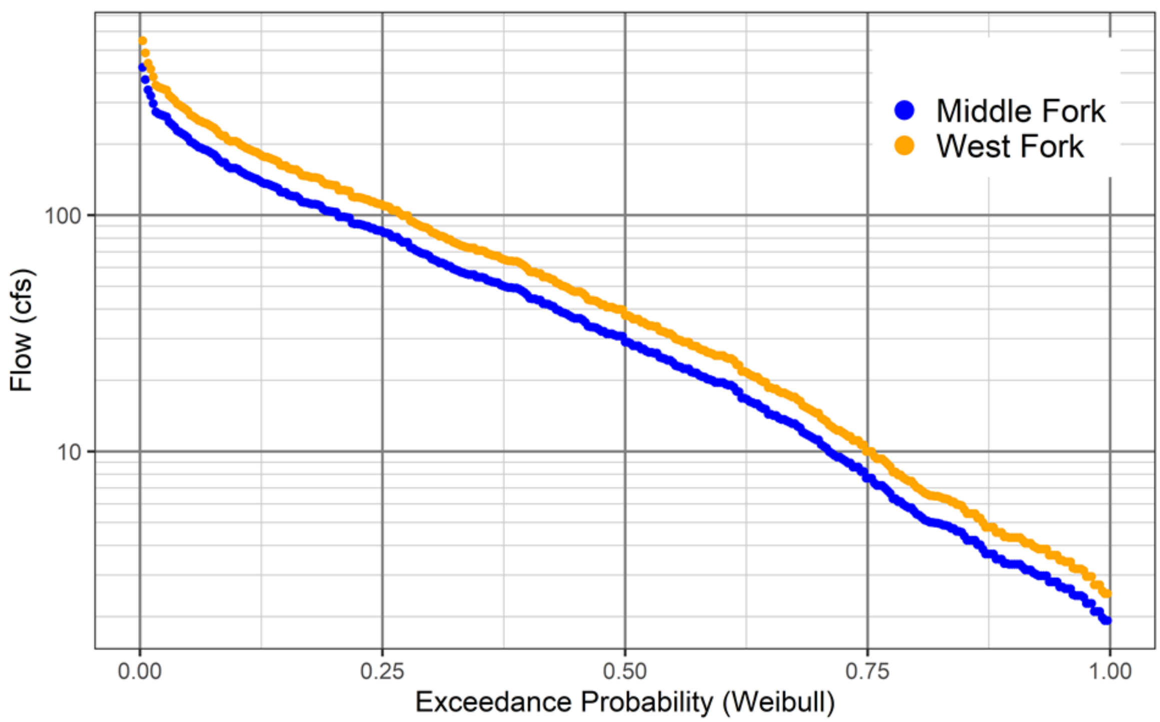

Figure 11. Estimated exceedance flow probabilities for the MF and WF

Scaled from the mainstem Teanaway gage (USBR TNAW)

Table 3. Flow Exceedance Probabilities for the Teanaway and Forks (USBR TNAW Gage Data)

TYPE	TNAW GAGE (CFS)	MIDDLE FORK (CFS)	WEST FORK (CFS)	NORTH FORK (CFS)
3-month exceedance	492	86	112	271
9-month exceedance	47	8	11	26
90% exceedance	19	3	4	10

4.3 Peak Discharge

Annual peak flows in the Teanaway have been intermittently measured at the USBR TNAW gage site since 1969 (Figure 12). Chris Lynch with the USBR extracted the winter (n = 37) and spring (n = 34) peak flow event for each water year, for a total of 71 peak flows. These peaks were then used to estimate peak flow recurrence intervals following USGS Bulletin 17B and a log Pearson III distribution. The resulting peak flow estimates for the mainstem Teanaway at the USBR gage and scaled estimates for the MF and WF are shown in

Table 4. Review of these estimates compared with those derived in USGS StreamStats or on shorter gage records at the USGS or WA Ecology gage sites suggests these peak flow recurrence intervals provide a reasonable estimate of peak flow runoff in the Teanaway.

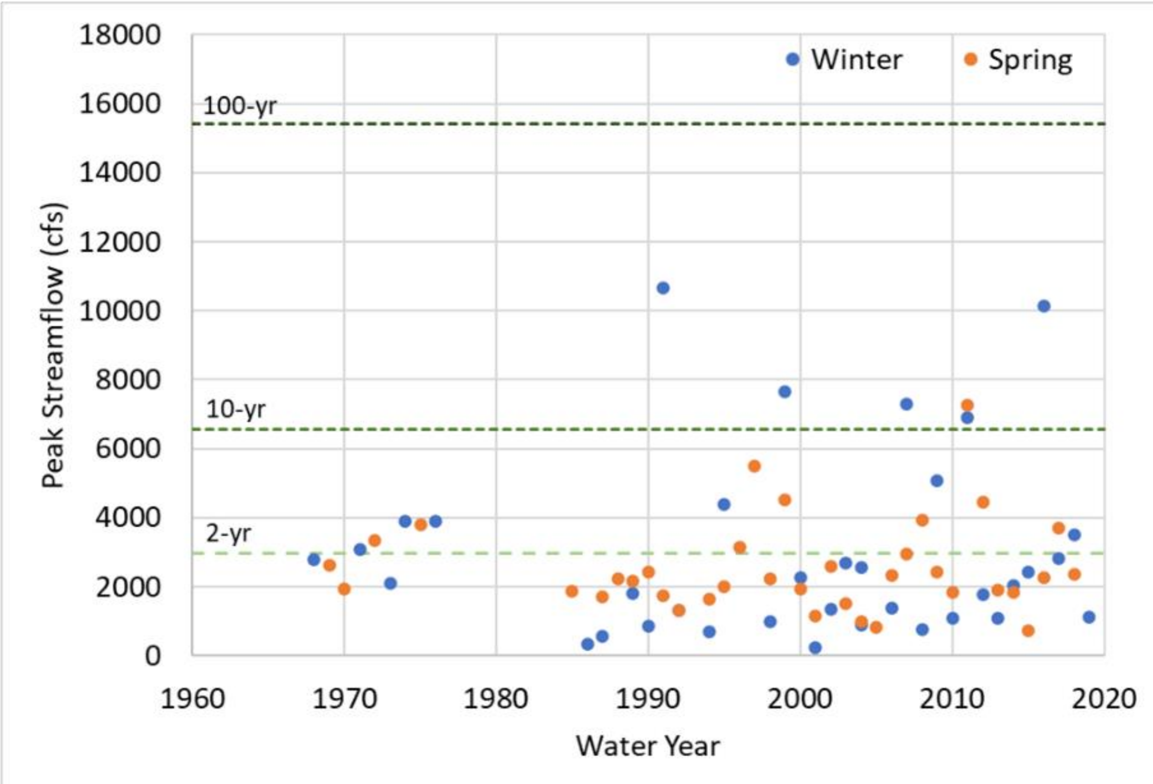

Figure 12. Peak Flows for the TNAW Gage Site Below the Forks

Dashed horizontal lines indicate peak flow recurrence estimates determined by Chris Lynch (USBR).

Table 4. Peak Flow Recurrence Estimates for the TNAW Gage and Scaled Estimates for the Three Forks
Analysis by Chris Lynch

FREQUENCY	RECURRENCE INTERVAL (YRS)	PEAK ESTIMATE AT GAGE (CFS)	MIDDLE FORK (CFS)	WEST FORK (CFS)	NORTH FORK (CFS)
0.01	100	15410	2695	3502	8502
0.02	50	11951	2090	2716	6594
0.04	25	9384	1641	2133	5178
0.05	20	8578	1500	1950	4733
0.1	10	6575	1150	1494	3628
0.2	5	4896	856	1113	2701
0.3	3.3	3973	695	903	2192
0.4	2.5	3460	605	786	1909
0.5	2	2965	519	674	1636

4.4 Snowpack

Snowpack and precipitation in the watershed is measured at the NRCS Sasse Ridge SNOTEL station (#734), located just on the other side (i.e., the west side) of the ridge that delineates the headwaters of the WF Teanaway, with data spanning from 1983 to present. Snow water equivalent (SWE) typically peaks in early April, declining rapidly in April and June (Figure 13). Winter precipitation and snowpack for WY 2021 were above the long-term average and median, respectively. Snowpack for WY 2021 rapidly declined to the long-term median in April and May with warmer than average temperatures and roughly two inches of rainfall over the course of two months. Average April 1st snow water equivalent (SWE) at the Sasse Ridge site has generally seen a significant decline (95% CI) decline of -3.8% per decade since 1985 (Figure 14).

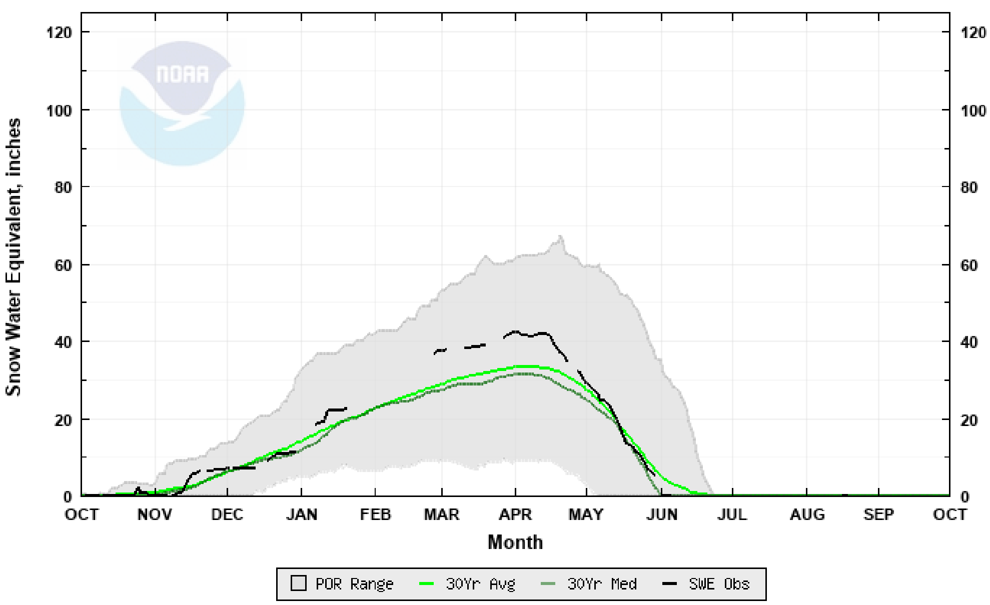

Figure 13. Sasse Ridge SNOTEL Site Data

1983-2010 average, median, and WY 2021 data to date. Data from NRCS, plot from NOAA Northwest River Forecast Center.

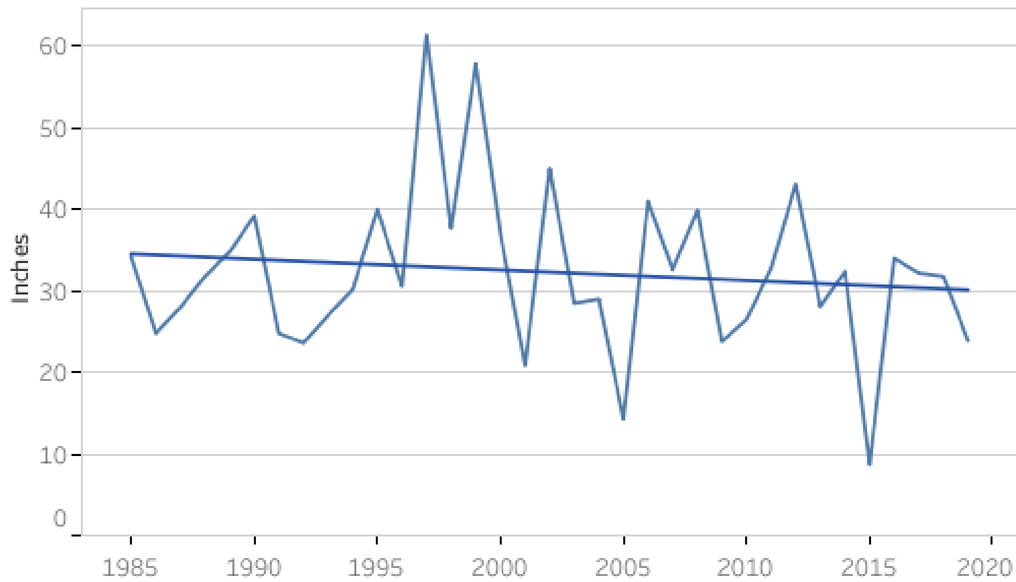

Figure 14. April 1 Snow Water Equivalent for the Period from 1985 - 2019

Data and plot from UW CIG PNW Temperature, Precipitation, and SWE Trend Analysis Tool; data from US Historical Climatology Network.

4.5 Stream Temperature

Stream temperatures in the MF and WF were measured via thermal infrared (TIR) remote sensing in 2001 (Watershed Sciences, 2002). Longitudinal temperature data are shown in Figure 15 and Figure 16 below, along with land ownership and thermal tolerances for spring Chinook and steelhead (Richter & Kolmes, 2006). For both the MF and WF, temperatures generally increase as water moves downstream, with the exception of the confined, canyon-like segment in the MF, where temperatures are 4 °C lower than upstream. Watershed Sciences noted a cold side channel above the confined reach, which may be attributed with a floodplain spring brook (Watershed Sciences, 2002). Thermal variability in both the MF and WF is shaped by cold tributary inflows and subsurface exchange within the floodplain, however Watershed Sciences did not sample tributaries to the WF. Review of longitudinal data for the WF shows several locations where coldwater inflows or groundwater exchange reduce stream temperatures in the mainstem WF, such as below the confluence with Corral Creek (RM 6.5) and near RM 1, where several small, unnamed tributaries or springs enter the valley bottom from the north and south (Figure 16). Portions of the lower MF and WF both exceeded thermal tolerances for Chinook during the late summer period when TIR data were collected. Spawning spring Chinook using the MF and WF would need to migrate upstream to cool water habitat from March through May when water levels are higher and temperatures are lower than in the warm summer months (Keefer et al., 2018).

Increasing shade and hyporheic exchange will both reduce the rate at which water temperatures increase downstream. Increasing shade is not just a function of restoring mature riparian trees, but restoring channel anabranching by establishing forested islands within the river. This narrows channel widths and provides a much faster means of increasing shade. Anabranching is also one of the most effective means of increasing hyporheic exchange due to the greater cumulative edge length of the channels, their more complex morphology and greater wood retention potential.

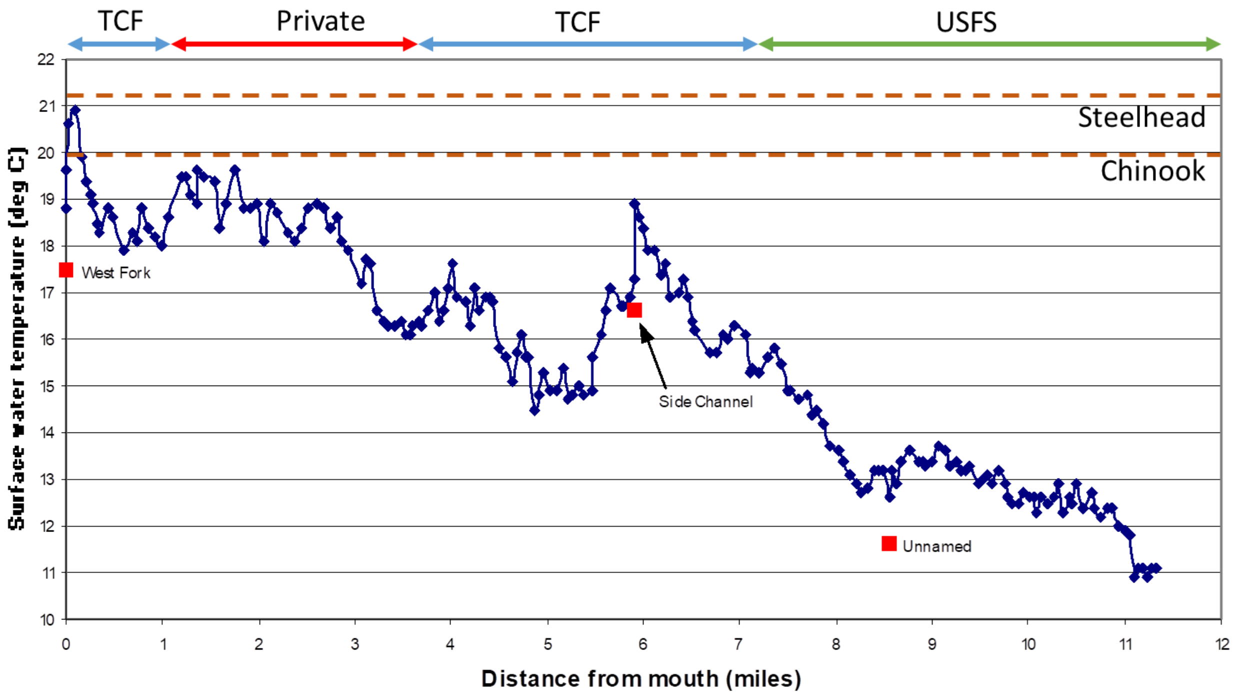

Figure 15. TIR Temperature Profile for the Middle Fork Teanaway (Watershed Sciences, 2002)

Data collected on September 2, 2001. Thermal tolerances (orange dashed lines) from Richter & Kolmes, 2006.

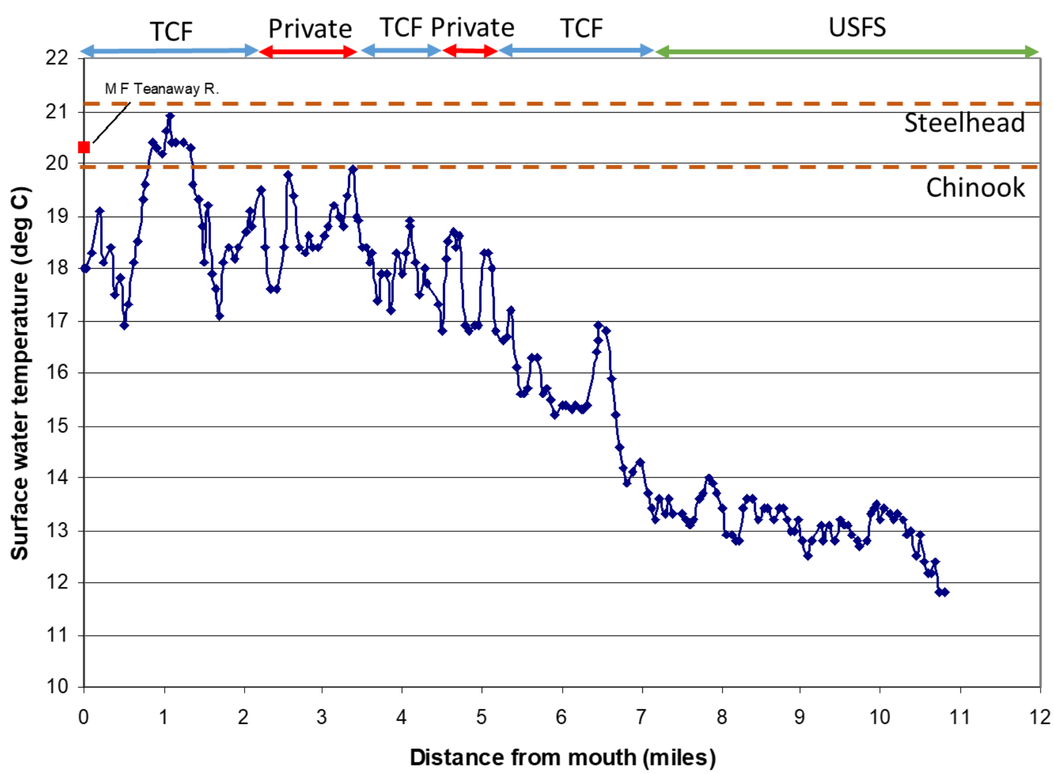

Figure 16. TIR Temperature Profile for the West Fork Teanaway (Watershed Sciences, 2002)

Data collected on September 2, 2001. Thermal tolerances (orange dashed lines) from Richter & Kolmes, 2006.

5. CLIMATE CHANGE

Climate change in the Teanaway watershed has already resulted in long-term declines to snowpack, and future increases in air temperature are expected to shift the hydrologic regime of the Teanaway and its forks. An increase in mean annual average temperature of 8.9 °F and an annual precipitation increase of up to 5.3 in yr^{-1} are projected for the Teanaway area (Abatzaglou & Brown, 2012; Mote et al., 2014, 2017). The increase in temperature coupled with higher winter precipitation is expected to shift the snowmelt-dominated hydrograph to a more transitional hydrograph with high winter floods driven by rain and rain-on-snow events and a second peak in the spring with snowmelt.

To estimate the future distribution of winter precipitation patterns in the MF and WF basins, temperature projections from Taylor et al. (2012) were combined with an adiabatic lapse rate of 3.5 °F 1000 ft^{-1} to adjust the historic (1981-2010) snow level (2000 ft) for projected future conditions (Figure 17). Historic snow level utilized the average gridded (PRISM) temperatures for December – February. Winter precipitation regime zones were then delineated using the adjusted freezing elevation based on projected future temperatures from Taylor et al. (2012).

For a moderate emissions scenario (RCP 6), this results in a 51% increase in the portion of the watershed within a transitional or 'rain-on-snow' winter precipitation regime. For a higher emissions scenario (RCP 8.5), 29% of the watershed is expected to have a rain-dominant winter precipitation regime, with 45% of the basin within the transitional regime and the remaining 26% receiving snowfall (Figure 18). This upward shift in the snow line is also expected to reduce April 1 SWE by up to 18 inches and May 1 SWE by up to 28.8 inches by 2080 (Mote et al., 2017). In addition to the effects of warming on the amount of snow storage and timing of snowmelt, the overall effect of forest cover on snow storage is likely to change. Historic conditions in the Teanaway suggest that more snow accumulates in gaps and openings but that snowmelt timing between openings and forests is similar due to the shading effect of the forest canopy to slow snowmelt. As winter climate warms and the onset of snowmelt shifts earlier in the year, snow storage may be longer in forest gaps and openings, particularly on N-facing slopes (Dickerson-Lange et al., 2017, 2021).

The effect of reduced snowpack has two main impacts to streamflow: higher winter runoff and lower summer baseflows. Projections for long-term gage data on the Yakima River suggest that peak flows could increase by as much as 77% by 2080, largely driven by increased winter rain and rain-on-snow events (Queen et al., 2021). Lower summer streamflows will also further impair stream thermal conditions for fish, with a higher proportion of streams in the Columbia basin exceeding thermal tolerances for salmonids by 2099 (Isaac et al., 2017).

Historic channel incision exacerbates hydrologic changes associated with warming climate by increasing the rate at which water is routed out of the watershed. Transformation from a snow-melt to rainfall dominated hydrologic regime will reduce the duration and increase peaks of runoff hydrographs. Increased peak flows will compound channel incision, which in-turn increases the rate at which groundwater enters the river and the celerity of flood peaks (speed at which water is routed down the river). Slowing runoff is critical in mitigating impacts of the warming climate and the most effective means of doing this will be reversing channel incision.

Within the Teanaway, hotter and drier summers are also expected to increase the number of 'very high' fire danger days by 17 days per year and 'extreme' fire danger days by 11 days per year by 2080 (Abatzaglou & Brown, 2012). Prolonged drought conditions are expected to reduce soil moisture, increasing stress on trees and exacerbate the impacts of insect outbreaks and fires on forest health (Bommarito, 2019).

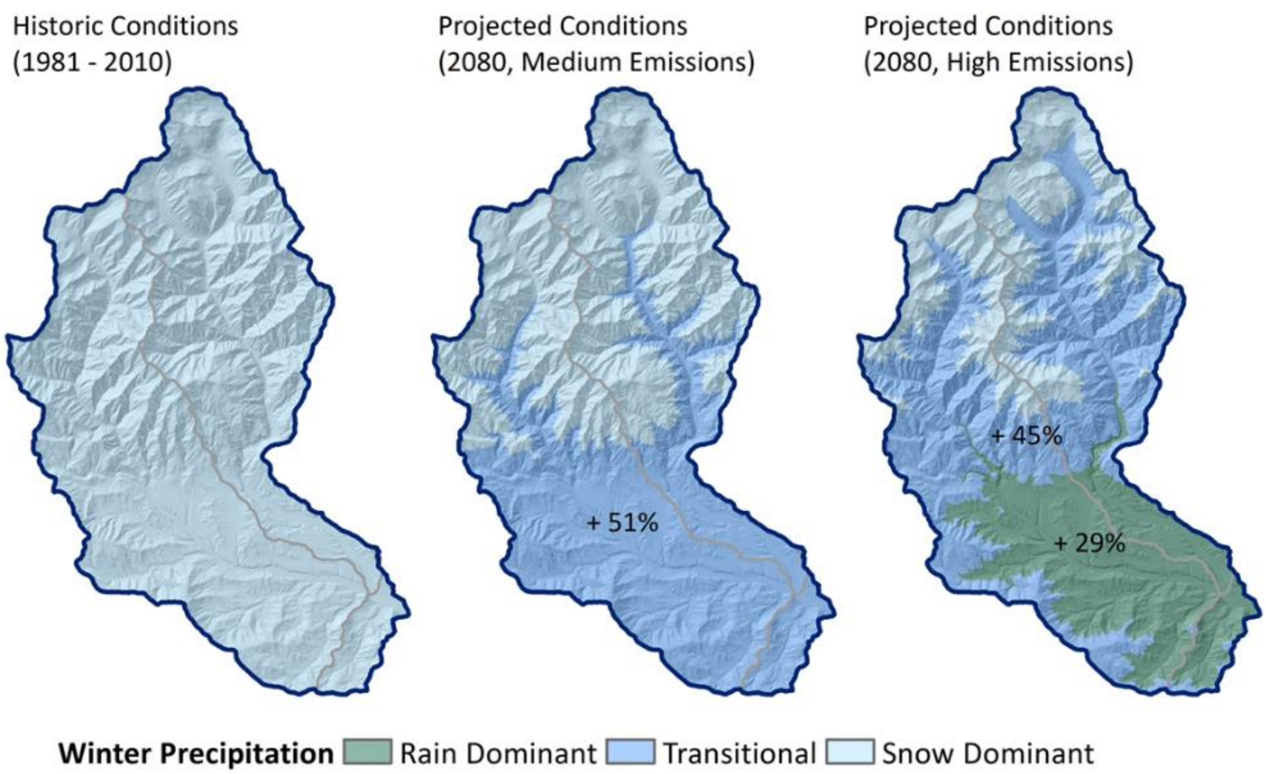

Figure 17. Historic and Projected Winter Precipitation Regimes for the MF and WF Teanaway Watersheds

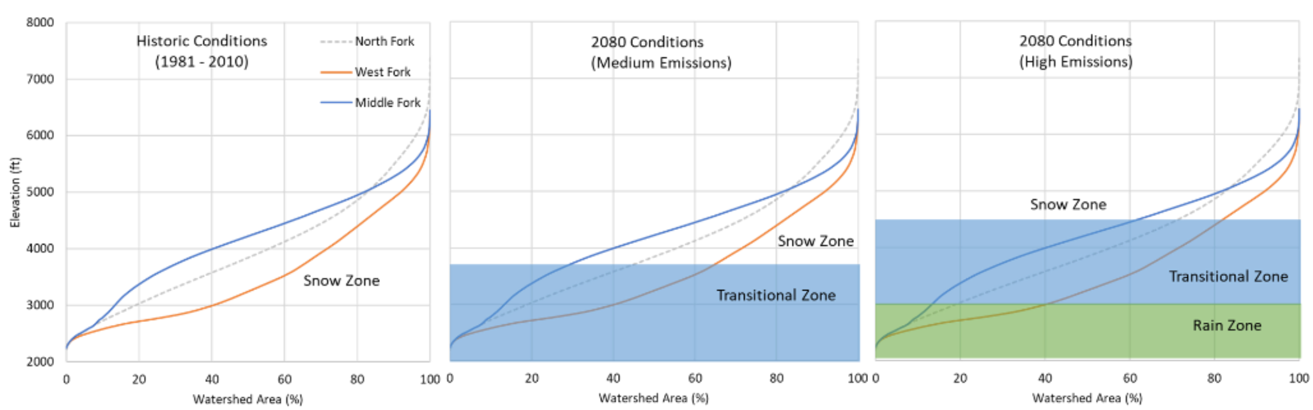

Figure 18. Hypsometric Curves and Winter Precipitation Regimes for Historic and Projected Conditions

6. EXISTING CONDITIONS

Conditions in the MF and WF Teanaway within the TCF were assessed using a combination of desktop geospatial analyses and a field survey of select reaches. The field survey was conducted by NSD, MCFEG, and YN staff on June 14-15, 2021. Data and observations from the NSD wetland inventory, conducted by NSD and MCFEG staff June 28 – July 1 and July 12-15, 2021, were also included, where appropriate. Field surveys for the geomorphic assessment were intended to validate findings from the desktop study and to identify and modify conceptual restoration actions. Field surveys included:

- Comparing relative elevations of channel and floodplain features to validate lidar-based analyses
- Documenting side channel connectivity and wetland presence/absence
- Validating presence/absence of floodplain modifications (e.g., levees, abandoned railroad grades, splash dams)
- Cross-validating sediment particle size from YN hydraulic model outputs
- Identifying riparian canopy structure and species
- Documenting evidence of beaver activity
- Identifying and modifying conceptual restoration opportunity actions
- Documenting in-stream habitat conditions
- Identifying access routes and constraints for conceptual restoration opportunity actions

Primary geospatial data used in this assessment include:

- 2015 lidar digital terrain model (DTM) and digital surface model (DSM)
- 2018 lidar DTM and DSM
- Alluvial water storage (AWS) model output from NSD (2019)
- Hydraulic model output from YN for the mainstem forks
- Beaver Intrinsic Potential (BIP) data from WDFW (2020)
- WDFW wetland assessment (Holcomb, 2015)
- WDFW bedrock mapping (2016)
- Aerial imagery spanning from 1954-2019
- WA DNR landslide inventory
- Kittitas County Channel Migration Zone (2012)
- FEMA FIRM data (effective 1981)

Desktop analyses were intended to quantify existing conditions and identify reaches with impaired or intact habitat. Lidar and aerial imagery data were leveraged extensively to quantify existing channel geometry, connectivity, and landscape disturbances. In-stream conditions were documented during NSD field visits, based on observations by MCFEG, YN, and WDFW staff, and using previous habitat characterizations conducted by Amec (2013) for MCFEG. River miles (RM) referenced in this report were derived from the 2015 channel centerline, digitized from aerial imagery by NSD in 2017.

Summary data for the WF, MF, and the mainstem below the MF-WF confluence downstream to the NF confluence are detailed in

Table 5 below. These analyses are further detailed in the sections below, with general descriptions of conditions in the MF and WF. Existing conditions are summarized within specific restoration opportunity areas in the 'Restoration Opportunities' section.

Table 5. Geomorphic Characteristics for the Middle and West Forks and the Mainstem Teanaway above the North Fork Confluence

METRIC	MIDDLE FORK	WEST FORK	MAINSTEM ABOVE NORTH FORK
Channel type	Meandering/straight	Meandering	Meandering
Substrate	Cobble & bedrock, some boulders and gravel pockets	Cobble & bedrock, some gravel pockets	Cobble & bedrock, some gravel pockets
Gradient (ft/ft)	0.016	0.012	0.007
Bankfull width (ft) [mean (min – max)]	75 (23 – 162)	89 (37 – 224)	103 (32 – 144)
Floodplain width (ft) [mean (min – max)]	490 (25 – 948)	365 (126 – 601)	576 (236 – 1114)
Sinuosity	1.15	1.20	1.20
Channel modifications	Straightened, dikes, levees, roads, riprap	Dikes, levees, roads	Dikes, levees, roads, riprap
Incision/Aggradation	Incised	Incised	Incised
Wood jams/mile[1]	1.1	1.9	2.6
Bedrock channel (%)	17.1	34.5	33.1
Active channel migration	Yes	Yes	Yes
Floodplain side channels	Yes	Yes	No
Floodplain wetlands	Yes	Yes	Yes
Riparian/floodplain landcover	Mixed forest – agriculture – residential	Mixed forest – agriculture	Mixed forest - agriculture
Alluvial Fans	Yes	Yes	Yes
Avulsion Hazards[2]	Yes	Yes	No
Landslides Hazards	Yes	Yes	Yes

1. Includes single, key-sized pieces visible in 2019 aerial imagery
2. Primary avulsion risks are via straight, wall base channels adjacent to bedrock

6.1 Terrain and Canopy Analyses

Lidar data from 2015 and 2018 (WA DNR) were combined to form a continuous DTM representing the ground surface and a DSM (includes tree canopy and other non-ground surfaces) for the study area within the MF and WF watersheds. Overlapping pixels with 2015 and 2018 coverage were assigned to 2018 lidar elevations.

6.1.1 Relative Elevation Model

A surface was derived from a plane representing the water surface from the lidar DTM by extracting a channel profile along the mainstem channel and extrapolated the water surface over the entire Teanaway valley bottom. The resulting water surface elevation (WSE) grid was subtracted from the DTM to obtain a detrended elevation model of ground heights relative to the water surface, or a 'relative elevation model' (REM). The REM shows channel and floodplain features above or below the water surface, and provides information about low-lying floodplain channels, relic channel features, and terraces in relation to the current low flow channel (Appendix A). Low-lying areas are shaded in purple and dark blue, with intermediate areas in green and higher ground in yellow and brown. Elevated floodplain features such as roads, berms, and dikes are also evident in the REM, typically several feet above adjacent floodplain and channel areas in darker tones of green, yellow, and brown.

The REM for the MF and WF shows areas of channel confinement or channel incision and areas with intact, low-lying floodplain (Figure 19, Appendix A). Elevated floodplain features and disturbances are mapped in Appendix B and detailed in the following section.

REM characteristics for the MF can be broadly divided into five reaches based on the degree of floodplain connectivity and valley bottom morphology:

- RM 7.3 – 5.9: Partially developed floodplain with low-lying relic channels and several intact side channels; localized areas with remnant levees where low-lying channels are disconnected from the mainstem
- RM 5.9 – 5.3: Highly confined, canyon-like single threaded channel segment
- RM 5.3 – 3.2: Broad, alluvial valley bottom with low-lying relic channels and disconnected side channels impacted by levees and MF Teanaway Road
- RM 3.2 – 1.1: Highly developed confined channel constrained by levees, with disconnected low-lying relic channel features along the left (northeastern) floodplain; substantial residential development
- RM 1.1 – WF confluence: Intact, low-lying floodplain channels and some disconnected relic side channels, with channel confinement and disconnected floodplain areas at the WF Teanaway Road bridge near RM 0.12. Field observations suggest these floodplain channels are frequently engaged during winter – early summer flow periods.

The REM for the WF shows evidence of relic channel features on high floodplain terraces throughout the study area, and can be broadly divided into sub-reaches based on the relative degree of floodplain connectivity and natural and human impacts that alter channel morphology:

- Upstream of RM 7.2: confined, canyon-like valley
- RM 7.2 – RM 6.8: Disconnected left bank floodplain area and relic channel where old berm obstructs inlet to low-lying relic channel
- RM 6.8 – 5.8: Moderately confined channel impacted by artificial features along left bank (WF Road, old railroad, levees), with intermittent high-lying terraces where disconnected active channel corridor is ~200 ft wide; substantial incision with bedrock outcrops throughout

- RM 5.8 – 5.25: Low-lying floodplain channels with intermittent connectivity, but obstructed by old railroad grade; unnamed tributary and associated wetland at RM 5.45 are disconnected by an abandoned road and berm
- RM 5.25 – 5: Incised channel with high terrace on left bank, exposed bedrock; West Fork Road ends near 5.05 but disconnects low-lying floodplain and relic channel swale along left bank
- RM 5 – 4.6: Low-lying left bank floodplain area disconnected from channel by old railroad grade and WF Teanaway road, some bedrock incision and limited side channel connectivity
- RM 4.6 – 3.95: High left bank terraces and relic channel areas disconnected through channel incision and obstructions at Dingbat Road bridge abutment, WF Teanaway Road, and old splash dam near RM 3.95
- RM 3.95 – 3.2: Some connected low-lying left bank floodplain channels, right bank terrace and relic channel features disconnected through incision and obstruction by old railroad or road grade
- RM 3.2 – 1.8: Moderately confined channel with relic floodplain features and perched floodplain terraces, with obstructions due to old railroad grades and levees
- RM 1.8 – 0.1: Severely incised channel with high (> 12 – 20 ft) left bank floodplain terrace and substantial bedrock incision; constriction by levees, roads, and Carlson Creek Road bridge abutment; remnants of Carlson camp logging railroad further confine channel near WF-MF confluence

  RM 0.1 – NF confluence: Channel confined by old rail and road prisms, with bedrock exposed in many locations; channel regains some side channel and floodplain connectivity between Camp 17 Creek and NF confluence but floodplain is impeded by old rail prism.

6.1.2 Floodplain Modifications

Lidar data was also used to identify elevated floodplain features such as roads, railroad grades, dikes, and ditches that influence floodplain inundation or channel migration (Figure 20, Appendix B). These elevated floodplain modifications were first mapped by using the lidar DTM hillshade to visually identify and digitize linear features. The features were then classified as 'roads,' 'rail,' 'berm,' or 'ditch' based on aerial photos, USGS topographic map data, and notes and historic mapping by Henderson (1990).

The geomorphic influence of some these features is noted in the REM descriptions above. Most floodplain modifications within the WF and MF valley bottom and floodplain areas have either existing or historic influence on channel morphology, through confining the active channel, preventing overbank flows, obscuring side channels, or concentrating overbank flow into artificial drainage ditches. Cumulatively, floodplain surface modifications have severely confined the MF and WF Teanaway in many locations, exacerbating historic channel incision by translating stream power into bed scour. Ongoing incision coupled with lateral constraints result in a loss of both vertical and lateral floodplain connectivity. Figure 20 shows two contrasting floodplain areas, where a floodplain modification such as a road grade or berm disconnects the mainstem channel from low-lying floodplain areas; and another where low-lying floodplain channels are well-connected with the mainstem due to a lack of floodplain modifications or artificial channel constraints.

Decommissioned or abandoned road or rail prisms continue to obstruct floodplain and side channel connectivity. Active roads within the historic floodplain generally cut off low-lying relic channel features or wetland areas, and could be relocated to the valley margins. In many areas, roads were placed along the historic railroad grade without consideration for channel forming processes or flood impacts. More recently, bridge abutments at locations such as Dingbat and Carlson Creeks have been placed within the active channel corridor, constricting the channel to a narrow, single threaded channel and promoting further channel incision. Not included in these floodplain modifications are features such as road cuts along the valley margins or upland areas, which can also intercept surface and groundwater, concentrate runoff into roadside ditches, and impact sediment delivery to the channel.

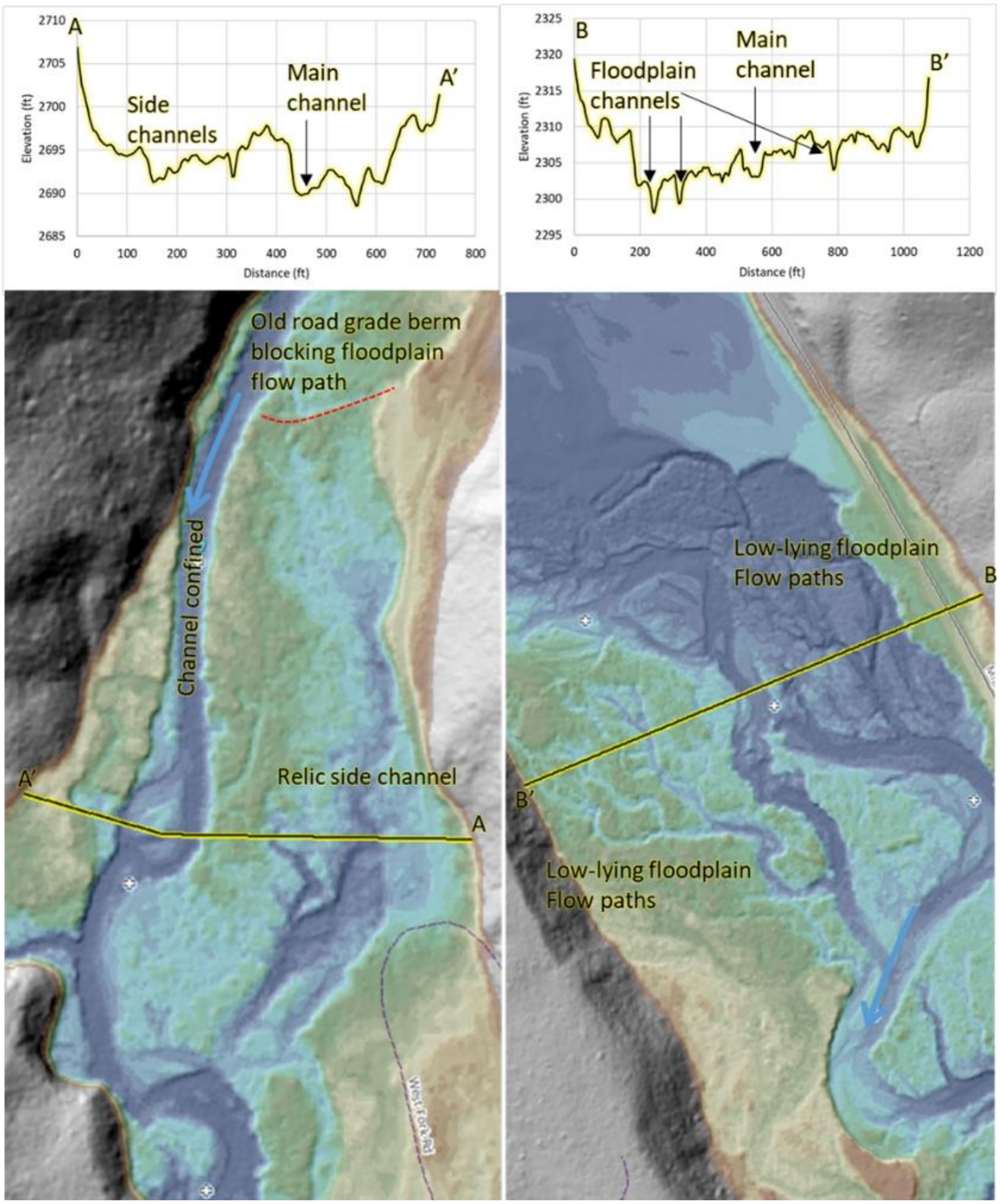

Figure 19. Relative Elevation Maps near WF RM 7 (Left) and MF RM 0.8 (Right)

See Appendix A for location context and relative elevation symbology. Flow is from top to bottom. Cross sections, which are oriented looking downstream (i.e., to the south) show disconnected side channels and low-lying floodplain areas. The WF RM 7 site has a perched wetland complex fed by cold water hillslope seeps on the left bank floodplain. Secondary channel excavation could be done to avoid wetlands. Raising the mainstem river bed and water table will enhance the benefits of the cold water inputs and existing wetlands. Large wood and in-stream fill would raise water surface elevations, while floodplain channel excavations would increase inundation frequency and connectivity in off-channel areas.

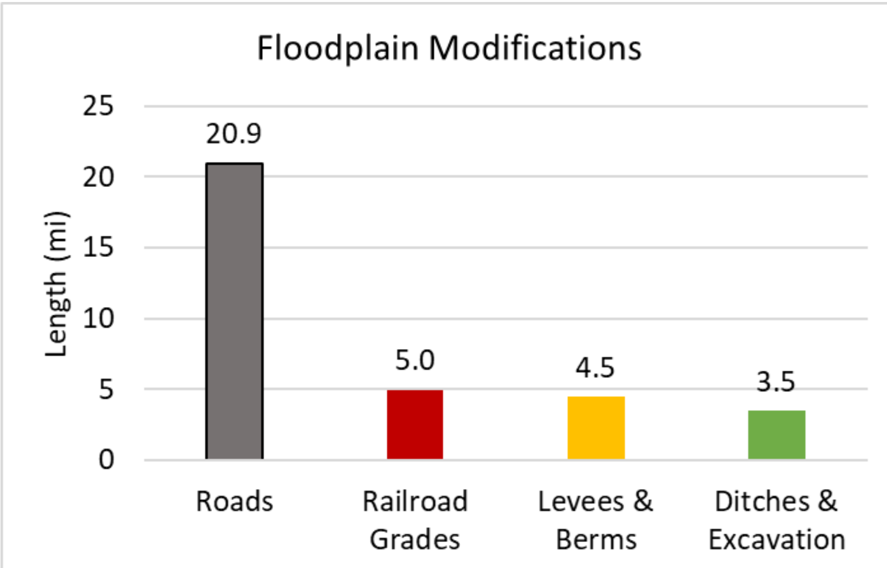

Figure 20. Floodplain Modifications Mapped in the West and Middle Fork Teanaway Rivers from 2015 and 2018 Lidar

Only elevated or entrenched (ditches) portions of features present in surface data are included in length tabulations (e.g., roadways with elevated road prisms).

6.1.3 Canopy Height

Tree canopy height was derived as the difference between the DSM and DTM surfaces (Appendix C). The legacy of historic and more recent logging in the watershed is evident in the canopy height mapping, with large tracts of the watershed having very little canopy with trees > 50 ft tall. Within the WF, stands of large trees (> 120 ft) are present along the mainstem riparian corridor upstream of RM 3, with overall lower (< 75 ft) canopy downstream of this point and large tracts of privately owned land with little or no canopy cover. Canopy cover in the MF valley bottom shows a sharp contrast between intact canopy (> 130 ft) upstream of RM 3.1 and points downstream of the boundary between TCF and privately owned lands, with large tracts of zero canopy and few patches of tall trees along the channel corridor. The southern slope along the MF has very few large trees, due in part to landslide disturbances but also historic logging. The northern slope above Middle Fork Teanaway Road has some intact, continuous forest, but within the floodplain much of the forest outside of the TCF has been cleared (Figure 21). Floodplain canopy cover is again intact within the TCF downstream of RM 1.1.

The overall lack of intact riparian forest in the lower MF and WF has implications for both channel morphology and stream shading. Large trees influence channel morphology in several ways: increasing bank stability through mass forces and root cohesion, arresting bank erosion when recruited into the channel, raising the water surface to increase floodplain and side channel engagement, trapping sediments and promoting complex hydraulics for gravel sorting and habitat formation, and creating stable hardpoints that encourage the development of forested islands. Large trees also shade the stream channel and reduce stream temperatures. Detritus and insects from trees can form an important component at the base of aquatic food webs.

Logging, subsequent replanting for commercial forest operations, and fire suppression throughout the watershed have increased stem density and simplified forest structural complexity and species diversity (Bommarito, 2019). This has impacts on the availability of large trees for recruitment to the river channel, on stream shading, and on the resilience of forests to disturbances from drought, insects, and fire. Overly dense forests with continuous canopy cover also reduce the total amount of snow storage by approximately 10-70%

due to the forest canopy intercepting snow that subsequently sublimates and melts (Dickerson-Lange et al., 2017). Dense forests also affect the duration of snow storage and therefore snowmelt timing, and preliminary data in the eastern Cascades suggests that the effect ranges from no difference in duration to snow lasting 2-4 weeks longer in small gaps (Dickerson-Lange et al., 2021).

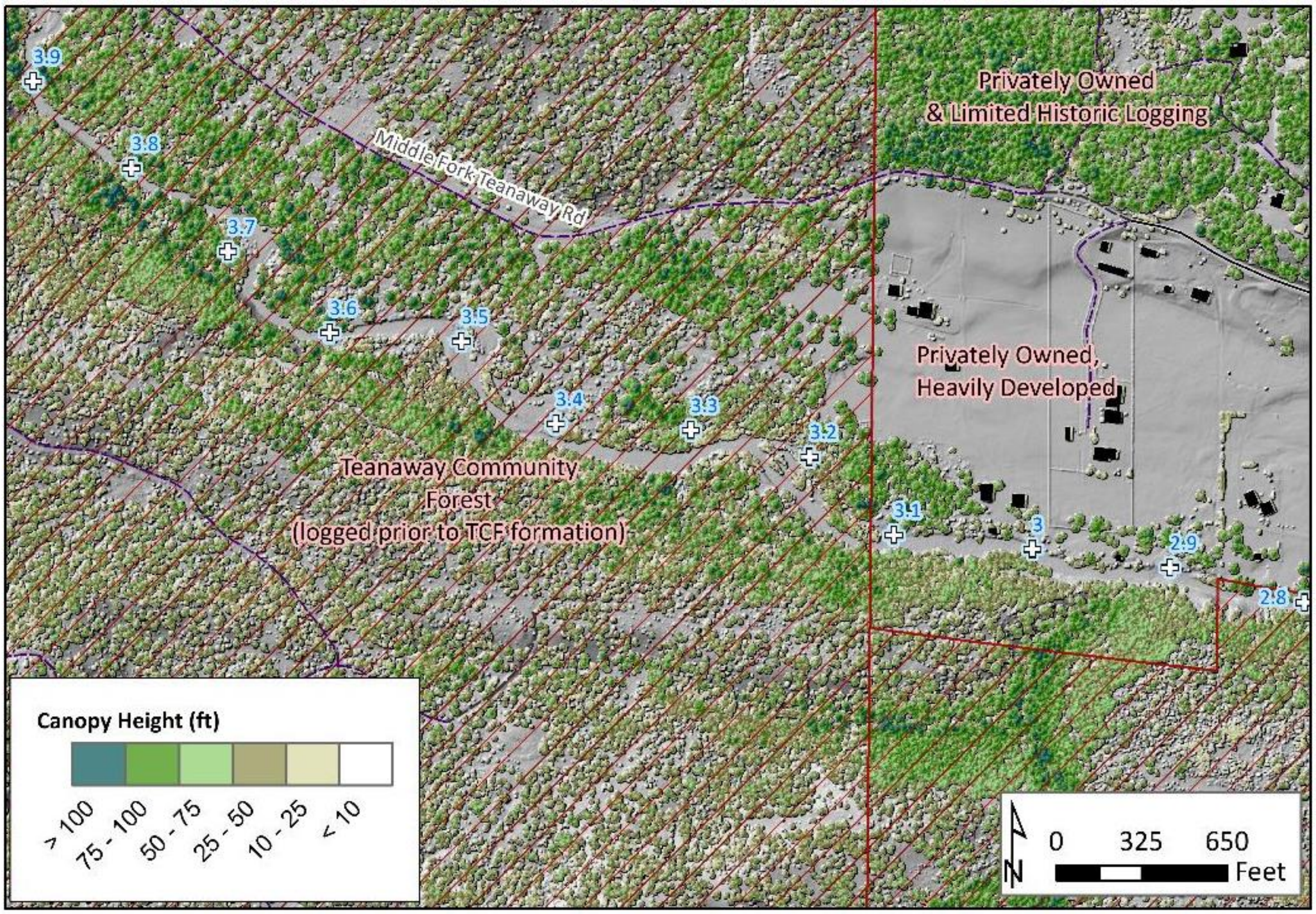

Figure 21. Example of 2015 Lidar-Based Canopy Height Mapping near TCF Boundary at RM 3.1 of the MF

Hashed red shaded area to left is within the TCF, and unshaded parcels with high floodplain development and very little canopy cover are privately owned. Some privately owned parcels (top right) are unlogged, while many areas within the TCF were historically logged under American Forest Holdings ownership prior to the TCF's establishment. Typical canopy heights in the riparian corridor are less than 100 ft, and previously logged uplands have typical heights less than 75 ft.

6.2 Wetlands & Riparian Conditions

The study area included in NSD's wetland inventory spans the mainstem and floodplain areas along the MF and WF within the TCF. NSD used soil, vegetation, and hydrologic characteristics to identify and delineate wetlands throughout the study area. Details on field delineations and desktop analyses used in the wetland study are detailed in a separate report (NSD, 2021).

The study area supports three general types of wetlands:

1. Complex, high-function wetlands formed by springs, seeps, and/or small tributaries to the MF and WF rivers. In terms of hydrogeomorphic class, these wetlands are typically either:

- A combination of Depressional and Riverine, supporting a diversity and complexity of vegetation classes and associated habitat functions, including portions influenced by the river's flow, or
- Riverine due to the influence of tributary creeks or springs. These wetlands also typically support a diversity of native vegetation species, including wet meadows and mature trees including western red cedar and black cottonwoods.

2. Riverine floodplain wetlands which are at least occasionally connected by overbank flow and periodic inundation of floodwaters. These wetlands are typically either:
    - Well-connected/frequently inundated areas characterized by flow paths and gravel deposits where the wetland most regularly interacts with the river. These wetlands support a dense tree and/or shrub overstory transitioning to sparsely vegetated gravel bars near the active river channel and have consequently higher comparative functions, or
    - Areas of limited but occasional connection and consequently a relatively more moderate level of function.
3. Wetlands not connected to riverine hydrology. These wetlands are typically either:
    - Depressional features with comparatively moderate functions, typically due to high capacity for water storage and a diversity of vegetation classes and habitat functions, or
    - Typically smaller, relatively lower function depressions. These lower function wetlands may have once been connected to riverine hydrology but are currently disconnected with limited soil and vegetation development.

Historic channel incision has resulted in over-steepened banks in many locations. Places where channel banks are actively eroding have potential for large wood recruitment, and in many areas these eroding banks have intact riparian canopy (Figure 22). Along the historic floodplain surface, much of this canopy is young coniferous forest with heights up to 100 ft. In low-lying floodplain areas within the active channel corridor, canopy is predominantly low (< 20 ft) alder and willow, with patches of taller (up to 100 ft) cottonwood trees where channel disturbances are limited. In bedrock channel segments, soil substrate is absent or is poorly developed, inhibiting the establishment of riparian vegetation. Locations where intact side channels flowed through floodplain forest or locations with groundwater expression had much greater riparian cover and shading, with channel widths generally between 6 – 20 ft (Figure 23). Numerous historic side channels and floodplain channels were observed during the field visits but few of these channels appeared active or had hydric soils.

Figure 22. Example of Eroding Bank near RM 5.1 in the Middle Fork

with coniferous forest on the historic floodplain surface, and low alder and willow vegetation in the areas recently occupied by the river channel

Photo: June 14, 2021.

Figure 23. Groundwater Expression and Riparian Shading in a Floodplain Side Channel near RM 4.7 on the Middle Fork

Channel width is 8 ft and max depth of the wetted area was 1.2 ft. Photo: June 14, 2021

6.3 Geomorphic Migration Zone & Hazards

Channel migration zones (CMZs) delineate the potential areas of current and future channel migration and channel position given a river's planform, bank material, and historic conditions. Previous channel migration studies for the Teanaway include a CMZ developed for Kittitas County's Shoreline Master Program (2012). Portions of the Kittitas County CMZ did not fully encompass the active channel corridor for the MF and WF. The CMZ boundary was updated by NSD to reflect the full extent of the potential geomorphic migration zone (GMZ, Appendix D). This planning-level GMZ also includes features such as landslides, alluvial fans, or other fluvial features that can influence channel migration or that may pose a risk to floodplain property and habitat. NSD delineated this planning-level GMZ for the MF and WF study area following guidelines detailed by Olson et al. (2014). The revised planning-level GMZ leveraged an interpretation of fluvial landforms identified from the lidar surface, aerial photographs, and YN hydraulic model outputs. Geospatial data were used to identify relic channel features, floodplain flow paths, alluvial fans, landslides, and erosional hazards. The GMZ generally spans the entire valley bottom for the WF and MF, with geotechnical hazards along the southern valley margins where erodible glacial drift deposits are prone to mass wasting. Alluvial fans at tributaries are identified in the planning-level GMZ for restoration opportunities that may include larger stream channel crossings to facilitate sediment delivery to the mainstem forks. Landslide hazards are also highlighted to identify potential risks associated with increasing lateral channel migration through the addition of LWM or engineered logjams. The GMZ for the MF and WF thus includes the current active channel corridor and floodplain, the historic migration zone, potential avulsion hazards, and areas with potential for future channel migration.

There are currently many homes, barns, and other structures within the GMZ in the lower MF and WF. Based on available photo records, some of these structures have been present since at least the mid-20th century, however more recent development and subdivision of parcels outside of the TCF has increased construction within the GMZ of the Teanaway. Roughly 225 acres (40% of MF GMZ within the study area) are privately owned, and include residential and agricultural structures and associated roads. Many of these structures are in historically flood prone locations that are currently outside of the floodway due to historic incision and/or channel confinement by berms, roads, or through artificial drainage ditches. In unconfined areas, the MF and WF active channel corridors and floodplain span the entire valley bottom with broad (>550 ft) meander bends and anabranching channel segments in some locations where logjams have created forested islands. This meandering or anabranching pattern is the natural tendency of the river's planform given its slope and sediment supply.

The GMZ was used during the development of restoration opportunities to identify locations where in-stream wood and fill additions might result in increased risk of sliding or channel migration into undesirable locations. The GMZ was also used to identify locations within restoration opportunities where channel migration or sediment inputs from tributary alluvial fans could be leveraged to help aggrade the channel bed.

6.4 Hydraulics & Sediment Transport Capacity

Historic disturbances from splash damming and active removal of LWM from the MF and WF channels has resulted in severe channel incision, disconnecting the mainstem MF and WF from floodplains and off-channel habitat areas in many locations (Appendix E). Historic channel incision and channel confinement has also led to a loss of spawning sized gravels and substrate that facilitates hyporheic exchange and alluvial water storage. The flow velocity and shear necessary to mobilize a sediment particle depends on the distribution of grain sizes and the embeddedness of material. The minimum stable particle size for the MF and WF mainstem forks was determined from YN hydraulic model output following the Shield's equation:

$$D = \frac{\tau}{(\rho_s - \rho_f)} g\, \tau c$$

In which D = stable particle size (D_{50}); τ = shear stress; ρ_s = density of the particles (165.4 lbs/ft^3); ρ_f = density of water (62.4 lbs/ft^3); g = force of gravity (32.2 ft/s^2); and τ_c = Shield's constant (0.045).

Hydraulic model results for the 2-year flow indicate that transport capacity through both the MF and WF mainstem channels is sufficient to mobilize cobble and small boulder sized materials, leaving very little fine substrate available for aggradation and spawning habitat. Overall, the 2-year flow is largely confined to the mainstem channel, with limited floodplain connectivity and few side channels engaged. This lack of off-channel habitat is further evidence for channel incision, and impairs habitat, the persistence of wetlands, and water storage.

The historic impacts of wood removal and splash damming coupled with localized areas of channel confinement have dramatically changed transport capacity and alluvial sediments in the MF and WF. Bedrock is exposed in numerous places within the alluvial valley bottom, and in some locations the channel has incised by more than 9 ft into sandstone bedrock and more than 20 ft from its historic floodplain surface. The general lack of fine gravels and material in the mainstem forks indicates that velocities in these channels are sufficient to mobilize material smaller than medium to large cobble, with higher flood flows capable of moving larger material.

Sediment transport and equilibrium can also be evaluated in terms of Lane's principle, which states:

$$Q_s d \propto Q_w S$$

Where Q_s = sediment discharge; d = particle diameter; Q_w = water discharge; and S = slope. Human modifications to this equilibrium such as changes in slope (e.g., due to channel straightening or confinement) or discharge (e.g., from splash damming) result in adjustments to sediment transport or particle size as the channel attempts to regain equilibrium. The presence of stable wood acts to reduce S by dissipating energy. Wood removal effectively increased S, resulting in an increase in Q_s and when Q_s diminished due to a reduction in supply, d increased, coarsening the bed or removing alluvium entirely.

The slope of the MF and WF has been increased in some locations by a shortening of the channel length in areas of channelization by roads or other elevated features due to historic and recent floodplain development, thereby increasing sediment transport in these locations as the channel attempts to achieve equilibrium. In many locations the channel is bound by bedrock and has little opportunity to migrate and recruit sediment.

In locations with lower channel slope (e.g., anabranched or meandering reaches or areas of backwater), the channel has lower sediment discharge, aggrading the channel to maintain these planforms (e.g., lower MF near RM 1). The channel has a natural tendency to meander or form anabranches where the active channel width is not constrained and where there is sediment supply from upstream or adjacent areas. This process reduces channel slope, which suggests that the Teanaway, in an equilibrium state, tends toward a meandering or anabranched planform given its natural sediment supply and flow regime. In areas where this equilibrium has been disrupted, such as channelized segments or areas scoured down to bedrock, the creek channel would normally reduce its slope through aggradation. When constrained by hydraulics, this process is only able to occur where flow velocity and sediment transport diminishes, such as unconfined areas.

6.5 In-stream Habitat Conditions

Stream conditions in the Teanaway are rated as 'fair' due to combined effects of degraded forest, vegetation, and road impacts (USFS, 2009). Channel incision and human modifications to the valley bottom described above have effectively simplified the channel in many locations, resulting in a straightened, single threaded channel with little habitat complexity and limited vertical and lateral connectivity to floodplain areas and off-channel wetlands.

Wood loading in the MF and WF is less than 1.6 logjams per mile, whereas nearby unmanaged watersheds have wood loading of 13 – 22 logjams per mile (Schanz et al., 2019 and references therein). Review of aerial photo records from 2019 suggests that wood accumulations in the study area are severely limited, with only 1.1 wood accumulations per mile in the MF, 1.9 per mile in the WF, and 2.6 per mile in the mainstem Teanaway below the MF and WF confluence and the NF confluence. Many of these large wood occurrences are single pieces of large wood, most of which appear to have an intact rootwad for increased stability. Bedrock channel segments have low probability for local wood recruitment, given the absence of lateral channel migration and little to no riparian forest on bedrock slopes.

The overall lack of in-stream wood throughout the study area limits habitat complexity in several ways (Abbe & Montgomery, 2003; Montgomery & Abbe, 2006):

- Wood encourages pool formation
- Wood provides complex cover
- Wood creates stable hardpoints in the channel corridor that encourage multiple flow paths
- Wood raises WSE, increasing vertical and lateral floodplain connectivity

- Wood creates hydraulic complexity, promoting sediment sorting and deposition

Where stable logjams have formed in the Teanaway, multiple flowpaths are wetted, floodplain side channels are engaged, wood-forced pools have formed, and in one location a forested island is present (Figure 24). Without key-sized pieces with intact rootwads, even logjams that remain stable for several years can be broken-up or washed-out during larger flood events. The logjam complex near RM 0.7 on the MF formed following rapid channel expansion upstream during heavy flooding in March 2007 (10 – 20 year flood; Figure 25). In subsequent years, the anabranching channel segment that is still present formed around this logjam, creating a forested island. Ongoing channel expansion during a 2009 flood event (~5 year flood) delivered more wood to the logjam complex, expanding upstream to engage side channels in the left bank floodplain (Figure 25). By 2014 the logjam had grown to nearly half an acre in size, but then broke up prior to the 2017 aerial image, likely during the 2016 flood (25 year flood; Figure 26). Additional wood recruitment in this location occurred in water year 2021. Without large, stable wood pieces, even these large logjams can mobilize downstream during high flow events.

Based on previous work (e.g., Amec, 2013) and field observations, most pools in the MF and WF are associated with boulder or bedrock scour, with few wood-forced pools. These bedrock pools often lack complex cover, and bedrock segments lack substrate for soil and riparian plant development to provide shading and food sources to the channel. Substrate throughout the reaches observed during summer 2021 is predominantly bedrock and cobble and few areas with smaller cobbles or gravels. Channel slope through much of the MF and WF mainstems is too great to accumulate bedload, and sediment retention will require lowering of slope through erosion in the form of logjams (Schanz et al., 2019). Buried logjams documented on strath terraces by Schanz and others (2019) and observed within the sandstone substrate in the WF indicate the presence of logjams prior to- and during terrace planation.

Figure 24. Logjam and Forested Island near Middle Fork RM 0.7

Gravels have deposited in the lee of logjams, with scour pool formation and multiple wetted flow paths. Photo: June 14, 2021.

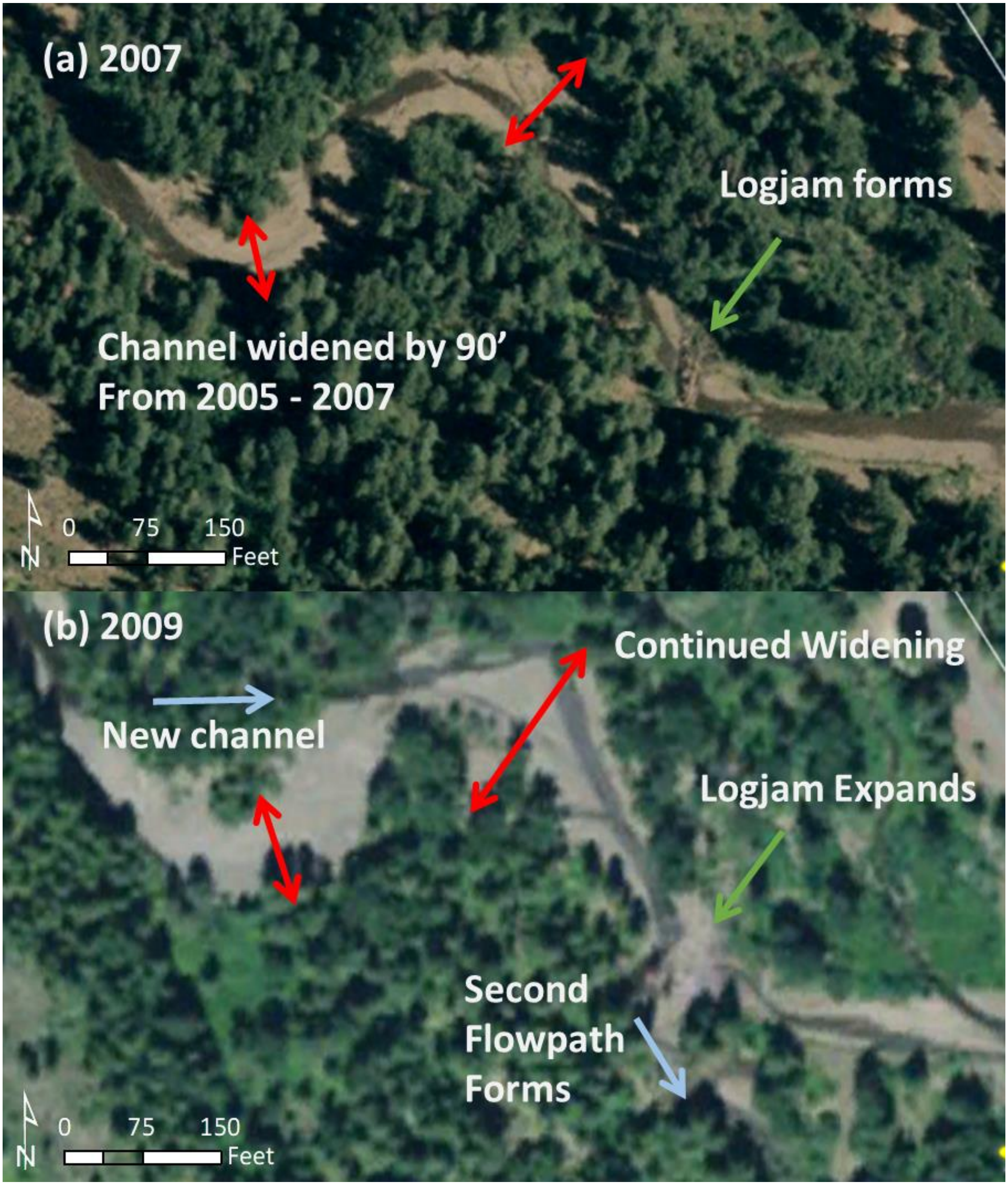

Figure 25. Middle Fork RM 0.7 where Logjam Formed following Flood Events in 2006, 2007, and 2009

Flow is left to right.

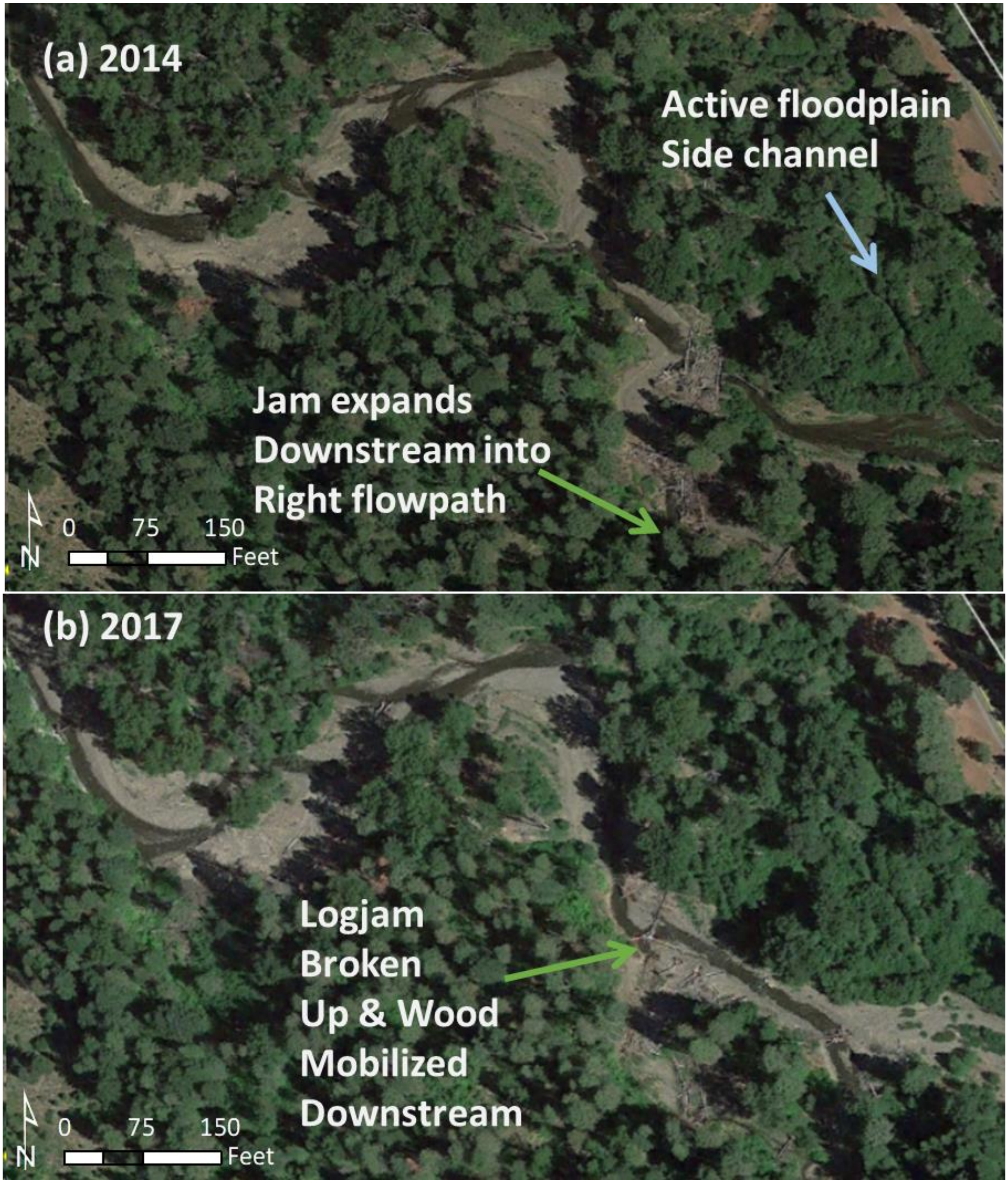

Figure 26. Middle Fork RM 0.7 where Logjam Expanded

A secondary flow path formed, and then the logjam partially broke-up during subsequent flooding in 2016. Flow is left to right.

7. RESTORATION OPPORTUNITIES

> *"River-wetland corridors are, like the floodplains within which they exist, built and maintained by net deposition of sediment…a river-wetland corridor cannot long persist if its river is actively incising." -Wohl et al., 2021*

The Teanaway is the most important watershed for steelhead and salmon production in the upper Yakima River basin and is critical habitat for mid-Columbia steelhead (USFS, 2009). The MF and WF support both threatened steelhead and spring Chinook in addition to resident fish species such as rainbow and westslope cutthroat trout. Historically the Teanaway also supported threatened bull trout, however no bull trout have been observed in the basin since 2005 (WDFW, 2015). Habitat conditions for fish have been severely impacted by more than a century of human impacts, and have created watershed and in-stream conditions that are less resilient to natural disturbances. Without intervention, channel incision in both the MF and WF will further reduce vertical and lateral connectivity with floodplain wetlands, while limiting the natural development of complex in-stream habitat. Ongoing channel degradation has implications for fish, wildlife, and plant communities, and for water quality and quantity in the Teanaway. Restoring the rivers' natural capacity to store sediment will help create and sustain off-channel habitat and floodplain wetlands, while building future resiliency to disturbances from flooding, climate, and fire.

The TCF was created to provide for a diverse suite of recreation opportunities while also protecting and restoring fish and wildlife habitat and water quality and quantity. MCFEG, the YN, and WDFW are working in partnership with Washington DNR to achieve these goals in the MF and WF through stream restoration actions. Restoration objectives for the MF and WF within the TCF are to:

- Improve suitability for beaver,
- Increase frequency of floodplain engagement,
- Increase off-channel habitat,
- Increase water storage on the landscape,
- Increase summer seasonal flows, and
- Improve water temperatures and hyporheic flow.

NSD worked with MCFEG and project stakeholders to identify restoration opportunity areas (ROAs) throughout the MF and WF within the TCF to achieve these restoration objectives. Previous restoration opportunities assessed by Amec (2013), Holcomb (2015), and WDFW (2016) were also included in the suite of ROAs evaluated by NSD. Both the MF and WF have excellent potential for "valley reset" large scale restoration, which would dramatically improve in-stream and floodplain habitat, increase alluvial water storage and supplement base flows.

7.1 Restoration Metrics

Following discussions with MCFEG, YN, and WDFW, a total of 53 ROAs were scored based on their potential to achieve specific, measurable restoration goals for the project area (Table 6). For each goal, data from the desktop geomorphic assessment and NSD's wetland assessment were used to evaluate the potential of conceptual restoration actions.

Table 6. Restoration Goals and Metrics Used in Evaluating Restoration Opportunity Areas

RESTORATION GOAL	METRICS	DATASETS	WEIGHTING (%)
Improving suitability for beaver	Beaver Intrinsic Potential, channel slope	WDFW BIP (2020); lidar DTM (2015, 2018)	5
Increasing floodplain engagement	% change in inundated area	YN hydraulic model (2 yr flow) and conceptual WSE model based on potential projects (NSD, 2021)	20
Increasing side channel length	% change in inundated channel length	YN hydraulic model (2 yr flow) and conceptual WSE model based on potential projects (NSD, 2021)	20
Increasing water storage and retention	Alluvial and surface water storage potential (acre-ft per mile)	Alluvial water storage model output (NSD, 2019)	10
Reducing substrate size	Extent of bedrock channel (acres) and existing sediment stable particle size	WDFW bedrock mapping (2016); YN hydraulic model (2 yr flow)	10
Reducing stream temperature	Mean tree height (ft)	Lidar-derived canopy height	5

7.1.1 Suitability for Beaver

Beaver (*Castor spp.*) are ecological engineers with the capacity to dramatically change a river-wetland corridor by raising WSE, partitioning flows, and influencing the regeneration of riparian forest (Wohl et al., 2021). Although beaver ponds can result in warming of streams along their flowpath, bottom water in beaver ponds is generally cooler than the incoming stream, with temperature reductions positively correlated with beaver dam height (Means, 2018). Beaver ponds store water, sediment, and organic material and can create and sustain wetland habitat. Beaver abundance throughout the West was severely impacted by widespread trapping in the 19th century, but beaver populations are slowly recovering where suitable habitat exists. Beaver prevalence in Washington state is negatively correlated with stream power (Ditbrenner et al., 2018), which is a function of channel slope and discharge. Beaver intrinsic potential (BIP) models for Washington state also include proximity to food sources and human impacted areas such as roads or agricultural land uses (WDFW, 2020). BIP within the Teanaway is currently low for nearly all mainstem areas and is limited in tributary areas, due largely to high stream power in the simplified, incised mainstem channels. Due to the nature of stream network data used in deriving BIP scores, BIP is often underestimated for streams where a multi-threaded planform can be achieved through restoration actions. In ROAs where multi-threaded channels can be restored through excavation or large wood placements, beaver suitability will increase. Reducing channel gradient by increasing channel length and roughening the channel with wood or fill will also improve beaver suitability. Channel slope was thus used as a proxy for beaver suitability within the ROAs evaluated for this project.

7.1.2 Floodplain Engagement & Channel Length

Historic incision and floodplain modifications in the Teanaway have led to an overall reduction in channel length and the frequency and extent of floodplain engagement. Restoring vertical and lateral connectivity with the floodplain will increase water storage and habitat availability, promote the formation of wetlands, and reduce stream power and sediment losses by partitioning flows. The existing conditions hydraulic model output from YN was used to assess current inundation and channel length for the 2-year flow. For locations where large wood and/or fill are proposed in the stream channel, the existing WSE was raised by the conceptual design height for those restoration treatments (typically 2-4 ft). Similarly, for locations where side channel excavations are proposed in ROAs, the ground surface was lowered by the conceptual design height (typically 1-4 ft). The resulting conceptual WSE was then used to evaluate potential floodplain inundation and channel length resulting from restoration treatments. Each ROA was then scored based on the percent increase in inundated area and channel length. Channel-spanning (valley) logjams have been successfully used to aggrade the South Fork Nooksack (Abbe et al., 2015) and South Prairie Creek (Figure 27). Arrays of large bar apex jams have been successfully used on numerous rivers to restore anabranching, channel complexity and trigger channel aggradation (Abbe and Brooks 2011, Abbe et al., 2016, 2018).

Figure 27. Channel-Spanning Engineered Logjam in South Prairie Creek, Pierce County, Washington Immediately following Construction

The structure raised the channel bed about 4 ft. The channel upstream aggraded several feet upstream in the first year. Photo: August 6, 2020.

7.1.3 Water Storage & Retention

River corridors and floodplain wetlands are groundwater-dependent, characterized by the continual exchange of surface and subsurface water and sustained by inputs from upslope areas, local precipitation, and the regional aquifer (Wohl et al., 2021). This exchange is regulated by alluvial water storage, which affects streamflow, stream temperature, and biogeochemical cycles forming the base of aquatic food webs. Alluvial water storage is largely a function of substrate, valley morphology, and lateral and longitudinal gradients between floodplain groundwater tables and the stream channel. Historic channel incision in the Teanaway has lowered the channel WSE, thereby increasing groundwater gradients and reducing alluvial water storage (NSD, 2019). NSD evaluated alluvial water storage potential throughout the Teanaway watershed using a geospatial model accounting for valley morphology and substrate characteristics (NSD, 2019) and incision estimates from Schanz et al., (2019). Potential alluvial water storage for each valley bottom segment where ROAs were mapped is derived from a conceptual rise in the channel WSE, which effectively reduces the groundwater gradient between floodplain and channel areas (Figure 28). Outputs from the alluvial water storage model within each ROA were scored and ranked based on acre-feet per mile of stream channel. Logjams have also been used to raise groundwater elevations and increase alluvial water storage (Abbe et al. 2019).

Information from NSD's wetland assessment (companion report, 2021) was also used to determine which ROAs could benefit existing wetlands, create or restore wetlands, and which locations warranted additional treatments or revisions to avoid unwanted impacts to high functioning existing wetlands. Potential for uplift to existing wetlands inventoried by NSD are included in the wetlands assessment report. The highest functioning wetlands observed in the MF and WF are generally fed by cold water inputs from springs or tributaries. Raising the bed and WSE in the mainstem channel with large wood and fill placements will increase water storage in the alluvial aquifer, slowing the release of this cool wetland water to the stream channel and increasing the duration of wetland hydroperiods.

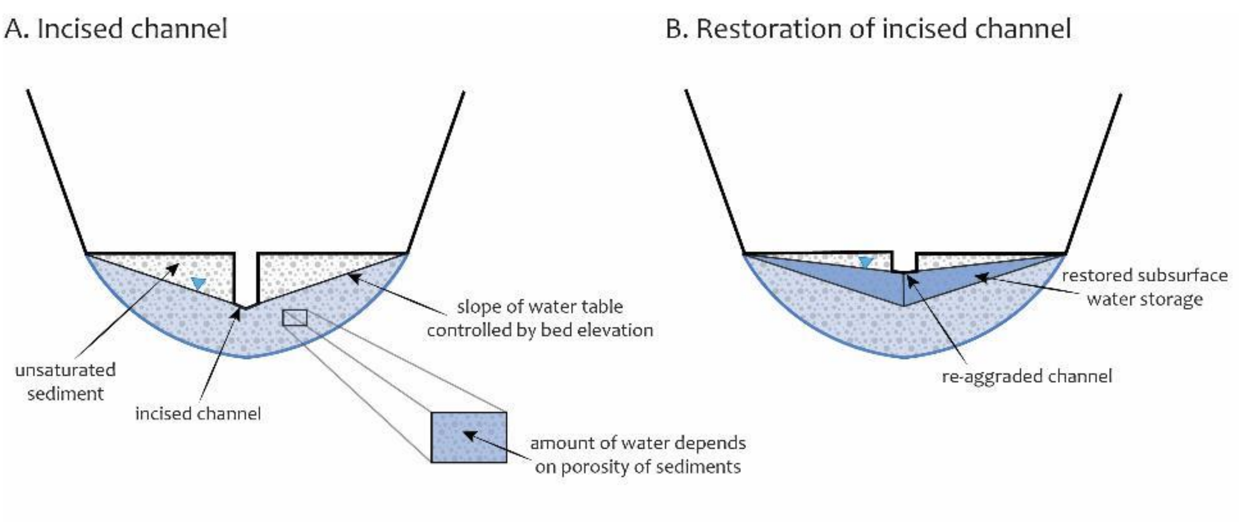

Figure 28. Conceptual Model for Alluvial Water Storage in an Incised (A) and Restored (B) Stream Channel

7.1.4 Substrate Size

Bedrock channel segments in the MF and WF have increased in extent and frequency due to historic splash damming and subsequent channel incision (Schanz et al., 2019). In many locations these bedrock channel segments are straight and high gradient, with low likelihood for natural recruitment of wood or lateral channel migration. Floodplain and channel modifications have further impacted channel form and slope, resulting in high transport capacity and few areas for sediment deposition. Minimum stable particle size under existing conditions was used to identify ROAs currently lacking potential for gravel deposition. The area of bedrock channel (WDFW, 2015) within each ROA was also included in ranking criteria. Restoration actions that include large wood and fill placements would reduce channel slope and partition flows into multiple flowpaths, reducing shear stress and lowering the minimum stable particle size. Over time, sediment aggradation would also reduce the number and extent of bedrock channel segments.

7.1.5 Stream Temperature

Stream temperature is a crucial factor affecting survival of fish species in the MF and WF study areas, and water temperatures throughout the upper Yakima basin are projected to increase under future climate warming with lower snowpack and late summer base flows (Isaac et al., 2017). Increasing alluvial water storage within floodplain areas and snowpack retention in the watershed will help alleviate thermal stresses during summer low flows, but riparian canopy and stream shading are important controls on stream temperature. The mean lidar-derived canopy height within each ROA was used to evaluate potential for stream shading, as well as the potential to supply a future source of large woody material to the channel as it adjusts to restoration actions over time.

7.1.6 Feasibility

The feasibility of implementing each ROA was evaluated during both the desktop and field analyses. Most of the ROAs are within the TCF, however some sites fall within the USFS National Forest or are within or adjacent to privately owned parcels bordered by TCF lands. Landowner outreach for ROA actions on private parcels would require ongoing coordination and was not included in the concept-level planning for this effort. For simplicity, ROAs with private ownership were flagged with a single value and a weight of 30%, which uniformly lowered the scores for privately owned ROAs in final rankings.

Other considerations that were evaluated but not directly incorporated into ROA rankings included:

- Construction access and machine requirements (e.g., excavation requires ground access),
- Risk to downstream property and infrastructure,
- Proximity to other ROAs with high potential for uplift, and
- Estimated project costs.

7.2 Restoration Actions

Descriptions and ranks for ROAs are in Table 7 below and mapped in Appendix F. Representative channel cross sections mapped in Appendix F are shown in Appendix G. The full scoring matrix for ROAs is in Appendix H. The majority of ROAs are based on several common project elements, which are detailed below. For the current scope of work, all restoration actions were planned at the conceptual level, without specifically designed/engineered plans for individual sites. The suite of actions for the MF and WF Teanaway is largely aimed at aggrading the channel bed to re-engage off-channel and floodplain areas, wetlands, and improve suitability for beaver. Individual ROAs or groupings of ROAs will require further evaluation during preliminary design stages to achieve these objectives.

7.2.1 Large Wood and Fill

Large wood additions are proposed throughout the MF and WF ROAs. For most locations, large wood additions are combined with fill placement to increase channel bed elevations, raise WSE, and re-engage floodplain areas. These additions would include a matrix of logs with intact rootwads and fill material composed of floodplain gravels and cobbles (e.g., Figure 27). In many cases, fill material is sourced from nearby actions such as side channel or floodplain grading to achieve an approximate mass balance of materials, reducing hauling costs. In some cases, the degree of incision and channel confinement necessitates a 'valley reset' approach wherein fill from adjacent floodplain surfaces is relocated into the channel with large wood to bring the entire channel up to match grade with a new inset floodplain (Figure 29, Figure 30). In locations where no locally sourced fill is available, wood and boulder matrices could be used to reduce hauling costs for fill, or fill material imported if deemed appropriate. Apex style logjams are proposed in some locations to raise the WSE and deflect flows into side channels or promote the formation of forested islands.

Any excavation or channel fill will require ground access, which is limited in portions of the upper MF. Further evaluation of access constraints are needed in future design phases. In locations with limited access, helicopter wood placements and/or boulder material could be used to aggrade the channel, allowing these structures to infill over time with natural sediment. These sites will take longer to aggrade and achieve the same rise in WSE, but could achieve similar benefits as log and fill matrices in the long-term (> 10 years).

For locations with existing low-lying side channels and floodplain, apex style engineered logjams are proposed to raise the WSE and deflect flows into multiple flowpaths. Channel-spanning wood matrices with interconnected logs and rootwads are also proposed in locations where channel roughness is needed to raise WSE and promote sediment deposition. Channel-spanning logjams and associated fill would be designed during future project phases to ensure that aggradation is achieved without propagating headcuts upstream or increasing scour and incision downstream of wood and fill placements. Channel-spanning logjams are generally designed to occupy enough of the active channel corridor to obstruct flows, thereby raising WSE to engage floodplain areas, reducing velocities, and promoting sediment deposition without impairing fish passage. Channel-spanning structures span the unvegetated channel and range from two to several channel widths in length. Length will depend on the targeted rise for WSE, with higher rise necessitating longer structures to ensure fish passage and energy dissipation over larger areas.

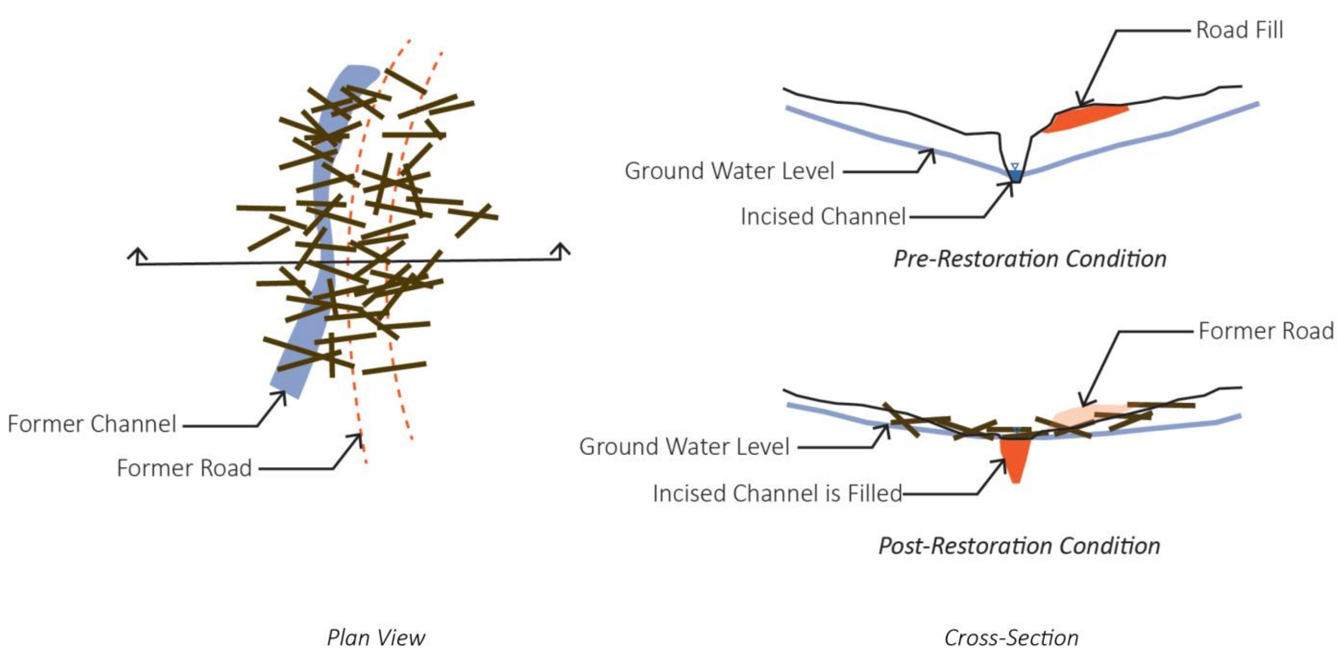

Figure 29. Conceptual Diagram of Valley Reset Style Restoration

Incised channel is aggraded and adjacent floodplain features (e.g., roads, berms, levees) are used for fill material in combination with wood to elevate the channel to a restored, inset floodplain.

Figure 30. Example of before (L) and after (R) Valley Reset Large Wood Restoration in Toppenish Creek

Photos: June 29, 2015 & June 12, 2017. Water storage increased approximately 20 ac-ft after stream restoration (Abbe et al. 2019).

7.2.2 Side Channel Inlet Grading

ROAs where floodplain channels or side channels are disconnected at higher flow stages will require some grading of side channel inlets and the upper portions of channel alignments. For these locations, grading of 1-4 vertical ft is intended to match grade with the conceptual channel bed, with a balance of side channel grading and increasing mainstem WSE through large wood and fill placements. In many cases, material from side channel grading could be used in nearby channel-spanning large wood placements, reducing hauling costs. Locations for side channel grading should be evaluated for channel migration potential, which will depend on the presence of robust riparian trees and bank material. In most cases, side channel excavations would also include large wood placements to reduce the likelihood of a channel avulsion into newly created side channels.

7.2.3 Floodplain Grading

Some ROAs include floodplain grading to remove artificial barriers and re-engage low-lying floodplain areas. Where floodplain modifications such as levees, dikes, or relic road and railway features confine the channel or impede floodplain connectivity, grading to the surrounding floodplain elevation is proposed. In many cases, this material is proposed for use in nearby large wood placements, reducing hauling costs. These locations would either be treated with large wood placements as part of valley reset style projects, or replanted with native trees to provide shade and a future wood source to the channel.

7.2.4 Road & Trail Relocations

Road relocations are proposed in several locations where the Middle Fork Teanaway Road or the West Fork Teanaway Road cross or impede connectivity with relic channels, low-lying floodplain areas, or wetlands. For these locations, relocating the road along the valley margin would retain vehicle access while improving floodplain connectivity. Material from road realignments could be used in nearby large wood placements, reducing hauling costs. In locations where road grading is required, material could be relocated to the new road alignment. Some locations on the West Fork Teanaway Road where vehicle access is no longer needed could be decommissioned and removed entirely. These actions require further discussion with WADNR to ensure recreational and management (e.g., fire) access is protected.

Trail relocation is recommended for ROA MF 7.3, where a high functioning wetland occupies the left bank floodplain. During NSD's wetland assessment, the existing trail was observed with concentrated flow draining the wetland area, and horse fecal matter entering the stream channel. Relocating this trail to the valley margin would improve water retention and water quality in the wetland.

7.2.5 Top 3 Ranking Restoration Opportunity Areas

MF 0.7

MF 0.7 spans from MF RM 0.9 downstream to RM 0.45, and includes 4 channel-spanning logjams and additional large wood to stabilize existing wood accumulations near RM 0.8 (Figure 31). Channel-spanning structures would raise WSE, engaging side channel areas and increasing inundation of the currently functioning left bank side channel complex near RM 0.8. Wood placements at RM 0.7 and 0.6 would re-engage relic side channels and the left bank floodplain near RM 0.6. Large wood at RM 0.8 is currently functioning to create complex hydraulics and promote gravel deposition and the formation of a forested island, but is not forming a stable logjam (Figure 24). Additional large wood pieces in this location would stabilize existing wood and further increase WSE to engage both the left and right floodplain and associated side channel areas.

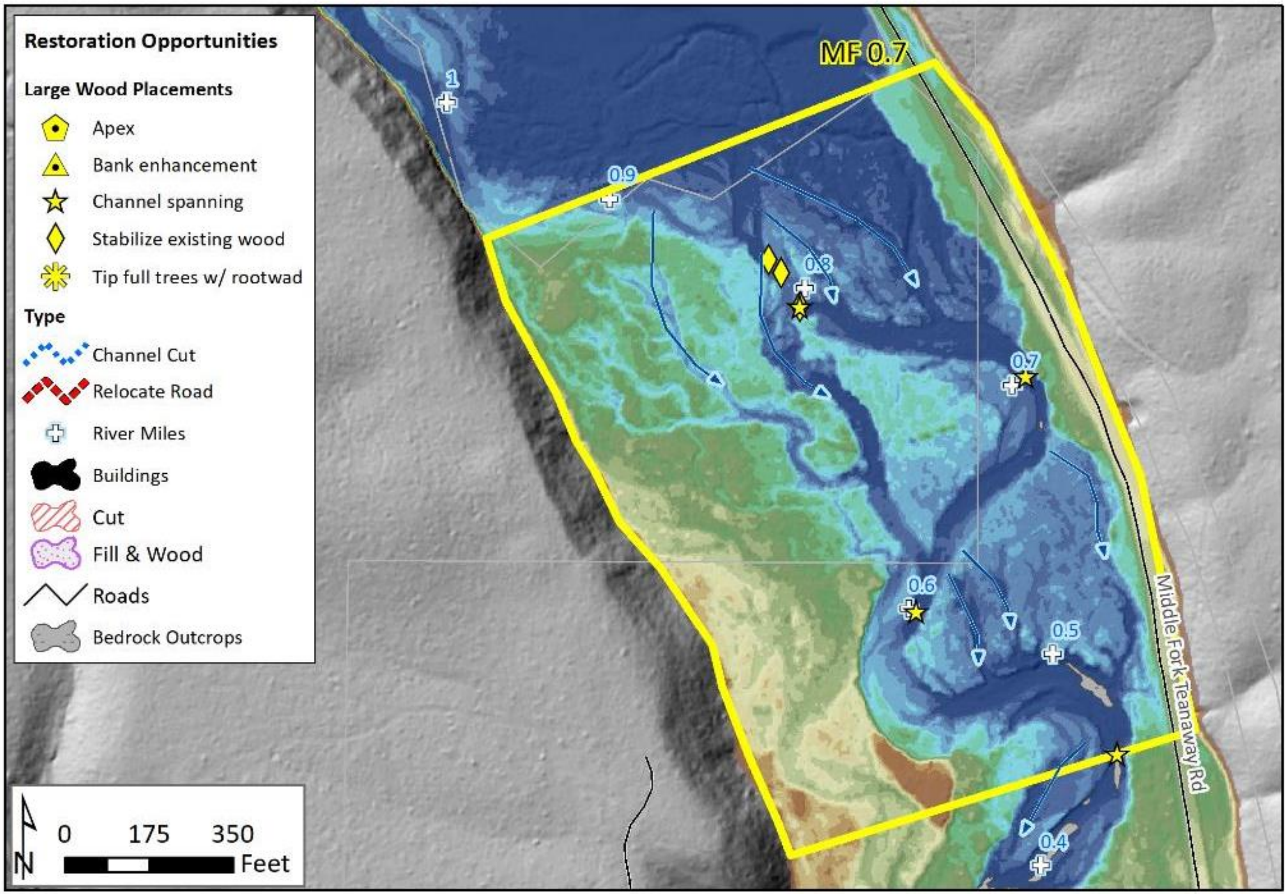

Figure 31. MF 0.7 Restoration Opportunity Area

Channel-spanning wood placements and additional large wood pieces to stabilize existing logjams would re-engage side channel and floodplain areas.

MF 4.25

Within ROA MF 4.25, sufficient WSE rise could be achieved with just large wood placements in channel-spanning structures and by augmenting existing large wood (Figure 32). Full trees with intact rootwads could also be tipped from the right bank near RM 4 to enhance an existing side channel along the toe of the eroding bank, slowing bank erosion and improving habitat. An apex style logjam is also proposed at RM 4 to increase engagement of the low-lying left bank floodplain in that location and to help partition flows into a proposed side channel excavation in ROA MF 3.9 just downstream. An existing dike along the left bank at RM 4 would also be removed, and material could be used in channel-spanning logjams within MF 4.25 or in adjacent ROAs. This ROA is part of a larger complex encompassing MF 3.9 and MF 4, which includes relocating Middle Fork Teanaway Road to the valley margin and utilizing existing road prism material in channel-spanning wood and fill structures.

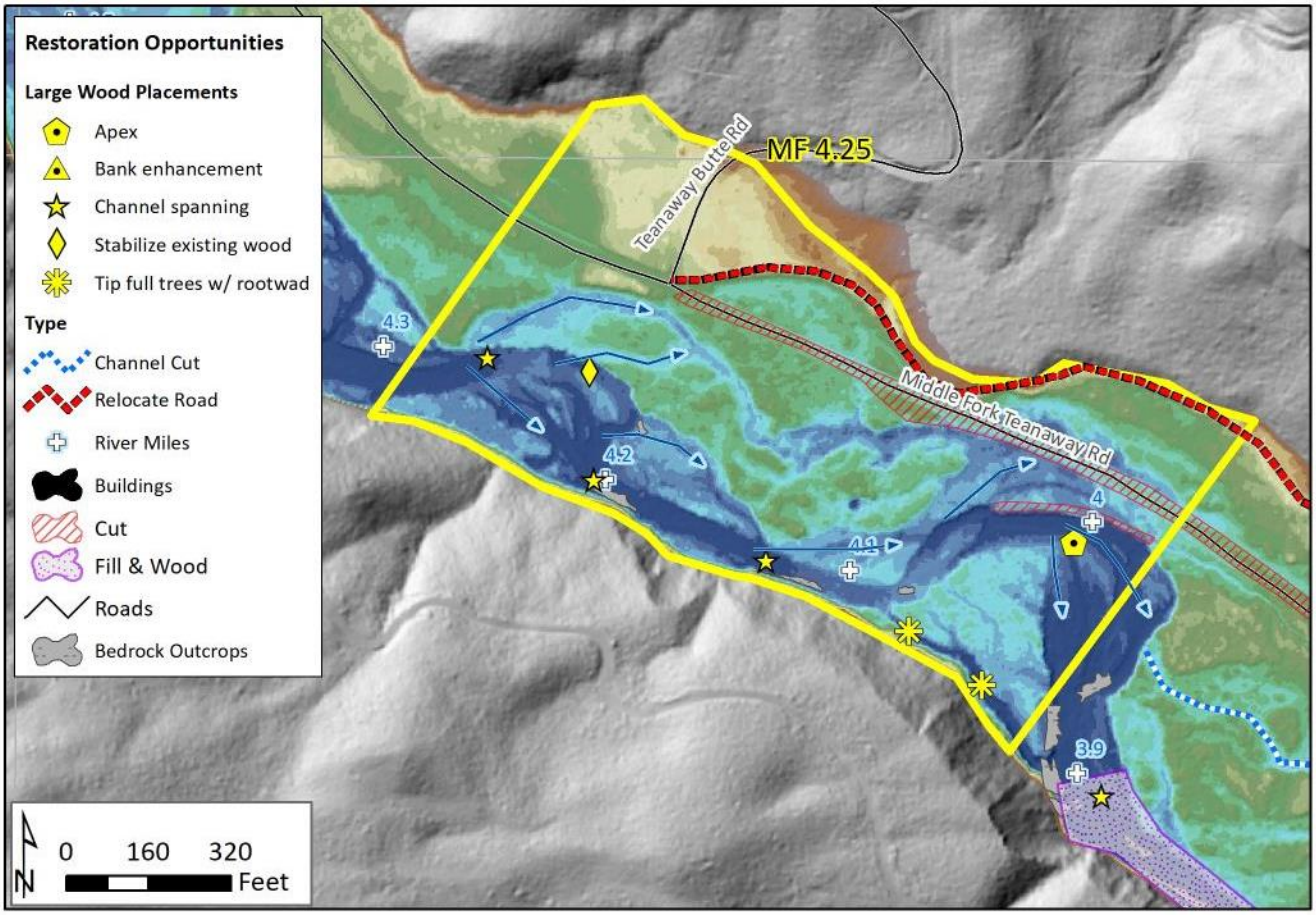

Figure 32. MF 4.25 Restoration Opportunity Area

Channel-spanning wood placements and additional large wood pieces to stabilize existing wood would re-engage side channel and floodplain areas. Removal of the left bank dike and relocating MF Teanaway Road (ROA MF 4) would allow the channel to re-engage the left bank floodplain.

MF 5

Restoration at MF 5 involves a valley reset style project wherein material from dikes along the left bank and Middle Fork Teanaway Road would be utilized in channel-spanning logjams at three locations and a channel-spanning logjam at one location (Figure 33). Relocating Middle Fork Teanaway Road to the valley margin in this reach would allow the channel to re-engage relic floodplain channels and wetland areas along the left bank. Channel-spanning wood and fill placements would raise WSE to re-engage the right bank floodplain and side channels at RM 5. A channel-spanning placement at RM 4.92 and a wood and fill placement at RM 4.8 would also increase engagement of the left bank floodplain and a relic side channel in the reach.

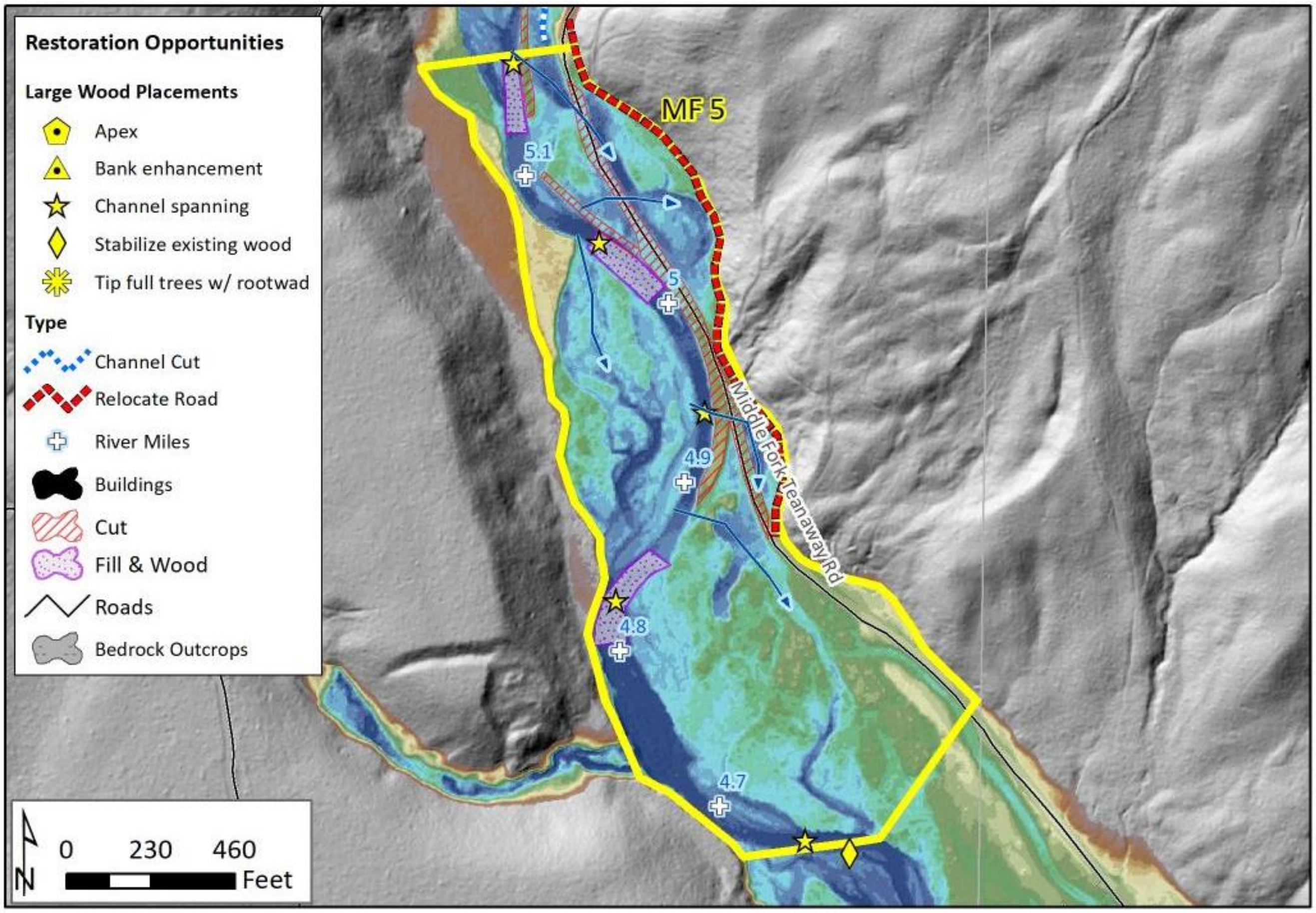

Figure 33. MF 5 Restoration Opportunity Area

Relocation of Middle Fork Teanaway Road and removal of the left bank dikes would provide material for channel-spanning large wood and fill placements to increase WSE, re-engage floodplain and side channel areas, and restore connectivity to relic wetlands.

7.2.6 Other Recommendations for the TCF

General recommendations for the MF and WF portions of the TCF that were not evaluated on a site-specific basis are detailed below. These actions could be implemented in many locations throughout the study area to aid in the recovery of in-stream habitat while increasing water storage potential within the watershed. Future project phases could evaluate site-specific treatments for tributaries and associated roads not assessed under the current scope of work.

Road Decommissioning

Roads no longer used for forest management or recreational access within the historic floodplain of the MF, WF, and low relief tributaries could be decommissioned, and road grades removed to allow the river channel to re-engage historic floodplain areas following other restoration activities. For example, portions of the West Fork Teanaway Road are currently preventing engagement of the left bank floodplain in numerous locations. While this road could be used for construction access at select ROAs, it could be decommissioned following construction, with material used for in-stream fill during construction sequencing in the upstream direction.

Forest Thinning

Historic forest management (logging, replanting, & fire suppression) has resulted in increased stem density throughout much of the Teanaway watershed and a shift toward drought intolerant tree species. Increased stem density and simplified stand structure (e.g., lower age and species diversity) has also made the forest less resilient to disturbances from fire and insects. Forest thinning in many areas could benefit forest resiliency while also improving snowpack, particularly in north-facing portions of the basin (see Climate Change and Canopy Height sections). Wood material from forest thinning operations could be utilized for in-stream restoration, reducing hauling and material costs. Small wood material could be used to form racking bundles for small wood structures or beaver dam analogs (Figure 34).

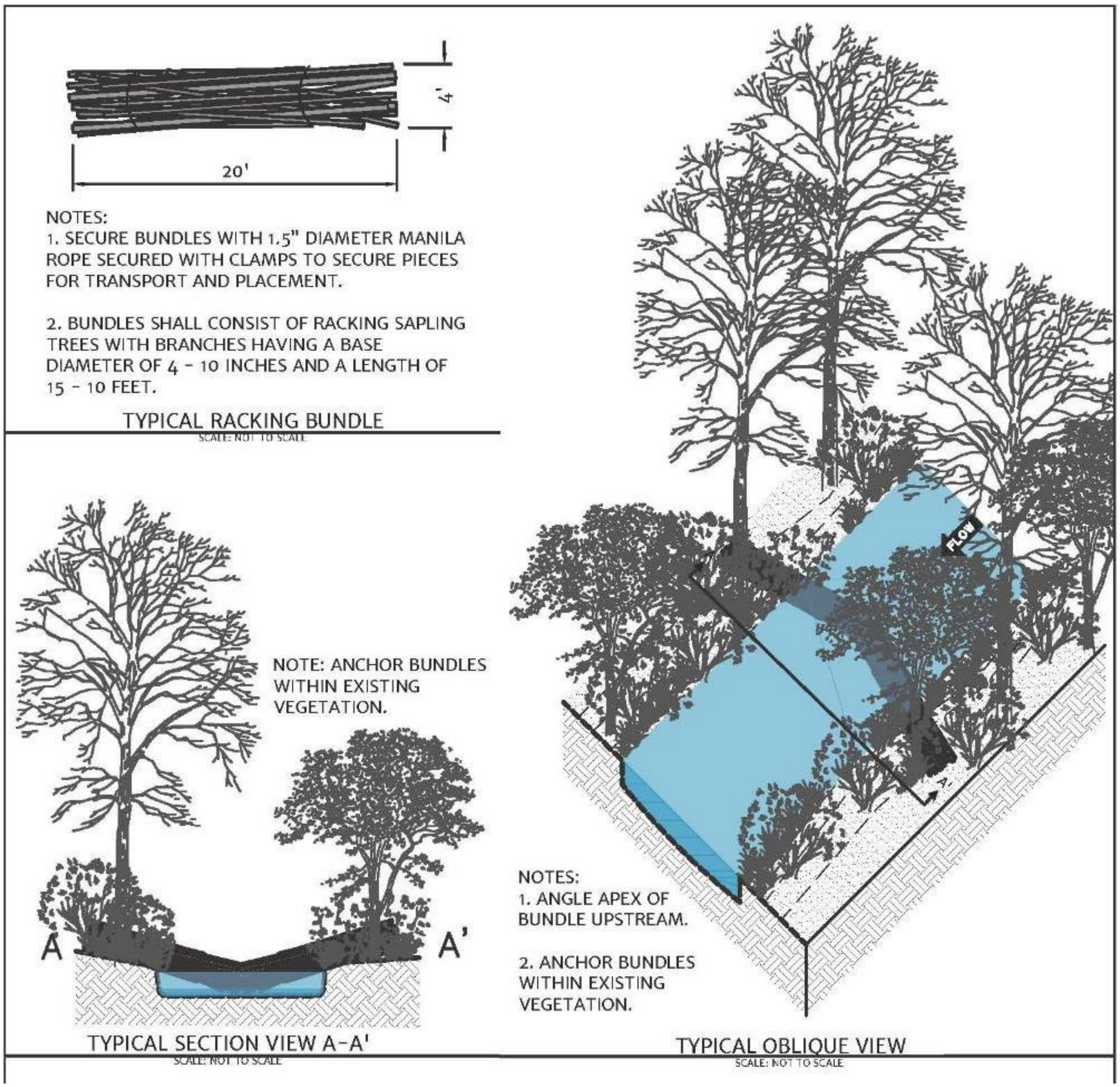

Figure 34. Use of Racking Bundles for Small Wood Structures or Beaver Dam Analogs to Create Backwater Pools in Smaller Tributaries

Beaver Dam Analogs

Low relief tributaries such as Carlson, Sandstone, Corral, and Dingbat Creeks have smaller channels that would be suitable for beaver dam analogs (BDAs) or similar, low-cost channel-spanning wood structures. Some of these tributaries have substantial water storage potential, and enhancing storage in these south-facing basins could augment summer baseflows in the WF. BDAs could be spaced to optimize water storage potential based on valley width and channel slope (Figure 35).

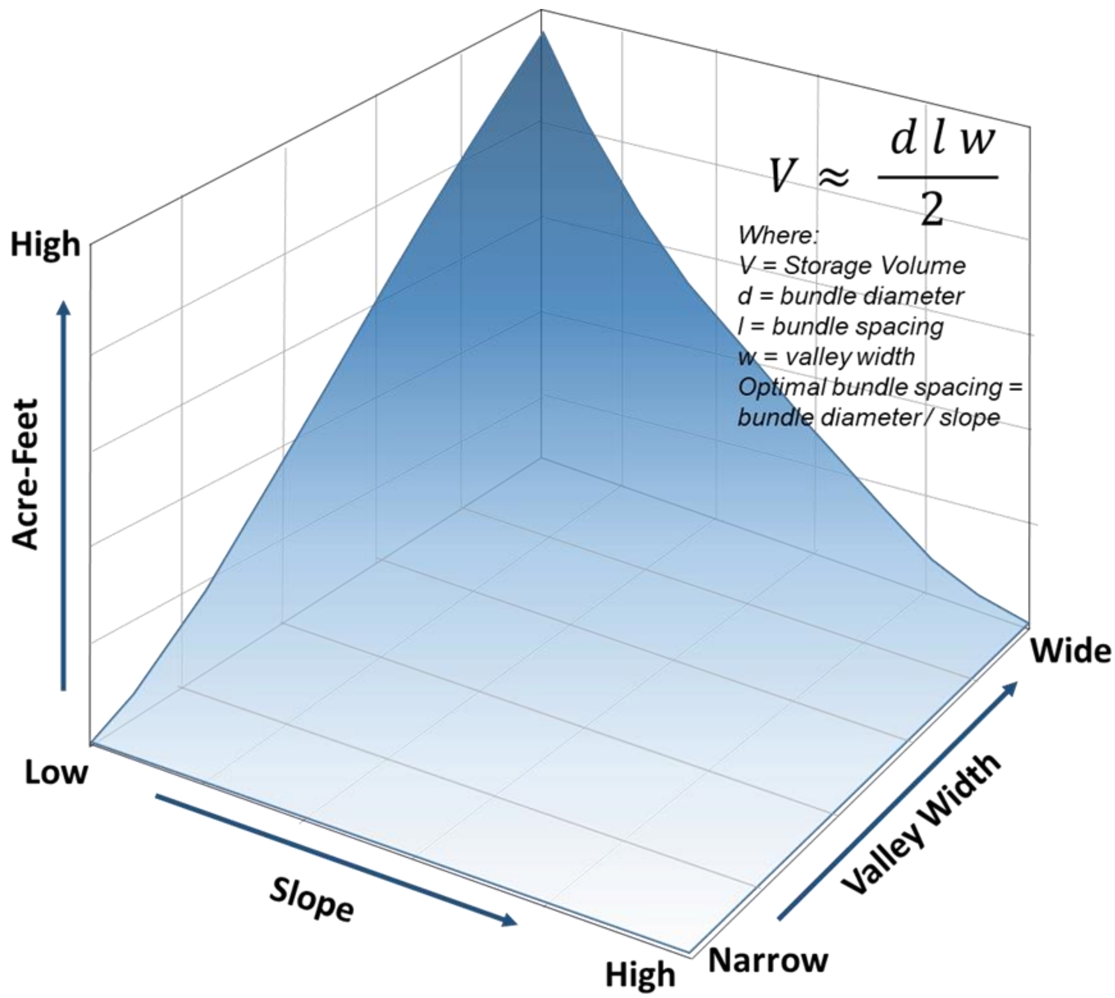

Figure 35. Small wood structure water storage potential as a function of channel slope and valley width

Structure spacing can be optimized to backwater upstream to the next BDA or small wood structure.

Table 7. Restoration Opportunity Area Ranks and Descriptions

SITE	OVERALL RANK	DESCRIPTION OF RESTORATION ACTIONS
MF 0.7	1	Channel-spanning wood at RM 0.8,0.7,0.6, 0.45 to re-engage low-lying floodplain areas and bury bedrock outcrops. Stabilize existing logjams with additional key pieces.

SITE	OVERALL RANK	DESCRIPTION OF RESTORATION ACTIONS
MF 4.25	2	Channel-spanning wood to engage left bank floodplain channels and raise bed and bury bedrock outcrops, remove left bank dike at RM 4 and place material in channel with wood.
MF 5	3	Relocate Middle Fork Teanaway Road, add fill and wood to channel, remove road prism and old dike to re-connect floodplain areas
MF 4	4	Relocate Middle Fork Teanaway Road to edge of valley, place fill and wood in channel
WF 4.7	5	Relocate West Fork Teanaway Road to edge of valley
WF 2.8	6	Remove left bank berm, excavate inlet to left bank floodplain channel, and place fill and wood in channel
WF 0.4	7	Remove Carlson Creek Road bridge abutment, road prism, and old road spur
MF 4.65	8	Channel-spanning wood
WF 4.6	9	Place channel-spanning wood and utilize fill from West Fork Teanaway Road removal
WF 3.3	10	Channel-spanning wood
WF 5.8	11	Remove berms on left bank floodplain, excavate channel, and place fill and wood in mainstem
WF 4.95	12	Channel-spanning wood to re-engage left bank floodplain
WF 3.95	13	Remove old splash dam berm and place material and wood in channel at RM 3.85 and RM 3.75 to raise bed and engage left floodplain surface.
MF 3.9	14	Cut channel alignment in low-lying left bank floodplain and place wood and fill in mainstem channel
WF 6.65	15	Relocate West Fork Teanaway Road to valley margin or remove and decommission road after construction
MF 4.5	16	Channel-spanning wood
WF 4.4	17	Cut channel to left bank relic floodplain areas and place fill and wood in mainstem
MS 11.7	18	Remove old railroad grade and place fill and wood in mainstem channel
MF 4.4	19	Channel-spanning wood
WF 2.2	20	Remove relic railroad grade berms from left bank floodplain and place material and wood in channel
WF 7.1	21	Remove left bank berm, excavate pilot inlet to left bank relic floodplain channel, and place material and wood in mainstem

SITE	OVERALL RANK	DESCRIPTION OF RESTORATION ACTIONS
WF 3.7	22	Channel-spanning wood to engage left bank floodplain
WF 1.6	23	Cut inlet to left bank relic meander channel and place wood and fill in channel
WF 0.6	24	Remove left bank berm, excavate channel, place wood and fill in mainstem
WF 6	25	Cut pilot channel to reconnect left bank floodplain, remove remnant road prism, and place fill and wood in mainstem
WF 5.3	26	Excavate channel to reconnect left bank floodplain and add fill and wood to mainstem
WF 4.75	27	Channel-spanning wood
WF 3.52	28	Channel-spanning wood to engage left bank floodplain
WF 2.5	29	Channel-spanning wood and fill
WF 2.3	30	Channel-spanning wood at RM 2.3
WF 0.3	31	Remove old railroad grade and place fill and wood in mainstem channel
MF 7.2	32	Cut pilot channel into relic left floodplain flowpath and place fill and wood in mainstem channel
MF 6.8	33	Cut pilot channel into relic left floodplain flowpath and place fill and wood in mainstem channel
MF 6.9	34	Cut pilot channel into relic left floodplain flowpath and place fill and wood in mainstem channel
MF 6.4	35	Remove berm on right bank and excavate inlet to right bank relic channel, place fill and wood in mainstem channel
WF 6.5	36	Cut inlet to relic left bank channel and place material and wood in mainstem at RM 6.52 and 6.48
MF 0.3	37	Expand bridge span at West Fork Teanaway road crossing, remove left bank dike and place material and wood in mainstem channel at RM 0.25
WF 6.75	38	Excavate inlet to relic left bank channel and place fill and wood in mainstem channel
MF 6	39	Channel-spanning wood at RM 6.05 and 5.95 to raise water surface and engage low-lying areas
WF 1.45	40	Channel-spanning wood
MF 6.6	41	Place channel-spanning wood structures to engage floodplain areas
WF 3.1	42	Excavate inset floodplain bench and place material and wood in mainstem

SITE	OVERALL RANK	DESCRIPTION OF RESTORATION ACTIONS
MF 5.3	43	Remove left bank berm, excavate pilot channel, and place wood and fill in channel
WF 1	44	Relocate road to higher floodplain surface, excavate inlet to relic meander, place fill and wood in channel
WF 6.3	45	Channel-spanning wood placements to raise bed and provide cover along meander bend pools
WF 6.6	46	Remove berm on left bank and place fill and wood in mainstem channel
WF 5.5	47	Channel-spanning wood to raise water surface and re-engage low-lying channels
MF 6.2	48	Cut to reconnect left floodplain meander and place fill and wood in mainstem channel
MF 7.3	49	Remove berm on left bank, cut inlet to left floodplain channel, and place fill and wood in mainstem channel to re-engage floodplain areas; relocate trail to valley margin to reduce concentrated flow in wetland and horse fecal inputs to stream
WF 6.2	50	Remove berm at West Fork Teanaway Road and place fill and wood in mainstem channel
WF 1.3	51	Channel-spanning wood at RM 1.33 and 1.23
MF 7	52	Cut pilot channel into relic left bank floodplain flowpath; place berm material and wood in mainstem channel
WF 4.45	53	Remove Dingbat Road bridge approach and place material and wood in channel near RM 4.4

8. REFERENCES

Abbe, T.B. and D.R. Montgomery. 2003. Patterns and processes of wood debris accumulation in the Queets River Basin, Washington. *Geomorphology 51*, 81-107.

Abbe, T. and A. Brooks. 2011. Geomorphic, Engineering and ecological considerations when using wood in river restoration. In Simon, A., Bennett, S., and Castro (Eds.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. Geophysical Monograph Series 194. AGU. pp.419-451.

Abbe, T., M. Ericsson and L. Embertson. 2015. Channel incision and floodplain abandonment due to historic wood removal in Washington State, USA. International Conference on Wood in World Rivers Conference. University of Padova, Padova, Italy.

Abbe, T., B. Belby, and F.D. Shields. 2016. Geomorphology and hydrology considerations. Chapter 4 in Bureau of Reclamation and U.S. Army Engineer Research and Development Center. National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure. 628 p. + Appendix. www.usbr.gov/pn/ and http://naturaldes.com/resources/

Abbe T, Hrachovec M, and Winter S. 2018. Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A., Reference Module in Earth Systems and Environmental Sciences, Elsevier. 30-Oct-18 doi: 10.1016/B978-0-12-409548-9.11031-0.

Abbe, T., Dickerson-Lange, S., Kane, M., Cruickshank, P., Kaputa, M. and Soden, J. 2019. Can wood placement in degraded channel networks result in large-scale water retention? Proceedings of the SEDHYD 2019 Conference on Sedimentation and Hydrologic Modeling, Reno, NV. Volume 1, p.408-428.

Abatzoglou J.T. & Brown T.J. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology. 32, 772-780.

Amec Environment & Infrastructure, Inc. (Amec). 2013. Teanaway Forks Large Wood Trapping Design Project. Preliminary Design Report prepared for Mid-Columbia Fisheries Enhancement group.

Babik, M. & W. Meyer. 2015. Yakima Basin Beaver Reintroduction Project: 2011-2015 progress report. Mid-Columbia Fisheries Enhancement Group & Washington Department of Fish & Wildlife.

Bommarito, S. 2019. Identifying the effects of land use and policy on disturbances regimes in the Teanaway Community Forest, Washington. M.S. Thesis. Central Washington University.

Bryant, F.G., and Z.E. Parkhurst. 1950. Scientific Report – Fisheries survey of the Columbia River and its tributaries. 40 Area III. Washington Streams from the Klickitat and Snake Rivers to Grand Coulee Dam. United States Department of the Interior. Oscar L. Chapman, Secretary of Fish and Wildlife Service, Albert M. Day Director Special.

Collins, B.D., D.R. Montgomery, S.A. Schanz, and I.J. Larsen. 2016. Rates and mechanisms of bedrock incision and strath terrace formation in a forested catchment, Cascade Range, Washington. GSA Bulletin. 128.5/6: 926-943.

Deichl, C., A. Hackett, D. Pierson, J. Sandberg, & J. Slavick. 2011. Gold Creek: Development to restoration. Report prepared for: U.S. Forest Service, Okanogan-Wenatchee National Forest, Cle Elum Ranger District.

Ditbrenner, B.J., M.M. Pollock, J.W. Schilling, J.D. Olden, J.J. Lawler, & C.E. Torgersen. 2018. Modeling intrinsic potential for beaver (Castor canadensis) habitat to inform restoration and climate change adaptation. PLoS One. 13(2):e0192538.

Dickerson-Lange, S. E., Gersonde, R. F., Hubbart, J. A., Link, T. E., Nolin, A. W., Perry, G. H., et al. (2017). Snow disappearance timing is dominated by forest effects on snow accumulation in warm winter climates of the Pacific Northwest, United States. Hydrological Processes, 31(10), 1846–1862. https://doi.org/10.1002/hyp.11144

Dickerson-Lange, S. E., Gersonde, R. F., Vano, J. A., & Lundquist, J. D. (2021). Ranking forest effects on snow storage: a decision tool for forest management. Water Resources Research (in Review).

General Land Office (GLO). 1900. Survey map and survey notes for Township 21 North, Range 15 East, Willamette Meridian, Washington. Bureau of Land Management. Office of the Surveyor General.

Hegewisch, K.C. & J.T. Abatzaglou. Historical Climograph web tool. Climate Toolbox. Accessed on February 20, 2021. https://climatetoolbox.org/

Henderson, E.M. 1990. The Pine Tree Express: A history of the Cascade Lumber Company's pine hauling railroad in Kittitas County, Washington 1916-1946.

Holcomb, C. 2015. Teanaway Community Forest major tributary area wetland report. Prepared for Washington Department of Fish and Wildlife. Conservation Northwest. Contract 15-03562.

Keefer, M.L., T.S. Clabough, M.A. Kepson, E.L. Johnson, C.A. Peery, & C.C. Caudill. 2018. Thermal exposure of adult Chinook salmon and steelhead: Diverse behavioral strategies in a large and warming river system. PLoS One. 13(9): e0204274.

Kittitas County Centennial Committee (KCCC). 1989. A History of Kittitas County, Volume 1. Kittitas County, Washington.

Kittitas County Shoreline Master Program. 2013. Kittitas County Shoreline Inventory and Characterization Report. Kittitas County Board of Commissioners.

Mayo, T., W. Ehinger, & C. Thomas. 2009. Teanaway Watershed Aquatic Species Environmental Baseline. U.S. Forest Service, Cle Elum Ranger District, Okanogan-Wenatchee National Forest.

Means, C.D. 2018. Stream temperature variability in headwater beaver dam complex in relation to hydrologic and environmental factors. M.S. Thesis. University of Washington, Seattle.

Montgomery, D.R. & T.B. Abbe. 2006. Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old growth forest valley, Queets River, Washington, USA. Quaternary Research. 65: 147-155.

Mote, P.W., J.T. Abatzoglou, D.P. Lettenmaier, D.P. Turner, D.E. Rupp, D. Bachelet, & D.R. Conklin. 2014. Integrated Scenarios of Climate, Hydrology, and Vegetation for the Northwest, Final Report. Corvallis, Oregon: Pacific Northwest Climate Impacts Research Consortium, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University.

Mote, P.W., J.T. Abatzoglou, D.P. Lettenmaier, D.P. Turner, D.E. Rupp, D. Bachelet, & D.R. Conklin. 2017. Final report for Integrated Scenarios of climate, hydrology, and vegetation for the Northwest.

Natural Systems Design (NSD). 2019. Potential for restoration of alluvial water storage in the Teanaway River watershed. Report prepared for The Nature Conservancy.

Natural Systems Design (NSD). 2021. Wetland inventory report: Community Forest areas along the Middle Fork & West Fork Teanaway River. Prepared for Mid-Columbia Fisheries Enhancement Group.

Olson, P.L., Legg, N.T., Abbe, T.B., Reinhart, M.A. and Radloff, J.K. 2014. A methodology for delineating planning-level channel migration zones (No. 14-06-025). Washington State Dept. of Ecology.

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan & J.M. Castro (Editors) 2015. The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains. Version 1.02. U.S. Fish and Wildlife Service, Portland, Oregon. 189 pp. Online at: http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp

PRISM Climate Group. 2021. 1981-2010 climate normals data. Oregon State University. Online: http://prism.oregonstate.edu

Queen, L.E., P.W. Mote, D.E. Rupp, O. Chegwidden, & B. Nijssen. 2021. Ubiquitous increases in flood magnitude in the Columbia River basin under climate change. Hydrology and Earth System Sciences. 25: 257-272.

Richter, A. & S.A. Kolmes. 2006. Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science. 13(1):23-49.

Schanz, S.A., D.R. Montgomery, & B.D. Collins. 2019. Anthropogenic strath terrace formation caused by reduced sediment retention. Proceedings of the National Academy of Science. 116(18): 8734-8739.

Stock, J.D., D.R. Montgomery, B.D. Collins, W.E. Dietrich, and L. Sklar. 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. GSA Bulletin. 117.11/12: 174-194.

Tabor, R.W., R.B. Waitt Jr., B.A. Frizzel Jr., D.A. Swanson, G.R. Byerly, & R.D. Bentley. 1982. Geologic map of the Wenatchee 1:100,000 Quadrangle, Central Washington. Miscellaneous Investigations Series, Map I-1311. U.S. Geologic Survey.

Tabor, R.W., V.A. Frizzel Jr., D.B. Booth, & R.B. Waitt. 2000. Geologic map of the Snoqualmie Pass 30x60 Minute Quadrangle, Washington. Geologic Investigations Series, Map I-2538. U.S. Geologic Survey.

Taylor, K.E., R.J. Stouffer, & G.A. Meehl. 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society. 93:4. https://doi.org/10.1175/BAMS-D-11-00094.1

U.S. Forest Service (USFS). 2009. Teanaway Wilderness Evaluation: Teanaway – 617048. U.S. Forest Service, Okanogan-Wenatchee National Forest, Cle Elum Ranger District.

University of Washington Climate Impacts Group (UWCIG). Trend analysis application. Accessed on February 18, 2021. Online: https://climate.washington.edu/climate-data/trendanalysisapp/

Washington Department of Fish and Wildlife (WDFW). 2015. Teanaway Community Forest fish and wildlife habitat baseline report. Report submitted to Department of Ecology's Office of Columbia River. Online: https://www.dnr.wa.gov/publications/abt_dml_tcf_habitatreport2016.pdf

Washington Department of Fish and Wildlife (WDFW). 2020. Beaver Intrinsic Potential Model data for Washington State. BIP ALL v20200515. Online ArcMap data layer.

Washington Department of Fish and Wildlife (DFW) & Washington Department of Natural Resources (WDNR). 2013. Deed of Habitat Restoration and Working Lands. DNR Easement No. 58-090537.

Watershed Sciences. 2002. Aerial surveys un the Yakima River sub-basin: Thermal infrared and color videography. Report to Pacific Watershed Institute.

Winford, E., & W. Meyer. 2017. Fish and aquatic restoration strategy for the Teanaway Community Forest (TCF). Report to Washington Department of Ecology.

Wohl, E. J. Castro, B. Cluer, D. Merritts, P. Powers, B. Staab, & C. Thorne. 2021. Rediscovering, reevaluating, and restoring lost river-wetland corridors. Frontiers in Earth Science. 9:653623. Doi: 10.3389/feart.2021.653623

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