ALLUVIAL WATER STORAGE ASSESSMENT

MIDDLE FORK SNOQUALMIE RIVER AND RAGING RIVER

Wild Fish Conservancy Northwest
15629 Main Street NE
Duvall, WA 98109
425.788.1167

Natural Systems Design

1900 N. Northlake Way, Suite 211
Seattle, WA 98103

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1 INTRODUCTION

Wild Fish Conservancy requested that Natural Systems Design (NSD) quantitatively and qualitatively assess the potential for restoring alluvial water storage functions in the Middle Fork (MF) Snoqualmie and Raging River watersheds, located in southeast King County, Washington.

Both watersheds provide important ecological functions including providing aquatic habitat and maintaining water quality for ecological, recreational, and out-of-stream uses. The Raging River also provides critically important spawning habitat for Chinook (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss irideus*) (WDFW, 2018). However, natural functions that form and maintain aquatic habitat and provide ecosystem services have been impaired by land use impacts and will be further impaired by climate change impacts. Climate change is projected to reduce snow storage, which will affect the timing and magnitude of spring flows in the mixed rain-snow dominated MF Snoqualmie River. In addition, changing precipitation patterns and rising temperatures are anticipated to increase peak flow events, reduce summer low flows, and warm stream temperatures in both watersheds (Lee et al., 2020; Mauger & Won, 2020; Yan et al., 2021). Restoration of natural functions to store and slowly release colder groundwater from the shallow alluvial aquifer, which have been diminished due to channel incision and simplification, has the potential to locally diminish impacts from climate change and land use. This analysis provides a spatially explicit estimate of the potential for restoring alluvial water storage functions and a screening-level identification of reaches with highest potential for restoring these natural functions.

2 CONCEPTUAL BASIS

A river and its surrounding valley serve as a critical reservoir for both alluvial sediment and water. However, much of the natural function of the alluvial corridor to store and slowly release water has been diminished across the Pacific Northwest due to historic and current impacts that have resulted in stream down-cutting (i.e., incision) and the evacuation of the sediments that constitute the alluvial groundwater aquifer. Historically, large wood was naturally recruited to river channels where individual logs and log jams functioned as dams, creating a natural reservoir for sediment and for storing water in the channel, underground in the surrounding floodplain sediments, and within floodplain water bodies. Across the western United States the systematic removal of in-channel wood from splash damming, timber harvest, stream cleaning, and beaver trapping resulted in wide-spread channel down-cutting, erosion of alluvial sediments, and a loss of *in-situ* water storage (Abbe et al., 2015, 2016; Collins et al., 2002; Phelps, 2011; Pollock et al., 2014). In one regional example, channel and valley down-cutting was mapped across 12 miles of the forks of the Teanaway River, Washington, with the timing of rapid erosion directly linked to the timing of local splash-damming operations (Collins et al., 2016; Schanz et al., 2019; Stock et al., 2005).

Reduced surface and subsurface water storage within the river network subsequently result in lower riparian water availability (i.e., a lower shallow groundwater table) and lower streamflow during the dry season for two key reasons: (1) Less water is stored during high flows for later release, and (2) the water that is stored drains faster and earlier due to a locally steepened gradient between the groundwater table and the incised channel. Stream restoration therefore has the potential to increase storage of sediment, surface water, and subsurface water (Abbe et al., 2019). This stored water is then potentially available for riparian water use and for contributing colder groundwater to low flows during the dry season. The conceptual basis for this approach to restoring water storage is that where local water elevation is raised, groundwater elevation is raised and sub-surface water storage is increased. Since the rate at which groundwater flows is more than four orders of magnitude slower than surface water, the groundwater aquifer acts like a sponge, receiving water during high spring flows and returning some of that water during low summer flows (Hunt et al., 2018; Tague et al., 2008).

Local water elevation can be raised via in-stream restoration actions that re-aggrade deep channels that have cut down into the underlying sediments or bedrock, or via the introduction of grade control that sets the downstream water level. The latter has a variety of natural analogs, such as landslides, resistant underlying rock layers, and log jams (Abbe & Montgomery, 2003; Hancox et al., 2005; Montgomery & Abbe, 2006).

Increased in-situ storage of sediment and water simultaneously provides aquatic and terrestrial ecosystem benefits, including improved water quality, riparian water availability, forest health, and fire resilience. Thus, actions designed to improve both water availability and habitat quality could be an effective multi-benefit restoration approach.

3 METHODS

The alluvial water storage assessment model is a geospatial and computational workflow that uses high resolution topographic data, relevant spatial datasets, geomorphic analysis, and field validation to:

1. Estimate the volume of restorable surface and subsurface water storage at a reach-scale;
2. Estimate the volume of in-channel sediment storage potential from restoration actions at a reach-scale; and
3. Determine reach-scale characteristics related to geomorphology, hydrology, vegetation, and infrastructure that are relevant for determining potential restoration approaches.

The model workflow components are described below.

3.1 Geospatial Modeling

The alluvial water storage assessment begins with a geospatial analysis of a composite lidar digital elevation model (DEM) to map the natural drainage network across the subject watersheds. Steps of this analysis include flow correction to account for flow paths that are not present in the DEM (i.e., culverts), mapping of the drainage network and stream reaches, measure of surface-derived geomorphic characteristics, estimation of bankfull discharge and depth, and mapping of approximate alluvial valley bottom (Figure 1). Outputs of the geospatial analysis are then used for the numeric and geometric analysis to estimate alluvial water and sediment storage potential.

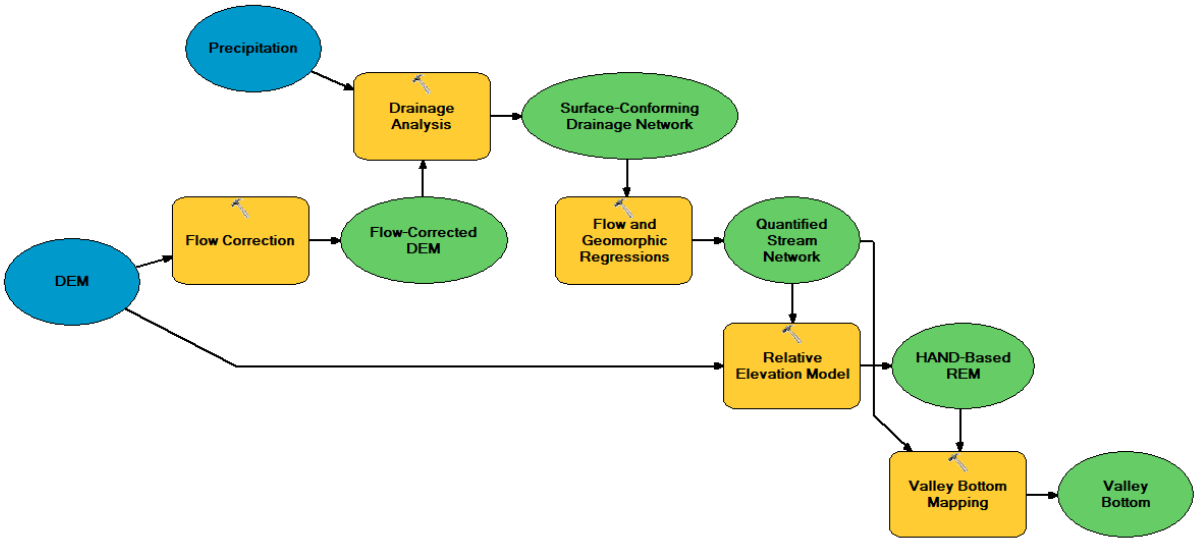


Figure 1. Conceptual Geospatial Analysis Workflow Diagram
Provides the quantified estimates of stream reach characteristics and spatial mapping of the approximate alluvial valley.

Inputs to the model include King County lidar DEMs from 2003 to 2016 with a mean annual precipitation overlay (PRISM Climate Group, 2012). The lidar DEM is down-sampled to a 9-foot cell resolution from the native 3-foot cell. The down-sampling uses the mean elevation of the underlying 3-foot cells and aids the analysis by removing noise from the data and speeding processing. Analysis was conducted in ArcMap 10.8 using the Spatial Analysis toolset.

3.1.1 Flow Correction

Recognizing that not all flow paths are represented in a DEM, flow correction measures were applied to the surface to account for culverts or other flow paths which may not be present in the DEM. The methods used for this processing were based on selective drainage methods for continuous surface flow for lidar-derived surfaces published by USGS (Poppenga et al., 2010).

The flow correction processing identifies isolated depressions on the surface in excess of a threshold size and depth. For our analysis, depressions had to be at least 1 foot deep and 5000 square feet to be included in flow correction steps. These depressions were evaluated and the lowest elevation point for each was isolated. The DEM was then analyzed within a 400-foot distance of the low point to identify the nearest point on the DEM with a lower elevation value to serve as an outlet. Each low point and outlet pair is then connected on the DEM with a one-cell wide, smooth gradient pathway between the two elevation points. Thus, outflow paths are 'burned' into the DEM out of select depressions, correcting most of the limitations to developing a continuously draining surface. Any depressions remaining on the DEM (those below the selected threshold values and those with no outlet found) are then filled to develop the flow-corrected DEM.

3.1.2 Drainage Analysis

The flow-corrected DEM is used to develop a surface-conforming, continuous drainage network within the subject watersheds. Mapping flow paths based directly on digital surface data allows for the direct query of elevations, gradient, and connected floodplain features. Flow paths with a minimum drainage area of 0.1 square miles were mapped, initially, as part of the drainage network. This threshold on drainage area conformed roughly with upper reaches of the headwater and intermittent streams of the National Hydrography Dataset (NHD) (USGS, 2019). The drainage network is split into stream reach units, with reach breaks occurring at flow line confluences and at boundaries of waterbodies mapped within the NHD, with a maximum length of 2500 feet.

For each stream reach, data was recorded for drainage area, minimum and maximum elevations, length, gradient, and stream order. The NHD flowlines were queried to identify and record any associated NHD reach code or stream name for a given stream reach.

The catchment area of each stream reach was analyzed to determine the spatial average for annual precipitation, canopy cover, and northness (i.e., a measure of aspect) of the receiving area. Average annual precipitation (PRISM Climate Group, 2012) varies from 59 to 164 inches per year in the MF Snoqualmie basin and 48 to 115 inches per year in the Raging River basin. Average canopy cover was derived as the percent canopy cover within a stream reach's drainage area. This data was extracted from the 2016 National Land Cover Dataset (Dewitz, 2019). Northness is an aspect- and slope- derived metric (based on Molotch et al., 2005) ranging from -1.0 to 1.0 which reflects the degree to which a slope faces due north (1.0) to due south (-1.0). This metric can prove valuable in the evaluating the potential degree of snowpack influence on stream temperature and base flow.

Table 1. Data Sources Utilized in the Modeling and Analysis

CATEGORY	DATA TYPE	SOURCE
Elevation	LiDAR digital terrain models. (King County 2016, Cedar River B 2014, King Co/Snoqualmie River 2011, Puget Sound Lowlands 2005, King Co 2003)	WA DNR lidar Portal
Hydrography	Watershed boundary dataset (HUC-10; HUC-12)	National Hydrography Dataset (USGS)
	National Hydrography Data 24K flowlines	National Hydrography Dataset (USGS)
	Waterbodies	National Hydrography Dataset (USGS)
	River miles	USGS/WDFW
Precipitation	PRISM 30-year climate normals (total annual precipitation)	OSU (Daly et al., 2008)
Land Ownership	Publicly owned parcels	King County
Land Cover	National Land Cover Database - 30 m Canopy Cover	USDA NLCD (Dewitz, 2019)
Infrastructure	WA DNR Roads	WA DNR
	Microsoft Building Footprints Dataset	Microsoft/ESRI
	Road Crossings (Fish Passage and Diversion Screening Inventory)	WDFW
	National Dam Inventory	USACE

3.1.3 Flow and Geomorphic Regressions

Using the drainage area and average annual precipitation calculated for each stream reach, the Q2 flow discharge was estimated using USGS Region 3 regression equations (Mastin et al., 2017). The Q2 discharge values were used as an approximated bankfull flow when calculating an estimated bankfull depth for each reach. Estimates of bankfull depth used the regional hydraulic geometry equations for Pacific Maritime Mountain Streams (Castro & Jackson, 2001).

The Q2 discharge and bankfull depth estimates are valuable parameters in determining the relative scale and complexity of potential restoration implementation.

3.1.4 Valley Bottom Mapping

In order to assess the geomorphic conditions of the valley at each stream reach, we returned to the DEM for further analysis. The DEM was analyzed to determine the relative position of each elevation point in relation to the stream to which it drains. Relative elevation models (REM) are commonly used tools in geomorphology. REMs are derived by subtracting a smoothed plane of the water surface elevation along a valley from the elevations of the full topography, essentially removing the slope of the valley from the topography.

The creation of a REM map is complicated within a full drainage network, as each position on the landscape needs to be related to only one stream reach. To overcome this challenge, a flow direction-based height above nearest drainage methodology was used to determine surface position relative to the drainage network. Developed by Nobre et al., (2016) the height above nearest drainage (HAND) analysis uses the elevation of the stream channel at the point where any contributing area joins the flow path to derive the relative elevation of that immediate catchment rather than a cross sectional methodology used by traditional REM.

This comprehensive mapping of relative geomorphic position above each stream reach was used to delineate the extent of the alluvial valley bottom for each stream each. As the scale of each stream or river reach varies widely across the watershed, no single relative elevation value was appropriate for all stream reaches. Rather, a 5x multiple of the estimated bankfull depth was used as a relative elevation value for mapping valley extent in each stream reach. This method of valley bottom mapping is informed by the U.S. Forest Service's Valley Confinement Algorithm (Nagel et al., 2014), which found a bankfull depth derived flood factor to be a valid tool is determining valley confinement.

3.1.5 Infrastructure

Road and building footprint geospatial data were evaluated to determine the density of development and infrastructure with in the valley bottom of each stream reach. Using the comprehensive road database from Washington Department of Natural Resources (WA DNR), the total length of road present within the valley bottom of each stream reach was appended to the data table. The number of building footprints within the valley bottom was measured using the Microsoft Building Footprints (https://www.microsoft.com/en-us/maps/building-footprints) and added to the data table. These building footprints are computationally derived through analysis of aerial imagery.

3.2 Field Verification

Field verification visits were conducted to measure channel and valley morphology, characterize channel, bank, and floodplain sediments, investigate for evidence of channel incision, and interpret geomorphic setting. Site visits were conducted on August 27, 2021. Locations were selected based on ease of access while providing a sample range of locations and geomorphic conditions within the study area.

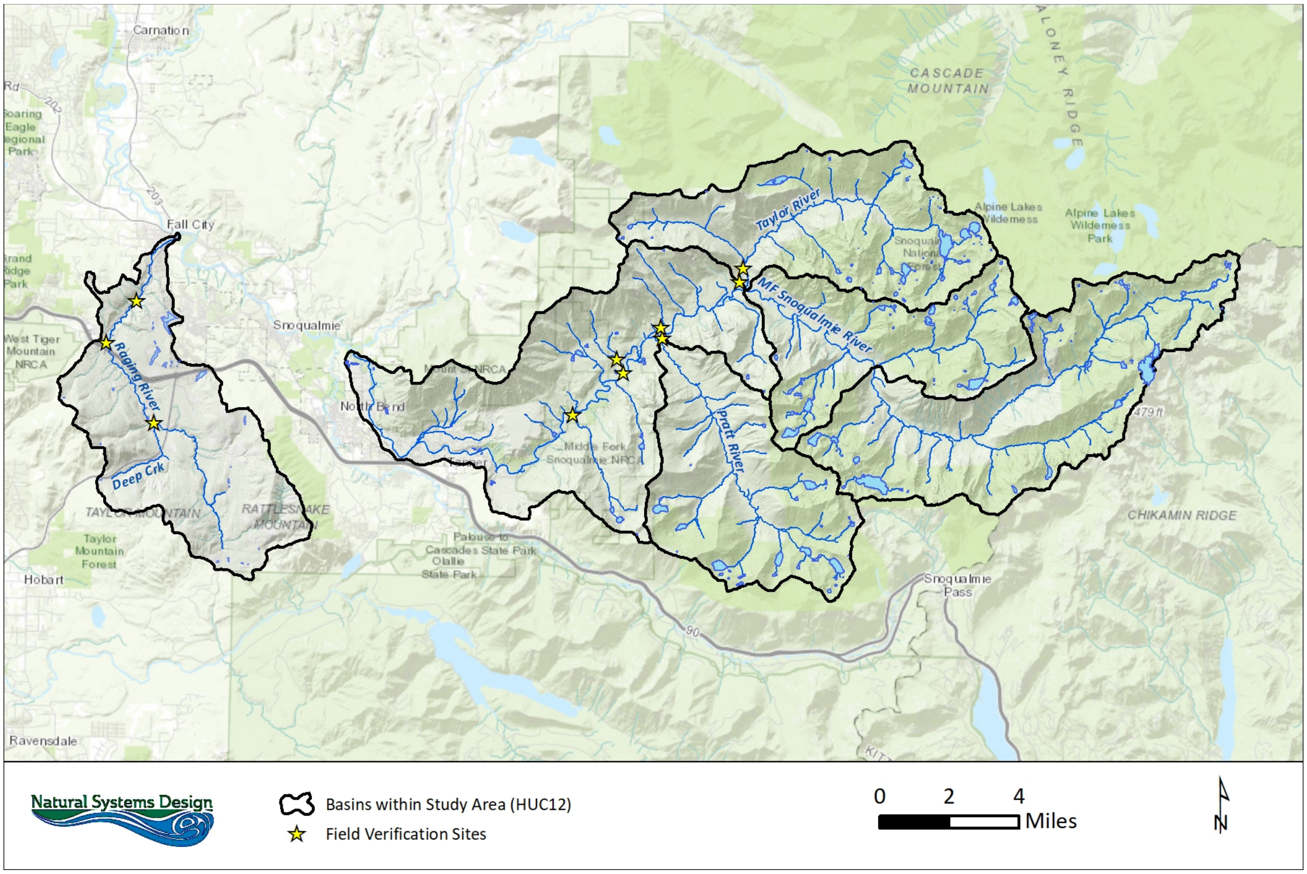


Figure 2. Middle Fork Snoqualmie and Raging River Study Areas and Field Verification Sites

Field visits and observations were informed by georeferenced preliminary model results of alluvial valley extents. The valley extents, as well as geomorphic characteristics of stream reaches were loaded into a web map, and available to field staff via tablet, relative to their current position.

Field visits were conducted at locations on the Raging River, Middle Fork Snoqualmie, Granite Creek, Pratt River, and Taylor River (Figure 2). In general, model output of valley mapping was consistent with conditions observed on the ground. Some deviations were found between mapped valley bottoms and observed conditions in the vicinity of tributary and mainstem confluences. These observations supported an adjustment to our valley mapping workflow to ensure tributary catchments were not excluded from mainstem valley mapping.

General conditions observed in the field support the assumption of degraded geomorphic processes resulting in channel incision. No functional wood was observed in the majority assessed channel reaches, with very few exceptions. As a result, at the sites we visited, channels had plane bed morphologies with few or no pools and were disconnected from their floodplains (Figure 3).

Sites observed in the Raging River watershed were limited to the lower watershed due to access constraints to WA DNR lands in the upper portions of the watershed. Significant restoration potential was observed on Raging River at sites such as Preston Mill Park, with multiple perched floodplain terraces that appear to be infrequently inundated. However, numerous infrastructure constraints exist on the lower Raging River, including roads, road crossings, buildings, and extensive private property.

Figure 3. Raging River Looking Downstream from SE 68th Street Bridge
Channel has plane bed morphology with heavily armored bed. Photograph taken on August 27, 2021.

Sites observed in the MF Snoqualmie watershed included both mainstem (Figure 4) and tributary reaches (Figure 5 through Figure 7), all of which were located in the Mt Baker-Snoqualmie National Forest. We walked along some of the extensive floodplain features, including a disconnected oxbow lake, in the floodplain of the lower MF Snoqualmie River. We also visited two major tributaries, the Taylor and the Pratt Rivers, near their confluences with the MF Snoqualmie. The lower Pratt River displayed a wide floodplain and a plane bed with cobble substrate, with no functional wood and little channel complexity (Figure 5). The lower Taylor River appears to have more stream power than the lower Pratt River, as evidenced by boulder-dominated substrate (Figure 6). The lower Taylor also displayed evidence of functional wood that previously triggered side channel engagement.

Lastly, we also visited a few of the tributaries that drain the northwestern valley wall directly into the lower MF Snoqualmie River. These tributaries generally have small drainage areas, moderate to steep gradients, and relatively narrow floodplain surfaces. At one unnamed tributary off of Bessimier Road, we observed bar deposition and sand, gravel, and cobble substrate (Figure 7).

Overall, field verification efforts provided validation of our valley mapping and modelling approach. Observed discrepancies between alluvial valleys and mapped extents demonstrated the need for minor corrections to mapping methodologies to bring results more consistently in line with on the ground conditions.

Figure 4. Middle Fork Snoqualmie at Confluence with Granite Creek and SE Lake Dorothy Road Bridge
Photograph taken on August 27, 2021.

Figure 5. Lower Pratt River
Wide, simplified channel shown with no functional wood. Photograph taken looking upstream on August 27, 2021.

Figure 6. Lower Taylor River
Shown with boulder-dominated substrate with no functional wood. Photograph taken looking downstream on August 27, 2021.

Figure 7. Unnamed Tributary to the MF Snoqualmie
Located off of Bessimier Road; demonstrates an example of a reach with lower stream power. Photograph taken looking downstream on August 27, 2021.

3.3 Numerical Analysis

3.3.1 Alluvial Water Storage Estimates

Some refinements to the modelling approach were made following the field assessment. A sequential iteration of valley mapping across stream order, rather than a global mapping approach, was found to correct mapping errors observed at tributary confluences while in the field. After updating valley width and other key attributes with the refined model, the stream reach attribute table was transferred to into a numerical processing framework for estimates of restorable alluvial water and sediment storage.

The analysis utilizes a geometric approach to quantifying restorable water storage, along with literature-based parameter values for the hydrologic properties of earth materials, based on the conceptualization of the wedge of groundwater that would be saturated with a local change in surface water elevation (Table 2). The geometric approach relies on the spatially variable delineation of valley bottoms and the extraction of channel and valley characteristics, developed as part of the geospatial analysis, such as width, depth, and gradient (Figure 8). These characteristics, along with estimates of incision depth and specific yield of the alluvial aquifer, are used to compute volumetric groundwater storage through a reach (Figure 9).

Table 2. Parameter Values used in Water Storage Modeling

PARAMETER	VALUE(S) USED	SOURCE
Specific yield (ratio)	0.20	Median of values for sand (Johnson, 1967). Conservative for gravel and cobble alluvium.
Porosity (ratio)	0.3	Conservative ratio; porosity of sandy loam typically given as ~0.4
Incised Channel Depth (ft)	3	Conservative incision estimates based on ad hoc analysis of channel incision in both watersheds, and on a readily achievable target for aggradation using a variety of restoration treatment methods.

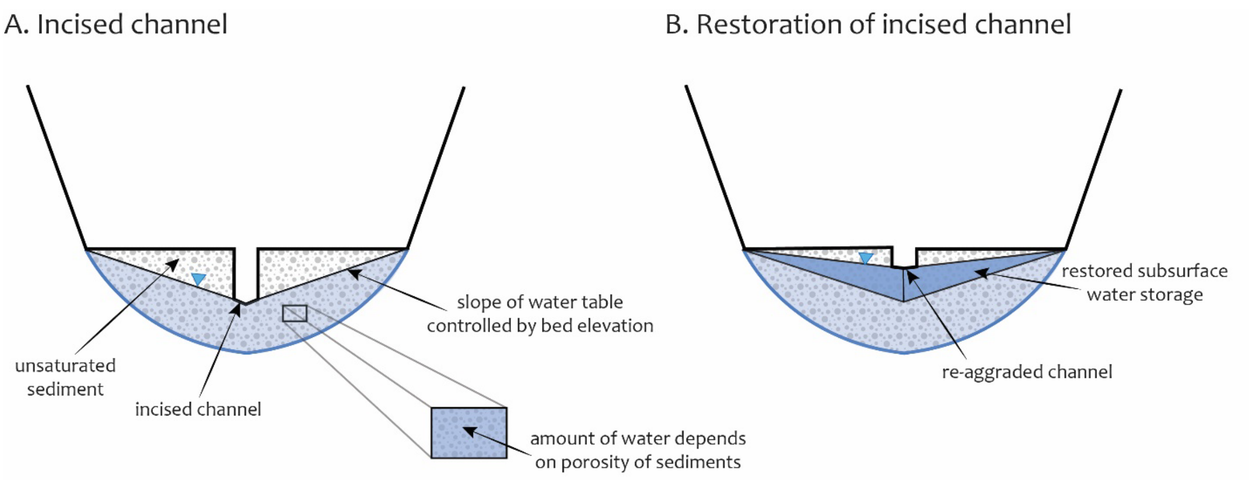


Figure 8. Conceptual Diagram of Geometric Approach to Estimating the Area
(A_s in Figure 9) of a wedge of restorable subsurface water storage based on a valley cross-section under existing (a) and restored (b) conditions.

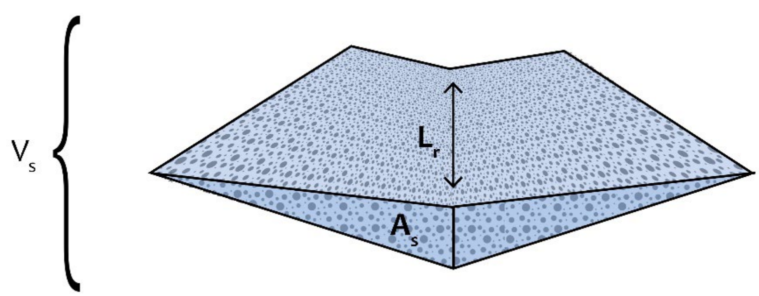


Figure 9. Conceptual Diagram of the Estimation of the Reach-Scale Volume
(V_s) of water storage restored from channel aggradation, based on the area (A_s) of the saturated wedge, the porosity of the sediments, and the length of the reach (L_r).

For estimation of increased surface water storage resulting from local impoundment of water behind log jams and storage within local surface depressions on the floodplain, we used the stream gradient of each reach and incision depth. Based on these attributes we determined the longitudinal extent of backwatering effects and estimated volumetric increase in surface water storage assuming a treatment intensity that would create a continuous longitudinal effect on surface water storage.

3.3.2 Analysis to Support Restoration Planning

In addition to using the geospatial modeling framework for estimating restorable alluvial water and sediment storage, we analyzed the resulting attribute table and mapped stream segments by attributes in order to develop data-driven groupings to support restoration planning. As with the alluvial water estimates, all of the associated spatial relationships and groups are intended to serve as a screening-level tool to identify and prioritize individual reaches and sub-watersheds for reach-scale analysis, and to estimate total values from extensive implementation of restoration actions.

We used spatial relationships to quantify the presence and amount of infrastructure present in each delineated valley bottom, including the length of road, number of stream crossings, and number of buildings present (See Table 1). These values are then available at the reach scale to inform restoration planning from the perspective of both risk and constraints as well as access and restoration approach.

We combined the geospatial analysis with field observations to group stream reaches by hydrology, geomorphology, and infrastructure in order to make broad categorical recommendations for continued restoration planning. Whereas the restoration approach for a given stream reach requires site-specific assessment and design, these groupings provide a screening-level indication of the type of approach or level of effort that may be required for restoration of alluvial water storage.

4 RESULTS

4.1 Channel Incision

Estimates of restorable water storage are based on a uniform value of 3 ft of potential channel aggradation, and the associated rise in low flow water surface elevation, primarily to support cross-basin comparison of model results without confounding estimates with spatially variable channel incision. From a practical perspective, restoration treatments to achieve 3 ft of aggradation are generally achievable with a range of methods. However, channel incision is likely spatially variable, and therefore, there may be more potential restorable water storage in reaches where there is increased potential to re-aggrade the more deeply incised channel.

We used analysis of the lidar digital elevation model and limited field observations to complete some ad hoc estimates of the extent of channel incision. In particular, we estimated channel incision by using a relative elevation model (i.e., digital elevation model that is detrended to account for valley slope) to identify perched curvilinear features in the alluvial valley that may have been formed via fluvial processes. In these locations, we used a cross-section to estimate the vertical difference between the current channel and the perched relict channel feature.

The cursory analysis suggests that channel incision is deeper in the Raging River than in the MF Snoqualmie River watershed. This difference may be due to the presence of Snoqualmie Falls downstream from the MF Snoqualmie, which would provide a geologic constraint on the extent to which the channel could incise. In the lower Raging River we identified 5-6 ft of vertical offset in 3 locations whereas we identified values around 3-4 feet in the MF Snoqualmie River.

4.2 Longitudinal Profiles

Longitudinal profiles were developed from the high-resolution flow accumulation network created in the modeling workflow. These profiles were used primarily to provide geomorphic context when analyzing the results and considering restoration planning and are provided for reference in Appendix A.

4.3 Cumulative Values

Across the model domain, we estimate a total restorable water volume of over 2700 ac-ft in the MF Snoqualmie River watershed and of over 400 ac-ft in the Raging River watershed (Table 3 and Figure 10). The larger value in the MF Snoqualmie can be attributed to a larger stream network as well as to more wide alluvial valley surfaces. We note, however, that the values are based on a spatially constant value for estimated incision whereas preliminary analysis suggests that channel incision may be deeper in the Raging River. In this case, with more vertical potential for aggradation than was represented in the model workflow, the estimates for restorable water storage in the Raging River may be biased low.

The model results are spatially explicit at a stream segment level and the output is a polyline feature class with an extensive attribute table of physical characteristics and modeled quantities. Thus, in addition to summing the model results, they can be mapped and symbolized by restorable water volume (or another attribute of interest) to support a screening-level analysis of where to look for restoration opportunities. The model domain on which these summary numbers are based includes all reaches with less than 8% gradient and not located within an NHD-mapped waterbody. The map book in Appendix B illustrates the alluvial water restoration potential of each stream reach in acre-feet per mile.

Table 3. Summary of Estimated Total Restorable Water Storage and Stream Length across the Model Domain*

WATERSHED	TOTAL RESTORABLE WATER STORAGE (AC-FT)	TOTAL STREAM LENGTH (MI)
MF Snoqualmie River	2750	340
Raging River	440	120

**includes all reaches with less than 8% gradient and not located within an NHD-mapped waterbody.*

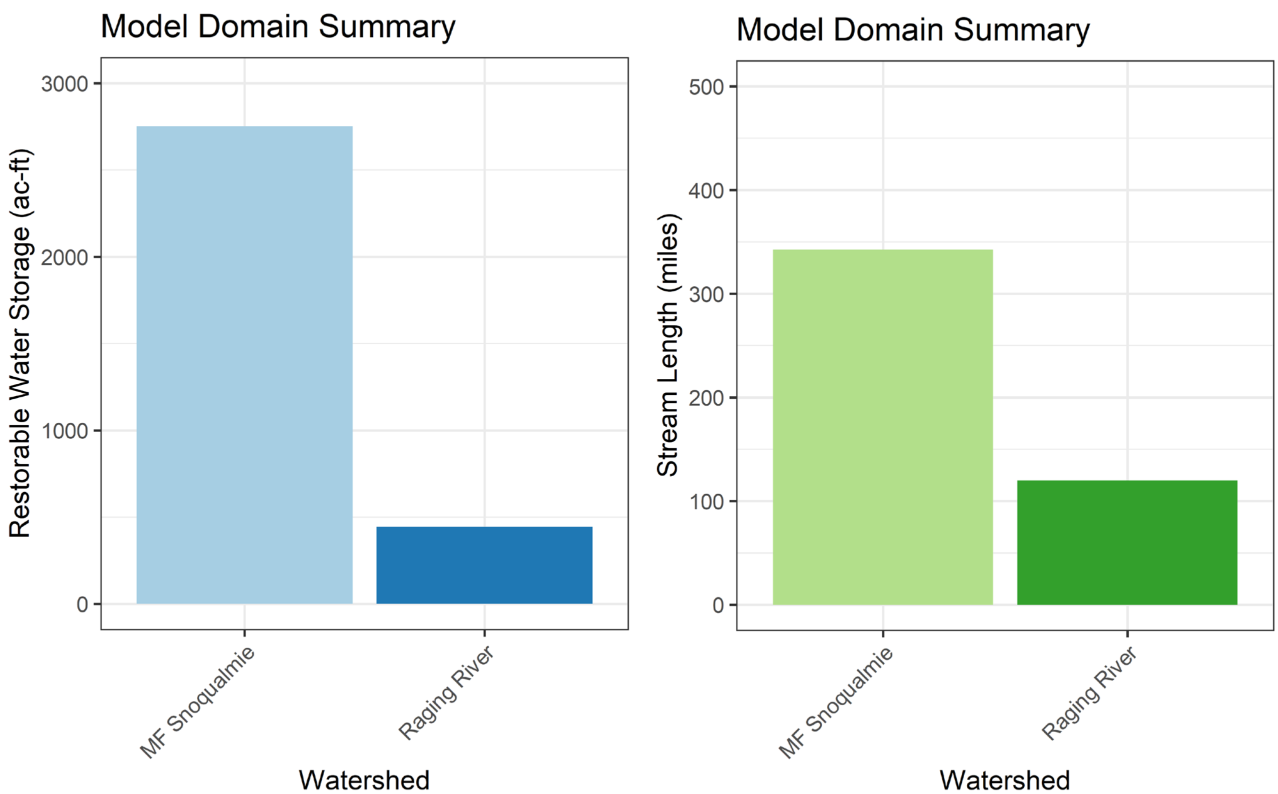


Figure 10. Summary of Estimated Total Restorable Water Storage and Stream Length across the Model Domain

4.4 Restoration Reach Types

In addition to the complete output dataset, we provide a framework of restoration groupings within this analysis to illustrate how these data can be used to support restoration planning efforts. However, we note that there is subjectivity introduced in by choosing attributes and threshold values, and that there are several ways to use and consider these data for identification and prioritization of restoration actions.

We classified restoration reach types within each watershed based on analysis of the physical and modeled characteristics of the reaches. This classification provides a framework and some general guidance for selecting individual reaches for future analysis and restoration planning. The reach type groupings provide a screening-level characterization of restoration opportunities, with the critical caveat that reach-scale assessment is needed to discern restoration value, feasibility, and approach.

Groupings for each contiguous watershed were considered independently, given that the two areas are markedly different in terms of the presence of anadromous fish and surrounding land ownership. The MF Snoqualmie River watershed is upstream of the limits of anadromy due to the presence of Snoqualmie Falls downstream and is primarily surrounded by Mt. Baker-Snoqualmie National Forest land. The Raging River provides spawning habitat to Chinook salmon and steelhead, and the alluvial corridor is surrounded primarily by private lands in the lower 10 miles and WA DNR lands for the additional 6 miles upstream.

4.4.1 Middle Fork Snoqualmie River Watershed

The reaches of the MF Snoqualmie River Watershed separate out primarily by drainage area and gradient, which directly relate to stream power and therefore to restoration approach (Table 4). The presence or absence of a valley-parallel road is an additional feature that further distinguishes the Lower and Upper MF Snoqualmie from the other groups.

Table 4. Restoration Reach Types within a Focus Subset of Reaches in the MF Snoqualmie Watershed with the Highest Potential for Restoration of Alluvial Water Storage*

RESTORATION REACH TYPE	HYDROGEOMORPHIC CHARACTERISTICS	NOTES	INITIAL GUIDANCE REGARDING RESTORATION PLANNING
Valley Wall Tributaries	Low drainage area (< 3 sq mi), higher slope (1-4%), lower order (2nd to 4th order)	Approximately 10-20 reaches located on the northwest valley wall of the lower mainstem MF Snoqualmie River.	Relatively low potential but best opportunity for lower tech/less engineered approaches, which could allow for more extensive implementation.
Lower MF Snoqualmie	Highest drainage area (90-160 sq mi), low gradient (0.1 to 1 %), highest order (7th)	Approximately 20 miles of the lower mainstem MF Snoqualmie River, with a road running parallel along the right floodplain/valley wall for most of the length.	High potential but key issues to consider related to designing for high stream power and potential risk to recreational access
Upper MF Snoqualmie	Medium drainage area (25-60 sq mi), low gradient (0.7 to 1.5%), 6th order	Approximately 10 miles of the upper mainstem MF Snoqualmie River, with a USFS road running parallel along the right floodplain/valley wall for most of the length.	Medium-high potential in this area, with low gradient reaches and wide alluvial floodplain. Road access for restoration, but lower risk related to impairing recreational access since road dead ends at upper end
Major Tributaries	Medium-low drainage area (10-30 sq mi), range of gradients (0.05 to 4%), 5th to 6th order	Includes Pratt River and Taylor River.	Low-medium potential with the exception of a few reaches, which include Pratt Creek near the confluence and low gradient reaches within upper Taylor Creek, both of which would have substantial access issues. Could consider possible helicopter approach here.
Headwaters and headwater tributaries	Medium-low drainage area (6-18 sq mi), range of gradients (1 to 4%), 4th to 5th order	Includes Dingford Creek, Burnboot Creek, and headwaters of MF Snoqualmie.	Low potential here with little to no access.

**as defined by reach length > 500 ft (i.e., to screen out model artifacts), alluvial water storage potential > 4 ac-ft/mile, and gradient < 4 % (i.e., to screen for restoration implementation). "Potential" in the table refers to the estimated potential to restore alluvial water storage, in ac-ft/mile.*

The highest potential for restoring alluvial water capacity is present where the alluvial valley is widest, in the lower MF Snoqualmie River (Table 5 and Figure 11). There is also potential within the mainstem MF Snoqualmie to re-connect floodplain features, with a large natural water storage uplift. However, these reaches have the highest stream power, a valley-parallel road that is heavily used for recreational access, and trails and other recreational facilities, which will affect the complexity of restoration approaches. On the other side of the spectrum are the valley wall tributaries on the northwest side of the lower MF Snoqualmie, including the unnamed tributary off of Bessimier Road (Figure 7), which may hold possibility for applying a lower tech approach for stream restoration. The Upper MF Snoqualmie jumps out as an area with high potential for restoring water storage that has only a limited access recreational road nearby. Restoration reach types are illustrated for the subset of highest potential stream reaches in Appendix C.

In addition to the restoration reach types provided in Table 4, additional attributes of the model results can be used to sort and prioritize reaches for further consideration of restoration. For example, the model captures the amount of infrastructure within the delineated valley bottom for each reach, which allows for summation by presence of infrastructure (Figure 12) as well as exploration of the spatial data by infrastructure attribute. When summing values across infrastructure categories, we included a reach in the building category if it has 1 or more building footprints in the alluvial valley, in the roads category if it has more than 0.05 miles of road or 1 or more road crossings (but no buildings), or in the "none" category if it has neither buildings nor roads. Within the MF Snoqualmie, the presence of buildings in the valley bottom is largely limited to the lower-most portion of the watershed, with many miles of restoration opportunities where there is little to no infrastructure.

Table 5. Summary of Estimated Total Restorable Water Storage and Stream Length within the Restoration Reach Types in the Focus Subset of the MF Snoqualmie River Watershed

WATERSHED	RESTORATION REACH TYPE	TOTAL RESTORABLE WATER STORAGE (AC-FT)	TOTAL STREAM LENGTH (MI)
MF Snoqualmie River	Headwaters	90	8
	Major Tributaries	190	11
	Upper MF Snoqualmie	330	14
	Valley Wall Tributaries	140	14
	Lower MF Snoqualmie	940	30

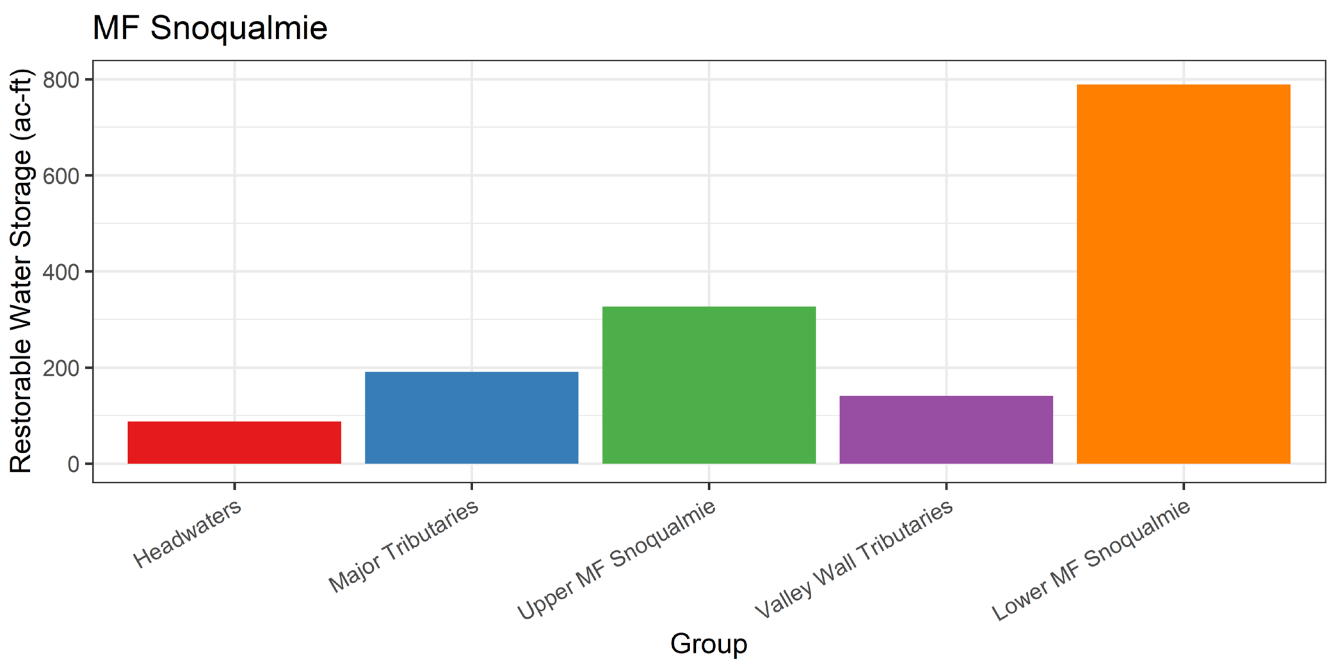


Figure 11. Total Restorable Water Storage (ac-ft), Shown by Restoration Reach Types in the MF Snoqualmie River Watershed

Shown for the focus subset of highest potential reaches

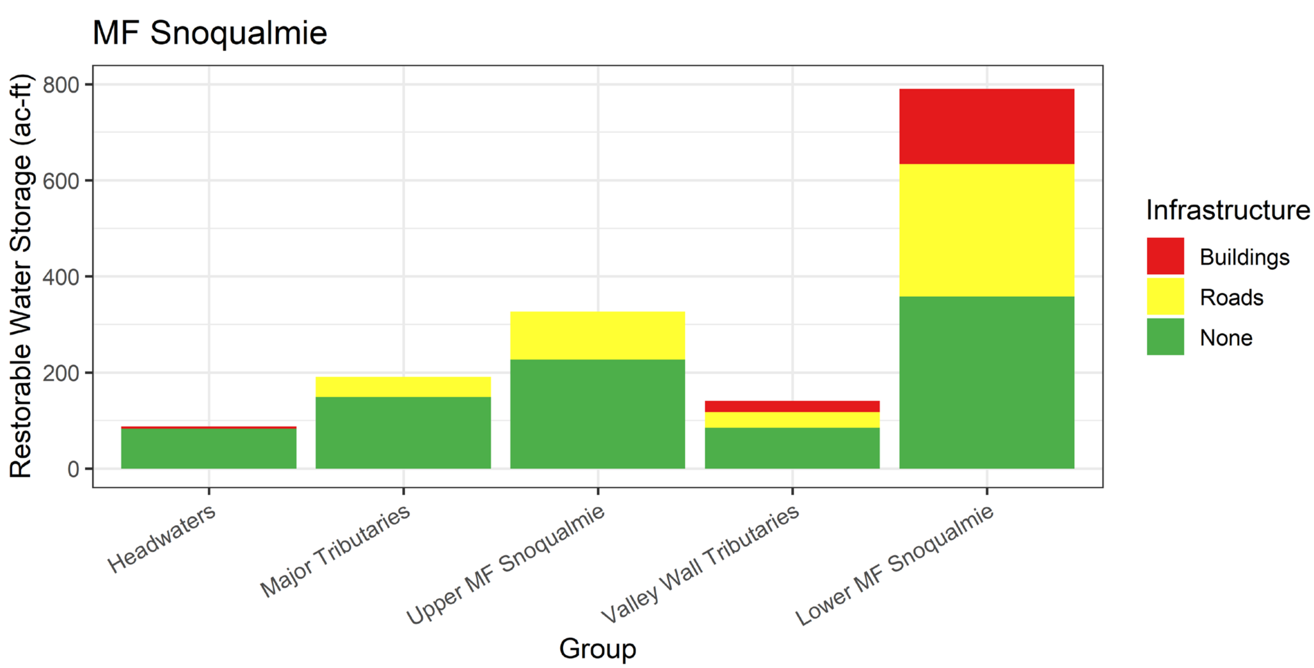


Figure 12. Total Restorable Water Storage (ac-ft), Split by Infrastructure Presence in Each Restoration Reach Type in the MF Snoqualmie River Watershed

Shown for the focus subset of highest potential reaches. Note that the building footprint data is computationally derived and a false positive, was identified in the Headwaters restoration group (see thin red bar in Headwaters group, above).

4.4.2 Raging River

The reaches of the Raging River Watershed separate out primarily by location in the watershed and land ownership (Table 6). The lower Raging River has the highest potential for restoring alluvial water storage, but restoration will need to be focused in reaches where there are willing land owners and public parcels (Table 7 and Figure 13). Infrastructure intensity is linked to landownership, and a high proportion of the estimated restorable water storage volume is located in reaches that have at least one building present in the delineated alluvial valley bottom (Figure 14). Restoration reach types are illustrated for the highest potential stream reaches in Appendix C.

Table 6. Restoration Reach Types within a Focus Subset of Reaches in the Raging River Watershed*

GROUPING	HYDROGEOMORPHIC CHARACTERISTICS	NOTES	INITIAL GUIDANCE REGARDING RESTORATION PLANNING
Lower Raging River	Highest drainage area (20-30 sq mi), lowest gradient (mostly 0.5 to 1.5%), highest order (6^{th} order)	Primarily surrounded by private lands with a few public parcels.	High potential for restoring water storage but constrained by private lands and infrastructure
Upland lakes and wetlands	Small drainage area (<1 sq mi), lowest gradient (mostly 0.5 to 1.5%), low order (1^{st} to 3^{rd}) reaches draining and connecting lakes	Small streams draining lakes (e.g., Lake Kittyprince and Echo Lake) and wetlands that are perched approximately 400 vertical feet above the Raging River on a glacial terrace in the northeastern portion of the watershed.	Needs more assessment to understand water balance, existing conditions, and constraints, but consider lower tech options such as beaver dam analogs to increase water storage in wetlands and diminish upstream propagation of ravine development
Upper Raging River	Medium drainage area (5 to 13 sq mi), 4^{th} to 5^{th} order, and moderate gradient (1.5 to 2.5%)	6 miles of upper Raging River surrounded by WA DNR land (Tiger Mountain and Raging River State Forests), on which public hiking and biking trails are being developed	Moderate potential for restoring water storage but opportunity to work with one landowner over 6 miles. Access unclear but likely a network of forest roads.
Deep Creek	Medium drainage area (5 sq mi), 5th order, moderate gradient (1.9%)	Approximately 2 miles through WDNR land, with highest potential reach running 0.75 mi from Hwy 18 to the confluence with Raging River	Similar to Upper Raging River.

**with the highest potential for restoration of alluvial water storage, as defined by reach length > 500 ft (i.e., to screen out model artifacts), alluvial water storage potential > 4 ac-ft/mile, and gradient < 4 % (i.e., to screen for restoration implementation). "Potential" in the table refers to the estimated potential to restore alluvial water storage, in ac-ft/mile.*

Table 7. Summary of Estimated Total Restorable Water Storage and Stream Length within the Restoration Reach Types in the Focus Subset of the Raging River Watershed

WATERSHED	RESTORATION GROUP	TOTAL RESTORABLE WATER STORAGE (AC-FT)	TOTAL STREAM LENGTH (MI)
Raging River	Upper Raging River	50	6
	Deep Creek	10	2
	Upland Lakes and Wetlands	50	6
	Lower Raging River	140	10

There may be some water storage opportunities within the streams that connect the upland lakes and wetlands (e.g., Lake Kittyprince) that are perched on a glacial terrace to the east of the mainstem Raging River. More assessment is needed to understand the current water balance, existing conditions, land use, and recreation constraints. However, preliminary assessment of the lidar DEM indicates that a ravine has formed at the transition from the drainage of each water body to the hillslope of the alluvial valley. Restoration actions to slow and store water in the upland could affect both water storage and slow the upstream propagation (and evacuation of sediment) from ravine formation.

Upstream of the lower Raging River, the alluvial valleys are narrower, reaches are steeper, and there is moderate potential for alluvial water storage restoration. However, the reaches of Upper Raging River and Deep Creek are surrounded mainly by WA DNR state forest land with limited infrastructure in the alluvial valley, which could make more extensive implementation feasible. The surrounded State Forests are currently managed for natural resources (e.g., timber) as well as for hiking and mountain biking access (https://www.evergreenmtb.org/trails/raging-river).

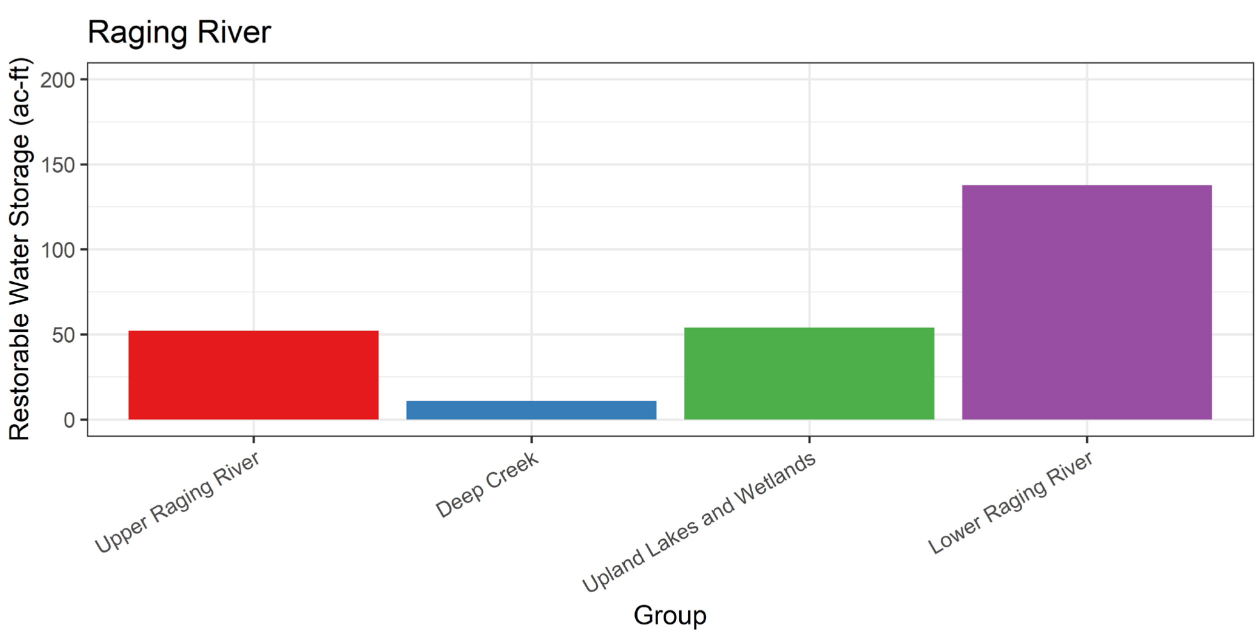


Figure 13. Total Restorable Water Storage (ac-ft) by Restoration Reach Type for the Raging River Watershed

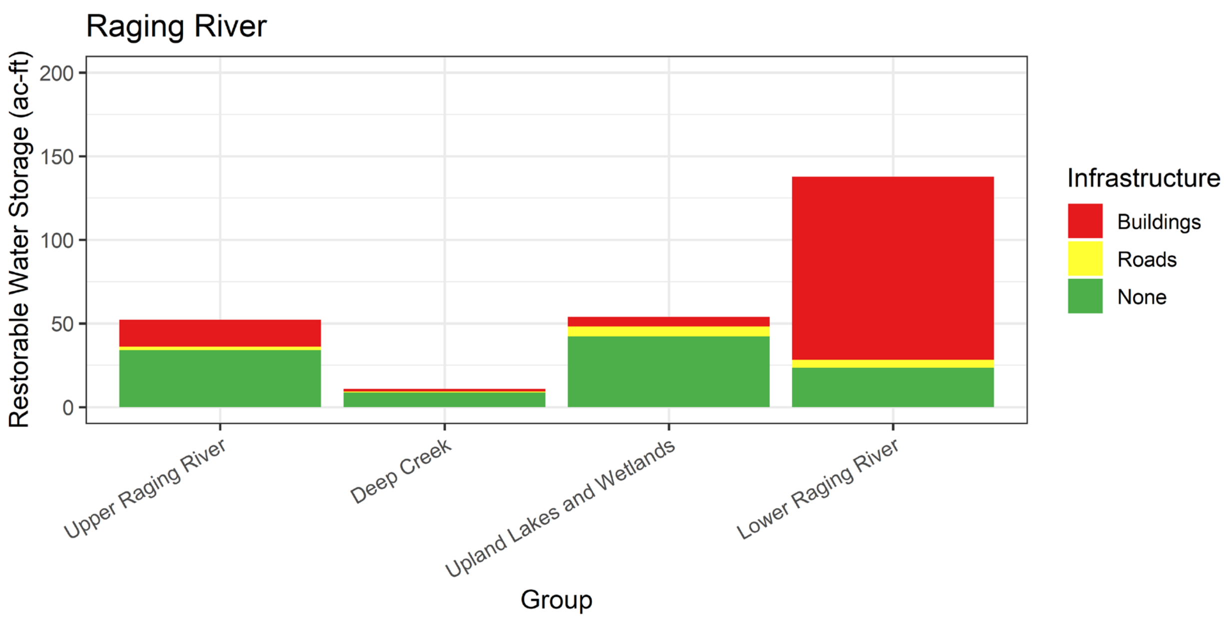


Figure 14. Total Restorable Water Storage (ac-ft), Split by Infrastructure in Each Restoration Reach Type the Raging River Watershed

5 APPLICATION

The Middle Fork Snoqualmie and Raging River alluvial water storage assessment is intended as a preliminary screening tool to aid in the identification of potential high value restoration project sites. Restoration of natural water and sediment storage functions has benefits for water quality, water quantity, habitat complexity, and climate change resilience. This assessment provides a broad-scale inquiry into stream reach characteristics and potential for restoration of alluvial water resources. The goal is that the assessment is used as a tool to support future investigation and implementation of restoration and incision correction efforts across a variety of geomorphic conditions within the subject basins.

As a comprehensive assessment and categorization effort, assumptions and approximations are integrated into the data compiled. As such, data and categories included with this assessment should be considered an estimation of likely conditions. These estimates are volumetric estimates of in-situ water and sediment storage, assuming that channel aggradation occurs as a result of restoration actions. Whereas it is likely that water storage and increasing the residence time of water in the floodplain will have benefits to riparian water availability and to baseflow contribution, the amount and timing of an additional flux is undefined. Estimates can be made with simplifying assumptions of drainage rates based on the cross-valley gradient and hydraulic properties of the sediments, but many factors complicate actual groundwater flow.

Restoration design and implementation varies greatly in its complexity, logistics, and risk across the sites analyzed in this assessment. The cursory analysis of these factors, based on estimates of stream power and presence or absence of infrastructure provides a starting point for site investigation. A full site investigation and assessment by qualified professionals is essential to successful restoration design and implementation.

The stream features and compiled data carry certain uncertainties stemming from the data from which they were derived. The lidar digital elevation model is dated and not always well resolved in the middle to upper portions of the MF Snoqualmie watershed, resulting in interpolated surface data. Since flow path and valley bottom delineation are based on the lidar DEM, the lidar resolution introduces uncertainty in the estimates.

The approach to the data analysis described in this report is only a sample approach to leveraging the data compiled for site selection and prioritization. The database compiled through the process model workflow includes hydrologic and physical attributes of the stream reaches, such as gradient, estimated bankfull depth, and estimated Q2 discharge. These attributes provide additional context for restoration planning.

The mapped spatial data allows for cross-referencing of high potential reaches with other existing datasets such as fish presence, temperature, or land ownership (illustrated in Appendix B) data. The dataset likewise contains derived values such as estimated stream power, which can aid in planning for potential project complexity. Also, the model provides an accumulated northness index for each reach. A northness index is a numerical indication of the amount of drainage area contributing to the reach that is north-facing. Since snowmelt contributes substantially to streamflow in the MF Snoqualmie, one could choose to prioritize water storage restoration in reaches that have more north-facing drainage area, targeting cooler water temperatures of later-melting snow. Such a filter indicates that reaches of the Upper MF Snoqualmie have the largest north-facing contributing areas (Figure 15).

This assessment can serve as a road map for future restoration planning efforts within the Middle Fork Snoqualmie and Raging River basins. The unique character of each of these watersheds will best make use of different aspects of this assessment. Our intention is to provide a robust and flexible tool that can be leveraged for restoration efforts, be they aimed at improving habitat, forest health, or climate resiliency. As such, we see great potential for continued improvements to the model workflow and a variety of applications of the integrated tools as we work to support restoration efforts throughout the region.

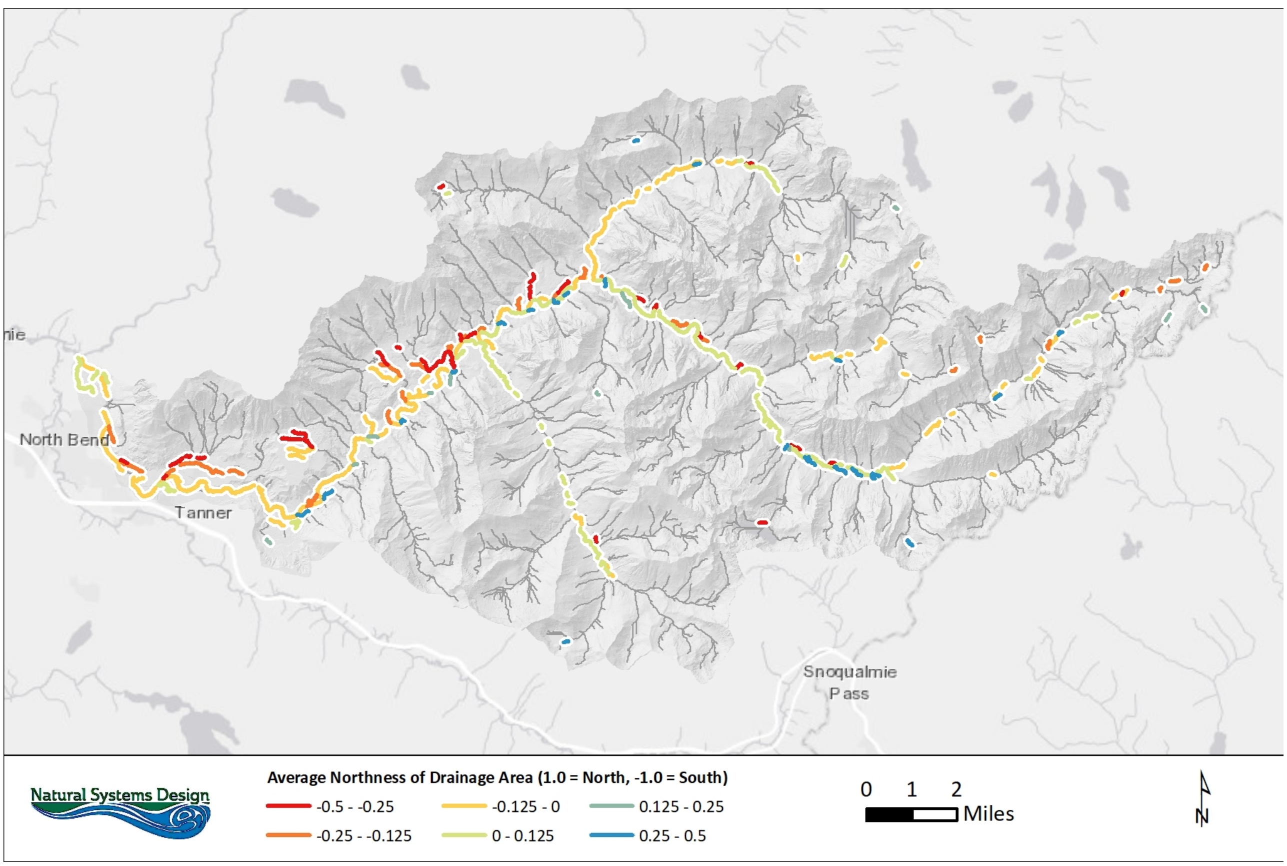


Figure 15. Spatially-Averaged Northness Index Values

Shown for the focus subset reaches of the MF Snoqualmie, which range from 1.0 (due north facing) to -1.0 (due south facing) at a single pixel and are aggregated based on catchment delineation.

6 REFERENCES

Abbe, T. B., & Montgomery, D. R. (2003). Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology*, *51*(1–3), 81–107. https://doi.org/10.1016/S0169-555X(02)00326-4

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

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

Abbe, T. B., Dickerson-Lange, S. E., Kane, M., Cruickshank, P., Kaputa, M., & Soden, J. (2019). Can wood placement in degraded channel networks result in large-scale water retention? In *Federal Interagency Sedimentation and Hydrologic Modeling Conference* (p. 20). Reno, NV.

Castro, J. M., & Jackson, P. L. (2001). BANKFULL DISCHARGE RECURRENCE INTERVALS AND REGIONAL HYDRAULIC GEOMETRY RELATIONSHIPS: PATTERNS IN THE PACIFIC NORTHWEST, USA. *Journal of the American Water Resources Association*, *37*(5), 1249–1262. https://doi.org/10.1111/j.1752-1688.2001.tb03636.x

Collins, B. D., Montgomery, D. R., & Haas, A. D. (2002). Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(1), 66–76. https://doi.org/10.1139/f01-199

Collins, B. D., Montgomery, D. R., Schanz, S. A., & Larsen, I. J. (2016). Rates and mechanisms of bedrock incision and strath terrace formation in a forested catchment, Cascade Range, Washington. *Geological Society of America Bulletin*, *128*(5–6), 926–943. https://doi.org/10.1130/B31340.1

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., et al. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *28*(15), 2031–2064. https://doi.org/10.1002/joc.1688

Dewitz, J. (2019). National Land Cover Database (NLCD) 2016 Products. U.S. Geological Survey data release. https://doi.org/10.5066/P96HHBIE

Hancox, G. T., McSaveney, M. J., Manville, V. R., & Davies, T. R. (2005). The October 1999 Mt Adams rock avalanche and subsequent landslide dam-break flood and effects in Poerua river, Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*, *48*(4), 683–705. https://doi.org/10.1080/00288306.2005.9515141

Hunt, L. J. H., Fair, J., & Odland, M. (2018). Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California. *JAWRA Journal of the American Water Resources Association*, *54*(5), 1127–1136. https://doi.org/10.1111/1752-1688.12675

Johnson, A. I. (1967). *Specific Yield - Compilation of Specific Yield for Various Materials (Water Supply Paper 1662 D)*. Washington, DC.

Lee, S.-Y., Fullerton, A. H., Sun, N., & Torgersen, C. E. (2020). Projecting spatiotemporally explicit effects of climate change on stream temperature: A model comparison and implications for coldwater fishes. *Journal of Hydrology*, *588*, 125066. https://doi.org/10.1016/j.jhydrol.2020.125066

Mastin, M. C., Konrad, C. P., Veilleux, A. G., & Tecca, A. E. (2017). *Magnitude, Frequency, and Trends of Floods at Gaged and Ungaged Sites in Washington, Based on Data through Water Year 2014*. Reston, Virginia. Retrieved from https://pubs.er.usgs.gov/publication/sir20165118

Mauger, G. S., & Won, J. S. (2020). *Projecting Future High Flows on King County Rivers: Phase 2 Results. Report prepared for King County.* Seattle, WA.

Molotch, N. P., Colee, M. T., Bales, R. C., & Dozier, J. (2005). Estimating the spatial distribution of snow water equivalent in an alpine basin using binary regression tree models: The impact of digital elevation data and independent variable selection. *Hydrological Processes*, *19*(7), 1459–1479. https://doi.org/10.1002/hyp.5586

Montgomery, D. R., & Abbe, T. B. (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*(01), 147–155. https://doi.org/10.1016/j.yqres.2005.10.003

Nagel, D. E., Buffington, J. M., Parkes, S. L., Wenger, S., & Goode, J. R. (2014). *A landscape scale valley confinement algorithm: Delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications*. https://doi.org/10.2737/RMRS-GTR-321

Nobre, A. D., Cuartas, L. A., Momo, M. R., Severo, D. L., Pinheiro, A., & Nobre, C. A. (2016). HAND contour: a new proxy predictor of inundation extent. *Hydrological Processes*, *30*(2), 320–333. https://doi.org/10.1002/hyp.10581

Phelps, J. D. (2011). *The Geomorphic Legacy of Splash Dams in the Southern Oregon Coast Range*. University of Oregon.

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. (2014). Using Beaver Dams to Restore Incised Stream Ecosystems. *BioScience*, *64*(4), 279–290. https://doi.org/10.1093/biosci/biu036

Poppenga, S. K., Worstell, B. B., Stoker, J. M., & Greenlee, S. K. (2010). *Using Selective Drainage Methods to Extract Continuous Surface Flow from 1-Meter Lidar-Derived Digital Elevation Data: U.S. Geological Survey Scientific Investigations Report 2010–5059*.

PRISM Climate Group. (2012). PRISM Climate Group. Retrieved from http://prism.oregonstate.edu

Schanz, S. A., Montgomery, D. R., & Collins, B. D. (2019). Anthropogenic strath terrace formation caused by reduced sediment retention. *Proceedings of the National Academy of Sciences*, *116*(18), 8734–8739. https://doi.org/10.1073/pnas.1814627116

Stock, J. D., Montgomery, D. R., Collins, B. D., Dietrich, W. E., & Sklar, L. (2005). Field measurements of incision rates following bedrock exposure: Implications for process controls on the long profiles of valleys cut by rivers and debris flows. *Geological Society of America Bulletin*, *117*(1), 174. https://doi.org/10.1130/B25560.1

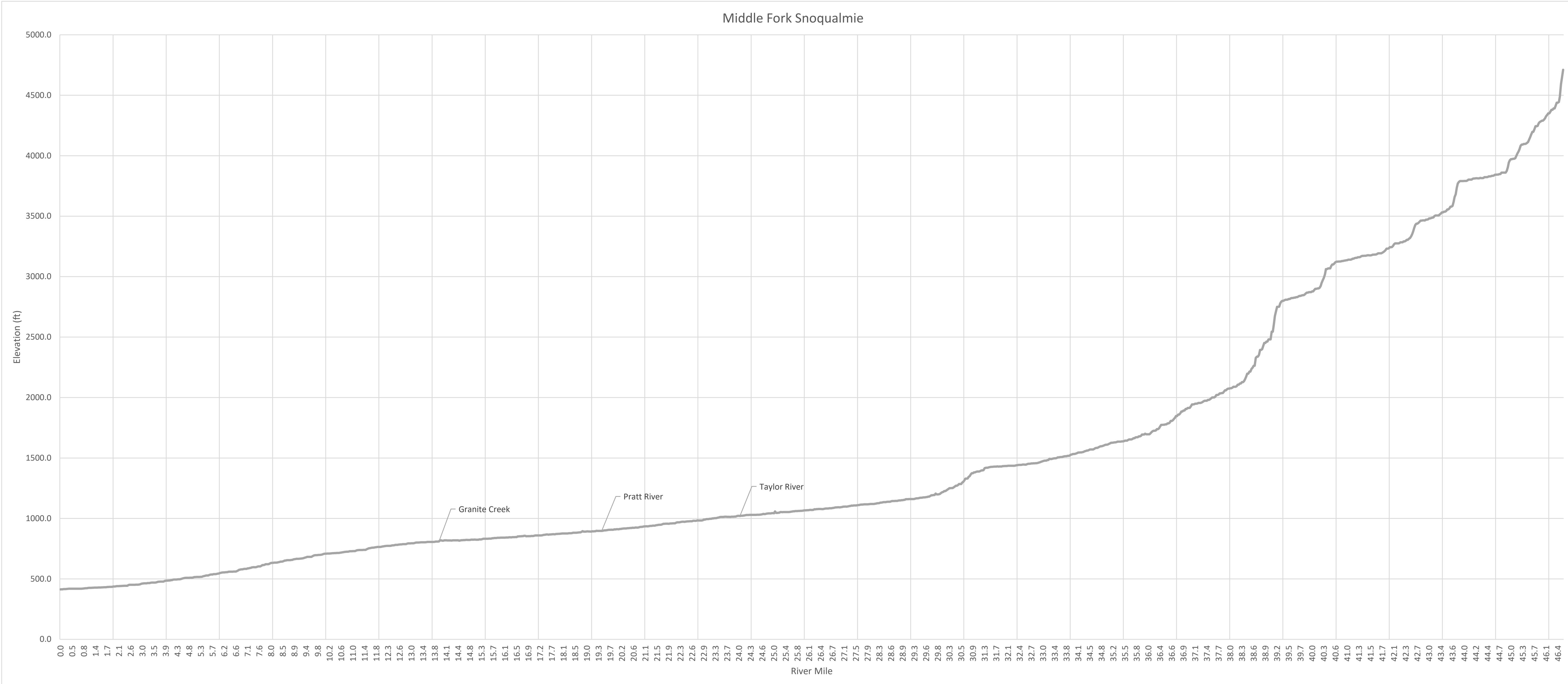
Tague, C., Valentine, S., & Kotchen, M. (2008). Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed. *Water Resources Research*, *44*(10), n/a-n/a. https://doi.org/10.1029/2007WR006418

Yan, H., Sun, N., Fullerton, A., & Baerwalde, M. (2021). Greater vulnerability of snowmelt-fed river thermal regimes to a warming climate. *Environmental Research Letters*, *16*(5), 054006. https://doi.org/10.1088/1748-9326/abf393

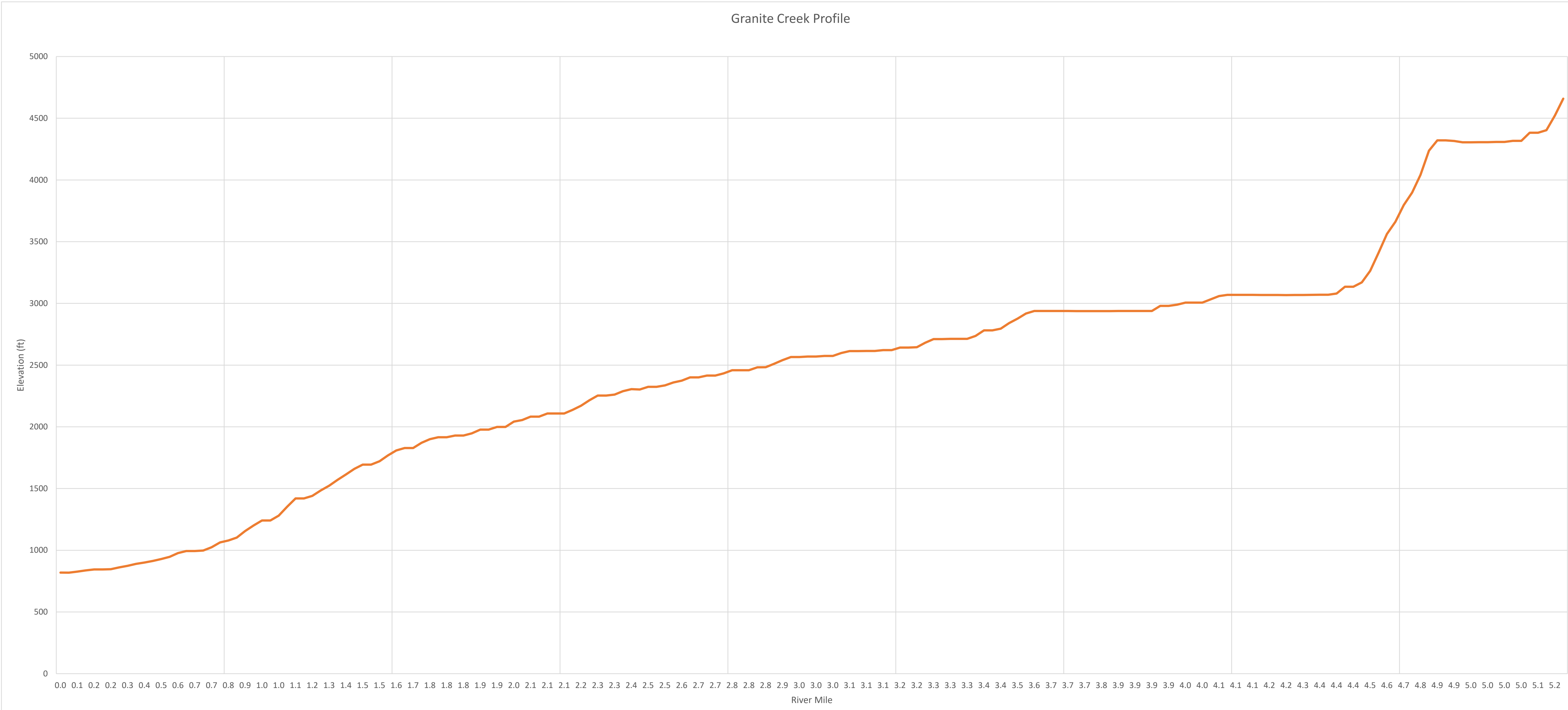
Appendix A

Longitudinal Profiles

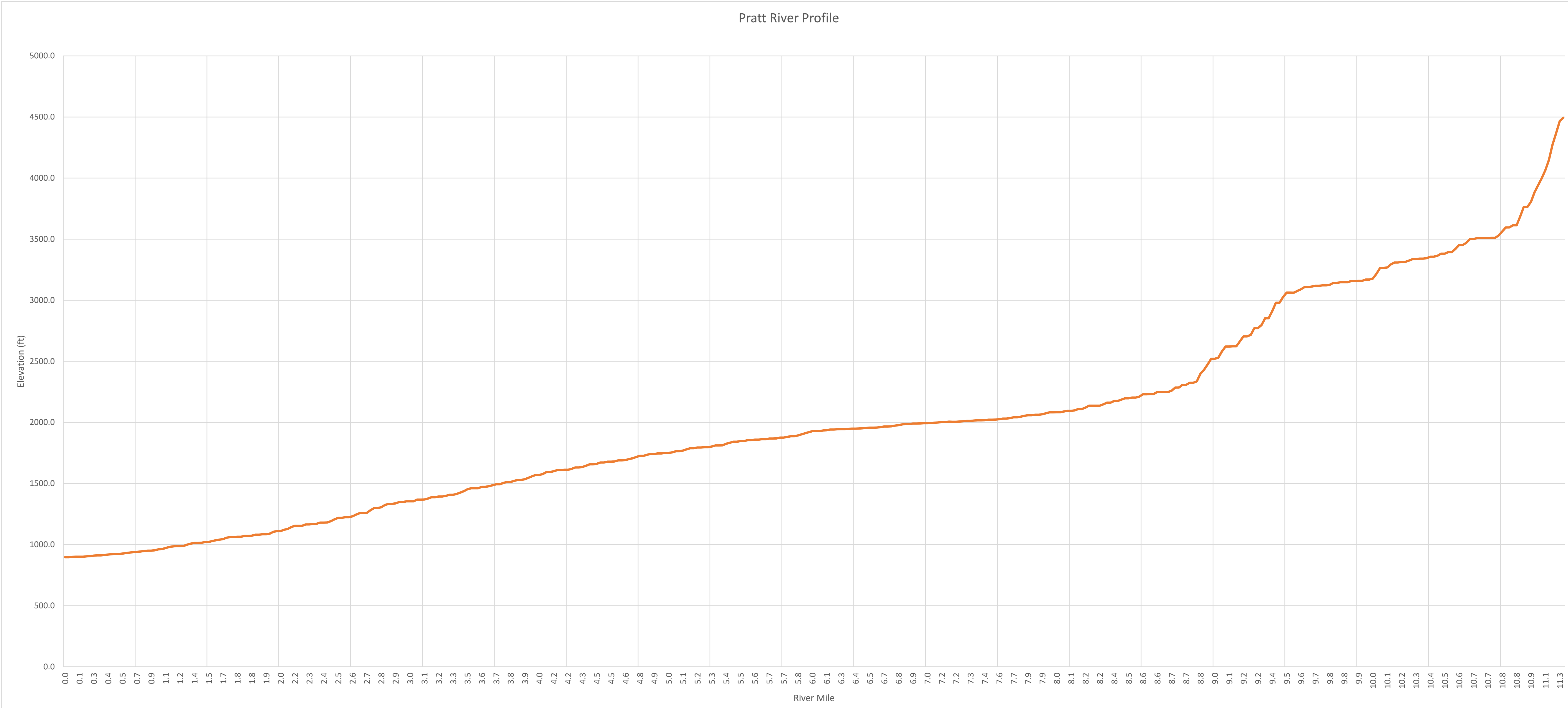
Natural Systems Design

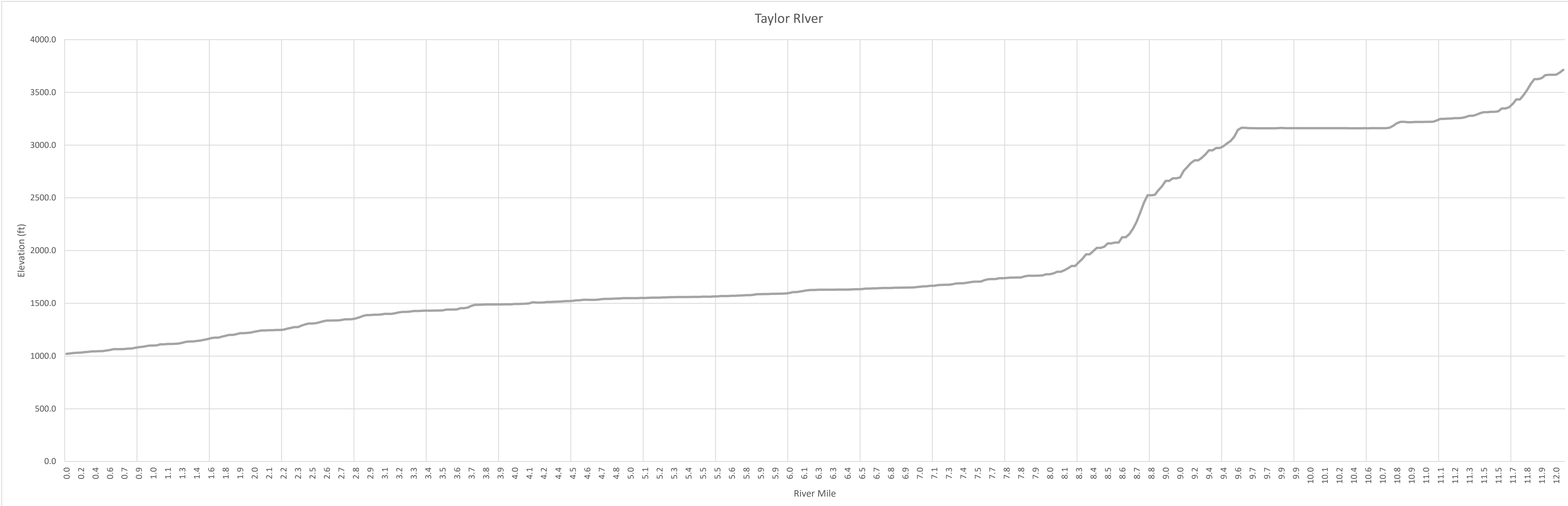


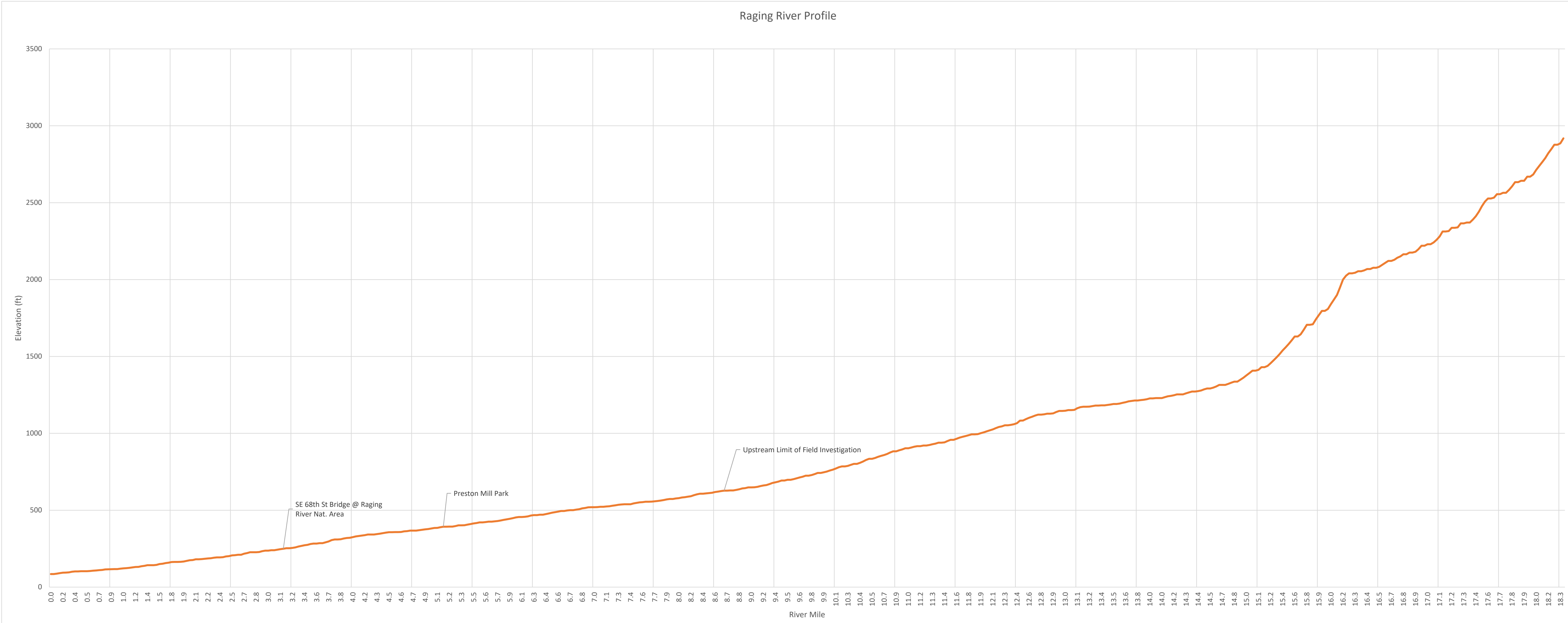
Middle Fork Snoqualmie
Elevation (ft)
River Mile
Granite Creek
Pratt River
Taylor River



Granite Creek Profile
Elevation (ft)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.0 0.1 0.2 0.2 0.3 0.4 0.5 0.6 0.7 0.7 0.8 0.9 1.0 1.0 1.1 1.2 1.3 1.4 1.5 1.5 1.6 1.7 1.8 1.8 1.8 1.9 1.9 2.0 2.1 2.1 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.6 2.7 2.7 2.8 2.8 2.8 2.9 3.0 3.0 3.0 3.1 3.1 3.1 3.2 3.2 3.3 3.3 3.3 3.4 3.4 3.5 3.6 3.7 3.7 3.7 3.8 3.9 3.9 3.9 3.9 4.0 4.0 4.1 4.1 4.1 4.2 4.2 4.3 4.4 4.4 4.4 4.5 4.6 4.7 4.8 4.9 4.9 5.0 5.0 5.0 5.0 5.1 5.2
River Mile


Pratt River Profile
Elevation (ft)
River Mile
5000.0
4500.0
4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0

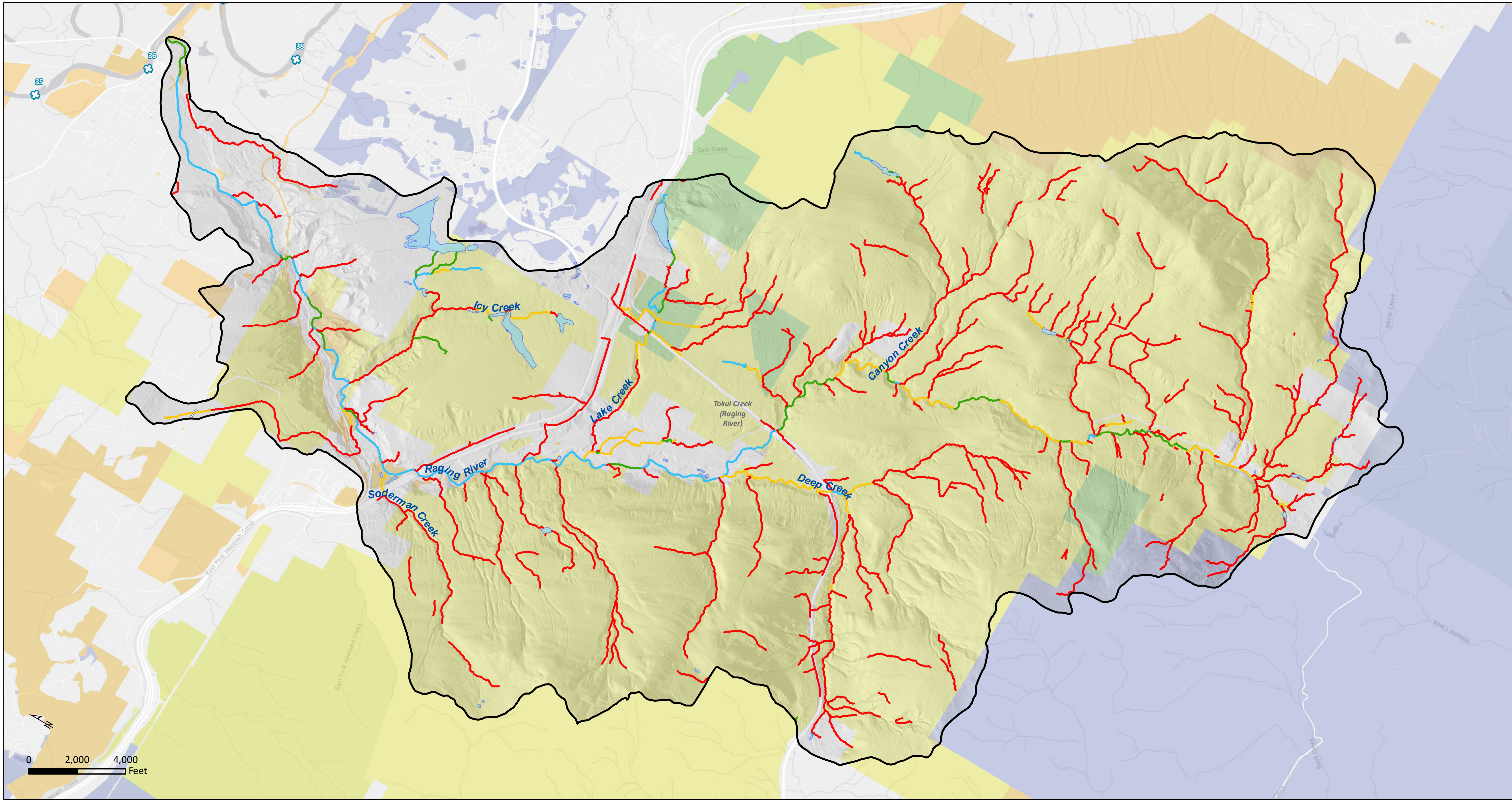

Taylor RIver
Elevation (ft)
River Mile
4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0


Raging River Profile
3500
3000
2500
2000
1500
1000
500
0
Elevation (ft)
River Mile
SE 68th St Bridge @ Raging River Nat. Area
Preston Mill Park
Upstream Limit of Field Investigation

Appendix B

Alluvial Water Storage Potential

Natural Systems Design



Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Tokul Creek (Raging River)

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

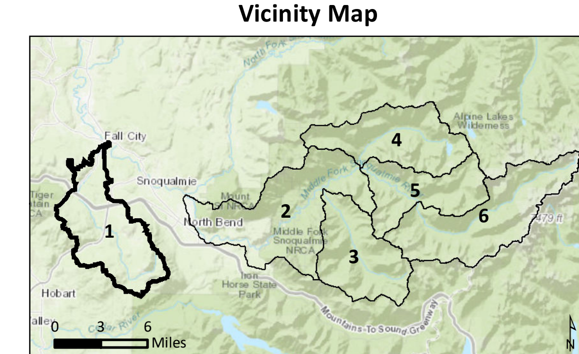
Restorable Alluvial Water Storage Potential (acft/mi)

- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

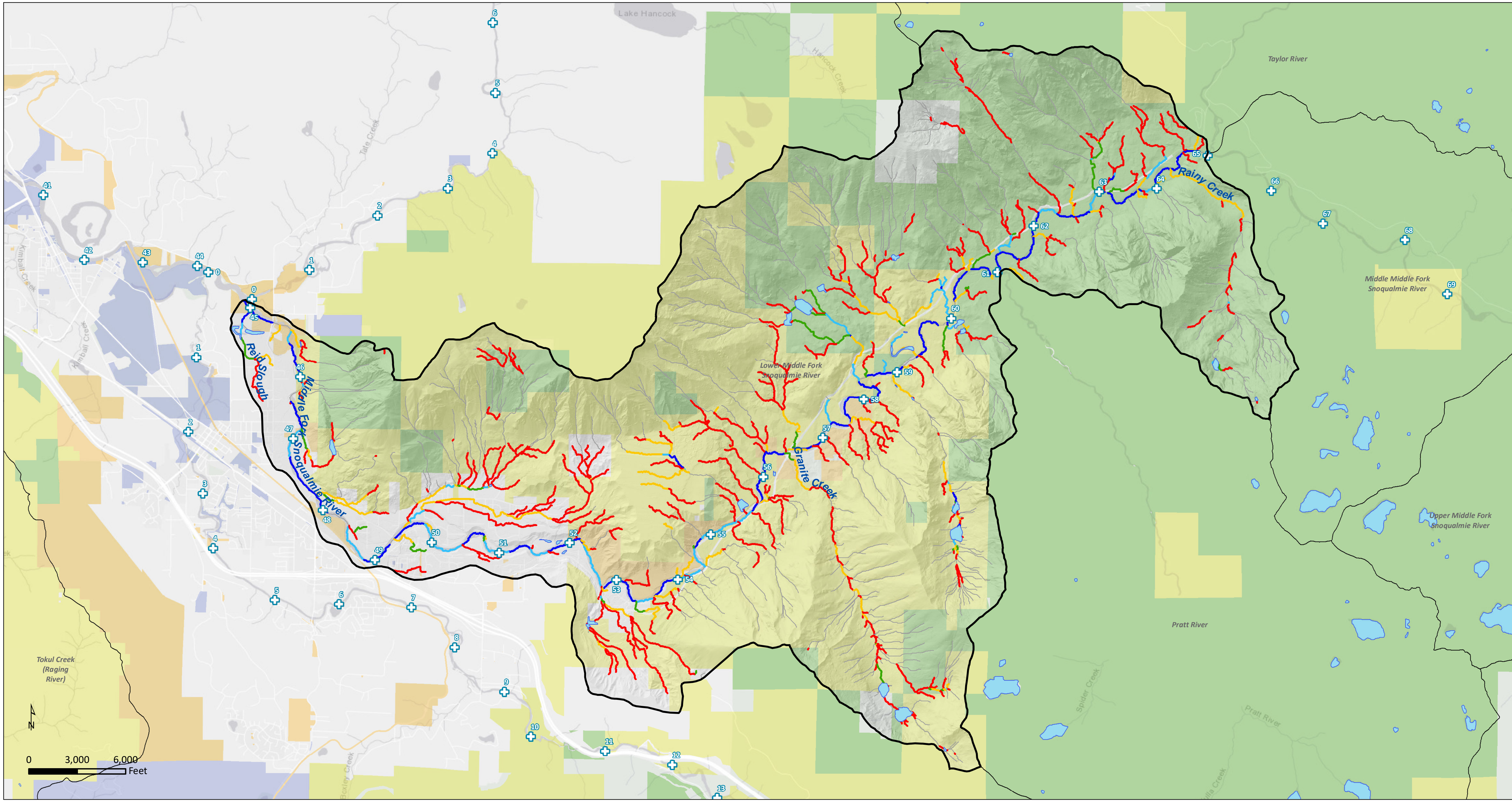
Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Vicinity Map



Natural Systems Design



Author: NSD Staff Date: 12/7/2021 Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\MFSnoqRR_AWSMapbook.mxd

Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Lower Middle Fork Snoqualmie River

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

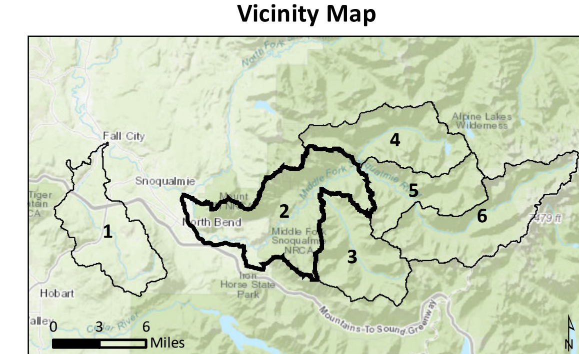
Restorable Alluvial Water Storage Potential (acft/mi)

- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

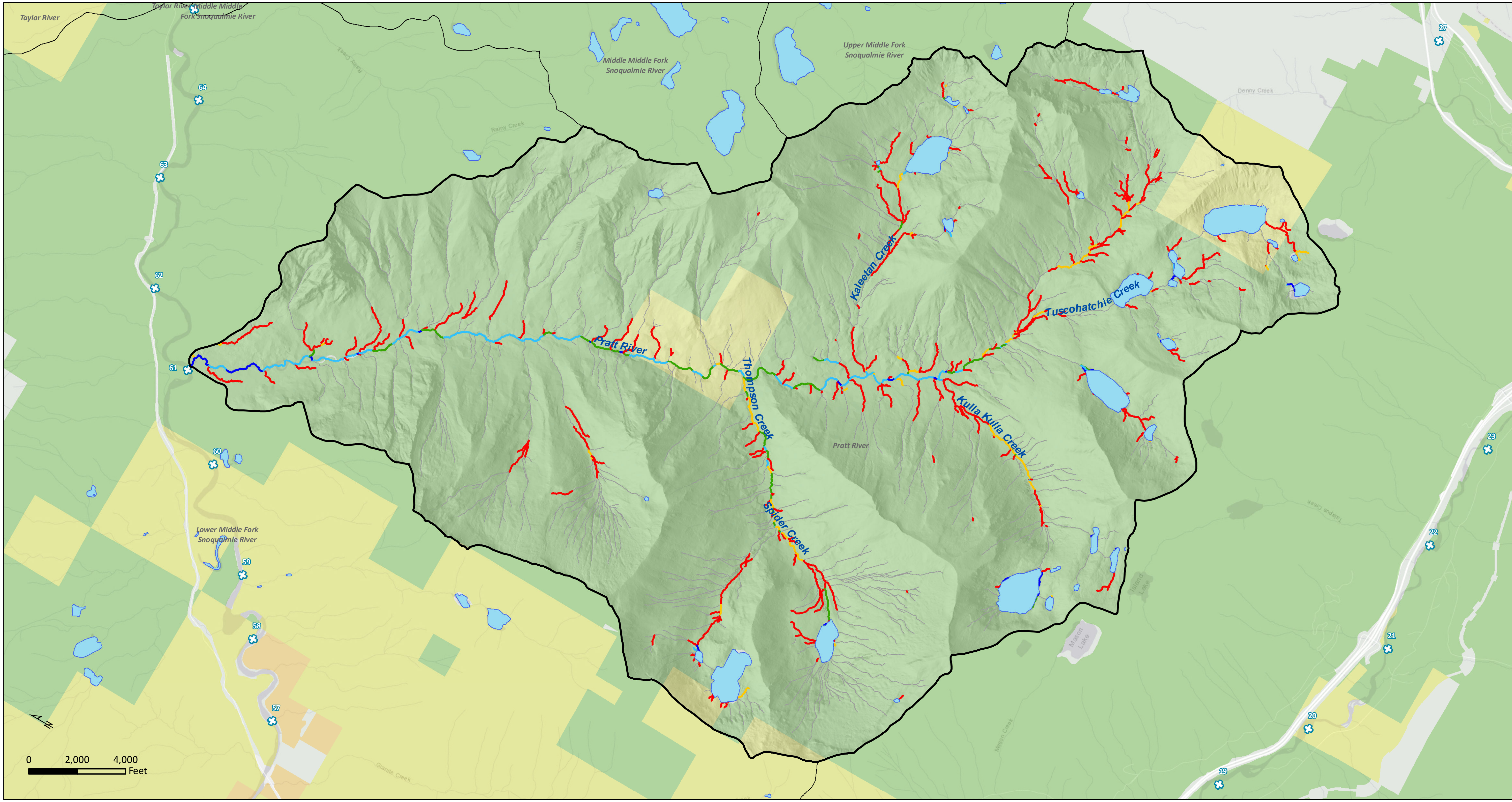
Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Vicinity Map



Natural Systems Design



Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Pratt River

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

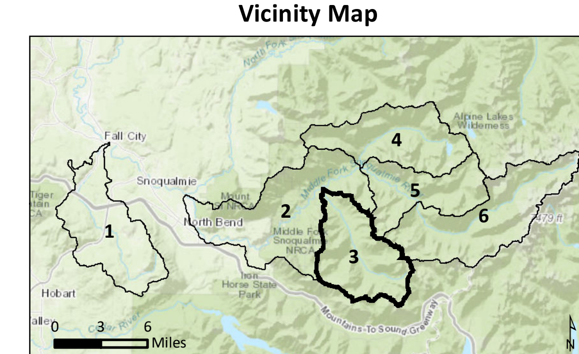
Restorable Alluvial Water Storage Potential (acft/mi)

- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

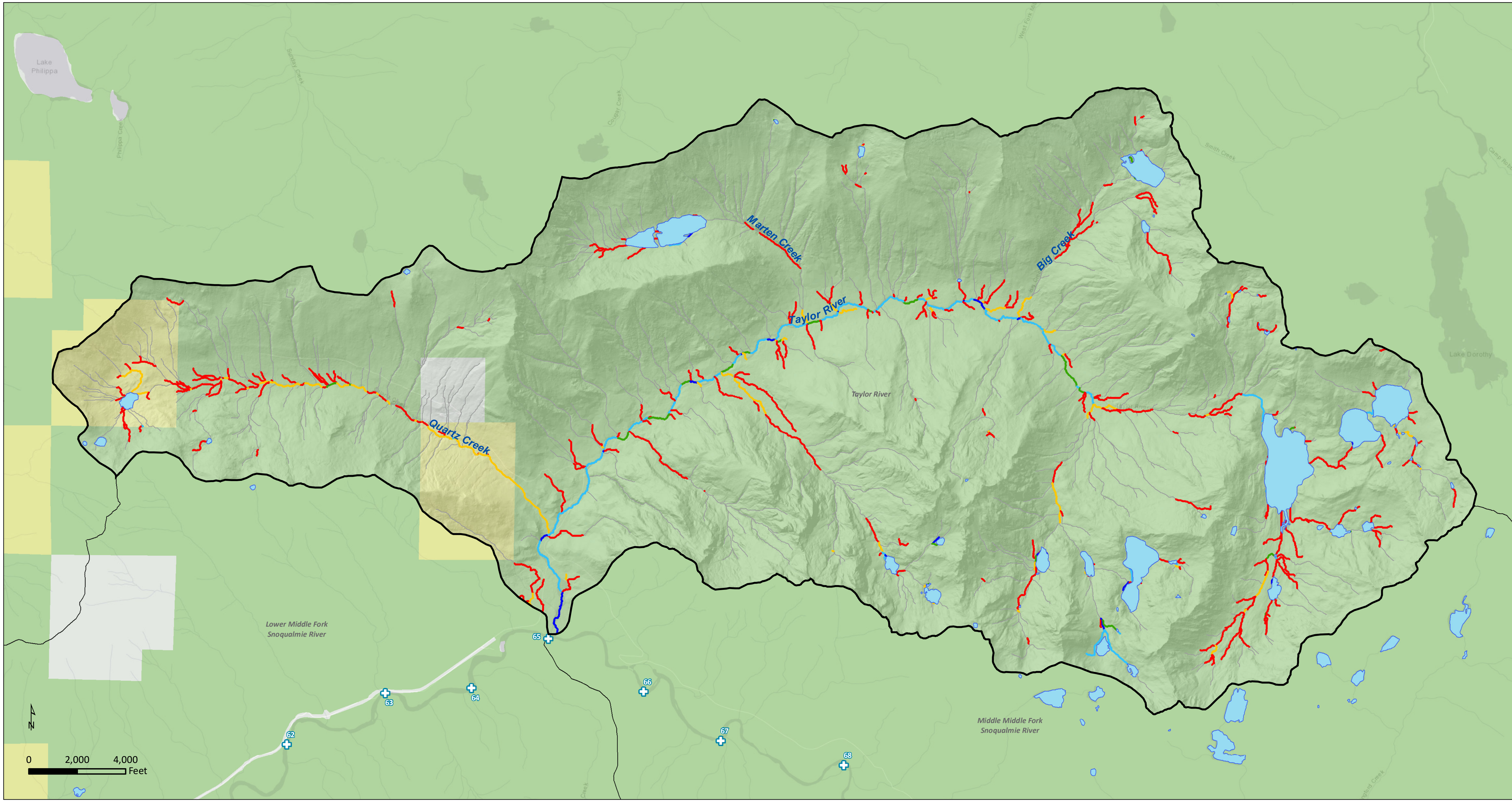
Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Vicinity Map



Natural Systems Design



Author: NSD Staff Date: 12/7/2021 Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\MFSnoqRR_AWSMapbook.mxd

Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Taylor River

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

Natural Systems Design

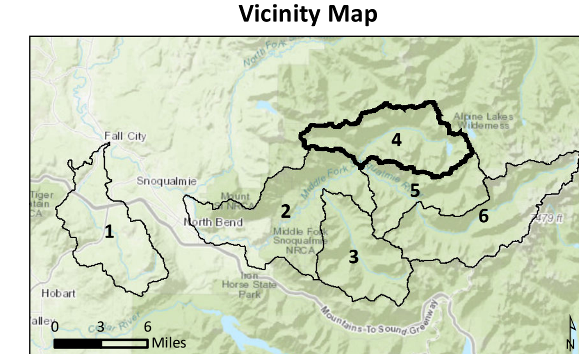
Restorable Alluvial Water Storage Potential (acft/mi)

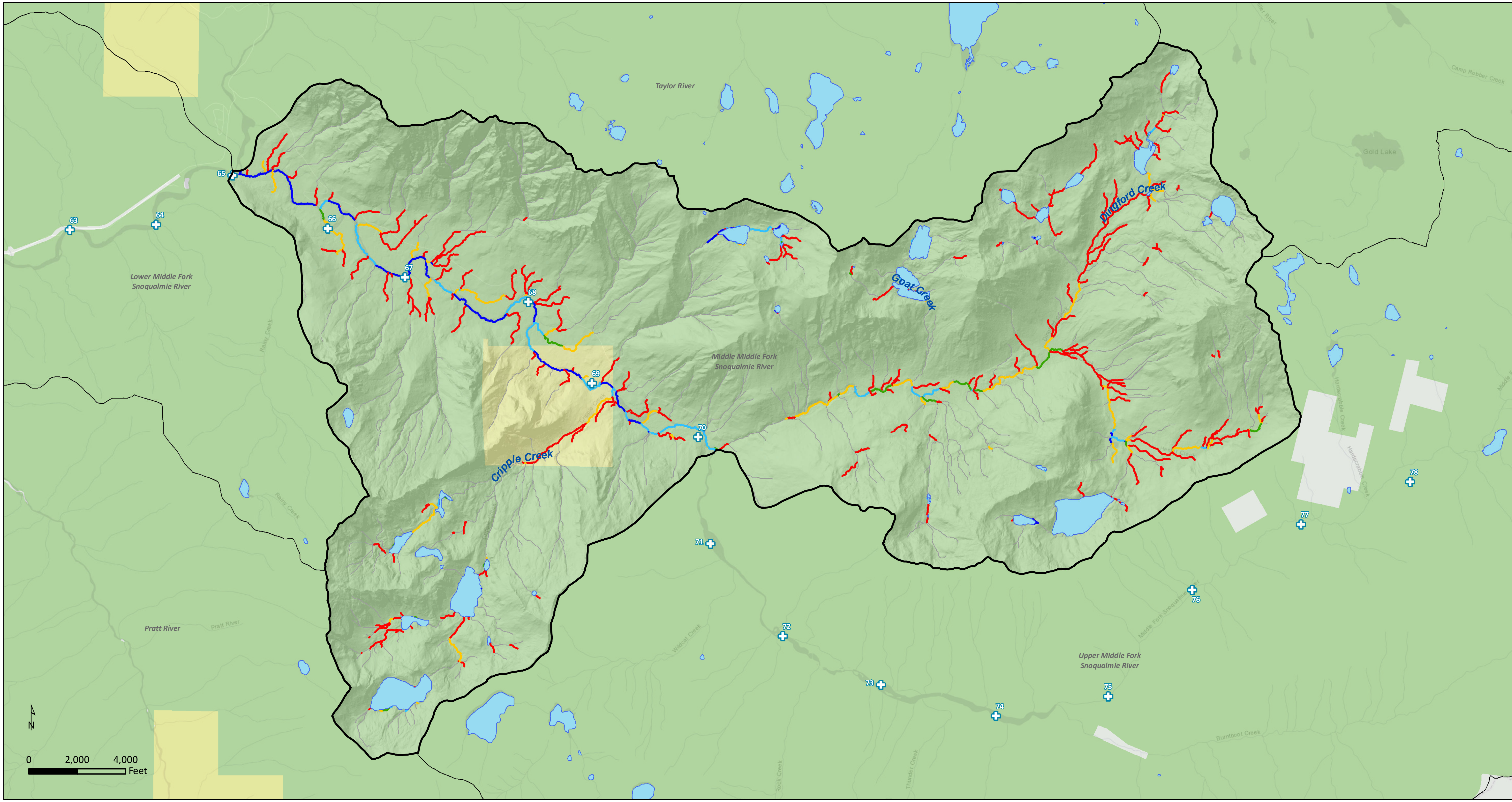
- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Vicinity Map





Author: NSD Staff Date: 12/7/2021 Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\MFSnoqRR_AWSMapbook.mxd

Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Middle Middle Fork Snoqualmie River

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

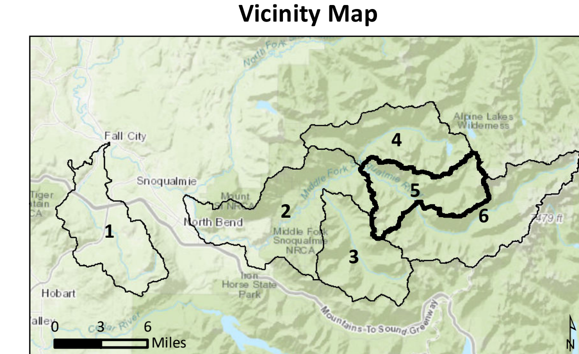
Restorable Alluvial Water Storage Potential (acft/mi)

- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

Publicly-Owned Property (King Co.)

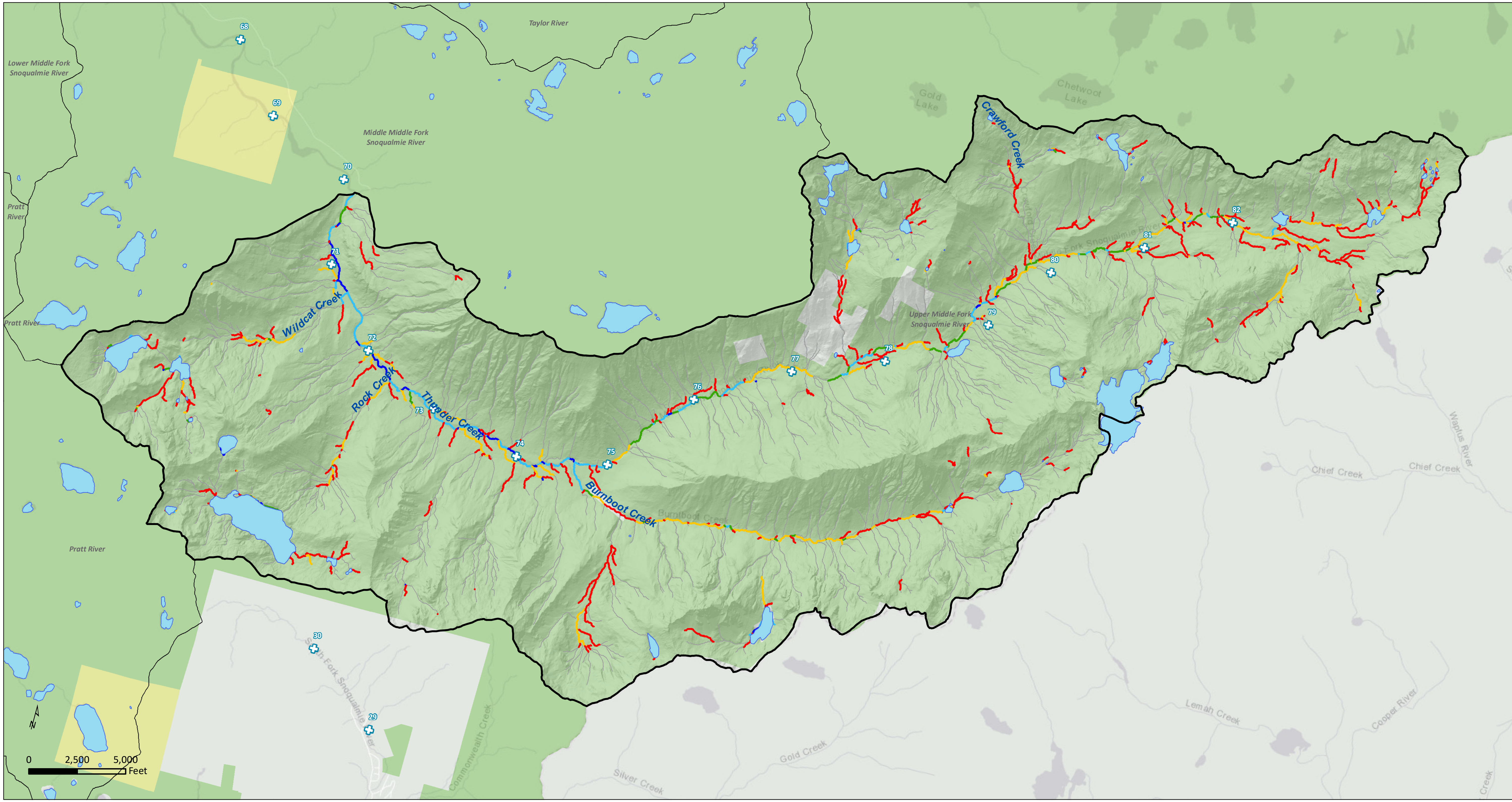
- Municipal
- County
- State
- Federal

Vicinity Map



Natural Systems Design

Author: NSD Staff Date: 12/7/2021 Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\MFSnoqRR_AWSMapbook.mxd



Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Upper Middle Fork Snoqualmie River

Summary restorable alluvial water storage in acre-feet per mile for each HUC12 within the model domain. Illustrated reaches include all reaches with less than 8% gradient that are not located within an NHD-mapped waterbody.

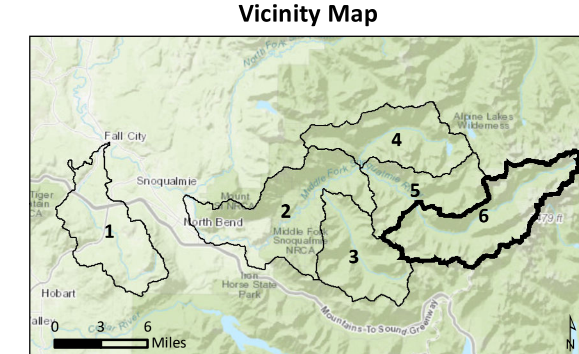
Restorable Alluvial Water Storage Potential (acft/mi)

- < 4
- 4 - 8
- 8 - 12
- 12 - 30
- > 30
- Unevaluated Stream Reaches

Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Vicinity Map

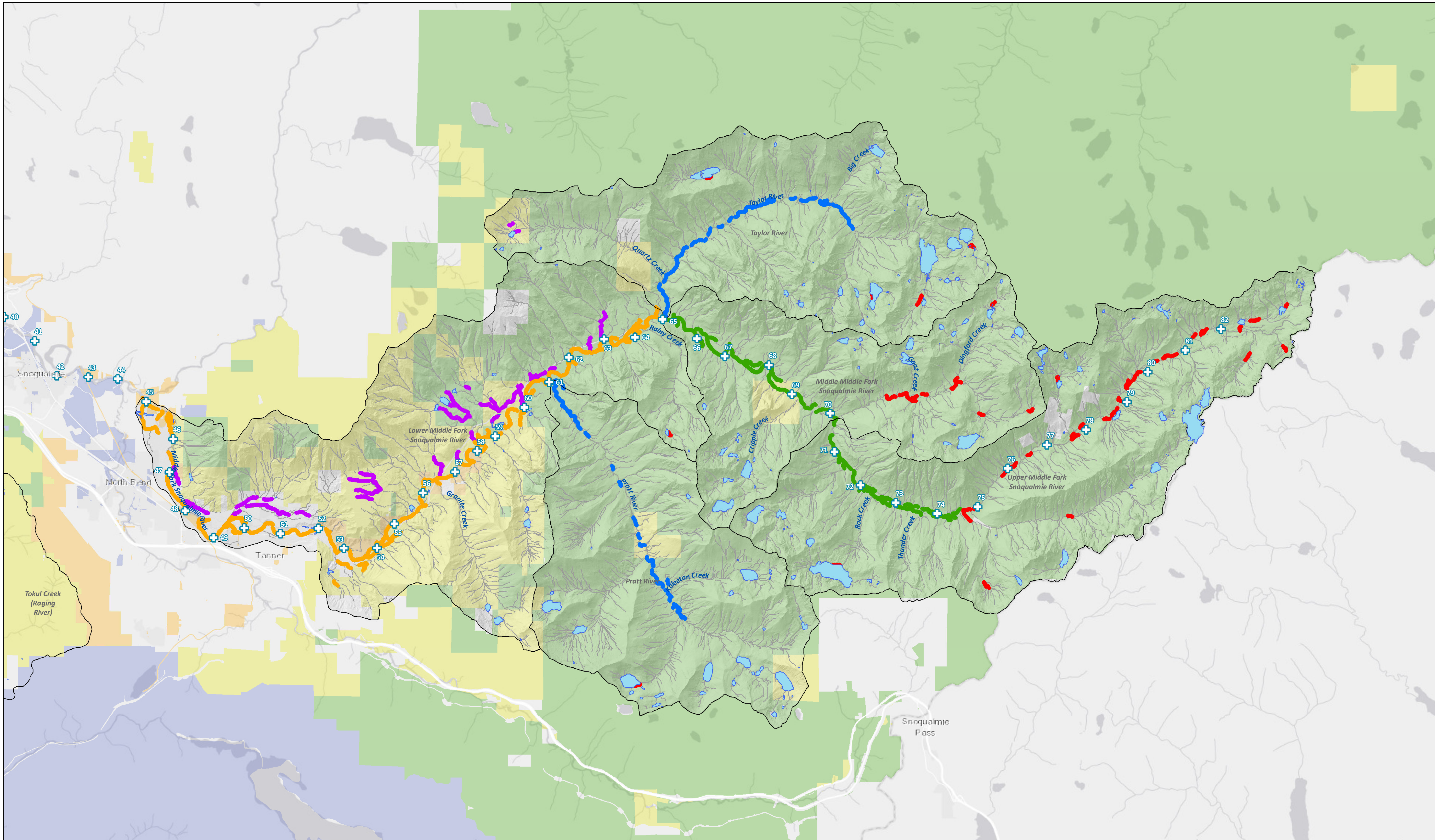


Natural Systems Design

Appendix C

Restoration Reach Types

Natural Systems Design



Author: NSD Staff Date: 12/7/2021 Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\MFSnog_RestGrouping.mxd

Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Restoration Reach Types - Middle Fork Snoqualmie

Restoration reach types within a focus subset of reaches in the MF Snoqualmie watershed with the highest potential for restoration of alluvial water storage, as defined by reach length > 500 ft (i.e., to screen out model artifacts), alluvial water storage potential > 4 ac-ft/mile, and gradient < 4 % (i.e., to screen for restoration implementation).

N

0 1 2 Miles

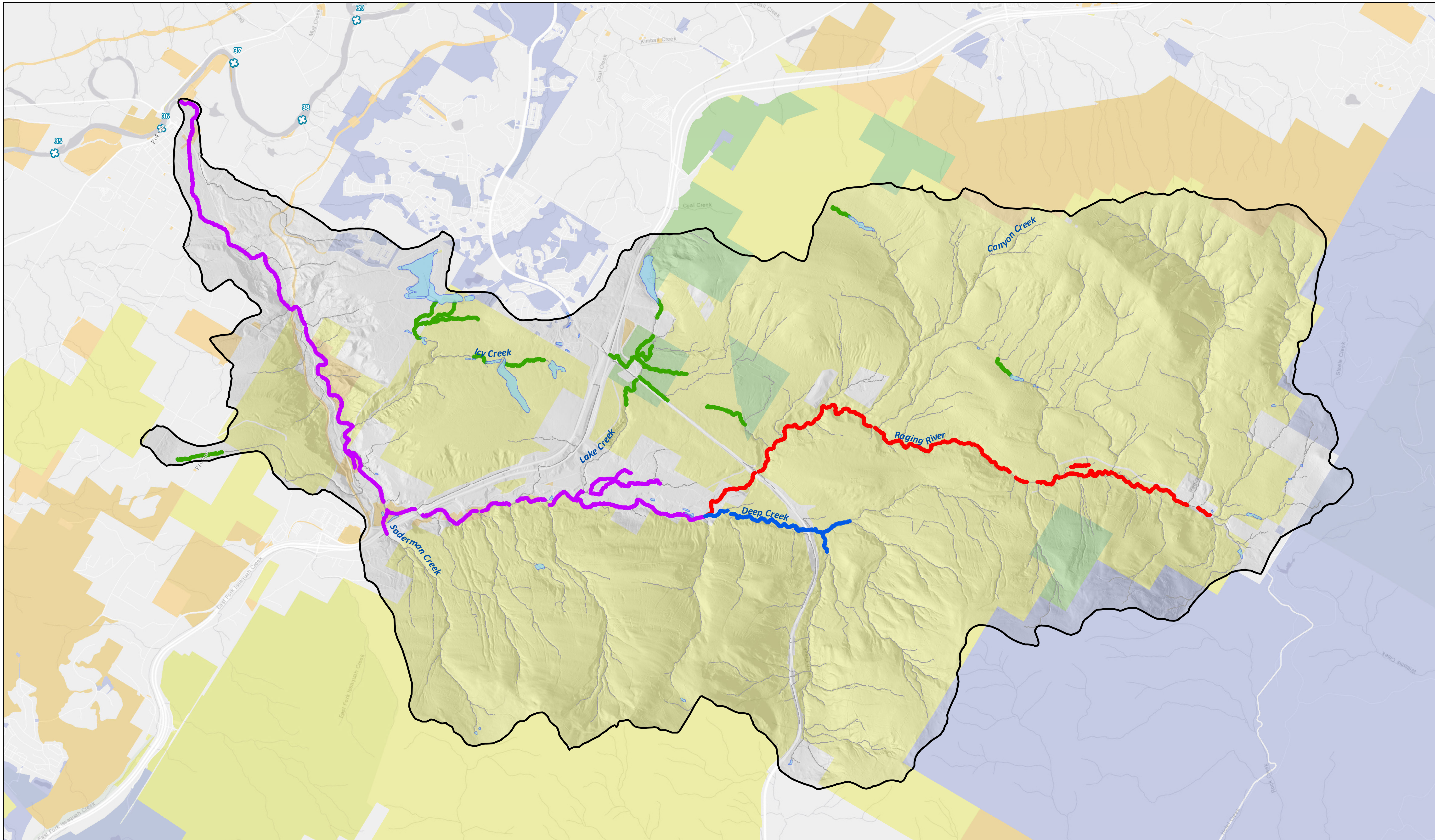
Restoration Reach Types

- Lower MF Snoqualmie
- Upper MF Snoqualmie
- Major Tributaries
- Valley Wall Tributaries
- Headwaters

Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Natural Systems Design



Author: NSD Staff   Date: 12/7/2021   Path: N:\Projects\Wild_Fish_Conservancy\Snoqualmie_AWS\GIS\maps\mxd\RagingR_RestGrouping.mxd

Middle Fork Snoqualmie and Raging River Alluvial Water Storage Assessment

Restoration Reach Types - Raging River

Restoration reach types within a focus subset of reaches in the Raging River watershed with the highest potential for restoration of alluvial water storage, as defined by reach length > 500 ft (i.e., to screen out model artifacts), alluvial water storage potential > 4 ac-ft/mile, and gradient < 4 % (i.e., to screen for restoration implementation).

0 2,000 4,000 Feet

Restoration Reach Types

- Lower Raging River
- Upper Raging River
- Deep Creek
- Upland Lakes and Wetlands

Publicly-Owned Property (King Co.)

- Municipal
- County
- State
- Federal

Natural Systems Design