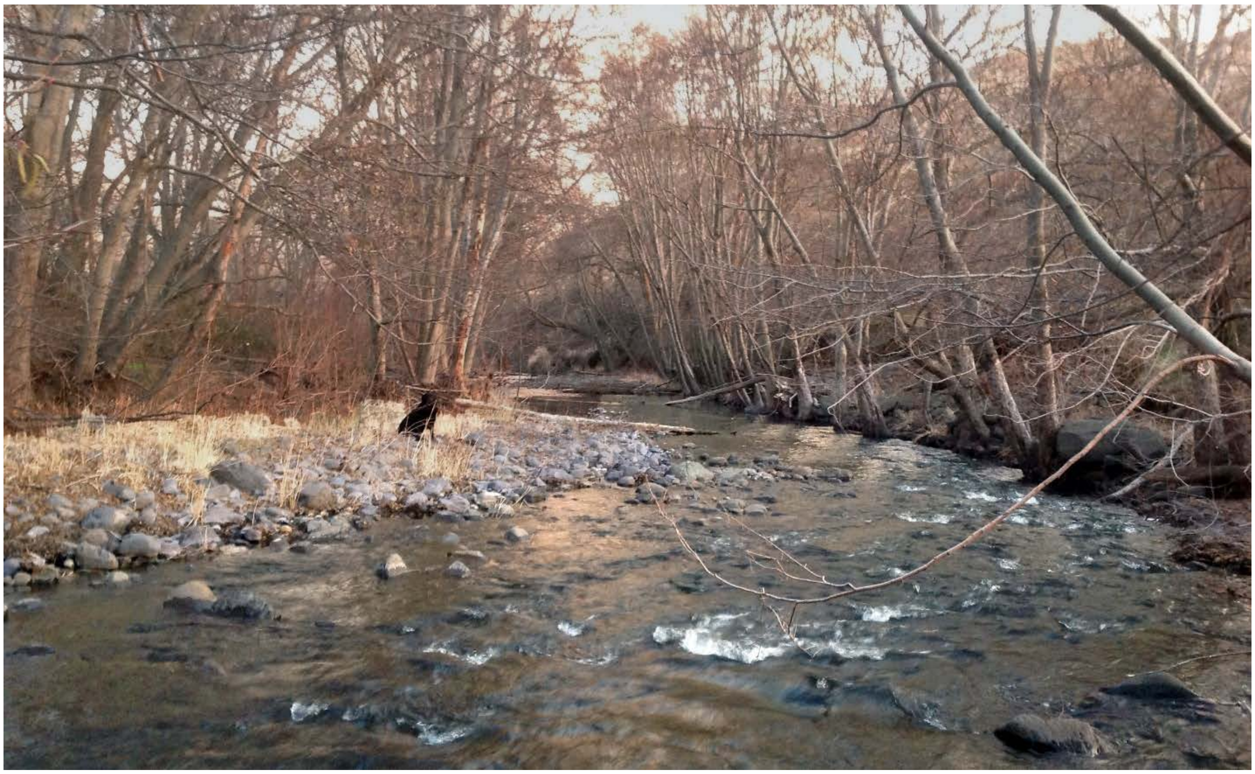
Fluvial Reconnaissance of Rock Creek and Selected Tributaries with Implications for Anadromous Salmonid Habitat Management

Rock Creek, Klickitat County, WA



Prepared by:

Will Conley, Hydrologist/Geomorphologist
Yakama Nation Fisheries Program
Klickitat Field Office
Wahkiacus, WA

Prepared for:

United States Department of Energy
Bonneville Power Administration
Environment, Fish, and Wildlife Program
Portland, Oregon

Project Number: 2007-156-00

December 21, 2015

(THIS PAGE INTENTIONALLY LEFT BLANK)

EXECUTIVE SUMMARY

Rock Creek drains 226 square miles of eastern Klickitat County in south-central Washington State and flows into the Columbia River at river mile (RM) 230. It occurs within the geographic region of the Mid-Columbia River Distinct Population Segment (DPS) of steelhead trout (*Oncorhynchus mykiss*) which are "threatened" under the Endangered Species Act (ESA). This study was undertaken to identify needs and limitations of potential habitat restoration, protection, and enhancement for steelhead in the Rock Creek watershed. A combination of field observations, pre-existing information review, habitat data reprocessing, and remote sensing data were collected, compiled, and evaluated.

Several intrinsic watershed characteristics contribute to challenging hydrologic conditions, specifically: south-facing facing aspect, equant shape, low elevation (83% below 3,000 feet), moderately-high relief, low mean annual precipitation (MAP, 16.6 inches), and no lakes, permanent snowfields, glaciers, or appreciable wetlands. The general lack of watershed storage increases sensitivity to climate change and increases the importance of groundwater contributions during an increasingly large portion of the flow duration curve.

Rock Creek's prevailing profile is bedrock-controlled. A boulder pavement routinely appears at the channel surface between Quartz Creek and the mouth, particularly in pools and runs. Less-confined valley segments have accumulated sediments which are generally poorly-sorted and frequently have a cohesive matrix. Squaw Creek likely provides the greatest tributary input of coarse sediments which, overall, appear limited in space and time. Most of the routine sediment supply seems to be from re-worked floodplain deposits, alluvial/debris fan toes, and terraces.

Air photo review indicates the 1964 peakflow was a signature event with significant changes in channel alignments and riparian vegetation. Similar, but less intensive changes are observed following large magnitude flow events in 1974 and 1996. Many reaches are still responding to geomorphic effects from one or more of these events. The duration of post-disturbance channel response combined with expected recurrence frequency of similar perturbances, suggest many of Rock Creek's alluvial reaches can be expected to be in a nearly continual state of adjustment.

Other key observations:

- Analysis of results produced by indirect regional magnitude-frequency peakflow equations indicates 55 to 63% under-prediction of flood peaks fit to local data.
- Active channel mapping based solely on high-resolution (6 inch pixels) color aerial photography alone undermapped secondary channels and 27% of total length for all active channels compared to mapping supported by LiDAR and field confirmation.
- Long, shallow, linear habitat features with planar cross-sections prevail. Shallow bedrock and boulder sub-armor contribute to infrequent and shallow pool structures that lack cover.
- Alluvial reaches primarily exhibit wandering or switching active channel behaviors with planform occupation (and reoccupation) strongly influenced by resistant features such as bedrock and cohesive valley margins, alluvial/debris fan toes, and mature riparian forest.
- Perennial channel units within alluvial valley segments tend occur in incised reaches.

- Density and spatial extent of human groundwater development has steadily increased with considerable entry into the watershed since the mid-1990s.
- Large woody debris is generally absent from the low-flow channel and not a habitat forming agent. However, transient habitat associated with accumulations of smaller wood pieces and leaf-litter may have greater value than typically recognized in other systems.
- Better quality salmonid habitats tend to be hydraulically-forced.
- Naturalized black walnut trees grow larger than, persist longer than, and displace native riparian vegetation. Greater hydraulic resistance (live and dead) and persistence can be expected to alter fluvial behavior where present and may also affect water-balance.

Prior assessments identified low baseflow and low instream cover to be the main limiting habitat conditions for steelhead. Baseflow habitat censuses conducted by Allen at al. (2014a) from 2009 through 2012 covered 14 miles of Rock and Squaw creeks and, effectively sampled 77% of the subbasin's total stream length where gradient is less than 0.025 feet/feet. Across years, perennial pools compose 17% and dry reaches account for 36% of total length, respectively. In 2012, a very dry year, nearly half (46%) of total surveyed length was dry and pools composed 14%. Underwater cover limited juvenile survival during summer baseflow in all years.

Run composition and uncertainty regarding Rock Creek's steelhead population viability raise several questions regarding potential habitat action relevance. Genetic sampling has documented the steelhead run to be highly introgressed with the Snake River DPS (Matala 2014). Preliminary results of an ongoing PIT-tagging study found 85% of adult detections of known juvenile origin to be Snake River DPS steelhead (Allen at al. 2014a). Ongoing tagging should reveal whether steelhead in Rock Creek are a viable naturalized Snake River DPS subpopulation or sustained solely by routine straying. Determination of whether the watershed is a meta-population "sink" is key to ensuring habitat actions are necessary and potentially effective.

Substantial planform and/or profile shifts combined with very low baseflow constrain habitat action effectiveness prospects and make the risk of unintended, negative consequences high. Improperly implemented actions have medium to high potential to convert perennial units to intermittent flow duration or entice and strand salmonids into existing intermittent habitats.

The lowest-risk habitat action with the greatest certainty for effectiveness is instream baseflow protection. Encouraging beaver colonization and/or manual additions of small, locally sourced branches and tops are low-cost and low-risk and potentially effective. Once population-level questions about Rock Creek steelhead are resolved, more active treatments may be locally appropriate. A list of sites for further evaluation prioritized by risk and effectiveness potential is provided. In the absence of instream flow protection, certainty of success for any physical treatment to generate a lasting positive population response is low.

Additional information needs include: documenting geographic distribution of perennial habitats over multiple years to characterize inter-annual variability, groundwater / surface water relationships, effectiveness monitoring of any instream treatments, and ongoing fish tagging to address questions of productivity and population status.

ACKNOWLEDGEMENTS

Project funding was provided by the Bonneville Power Administration via Project Number 2007-156-00 (contract 56662).

Pre-existing data were received from a variety of sources from the summer of 2013 through fall of 2014. John Foltz (Klickitat County), Elaine Harvey (Yakama Nation Fisheries Program (YNFP)), and Loren Meagher (Eastern Klickitat Conservation District (EKCD)) assisted in compiling these data. Greg Morris (YNFP) also shared field data from Quartz Creek and the upper portions of Rock Creek, particularly photos and GPS data for falls/bedrock.

Reviews of earlier drafts of this report were received from a variety of individuals from the YNFP, USGS, and EKCD. Suggestions and edits from the following reviewers were particularly constructive and greatly assisted the current product:

- Brady Allen, Fisheries Biologist, USGS
- Jeanette Burkhardt, Watershed Planner, YN Fisheries Program (YNFP)
- Scott Ladd, Hydrologist, YN Water Resources Program (YNWRP)
- Tom Ring, Hydrogeologist, YNWRP
- Joe Zendt, Fisheries Biologist, YNFP

In particular, David Lindley (Habitat Biologist, YNFP) reviewed multiple versions and was instrumental in refinement of the document.

The success of the field-based portion of this study was highly dependent on access to private lands and the author wishes to express his appreciation to all the landowners that granted access. Elaine Harvey greatly assisted efforts by contacting and obtaining permission from private landowners as well as assisting with vehicle shuttles and other field logistics.

AUTHOR'S NOTE

Core content and recommendations in this final report are largely the same as the draft issued in March 2015. Changes are largely editorial. Climate change content has been added to the Management Challenges and Uncertainties section as well as a graphic and some discussion to Channel Gradient, Pattern, and Behavior sub-section to be consistent with material I presented at the April 2015 Columbia Gorge Science Conference. Discussion in the Peak Flow Hydrology has been refined to reduce confusion on the need for adjusting the published average daily discharge value for the flood of record in peak magnitude-frequency analysis. While quantitative analysis and the predictive formula based on the instantaneous 1964 peak discharge are unchanged from earlier drafts, Table 6 has been updated to include computed results. Executive Summary, Synopsis and Management Implications, and Conclusions sections have all been updated to be more accessible to managers and stakeholders.

TABLE OF CONTENTS

FIGURES

TABLES

INTRODUCTION

Rock Creek drains 226 square miles of eastern Klickitat County in south-central Washington State and flows into the Columbia River at river mile (RM) 230, approximately 12 RM upstream of John Day Dam (Figure 1).

Rock Creek is located within the geographic region of the Mid-Columbia River Distinct Population Segment of steelhead (Oncorhynchus mykiss) which was listed as “threatened” under the Endangered Species Act in 1999. Multiple reaches within the Rock Creek watershed were listed on the Washington State 303d list for water quality impairment in 1996 due to high water temperatures. In recent years, there has been growing interest in actions that address watershed and fisheries concerns, but relatively little synthesis to inform on-the-ground treatments.

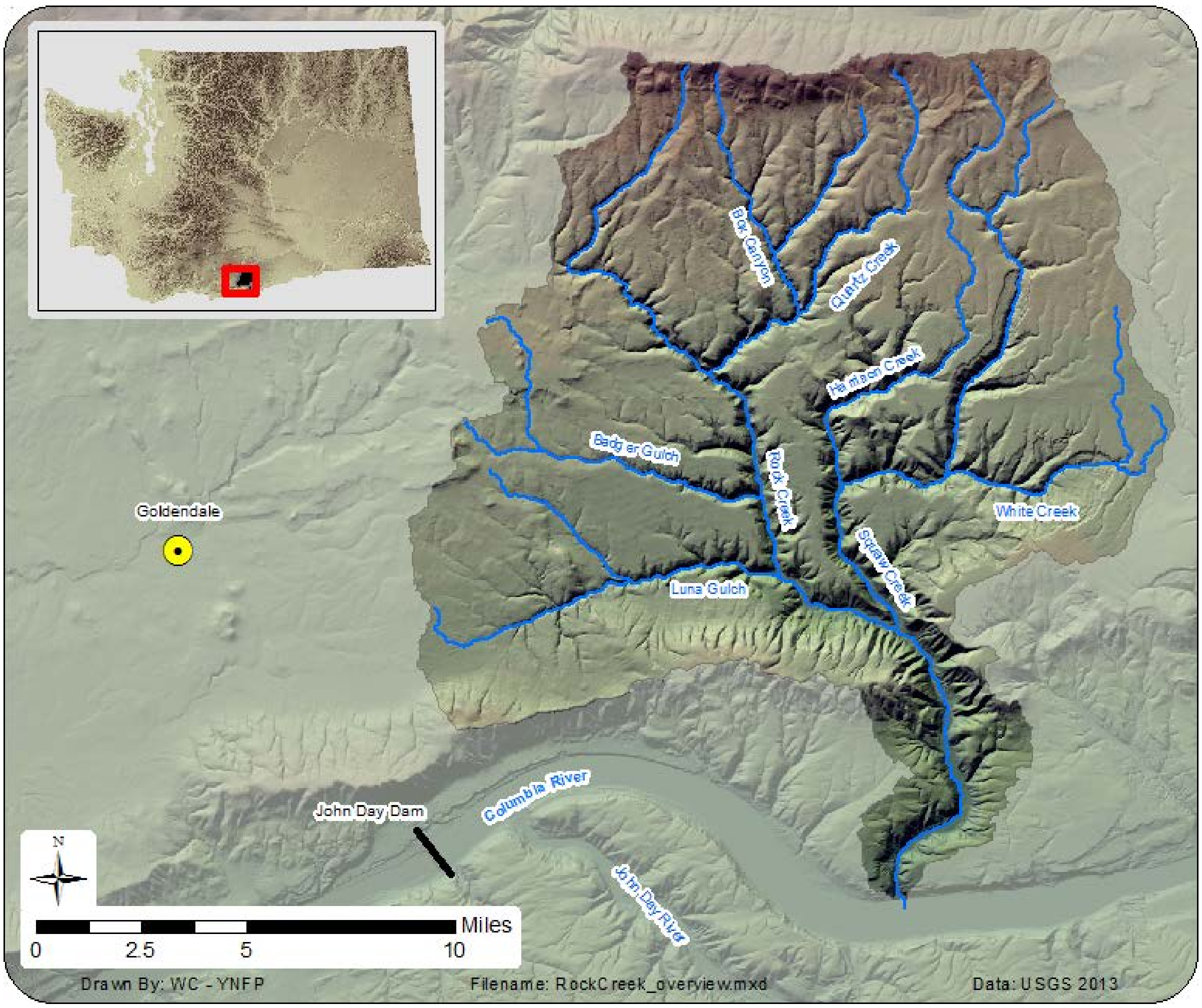


Figure 1. Hillshade relief map of Rock Creek watershed showing major tributaries.

Study Purpose

This study was undertaken to review information and perform analysis to identify limitations and needs for potential habitat restoration, protection, and enhancement for steelhead in the Rock Creek watershed. The study involved three components:

1) Synthesis of existing literature and data: Compile and review existing data, maps, and reports related to the Rock Creek subbasin, with an emphasis on those related to steelhead. The resulting report, "A Literature Review of Anadromous Salmonid Habitat, Rock Creek, Klickitat County, WA" was published separately (Lindley and Conley, 2013).

2) Fluvial reconnaissance: Conduct quantitative spatial analyses, modeling, and interpretation of hydrogeomorphic and physical habitat data. A combination of field observations, pre-existing habitat data, and high resolution terrain modeling were analyzed and interpreted. A channel migration study to be performed by others was unavailable for incorporation into this study.

3) Implications for physical salmonid habitat management: Incorporate synthesis and fluvial reconnaissance findings into management recommendations. Combine results of hydrologic and terrain analyses, interpretation of a wide range of hydrogeomorphic field indicators, and findings from prior fisheries studies to provide a guidance and general suitability recommendations for approaching stream habitat protection, restoration and/or enhancement actions. An emphasis is placed on the lower 17 miles of Rock Creek and lower 5 miles of Squaw Creek as that is where most of the existing data was concentrated. Specific information needs and locations for follow-up investigation and treatment are also provided.

STUDY AREA

Rock Creek drains 226 square miles of eastern Klickitat County in south-central Washington State and flows into the Columbia River at river mile (RM) 230, approximately 12 RM upstream of John Day Dam (Figure 1).

The study's geographic scope totaled approximately sixty valley miles (Figure 2) for which high resolution topography and aerial photography were available. This scope was previously identified by local biologists to encompass most of the stream reaches anticipated to support anadromous salmonid production, including portions of Rock, Luna, Quartz, Box Canyon, Harrison, White, and Squaw creeks.

The Rock Creek basin is a fifth-level HUC (1707010114), generally south-facing, and drains the western end of the Horse Heaven Hills. Elevations range from 266 feet at the confluence with the Columbia River to 4,700 feet in the headwaters. Evaluation of the National Elevation Dataset (NED, USGS 2013) indicates 98%, 83%, and 33% of the watershed is below 4,000 feet, 3,000 feet, and 2,000 feet, respectively, with only four percent under 1,000 feet. Overall, 79% of the watershed is between 1,000 and 3,000 of elevation.

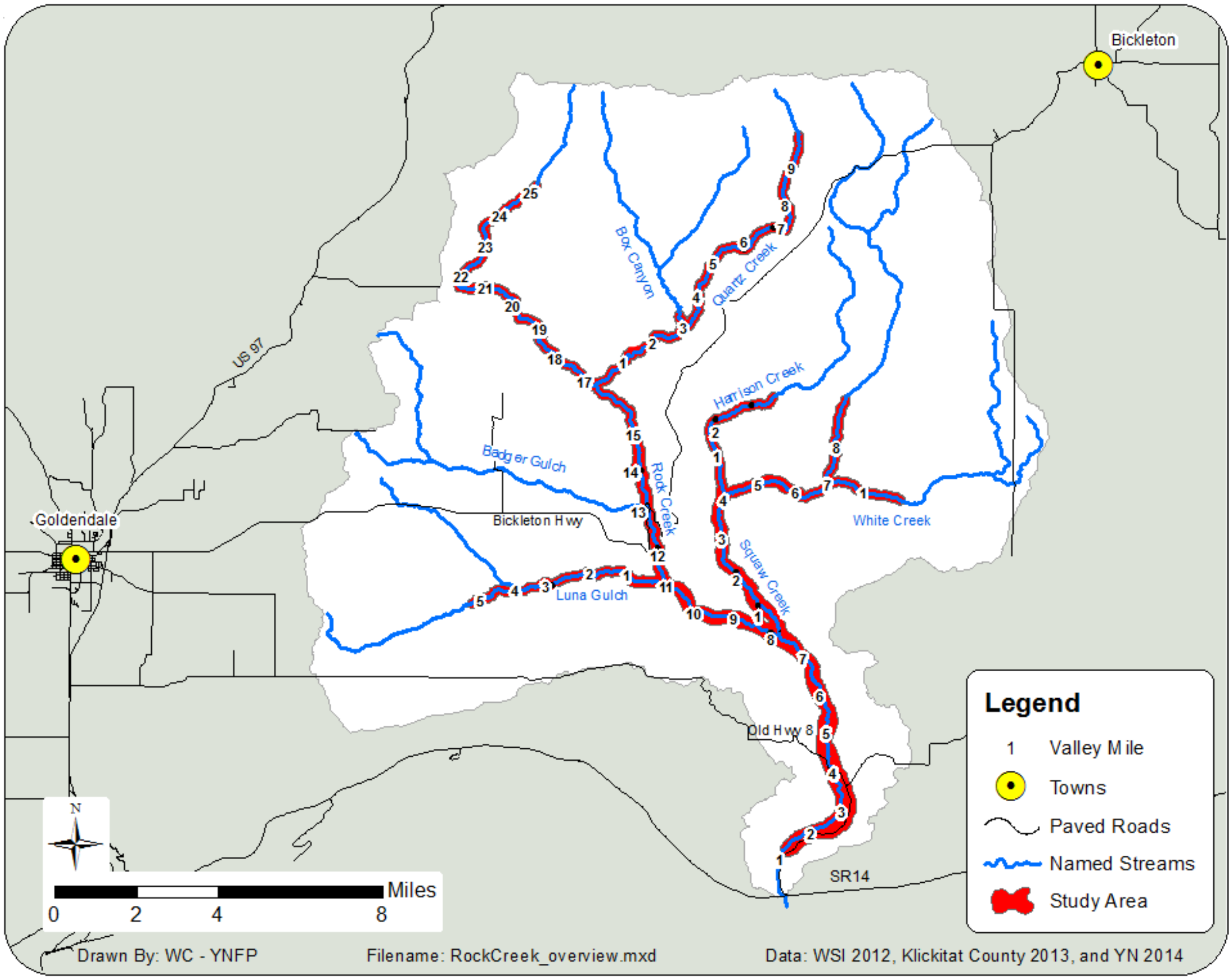


Figure 2. Study area map and valley-mile index

Mean annual precipitation (MAP) in the Rock Creek basin is calculated at 16.6 inches based on the 1981-2010 interval (PRISM 2014) and ranges from a 25.5 inch maximum in the Horse Heaven Hills to 9.5 inches near the mouth. MAP varies most strongly along a north-south axis (Figure 3), which generally follows a decreasing elevation gradient. Precipitation also decreases along an west to east gradeitn as the basin extends further into the rain shadow of Cascade Mountains.

Quartz, Squaw, and Box Canyon creeks and the mainstem of Rock Creek originate along the crest of the Horse Heaven Hills where coniferous forests are abundant (Figure 4). Badger, White, and Harrison creeks drain primarily shrub-steppe dominated plateaus. Luna Gulch drains plateau as well as a portion of the steeper, north side of the Goodnoe Hills and is predominantly vegetated by grasses and shrubs (Figure 5). Aspect (2004) reports statistics based on 1992 LANDSAT data indicating shrublands (46.9%), forested uplands (25.8%), and grasslands (16.2%) comprise most land cover types for the Rock Creek watershed.

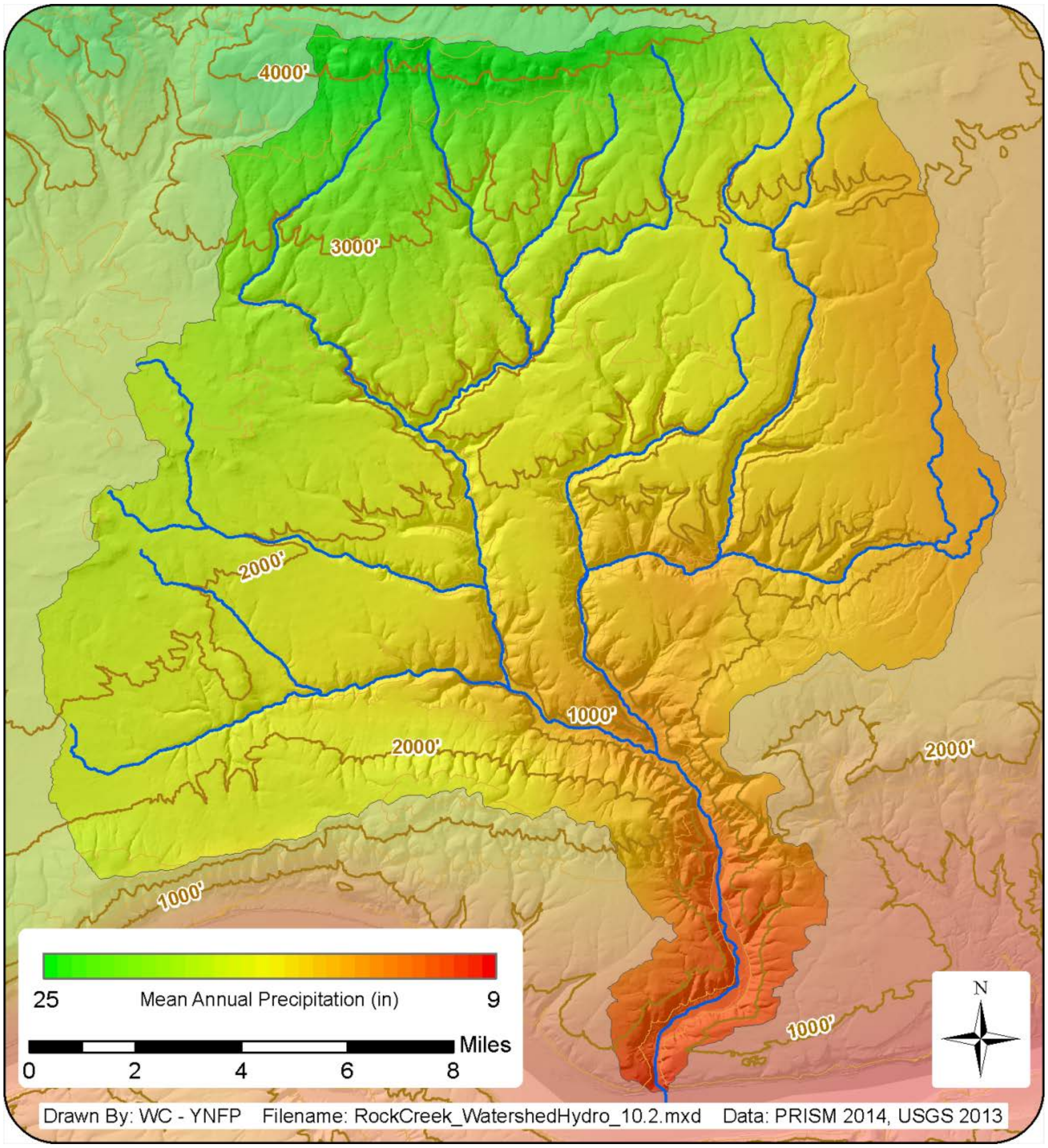


Figure 3. Elevation and mean annual precipitation for Rock Creek watershed.

Figure 4. Looking north across grass and shrublands (foreground) toward forested headwaters in the Horse Heaven Hills (horizon). Canyons dissect landscape between foreground and headwaters.

Figure 5. Looking south across agricultural lands on plateau draining into Luna Gulch. Goodnoe Hills on horizon.

Review of NED elevation data (USGS 2013) indicates all named streams cut canyons that vary from 400-700 feet deep at their respective mouths (Figure 6). The Rock Creek canyon reaches its greatest depth of approximately 1,700 feet where it transects the main axis of the Goodnoe Hills (horizon line gap in Figure 5) before resuming an approximate 600 foot depth as it enters the Columbia River (Figure 7).

Figure 6. Typical confined canyon (Rock Creek in vicinity of Quartz Creek confluence; ~VM 17).

Despite its small size, the watershed straddles a major ecoregion boundary (EPA 2010). Headwater areas lie mainly in the *Northwestern Forested Mountains* / *Western Cordillera* / *Eastern Cascade Slopes and Foothills* level I/II/III regions. This is the easternmost projection of that ecoregion into the Columbia Basin. The southern and eastern portions of the watershed including the larger canyons, lower elevation plateaus, and the Goodnoe Hills are within the *North American Deserts* / *Cold Deserts* / *Columbia Plateau* level I/II/III regions.


Figure 7. Less-confined canyon with loess terraces (Rock Creek canyon ~VM 3).


Figure 8. Typical moderately-confined canyon (Rock Creek in vicinity of Luna Creek confluence; ~VM 11).

The study area is within the southern domain of the Yakima fold belt (Watters, 1989), a highly faulted zone whose prevailing topographic expression is a series of east-west trending anticlines. Basal geology is basaltic and associated with several different units of the Columbia River Basalt Group (Figure 9). Units of the Saddle Mountains basalts have the greatest aerial abundance in the eastern portion of the watershed with most of the remainder composed of Wanapum units. Aspect (2004) reports the Wanapum (61%) and Saddle Mountains (19%) formations comprise most of the watershed area. However, Grand Ronde basalts have a disproportionate degree of valley bottom exposure despite minor overall surficial exposure basinwide (~1%). Analysis of GIS data (DNR 2013) indicates Grande Ronde lithology occurs along roughly 9.5 miles of the lower 18 miles of Rock Creek as well as 1, 0.8, and 0.5 miles of Quartz, Squaw, and Harrison creeks, respectively (Figure 9). Field observations in this study suggest the actual extent is greater. Maximum inundation elevation of late-Pleistocene glacial outburst flooding was approximately 1,115 feet at the mouth of Rock Creek (Benito and O’Connor, 2003). Slackwater terraces are well-pronounced throughout lower Rock and Squaw creeks and conditions would have extended to approximately the Bickleton Highway.

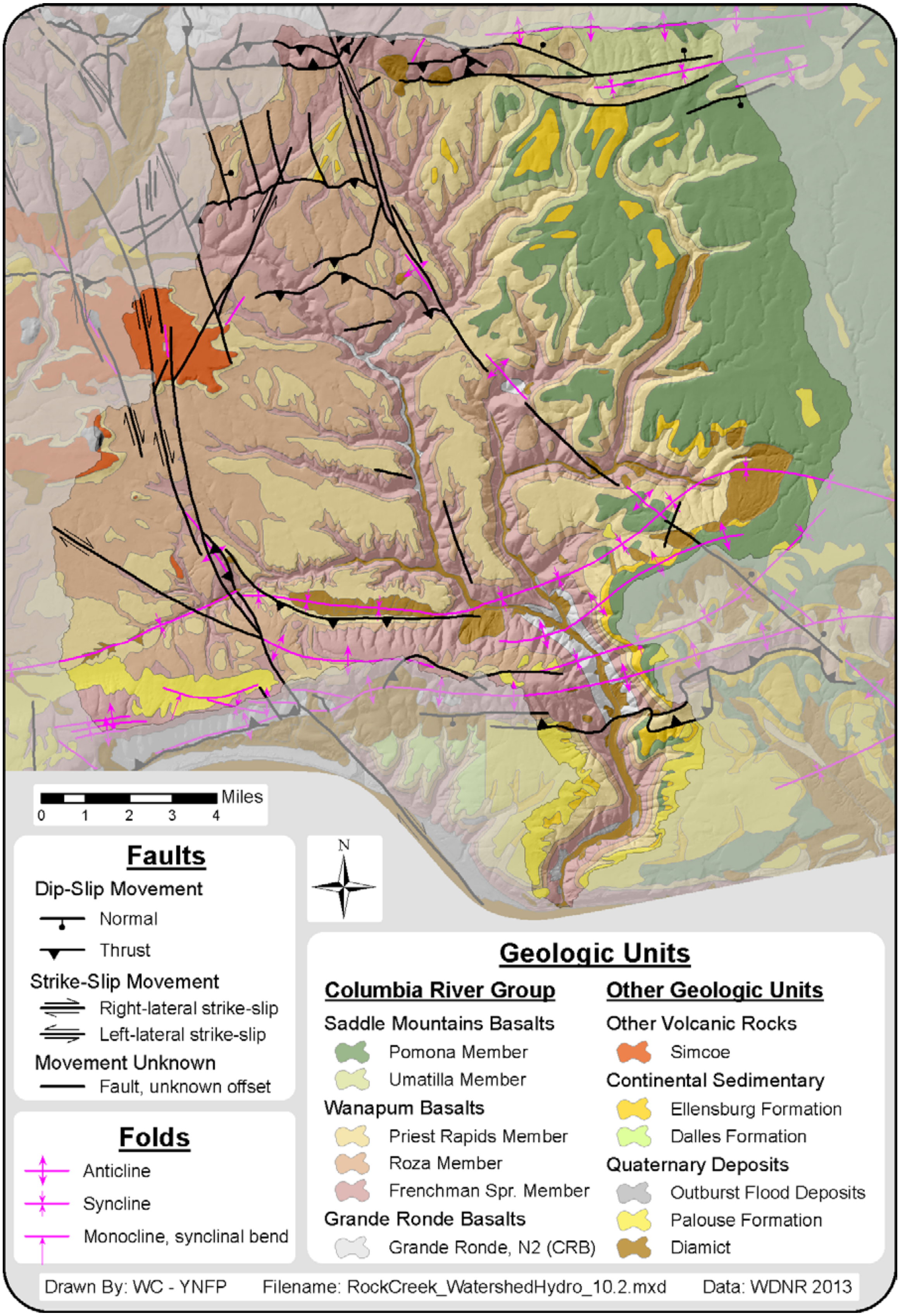


Figure 9. Major geologic units and structure of the Rock Creek watershed.

METHODS

Methods used for this report are categorized into “remote sensing”, “hydrology”, and “field”. Methods descriptions are accompanied by results from any sensitivity evaluations performed. Conventions used throughout the document are also described.

Report Conventions

While this report is largely of a technical nature, content is organized and illustrated to be increase accessibility to non-geomorphologists. A glossary is provided in Appendix A. Additional conventions used in this report are described below.

Relative reference “left” or “right” implies facing downstream/downvalley. For example, “left bank” (LB) is the stream bank appearing on the observer’s left when facing downstream. Similarly, “right valley toe” (RVT) is the valley floor / valley wall interface appearing on the right when facing down-valley.

Use of the term “bankfull” is generally avoided due to its ambiguity and tendency to imply flow-frequency and/or some idealized channel condition. These implications are generally inappropriate for non-regime systems such as Rock Creek that are forced and/or in ongoing adjustment. “Top-of-bank” is used to reference the topographic breakpoint adjacent to the active channel where a unit change in discharge begins to inundate proportionately more area and produces a diminishing incremental change in hydraulic forces. “Topwidth” is used to indicate the horizontal distance between opposite tops-of-bank.

The standard abbreviation for discharge, Q_n, is used to indicate flow event recurrence interval, n, in years. Table 1 cross-references some common terminology and usage related to event frequency. For example, an event with a magnitude of 100-year recurrence (Q100) has a probability of 0.01 (= 1% chance) of being equaled or exceeded in any given year. A good discussion of recurrence intervals can be found at: http://water.usgs.gov/edu/100yearflood.html

Table 1. Cross-reference of event frequency notation and common usage.

Shorthand	Probability Equaled or Exceeded in a Given Year	Recurrence Interval (years)	Percent Chance of Occurrence in Any Given Year	Colloquial Name*
Q1	0.99	1.01	99	yearly flood
Q2	0.5	2	50	2-year flood
Q10	0.1	10	10	10-year flood
Q100	0.01	100	1	100-year flood

* Colloquial usage is avoided in this report as it has misleading implications for real-world recurrence.

Common short hand for distance measurements in the report include use of ’ to represent feet and ” for inches.

The black Labrador used for scale in many of the photos stands 2.0 feet high at the shoulder and is 2.5 feet tall when sitting.

"River mile" (RM) and "valley mile" (VM) indicate a relative horizontal location along the length of a corridor from some starting point. Due to the tendency of stream channel alignments in the study area to change through time, valley mile is used as a primary spatial reference with indices provided at both coarse (Figure 2) and fine (Appendix B) scales. Mile 0.0 for the valley-mile index along Rock Creek is the railroad bridge at the Rock Creek confluence with the Columbia River. River-mile references are based on the alignment of the primary 2012 channel, with mile 0.0 adjacent to the downstream-end of the levee at the Army Corp of Engineers (ACOE) boat ramp at approximately VM 1.1.

Remote-Sensing

All geospatial data were managed in a Geographic Information System (GIS). ArcGIS v10.0 (ESRI 2012) with a full ArcInfo license, Spatial Analyst, and 3D Analyst extensions were the primary software used for data management and spatial analyses. Data were received in a variety of formats and projections. Geospatial data used in this study were projected in Washington State Plane South (Zone 5626), NAD83, Feet, GRS1980. Once screened and identified for use in this study, vector data were reprojected if necessary and stored in a file geodatabase. Raster files were maintained outside of the geodatabase.

Various geospatial data were received from the Eastern Klickitat Conservation District (EKCD) and Yakama Nation Fisheries Program (YNFP) Rock Creek Project between the summer of 2013 and fall 2014. Data received from EKCD and YNFP were supplemented with downloads of geology (WDNR 2013), wells (WDOE 2013), precipitation (PRISM 2013), elevation and 1:24,000 hydrography (USGS 2013), and soils (USDA 2013) layers.

High Resolution Topography, Aerial Photos, and Derived Products

Aerial Light Detection and Ranging (LiDAR) and true-color photography were acquired in late-April 2012 (WSI 2012) on a contract managed by EKCCD. Average first return point density was 1.31 points/ ft^2 and average ground point density was 0.34 points/ft^2. Average vertical error was -0.014 ft with a range of absolute vertical error of -0.269 to 0.170 feet. Digital copies of data were received from EKCD and included classified points (*.las format), area-of-interest (AOI) and index polygons, color photography tiles, and bare earth digital elevation model (DEM) tiles. Combined with field work, these data provided the foundation for much of this study. A variety of data products were derived from these data, including:

- Bare earth terrain model (vector-based)
- Stream channels
- Valley centerlines
- Relative-elevation DEMs
- Roads
- Hydromodifications

Unless otherwise specified, the mapping scale for manually-digitized products presented in this report is 1:1,200, though actual map-scale was generally finer.

Bare earth terrain models were built from both key-point and all-ground-point LAS files. In general, the key point terrain was used for most visualization and interpretation as the smaller number of nodes improved computer performance. One-meter DEMs created by the vendor were used for raster-based terrain analyses with uplands supplemented by NED as needed.

Stream channels were manually digitized using the bare earth terrain model and high-resolution (0.5 foot pixels) color photography. Channels were differentiated between primary (60.4 miles) and secondary (29.9 miles). Only approximately two-thirds of active secondary channels were delineated in the GIS due to time constraints.

Relative-elevation DEM (rDEM; also known as height-above rasters or HARs) scale cell-based elevation values to one or more arbitrary vertical datum(s) which can vary based on study objectives. This study used primary stream channel alignments as baselines (= relative vertical datum) since the primary objective was evaluation of geomorphic surfaces by their vertical proximity to the primary active stream channel. Topographic inputs for the process were 3.28 ft bare-earth DEMs (WSI 2012). While a subtraction-plane approach is more commonly used for rDEMs, this is largely for convenience. Concerns about distortion and error accumulation over the large horizontal extent of this study (including multiple fault lines) drove the decision to use a moving window approach along baselines. The "Riparian Topography Tools v10.0" ArcGIS toolkit (Dilts 2013) was used for this process. Multiple iterations were performed using search radii of 100, 200, 300, 400, 500, 600, 1000, and 2000 feet. Sensitivity was investigated and is described in the "Results and Discussion" section.

Road alignments were manually digitized using DEMs, terrains, and photography. Road status was not differentiated. Dozer-lines associated with wildland fire suppression operations were widespread in topographic data as well as in the field, but were not included in this data set.

Valley bottoms and centerlines were generated by filling rDEMs to a specified depth. Valley "filling" was performed iteratively and results were evaluated in planform against the terrain model for suitability. Generally, 14 to 16 vertical feet of fill produced a valley bottom approximation suitable for graphical and indexing purposes. This is considered the portion of the valley where fluvial processes are generally more active and excludes terraces. Centerlines based on valley polygons were delineated using the "Polygon Centerline to Polyline" tool (Dilts 2011).

Hydromodifications are features that alter hydraulic and/or hydrologic pathways. Polygons were manually digitized based on bare earth terrain model, rDEMs, and high-resolution photography and primarily include floodplain infrastructure (e.g. embankments, drains, etc.).

Aerial Photograph Interpretation

Historic georeferenced imagery was obtained from EKCD, Klickitat County, and Aspect Consulting and had a variety of spatial extents (Figure 10). Imagery for 1960, 1981, 1990, 2006, and 2009 covered the entire study area. Imagery for 1938 and 1969 was of a more limited extent and were not ortho-corrected. However, it was very useful in combination with the 1960 imagery to establish pre- and post- channel positions relative to the1964 floods. The Yakama Nation also provided black and white ortho-corrected imagery collected in 1996. Metadata were not provided for any of this imagery. The 2006 and 2009 appear to be the same as National Agriculture Imagery Program (NAIP) mosaics available for Klickitat county. File names for the 1960, 1981, and 1990 mosaics include “USDA” (as in United States Department of Agriculture).

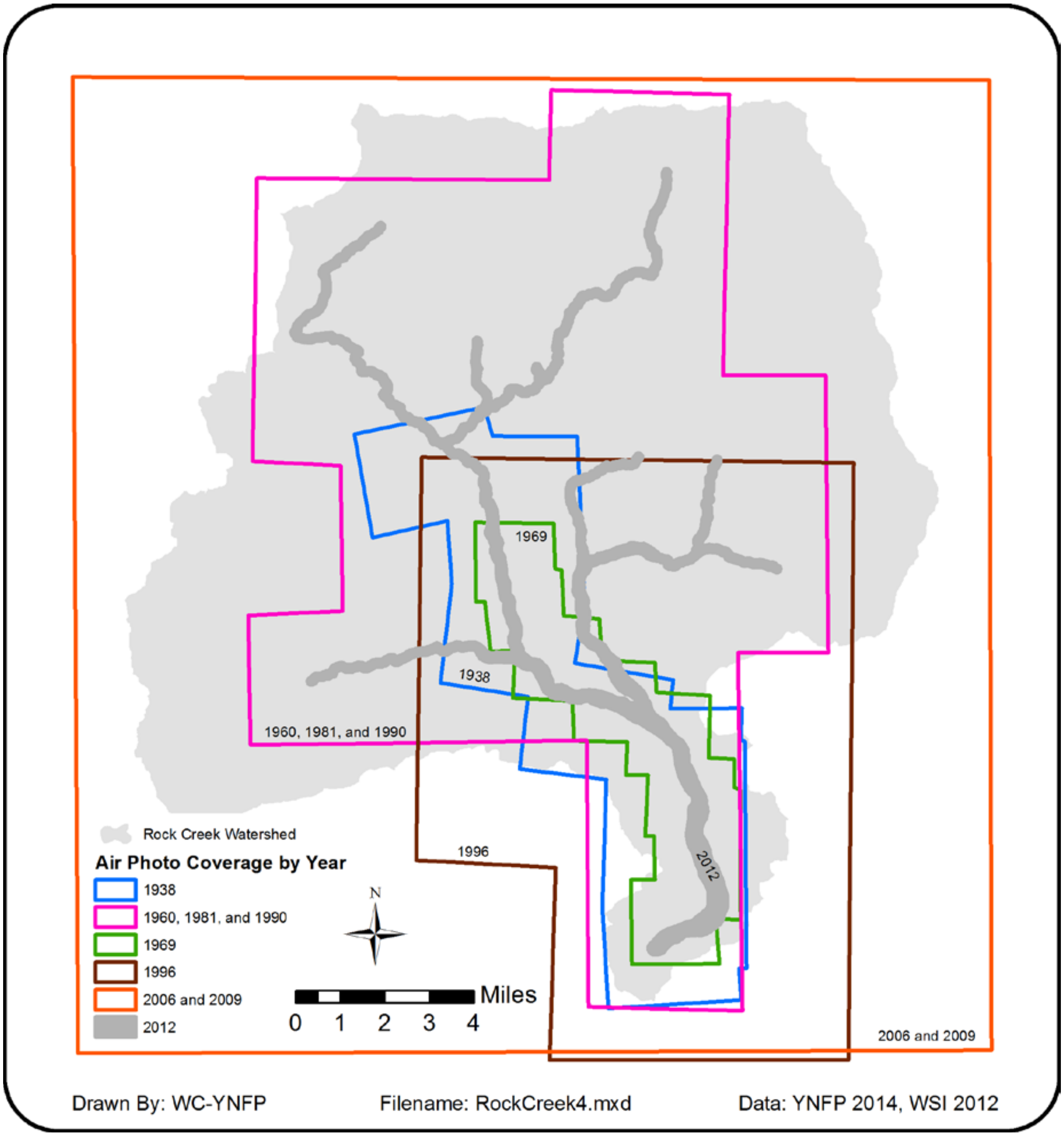


Figure 10. Spatial extent of aerial photography provided for study.

Historic aerial photography was used to review historic channel and vegetation patterns. A cursory review of georeferencing found generally good precision for USDA orthoimagery across years, likely 20-foot or better. However, 1938 and 1969 imagery was highly variable with horizontal errors over 150 to 200 feet observed for some valley bottom locations. While errors of that magnitude have little effect on the evaluation performed herein, they would be highly consequential for quantitative analyses such as a channel migration study.

Where historic streamlines were created, channel alignments were manually digitized via interpretation of digital orthophotography by respective year. Channel alignments were typically determined by presence of water (areas of low reflectivity), curvilinear seams in riparian tree canopy, areas of high reflectivity (presumed to be evaporite and/or algal crusts), and bank shadows.

Historic channel alignment delineation was complicated by channel-spanning tree canopy and shadows (vegetation, banks, and/or topography). Difficulty differentiating low-relief bars from dry channels in areas of absent riparian vegetation presented the single greatest potential error using when using imagery alone. Locations consisting of a dry mid-channel bar with dry low-flow channels on either side occupied by vegetation give the false impression of a single, dry channel. Relic alignments visible in field and LiDAR data were useful for reconstructing.

Delineation of 2012 channel alignments was used to quantitatively assess the effect of complicating factors described above. First, a subset of streamlines was manually digitized from photography (0.5 foot pixels) and attributed by channel type (primary or secondary), whether the channel was visible, and whether water was visible. Then, a second iteration was made using LiDAR-based topography as a base (and post field inspection). Of the 54.0 mile subset evaluated, 27% of channels by length (14.7 miles) were not visible from the aerial photographs. The most frequent error was associated with active, but dry channels lacking vegetation canopy in multi-thread reaches. By contrast to aerial photography usually flown in July or August, the 2012 photography had uncharacteristically favorable conditions, including more widespread streamflow (low reflectivity) and only partial leaf-out by riparian hardwood vegetation. Consequently, an even higher ratio of under-delineation should be expected associated with pre-2012 photography which was flown later in the summer, with grainier resolution (3.28 foot or coarser pixels), and/or lacking paired high-resolution topography.

Watershed Delineation

The National Elevation Dataset (NED; USGS 2013) was used for watershed-scale delineations and visualization. Data are 1/3 arc-sec which approximately equates to ~33 foot pixels in the study area. Data were reprojected to *WA State Plane South - feet* using cubic convolution.

Precipitation

Mean annual precipitation calculations were based on 30-year PRISM normals from 1981-2010. Downloaded data were originally projected in *GCS_WGS_1984* and reprojected to *WA State Plane South – feet* using cubic resampling and *WGS_1984_(ITRF00)_To_NAD_1983* transformation. Pixels were originally 2,264 foot and were resampled to 32.8 foot pixels using a bilinear method for spatial consistency with NED data and watershed-scale peak discharge computations.

Total Stream Power

Stream power can be useful for interpreting channel forms and patterns. NED data were processed for standard watershed delineation (sinks filled, flow-direction, flow-accumulation) then hydroconditioned by enforcing high-resolution streamlines generated in this study. High-resolution (3.28 ft pixels) bare-earth DEMs were then generalized (32.8 foot pixels) and snapped to the NED raster. Values from the LiDAR-based DEM were then overwritten onto the NED raster to enforce more accurate valley bottom topography. Primary channel geometry (1:1,200) was enforced onto the combined DEM, then an updated flow accumulation raster was produced. This raster was used with the re-sampled PRISM (2013) raster and combined DEM to calculate stream power inputs for each stream cell including stream slope (LiDAR-derived bed slope), mean annual precipitation, and drainage area. USGS regional equations (Sumioka et al. 1998) were used to compute discharge (from MAP and drainage area) for the Q2, Q10, and Q100 which were then converted to metric units. Finally, the specific weight of water was multiplied by the product of discharge and slope to calculate total stream power in Watts (a more standard unit for expressing power than Imperial units).

$$\Omega = \gamma Q s$$

Where $\gamma = \rho g$ is the specific weight of water (9.81 kN/m^3), Q is discharge (cms), and slope (s) is the dimensionless (m/m) expression of stream gradient.

Though specific stream power (e.g. total stream power expressed as a function of stream width) could be a better tool for interpretation of specific feature locations (e.g. bars, pools, etc.), project constraints precluded that level of investigation. Only total stream power for the Q10 is presented as the Q2 was very low power with little spatial differentiation and Q100 results probably aren't a great representation of reality as they don't reflect backwatering effects. Field indicators suggest that the Q10 magnitude is about where free-overflow at high-relief bed controls begins to disappear, but local bed gradient inflections are still present. Results are presented primarily for relative comparison of spatial distribution as USGS equations substantially under-predict flow magnitude for this area (see "Peak Flow Hydrology" sub-section of "RESULTS AND DISCUSSION").

Low-flow Habitat Spatial Distribution

Low-water habitat units were surveyed in a spatially-continuous manner in 2010, 2011, and 2012 by United States Geological Survey (USGS) and YNFP staff along the lower 12 free-flowing miles of Rock Creek and lower 5 miles of Squaw Creek (Allen et al. 2014b). Only data collected in 2012 had sufficient field-based geospatial accuracy for detailed analysis herein. Habitat units were field-mapped as "pool", "non-pool wet", and "dry". This was the most useful data set available given its spatial continuity and the patchy nature of low-flow surface water distribution in these systems.

Field data were incorporated into shapefile format on a stream alignment digitized by Columbia River Intertribal Fish Commission (CRITFC, 2013 and 2014). Comparison to 1:1,200 streamlines indicated CRITFC alignments to be reasonably representative at scales down to 1:24,000. However, several large exceptions where stream alignments differed significantly (noticeable at 1:100,000) had a strong negative effect on real-word positional accuracy of features because of the sequential nature and linear dependency of the mapping.

Given the importance of low-flow distribution to this study, 2912 habitat units were re-mapped from tabular data along 1:1,200 streamlines using linear referencing techniques. Field surveys followed stream alignments that, if present, had water (Brady Allen, USGS Fisheries Biologist, pers. comm.). This was usually the most incised channel, which was not always consistent with the primary channel (defined by largest hydraulic capacity). The 2011 survey was not re-mapped due to the general absence of paired GPS data (used for cross-validation). Given that horizontal field measurements (collected with reel tapes, electronic distance meters, or pacing) can and will differ from horizontal space in GIS, multiple elements were used to quality control unit locations.

Initially, cumulative field measured distance values were used working in the upstream direction. These were compared to GPS points for the upstream end of each unit. GPS points were of varying accuracy, sometimes greater than 50 feet, so patterns of sequential points were evaluated before off-setting GIS measures along the route. Additionally, comments from field notes were compared to spatially-referenced field notes and personal knowledge from this study to calibrate some points (e.g. bedrock contacts, bridges, etc.).

In general, adjustments of endpoints were not made unless the apparent spatial error was at least 30 feet. Adjustments were frequently necessary upstream of very long (several hundred or thousands of feet) units (usually “dry”, but occasionally “non-pool wet”). This was assumed to be due to the accumulation of horizontal error in field measurement.

Mapped features were evaluated over a relative-elevation, high-resolution DEM for geomorphic vetting (i.e. to ensure that pools were displaying where channel geometry and ground conditions tend to form pools). Comparison to recent (2006 and 2009) aerial photos taken during low-flow periods was also made. Finally, the re-mapped layer was reviewed by Brady Allen, the principal investigator for the low-flow habitat study. The resulting layer is suitable for presentation at 1:3,600 or better, though it is recommended that quantitative analyses of length remain based on the original field measures.

Environ (2013) performed a riparian vegetation survey in which they also recorded categorical field estimates of percent by length of dry channel for surveyed reaches. In terms of outright geographic extent, this is the most widespread survey that has been conducted. A shapefile of surveyed reaches was obtained through Klickitat County and compared to the geometry and attributes of the continuous low-flow layer based on 2011 and 2012 USGS/YN data (Allen et al

2013) as well as 1:1,200 stream geometry. A cursory review of geometry revealed incongruous channel alignments, with the Environ data apparently based on WDNR's 1:24,000 stream geometry (similar to CRITFC). Spot-checking of attributes revealed some agreement between data sets, but other line segments differed significantly. Most relevant from a limiting habitat factors perspective, there were multiple instance of Environ reaches attributed as having some amount of water while YN/USGS data showed reaches were dry. This difference was attributed to some of the Environ data collection occurring in June, July, and August (prior to periods of minimum surface water distribution) as well as in different water-years (2010 and 2011). Late-summer of 2012 when the YN/USGS data was collected was one on the driest periods on-record. Differences in stream geometry and seasonal and inter-annual confounding excluded Environ data from further consideration. Given the spatially continuous and temporally discrete nature of the YN/USGS data set collected under what were likely an excellent representation of the most seasonally-limiting flow conditions, only the YN/USGS data set was used for spatial analysis in this study.

Water Wells

Well data were downloaded from the Washington Department of Ecology (WDOE 2013) and grouped using the public land survey grid (Klickitat County via EKCD) for analysis. Grouping was performed by section (~ 1 mi^2) as location errors occur due to the tendency of some applicants/drillers to incorrectly record quarter-section and quarter-quarter-section values. Thus, potential spatial detail was sacrificed for a more robust level of spatial organization. Water wells by decade were counted for each section.

Hydrology

Peak streamflow data were obtained from historic USGS gages (NWIS 2014). Streamflow data were also obtained from the Washington Department of Ecology (Christensen 2014), which had more recently operated a gage at the same site as the old "Rock Creek near Roosevelt" site (vicinity of Old Highway 8 crossing) previously operated by USGS. Overall, data from nine gages within an area bounded by the Columbia River (south), City of Goldendale (West), Horse Heaven Anticline (North), and Alderdale (east) were evaluated. Sites used in this report are within 25 miles of the study area, have at least 5 years of record that include the December 1964 peakflow event, and drainage areas greater than 5 square miles (Table 2).

Table 2. Five gages with historic peak flow data selected for use in this study.

Site Name	USGS Gage #	Years of Record	Elevation (ft ASL)	Drain Area (sq-mi)	Lat	Long
Little Klickitat R. nr Goldendale	14112000	27	1,700	83.5	45.8444	120.7950
W. Prong L. Klickitat R. nr Goldendale	14111800	15	2,410	10.4	45.9250	120.7197
Rock Creek nr Roosevelt	14036600	6	420	213	45.7486	120.4344
Alder Cr nr Bickleton	14034325	15	2,840	8.35	45.9969	120.2753
Alder Cr nr Alderdale	14034350	8	265	197	45.8416	119.9250

Quantitative analyses were conducted using several software products. General data viewing, management, plotting, and simple linear regression were performed in Excel (Microsoft 2007b). Suitability screening of historic gages and initial frequency analysis was conducted in HEC-SSP (ACOE 2010). None of the limited number of frequency distributions offered by HEC-SSP (including Log-Pearson Type III), generated results that fit observed data particularly well. Consequently, Aquarius (Aquatic Informatics 2014) was used for curve-fitting to identify a suitable distribution and compute flow magnitudes for specified event return intervals.

Field Methods

Fourteen miles of Rock Creek and its floodplain were surveyed on foot in December 2013 and January 2014 and focused on lower-gradient (< 0.025) reaches of Rock Creek downstream of Quartz Creek. A GPS-enabled iPad with GISPro v3.12 was used for most data collection. GPS accuracy was generally 30 horizontal feet or better. GeoTiff base maps of LiDAR-based terrain at approximately 1:3,600 scale were used to manually fine-tune locations of mapped points in the field to an estimated 10 feet of accuracy.

Rock Creek, its floodplain, and many of its terraces were walked in a generally downstream direction from VM 17.0 to VM 3.0. Observations were made of geo-fluvial features such as historic stage indicators, channel and floodplain substrates, vegetation patterns, and habitat-forming elements. Channel dimensions and relative elevations were established with a Keson pocket-rod graduated in tenths of feet and a Leica Disto D5 laser distance meter and inclinometer. Stream channel contacts with bedrock were also mapped. The corridor was walked nearly continuously except for one small parcel where the landowner was non-responsive when access was requested. Flow conditions were uncharacteristically low and constant for the time of year providing excellent field survey conditions. A visit was made in late February 2014 following a small (high-frequency, < Q1.01) freshet to validate prior field estimations of stage and flow-frequency for likely side-channel activation and large woody debris (LWD) transport.

RESULTS AND DISCUSSION

Fluvial reconnaissance in Rock Creek included investigation of basin characteristics, hydrology, field and remote-sensing of geomorphic and physical habitat indicators, as well as review of a pre-existing hydraulic model.

Drainage Characteristics

Physical characteristics are very useful for interpreting and predicting watershed conditions and behavior with drainage area as the most universal indicator across the western United States. A wide range of drainage area values have been presented in previous Rock Creek reports, ranging from a low of 223 square-miles (-1% compared to the value calculated in this study; NPPC 2001) to a high of 258 square-miles (+14%; Aspect 2004). Another recent report (Environ 2013) presented a value of 248 square-miles (+10%). Given the importance of drainage area metric for analyses performed in this study, a GIS-based calculation of total drainage area was performed.

Using the railroad bridge at the mouth as the pour-point, Rock Creek was determined to have a drainage area of 226.1 square-miles.

Given the importance of drainage delineation and area for computation of MAP and other parameters, drainage area was cross-checked in Streamstats (USGS 2014) using a common pour-point (railroad bridge) to evaluate if coordinate and datum reprojection had a quantitative effect this study's 226 square-mile value. Streamstats produced a 225.9 square-mile value. Given agreement between this report and Streamstats, the 226 square mile value was considered robust and used for subsequent computations and text references.

Zonal calculations in ArcInfo yield minimum, mean, median, and maximum basin elevation values of 264, 2,293, 2,252, and 4,730 feet above sea level (ASL), respectively. Minimum and maximum values are consistent with the 266 and 4,728 values, but average elevation calculated for this report is greater than the 2,162 feet previously reported by Aspect (2004).

A suite of basin characteristics (Table 3) were calculated for major watersheds within Rock Creek for reference and interpretive purposes using Streamstats for Washington (USGS 2014).

Table 3. Basin characteristics for Rock Creek and selected watersheds.

Mainstem (DS to US) Tributary Tributary to Tributary	Drainage Area (mi2)	Mean annual precipitation (in)	Maximum Basin Elevation (ft)	Mean Basin Elevation (ft)	Minimum Basin Elevation (ft)	Relief (ft)	Mean basin slope (%)	% drainage area with slope >30%	Area-weighted forest canopy (%)
Rock Cr at mouth	225.9	18.0	4,730	2,290	268	4,460	13.8	12.3	4.7
Rock Cr at Old Hwy 8	216.8	18.2	4,730	2,350	422	4,300	13.6	11.9	4.9
Squaw Cr at mouth	78.1	16.5	3,970	2,350	638	3,330	13.2	12.4	3.1
Harrison Cr at mouth	17.3	17.9	3,150	2,340	1,000	2,140	14.3	15.7	5.1
Squaw Cr abv Harrison Cr	49.8	16.0	3,970	2,490	1,010	2,960	11.3	8.6	2.7
White Cr at mouth	18.3	15.2	2,720	2,210	1,300	1,420	9.1	4.7	1.0
Squaw Cr abv White Cr	27.2	16.4	3,970	2,790	1,300	2,660	10.6	6.8	3.5
Spring Cr at mouth	5.6	17.6	3,970	3,360	2,650	1,310	11.3	1.4	3.0
Squaw Cr abv Spring Cr	5.3	16.2	3,710	3,100	2,660	1,050	7.6	0.5	1.1
Rock Cr abv Squaw Cr	130.9	19.5	4,730	2,410	633	4,090	12.8	8.9	6.2
Luna Cr at mouth	41.4	17.9	2,690	1,940	898	1,790	9.0	3.9	2.3
Rock Cr abv Luna Cr	81.7	20.6	4,730	2,730	895	3,830	13.7	9.4	8.7
Badger Cr at mouth	11.4	21.4	2,630	2,180	1,070	1,560	8.4	5.4	3.1
Rock Cr abv Badger Cr	67.5	20.6	4,730	2,870	1,060	3,670	14.3	9.2	9.8
Quartz Cr at mouth	35.0	19.5	4,730	3,090	1,460	3,270	15.6	9.1	9.8
Box Cyn at mouth	17.4	19.9	4,730	3,300	1,870	2,850	16.9	9.1	13.1
Quartz Cr abv Box Cyn	11.0	18.5	4,330	3,160	1,870	2,450	13.3	5.9	7.6
Rock Cr abv Quartz Cr	20.8	22.5	4,600	2,960	1,440	3,160	12.6	6.4	13.0

It is noteworthy that Streamstats produces a MAP value (18.0 inches) that is considerably greater than those calculated in this report, most likely because of using different input data. This study calculates mean annual precipitation for the basin as 16.6 inches using PRISM (2013) data. Though slightly greater, there is general agreement with 16.2 inches reported by Aspect (2004).

Differences in reported values are not considered significant, but could be a function of differing precipitation source data (PRISM data for the 1961-1990 period were used for Aspect's 2004 report) or methodological differences associated with differing drainage areas. Minimum mean annual precipitation for the basin calculated for this report is 9.5 inches (near the mouth) and the highest value is 25.1 inches (in the Horse Heaven Hills).

Mean minimum January temperature was also calculated from PRISM data and found to be 28.5 degrees Fahrenheit. This value is an input for older indirect equations for calculating magnitude-frequency discharges for eastern Oregon (Harris and Hubbard 1983). While the north-central equations for eastern Oregon can be a useful check on Washington equations, particularly for basins lacking any gage data and closer to the Cascade crest. However, resulting values for the study area did not fit gage data well and are therefore not used in this report.

Peak Flow Hydrology

Most of the geomorphic work performed by streams happens during a relatively small percentage of time during large, but infrequent flow events. Stage field indicators of large historic events are highly useful for geomorphic interpretation and are ubiquitous throughout Rock Creek. Correlating field indicators with flow magnitude and frequency provides context and greatly increases interpretive utility relative to geomorphic process and behavior.

Regional streamflow records (NWIS 2014) identify peak events in December 1964, January 1974, and February 1996 as the three largest discharge events of the last 100+ years. Interpretation of historic aerial photos suggests the 1964 event (based on differences between 1960 and 1969) caused the most widespread and dramatic shifts in channel alignments and riparian vegetation in the Rock Creek watershed. A much smaller event on March 30, 2012 left nearly continuous indicators along Rock Creek, so correlation of that event within a magnitude-frequency context is also useful.

Gage data in the vicinity of the study area are not abundant, with continuous records particularly sparse. However, annual maxima records are more abundant and geographically widespread. Despite having fairly short periods of record (<10-15 years), many were in operation during the December 1964 peak flow event and several also captured the 1974 peakflow event.

When viewed in composite, historic gage data paint a better picture of basin peakflow hydrology. In general, most annual flow maxima occur in December through February (Figure 11). This is the time of year when frontal storms prevail and deliver a disproportionately high amount of the annual precipitation. Peak occurrence of annual maxima lags about one month behind average precipitation (Figure 11). The lagging relationship makes sense given very hot, dry summers and the need to recharge soils for antecedent conditions to be ripe for producing runoff.

Dates of peak events generally have good agreement across sites (Table 5), especially for events with recurrence intervals greater than 2 years. Left-to-right order of their presentation in Table 5 is indicative of their position along a west-to-east geographic axis. As event magnitude decreases, correlation between gage sites at the ends of the west-east axis diminishes.

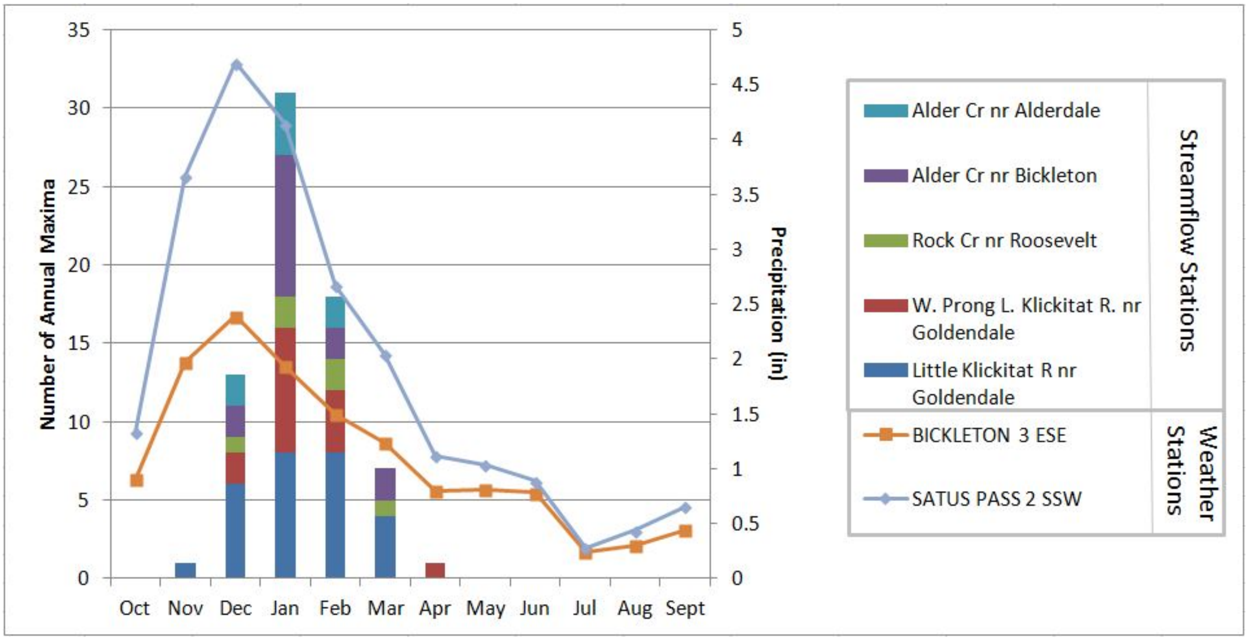


Figure 11. Monthly occurrence of annual flow maxima for 5 gages and average precipitation for two weather stations within 25 miles of study area.

Simple linear regressions were performed to evaluate relationships between gages with longer period of record (POR) with each other as well as between the *Rock Creek near Bickleton* and *Alder Creek near Bickleton* gages. A strong relationship exists between the *Little Klickitat River near Goldendale* and *Rock Creek near Roosevelt* gages (Figure 12). The relationship between the *Little Klickitat near Goldendale* and *Alder Creek near Bickleton* gages had a moderately strong relationship overall, though scatter increases for peak events of intermediate magnitude (Figure 13).

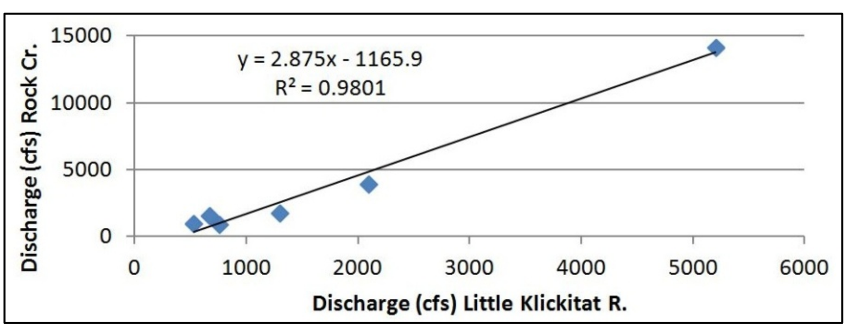


Figure 12. Regression of 6 concurrent peak flows for Rock Cr. near Roosevelt and Little Klickitat R. near Goldendale.

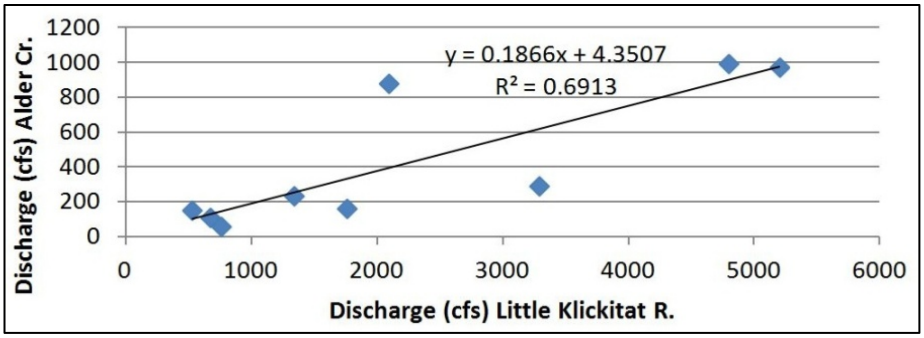


Figure 13. Regression of 9 concurrent peak flows for Alder Cr. near Bickleton and Little Klickitat R. near Goldendale.

Streamflow peaks for *Rock Creek near Roosevelt* not present in the gage record were calculated using regression from the *Little Klickitat near Goldendale* to provide magnitude-frequency context for *Rock Creek near Roosevelt*. Calculations (colored values without dates in Table 5) were not performed for events less than 1,200 cfs as temporal agreement of peaks amongst the five gages in the area declines as event frequency increases.

Based on regression results, geographic proximity, and strong predictive relationship for *Rock Creek near Roosevelt*, the *Little Klickitat near Goldendale* gage was selected for peakflow magnitude-frequency analysis. An initial graphical/visual curve-fitting review was conducted in HEC-SSP (ACOE 2010), but none of the limited statistical distributions (including Log-Pearson III) fit observed data well. Aquarius software (Aquatic Informatics 2014) was used for a more rigorous curve-fitting evaluation comparing eight different distributions (Table 4). Given absence of data from the 1996 event, the 1964 peak was assumed as a 100-year recurrence and the "Gamma" distribution was selected as the best fit. The Weibull distribution was only slightly less well-fit. Both distributions slightly over-predict Q25 and Q50 discharges. In general, other distributions overestimate low-frequency event magnitude and under-predict magnitude of high-frequency events, even with iterative removal of potentially low outliers.

Table 4. Computed discharges (cfs) for the *Little Klickitat River near Goldendale* for eight statistical distributions.

Return Period (years)	Log Pearson Type III	Log Gamma	Log Normal	GEV	Pearson Type III	Gumbel	Weibull	Gamma
2	1,024	1,061	1,092	1,010	992	1,251	1,225	1,219
5	2,119	2,077	2,129	2,022	2,226	2,122	2,346	2,262
10	3,218	3,000	3,018	3,108	3,244	2,699	3,094	2,983
25	5,176	4,495	4,378	5,254	4,644	3,428	4,006	3,895
50	7,153	5,878	5,567	7,690	5,728	3,968	4,657	4,566
100	9,678	7,517	6,910	11,176	6,827	4,505	5,282	5,226

Table 5. Published annual maxima (NWIS 2016) for five comparable stream gages within 25 miles of the *Rock Creek near Roosevelt* stream gage. Left-to-right order represents geographic order along a west-to-east axis. Bold values indicate concurrent dates across sites. Colored values calculated using Equation 1.

Water Year	Little Klickitat R. nr Goldendale		W. Prong Little Klickitat R. nr Goldendale		Rock Creek nr Roosevelt		Alder Creek nr Bickleton		Alder Creek nr Alderdale	
	Date	Flow (cfs)	Date	Flow (cfs)	Date	Flow (cfs)	Date	Flow (cfs)	Date	Flow (cfs)
1946	12/15/46	1,330				**3,013**				
1948	1/7/48	1,760				**4,700**				
1949	2/17/49	888								
1950	2/24/50	1,360				**3,131**				
1958	2/15/58	1,020								
1959	1/11/59	526								
1960	3/29/60	511								
1961	**2/9/61**	**2,830**	**2/9/61**	**192**		**8,898**				
1962	**12/24/61**	**456**	**12/24/61**	**38**						
1963	**2/3/63**	**2,090**	**2/3/63**	**98**	**2/3/63**	**3,940**	**2/3/63**	**880**	**2/3/63**	**5,560**
1964	**1/25/64**	**760**	**1/25/64**	**37**	**1/25/64**	**912**	**1/25/64**	**58**	**1/26/64**	**68**
1965	**12/22/64**	**5,200**	**12/22/64**	**569**	**12/22/64**	**14,200** *	**12/22/64**	**973**	**12/22/64**	**17,600**
1966	**3/9/66**	**530**	4/1/66	45	**3/9/66**	**962**	**3/9/66**	**149**	1/6/66	670
1967	**1/28/67**	**673**	**1/28/67**	**77**	**1/29/67**	**1,570**	**1/28/67**	**110**	**1/28/67**	**154**
1968	**2/23/68**	**1,300**	**2/23/68**	**144**	**2/23/68**	**1,760**	1/15/68	137	2/3/68	513
1969	3/17/69	618	1/7/69	72			1/6/69	251		
1970	**1/23/70**	**1,760**	**1/23/70**	**182**		**4,700**	**1/23/70**	**164**		
1971	**1/16/71**	**1,340**	**1/16/71**	**105**		**3,052**	**1/16/71**	**234**		
1972	**1/20/72**	**3,290**	**1/20/72**	**218**		**10,703**	**1/20/72**	**293**		
1973	12/21/72	720	**1/13/73**	**56**			**1/13/73**	**240**		
1974	**1/15/74**	**4,800**	**1/15/74**	**495**		**16,628**	**1/16/74**	**992**		
1975	**2/12/75**	**418**	**2/12/75**	**138**			3/1/75	165		
1976	12/4/75	1,230				**2,621**	12/26/75	115		
1977	11/30/76	776					2/12/77	0.5		
1978	12/13/77	2,550				**7,800**				

* USGS reports maximum daily average; see text (below) for computation of instantaneous maximum.

Computed gamma distribution values from the *Little Klickitat near Goldendale* were input to the regression equation (Figure 12) to calculate a frequency distribution for *Rock Creek near Roosevelt*. This approach only slightly under-predicts the 1964 peak reported value (Table 5). However, it is critically important to note that the USGS reports the 1964 value as a "maximum daily average" which means that the instantaneous maximum (all other values presented in Table 5) was higher. For example, instantaneous peak discharges for the *Klickitat River at Pitt* for the 1964, 1974, and 1996 events, were, on average, 128% of daily discharge.

The 1964 *Rock Creek at Roosevelt* maximum daily average was corrected using peak instantaneous unit discharge for *Alder Creek near Alderdale* given basin characteristic similarity. Multiplying Alder Creek's peak unit discharge of 89.3 cfs/mi^2 by Rock Creek's basin area produces an instantaneous peak estimate for *Rock Creek near Roosevelt* of 19,029 cfs. Substituting the unit-derived peak as the 1964 maximum maintains a strong quantitative relationship ($r^2 = 0.966$) and revises the regression equation with the Little Klickitat to:

$$y = 3.9235x - 2205.2 \qquad \text{(Equation 1)}$$

The period of record for the *Alder Creek near Bickleton* gage captured both the 1964 and 1974 events and the latter exceeded the 1964 peak. This relationship was also observed for the *Klickitat River at Pitt* (station #14113000, 88 years of record) where the 1974 peak is only slightly lower than the highest event on record (February 1996).

Consequently, it is reasonable to conclude that even the well-fit gamma distribution computed for Rock Creek peakflows based on the Little Klickitat (Table 6) using published USGS values underestimates actual magnitude frequency. Values calculated in Excel via direct input and ArcInfo via programmatic computation calculated using the indirect equations for Washington, Region 6 (Sumioka et al. 1998) both grossly under predict the data-fit distribution.

Table 6. Calculated discharges by recurrence interval for two historic gage sites.

	Little Klickitat nr Goldendale (cfs)		Rock Creek nr Roosevelt (cfs)			
	Frequency Analysis (Gamma) Gage Observations		Excel Calculation Region 6 USGS Regressions	GIS Value Calculated Using Region 6 USGS Regressions	Calculated from Little Klickitat Using Local Regression[a]	Calculated from Little Klickitat Using Revised Local Regression[b]
Q2	1,219		1,091	766	2,339	2,578
Q5	2,262		n/a	n/a	5,337	6,670
Q10	2,983		3,254	2,646	7,410	9,499
Q25	3,895		4,887	n/a	10,032	13,077
Q50	4,567		6,356	n/a	11,964	15,713
Q100	5,226		8,110	7,449	13,859	18,299

[a] local regression based on daily average value for 1964 peak [b] local regression with estimated instantaneous 1964 peak

It is noteworthy that stations used to develop Region 6 equations occur along an 80-mile west-east axis that spans the crest of the Cascade Mountains and extends well into the interior

Columbia Basin. Geographic distribution of the gages is heavily biased toward forested watersheds in the western half of the analysis region. Region 6 stations have considerably higher precipitation than the Rock Creek watershed, and include 15 (of 23) that have MAP exceeding 50 inches. Only two gages used in developing the equations had MAP of less than 20 inches, but the largest drainage area was only 8.35 mi^2. This finding does not completely discredit use of the Region 6 equations in the study area, but does beg the need for discretion when interpreting their results. Revised regional equations developed by Cooper (2006) for eastern Oregon developed generalized skew values. Development of the revised eastern Oregon equations included gages from the Washington side of the Columbia River, and may hold some promise for use in the Rock Creek vicinity though were not evaluated in this report.

With the above information as context, unless otherwise indicated, the peakflow distribution for *Rock Creek near Roosevelt* computed based on the local regression equation and published Little Klickitat data is used as the baseline for interpreting field indicators in this report.

The computed peakflow distribution establishes context for the March 2012 peakflow event as well. Widespread indicators from the 2012 peakflow were still fresh and intact at the time of field survey, proving particularly useful. Washington Department of Ecology (WDOE) operated a gage at the same site as the former USGS gage (Rock Creek near Roosevelt) from November 2007 through August 2012. The March 2012 peak estimate of 3,342 cfs exceed the highest value in the rating table (610 cfs) and the gage site experienced major scouring and filling (Christensen 2014).

Based on the computed gamma distribution values, that equates to between a 2 and 5-year recurrence. As a check on the event's frequency context, 3,342 cfs at Rock Creek equates to a ~1,410 cfs event for the Little Klickitat near Goldendale. The same event generated an observed 2,110 cfs peak on the Little Klickitat gage near Wahkiacus (~20 miles downstream), so the estimate at Goldendale is reasonable. This recurrence range is consistent with observations for the event elsewhere in Klickitat County. For the 27-year period of gage data evaluated for the study area (Table 5), annual maxima equaled or exceeded the 2012 magnitude eight times.

Consequently, even if absolute discharge magnitude were inaccurate due to a rating shift, multiple lines of evidence support a conclusion that the March 2012 peak exceeded a 2-year, but was less than a 5-year recurrence. For the purposes of interpreting field indicators in this report, it is considered a 3-year recurrence (Q3) flow event.

Relative Elevation DEMs

Relative elevation DEMs (rDEMs) are models that represent elevation values as a function of some user-defined feature. For this study, the primary stream channel was used as the baseline to control for (i.e. de-trend) valley slope and represent analogous geomorphic surfaces comparably across large horizontal distances (Figure 14). A map-set presenting relative elevation data for the entire study corridor is presented in Appendix B.

As noted in Methods, a moving window analysis using the primary stream channel as a baseline was performed. Initial review of results noted changes in search radii affected horizontal extent of outputs as well as elevation representation given a common color ramp. A sensitivity analysis was performed to assess search radius effects on interpretation as well as suitability of relative models for more quantitative assessment.

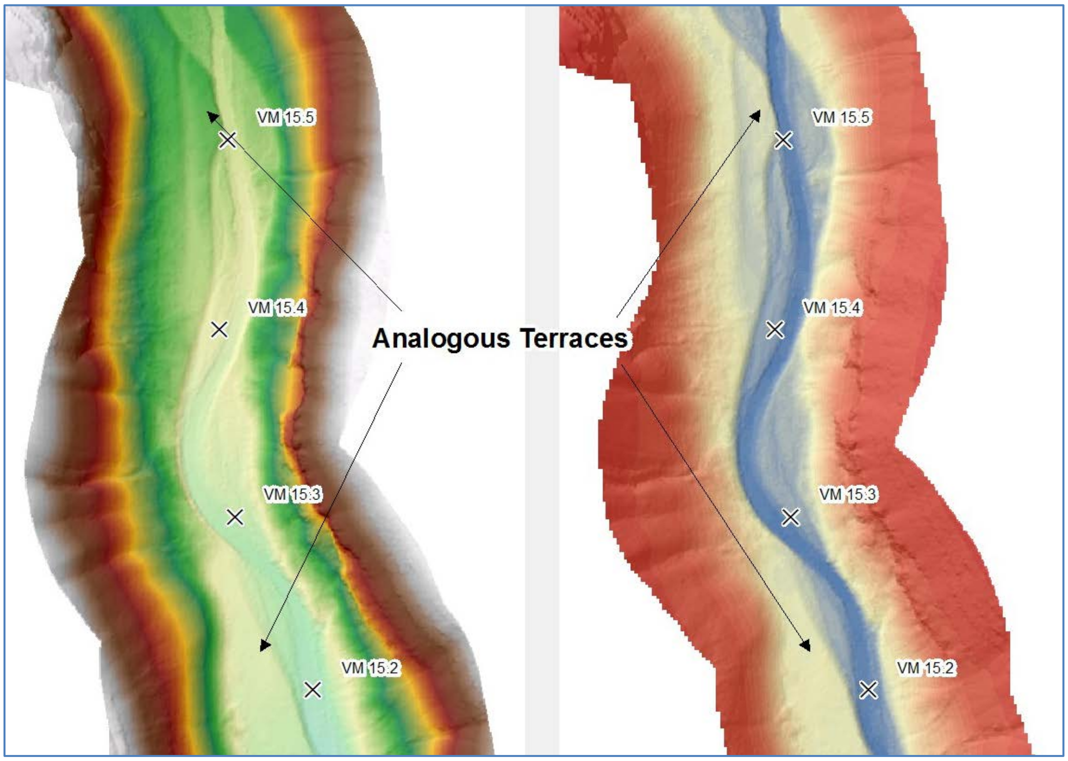


Figure 14. Similar geomorphic surfaces appear differently in absolute DEM (left) than relative DEM (right).

Figure 15 presents the same cross-section (XS) extracted from two different rDEMs generated from the same source data topography and baseline. Note the left valley margin is missing from the XS generated with the smaller search radius and the horizontal axis is truncated when the valley is physically wider than the search distance. Also, note that elevation averaging is greater with larger search radius and there is a differential effect with distance from the channel. For example, the feature under red arrow is roughly 4 vertical feet lower with the larger search radius while the elevation of the feature under the blue arrow (closer to the baseline) comparable between surfaces.

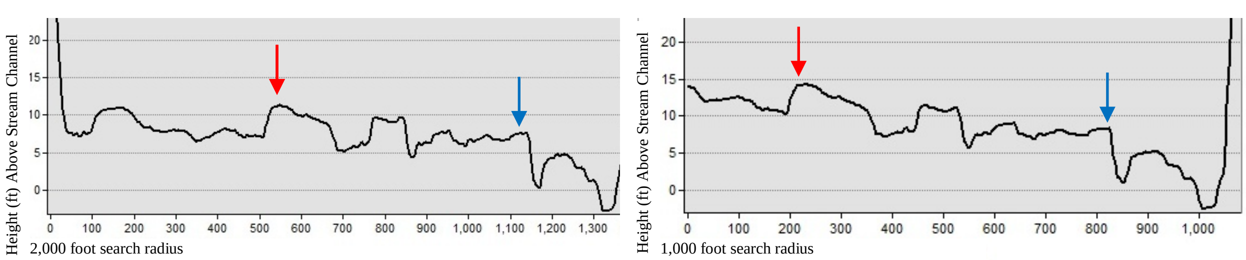


Figure 15. Cross-section at Rock Creek VM 2.6 extracted from rDEMs produced with different search radii.

Thus, relative elevations of real-world features change based on the search radius and the magnitude of the effect increases with increasing horizontal distance from the baseline (an inherent part of the search radius process). In other words, there is a fairly minor absolute effect in immediate proximity to the baseline and effects are greatest at the perimeter of the search.

Even along the baseline, there seems to be a scaling effect with regard to low-relief areas. Disproportionately large search radius values in narrow valleys diminish channel and floodplain relief (Figure 16).

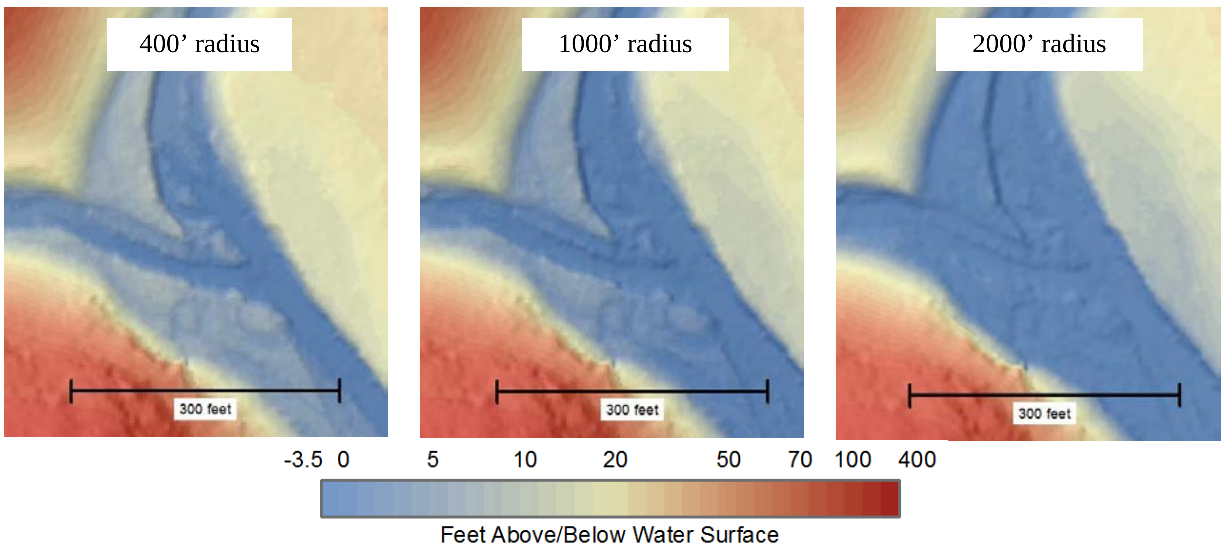


Figure 16. Increased search radius increases averaging and diminishes feature contrast in low-relief areas (i.e. stream channels and floodplains).

Table 7. Search radius values of rDEMs used for analytical vs. visualization purposes.

Valley	Segment	Search Radius (feet)	
		Valley Extent Delineation	**Map Presentation (Appendix B)**
Rock Creek	ACOE to Hwy 8	2,000	2,000
Rock Creek	Hwy 8 to Squaw Cr	1,000	2,000
Rock Creek	Squaw Cr to Badger Cr	1,000	1,000
Rock Creek	Badger Cr to upper extent	400	400
Squaw Cr	Mouth to Harrison Cr	600	1,000
Squaw Cr	Upstream of Harrison Cr	600	600
Harrison Cr	mouth to upper extent	600	600
White Cr	mouth to upper extent	600	600
Luna Cr	mouth to upper extent	300	400
Quartz Cr	mouth to upper extent	400	400
Box Canyon	mouth to upper extent	400	400

To maximize resolution of valley bottom relief, the search radius should be no larger than that required to encompass the valley bottom. However, having the baseline on one edge of the target area (e.g. the stream channel contacts a valley toe) may necessitate a large search distance. In confined and moderately-confined valleys, it is often desirable to show valley relief. However, increasing distances to show valley relief come at the expense of relative channel and floodplain relief. Ultimately, optimization depends on objectives and analytical judgment to balance spatial extent with vertical smoothing and resolution. Table 7 presents search radii associated with rDEMs used for analysis (e.g. delineation of valley extents) and visualization (e.g. cartography) in this study. For analytical purposes (e.g. channel delineations) rDEMs generated with 100’-300’ search radii were typically used.

Baseflow Habitat Distribution

Late-summer and early-fall surface flow duration and extent are the principal factors limiting salmonid populations in Rock Creek (Allen et al 2014a, Glass 2009). However, the general lack of accurate and precise locations of perennial reaches presents a significant challenge in making recommendations for aquatic habitat protection, restoration, or enhancement actions.

Only one study (Allen et al 2014a) has documented limiting habitat conditions in a spatially continuous manner and solely during the baseflow period (September and early-October). Other studies (Environ 2013, Glass 2009) have sampled stream reaches and categorically noted flow conditions (e.g. percent of channel that is dry). However, sampling has either occurred outside of flow-limited potions of the year, and/or has lacked the spatial continuity and precision to map at a scale to inform management actions.

As noted in Methods, delineating channels in Rock Creek based solely on 2D imagery can be challenging. Initial (pre-LiDAR) efforts to map the 2012 low-flow data (CRITFC 2013 and 2014) appeared generally acceptable at 1:24,000 or coarser. However, pre-LiDAR geometry diverges by several hundred feet in some valley segments from 1:1,200 stream geometry, particularly in areas of dense riparian tree cover (Figure 17). Aside from creating lateral inconsistencies, differing channel alignments combined with accumulated field discrepancies cause habitat unit position changes along the profile in some reaches (Figure 18). In combination, these precision complications create a practical problem when trying to evaluate unit persistence through time and/or establishing a spatial reference for revisitation. (e.g. for assessment, design, or treatment). Thus, the LiDAR-derived stream delineation provides a reliable and consistent alignment surveyed in 2012 and observed during this study.

On average, surveys conducted from 2009 through 2012 indicated 36% of stream (by length) dries seasonally and approximately 17% remains as perennial pools (Allen et al. 2014a). In 2012, a very dry year, 14% of surveyed stream channels were pools and 46% of total length was dry.

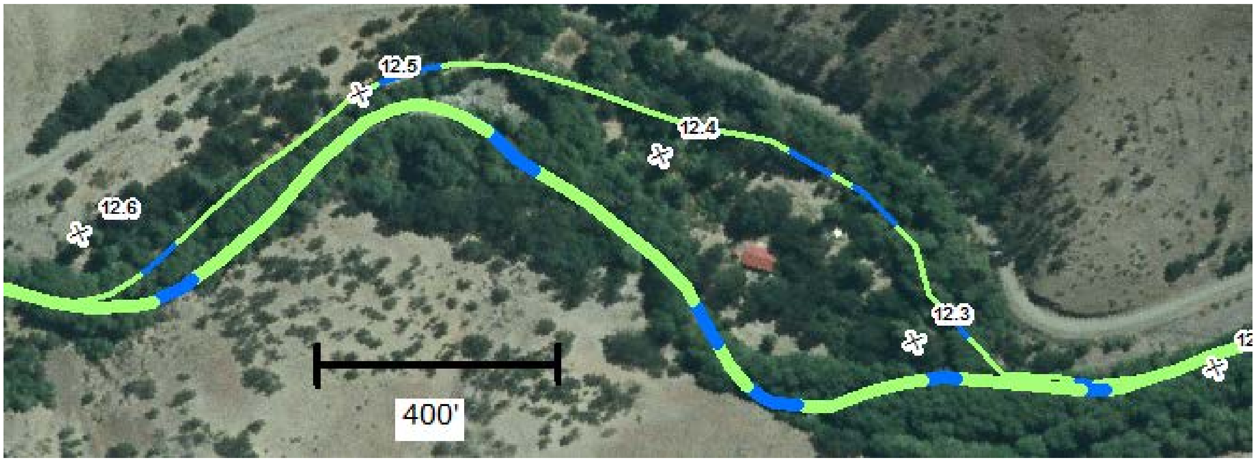


Figure 17. Valley segment where low-flow habitat units based on pre-LiDAR shapefile geometry (thin lines) and LiDAR-derived stream geometry (thick lines) diverge.

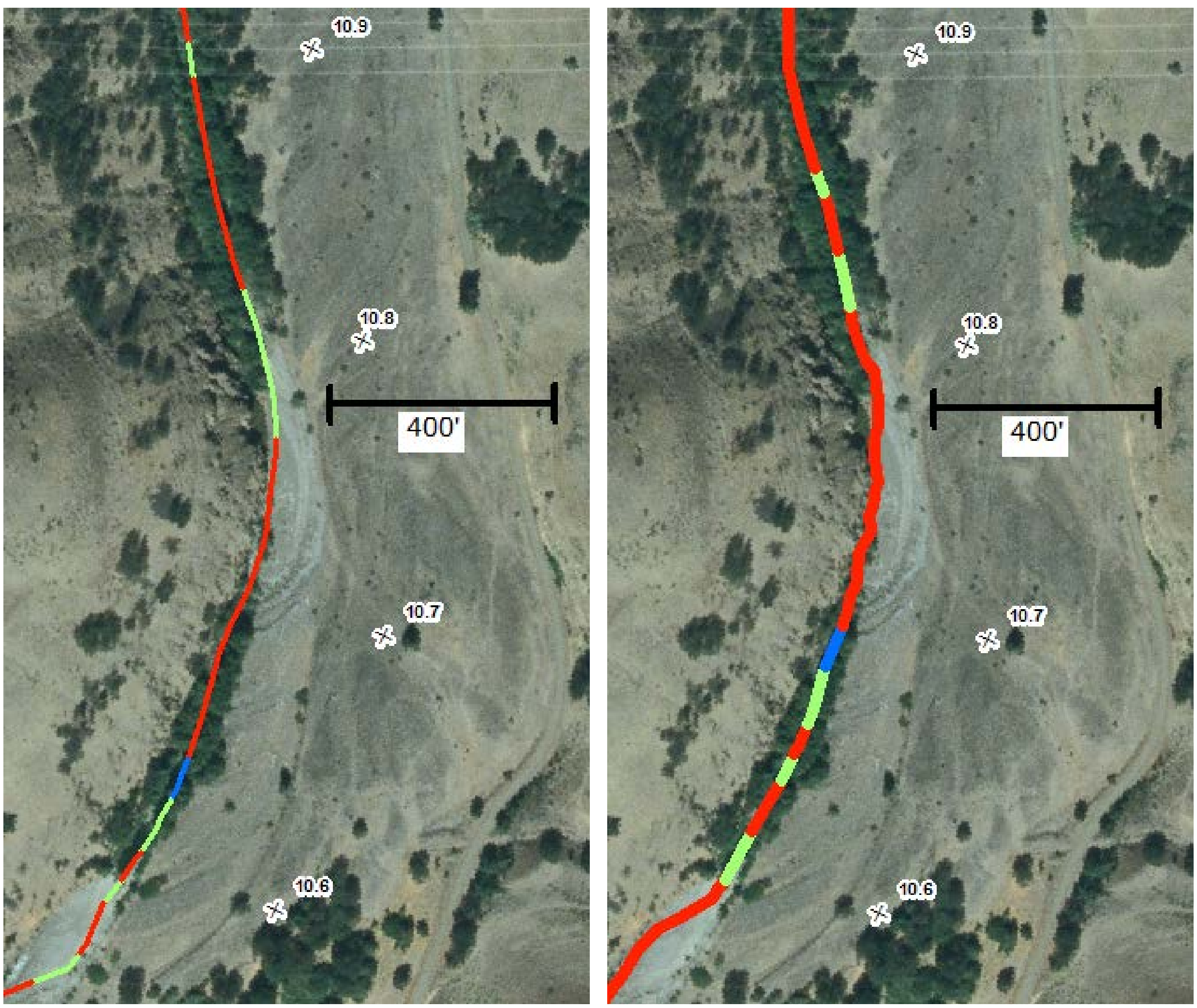


Figure 18. Differences in low-flow habitat units based on pre-LiDAR stream geometry (thin lines, left) and LiDAR-derived stream geometry (thick lines, right).

Table 8. Mostly perennial reaches based identified by 2012 low-flow surveys and referenced LiDAR-derived valley geometry.

Stream	Downstream End (VM)	Upstream End (VM)
Rock Cr	3.0	3.85
Rock Cr	5.55	7.45
Rock Cr	7.7	8.0
Rock Cr	8.65	10.35
Rock Cr	11.7	13.2
Squaw Cr.	0.1	0.5
Squaw Cr.	0.65	0.95
Squaw Cr.	1.25	1.5
Squaw Cr.	2.0	2.35
Squaw Cr.	3.4	3.7
Squaw Cr.	4.25	5.05

The thirteen miles of Rock Creek and 5 miles of Squaw Creek surveyed in 2012 and plotted on 1:1,200 stream lines are presented in the map set in Appendix B. For areas outside this survey area, data from Environ (2013) provides a cursory indication of hydroperiod, but interpretation is limited by data collected outside of flow-limited periods (e.g. June, July, November) and sampling different portions of the watershed in different years.

Indicators

Field evaluation encompassed a variety of habitat, ecological, and geo-fluvial elements including fisheries habitat, hydromodifications, woody debris, vegetation, beaver, sediment, bedforms, channel patterns, and flood stage indicators.

Fisheries Habitat

Literature review (Lindley and Conley, 2013) and level of effort by local biologists indicate anadromous salmonids are the principle fish stocks of interest in Rock Creek. While other species have been documented (Allen et al. 2014a), field observations and discussion herein focuses on habitat elements as they primarily relate to salmonids, specifically steelhead.

Field surveys found an abundance of long, linear, simple instream features in Rock Creek. Plane-bed conditions are prevalent and there is a general lack of pool structure (Figure 19). Long, shallow glides become increasingly common downstream of Bickleton Highway, often many hundreds of feet long.

Better quality pool habitats are almost all hydraulically-forced (Figure 21) and frequently involve bedrock and/or mature bank vegetation, though even the combination of those influences does not necessarily generate a quality pool. Underwater cover is typically low with very little woody debris within the wetted channel and generally low within-unit bed-relief (i.e. few large rocks projecting into water column). Allen et al (2014a) make similar observations about cover.

Figure 19. Simple, shallow plane-bed habitat conditions predominate throughout much of Rock Creek.

Figure 20. Long, shallow glides are common in entrenched reaches which occasionally have deeper pockets associated with alder roots.

Figure 21. Higher-quality salmonid habitat is uncommon and tends to be forced, typically by bedrock (left) and riparian trees (right).

Large (>3 feet in diameter) colluvial particles are reasonably common, particularly upstream of VM 10.5, but rarely produce more than small pocket habitat and, in many cases, produce little bed deformation, usually only a few tenths of a foot, if any at all. In other words, pocket-pools formed by large clasts were absent more than they were present. Clusters of large colluvial particles are infrequent, but were observed to generate channel-scale pool units in several instances (Figure 22).

Figure 22. Forcing by colluvial particle clusters is less common, but can produce channel-scale pool units in combination with mature trees that increase bank resistance as well as create refugia during high flows.

Figure 23. Pair of coho salmon spawning in the highest quality habitat observed; associated with bedrock-forcing, VM 6.9 to 7.5.

In general, the best physical habitats observed during this study (low-flow, winter conditions) were in the canyon downstream of Squaw Creek and upstream of the gas pipeline. Habitat that was exceptionally good (by comparison within Rock Creek) was found between VM 6.9 and 7.4. In this reach, bedrock contacts are frequent and generate pools, some deeper than 5 feet, and pockets of well-sorted gravels. Numerous (>10) adult coho salmon were observed spawning in this area in a single day in December 2013 (Figure 23). Groundwater influx was evident in this reach (Figure 24) and 2012 low-flow surveys indicate it is perennial even in a dry year.

Figure 24. Indicators of groundwater expression; rusty seepage (left) and emergent aquatic vegetation (right).

Winter side channel habitat is not uncommon, but habitat quality varies. Multiple chutes typically dissect diagonal bars and are active at different flows. Scour in areas where multiple high-flow chutes converge occasionally generate features that function as off-channel habitat during spring, summer, and some winter flows (Figure 25).

Figure 25. Secondary habitat feature that functions as off- and side-channel habitat depending on flow.

One of the more intriguing field observations was the frequency with which quality pools do *not* occur in places they might otherwise be expected to form. During field surveys, attention was paid to a variety of elements known to contribute to pool formation including: woody debris, tree roots, resistant banks, boulders, and bedrock (Pleus et al. 1999) as well as their geomorphic position, such as the outside of a bend or channel re-entry points. Except for some bedrock exposures, even combinations of multiple elements and channel position often did not produce quality (deeper) habitats. This appeared to be largely due to bed armoring (discussed further in “Alluvial Sediments” sub-section).

Hydromodifications

Hydromodifications are features resulting from human actions that alter hydraulic patterns and/or hydrologic pathways. Mapping in this report is limited to locations where earth-moving has occurred that otherwise altered or obstructed surface or groundwater flow patterns and does not include rip-rapped banks. Previous work (Glass 2009) identified the three county bridge crossings in the lowest 13 miles of free-flowing section of Rock Creek as hydromodifications, but notes it was not an all-inclusive list. This study observed hydromodifications throughout the lower 13 miles of Rock Cr and are mapped in Appendix B. Four main types of hydromodifications were identified: down-valley embankments, barbs/spurs, valley-spanning embankments, and drains.

Down-valley embankments are the most common hydromodification type, but appear to have the least relative geomorphic effect along Rock Creek. Instances include the historic (Figure 26) and current alignments of the Rock Creek Road and a number of mid-valley levees. Observed levees are all “sugar-dike” style, improvised of local granular materials (Figure 27).

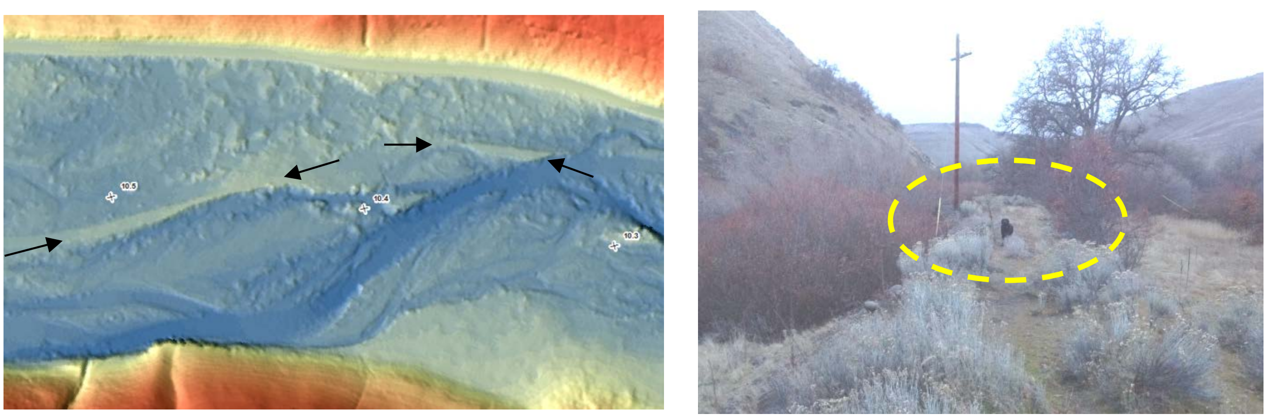


Figure 26. Remnants of the mid-valley, pre-1964 flood alignment of the Rock Creek Road persist 1-4’ above adjacent topography for approximately 1300 lineal feet; vicinity VM 10.4.

While their presence on the landscape is quite distinct, none of the levees are anchored to a valley hard-point and all are being flanked by primary and/or secondary stream channels. Effects are generally local and do not appear to fundamentally alter geomorphic processes on an appreciable scale, except perhaps at VM 8.75 (where levee construction appears to have been clearly coupled with active channel excavation). Given the nature of their construction, it’s conceivable the levees could be byproducts of excavation originally intended to increase channel capacity (as opposed to outright intent to construct a levee).

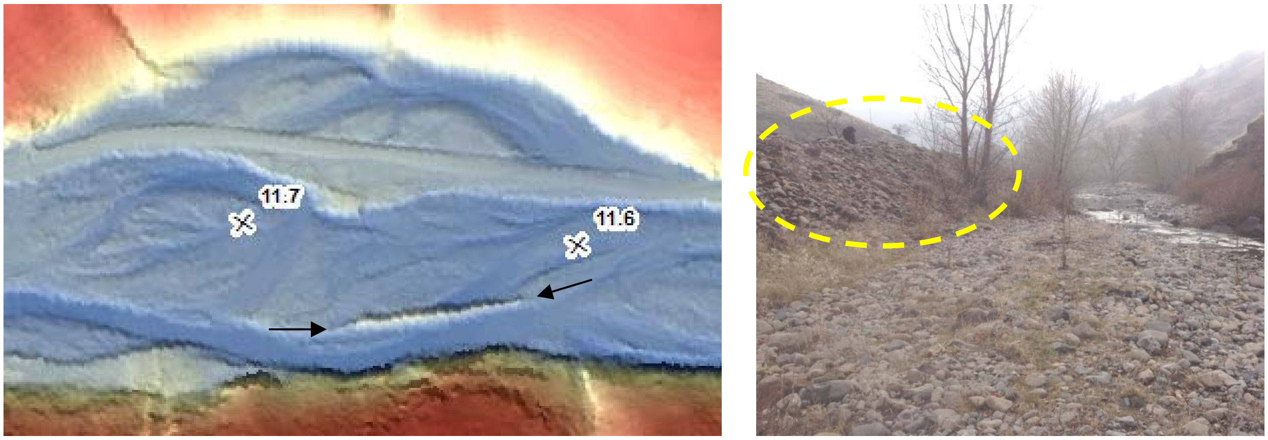


Figure 27. Mid-valley sugar-dike (between arrows) made of native, granular alluvial materials; vicinity VM 11.6 (left). Embankment of Rock Creek Road visible at top of DEM.

Barb and spur occurrence is sporadic and primarily associated with protecting utility poles and roads (Figure 28). While barbs and spurs alter flow patterns, their effects are generally localized. One possible exception is in the vicinity of the Luna Gulch and Rock Creek confluence, where spur presence obstructs overbank flow paths on the left side of the valley. Except during the largest floods, this area is generally erosional, but the barbs likely concentrate flow in the primary channel and may increase erosive force during more frequent peak flows.

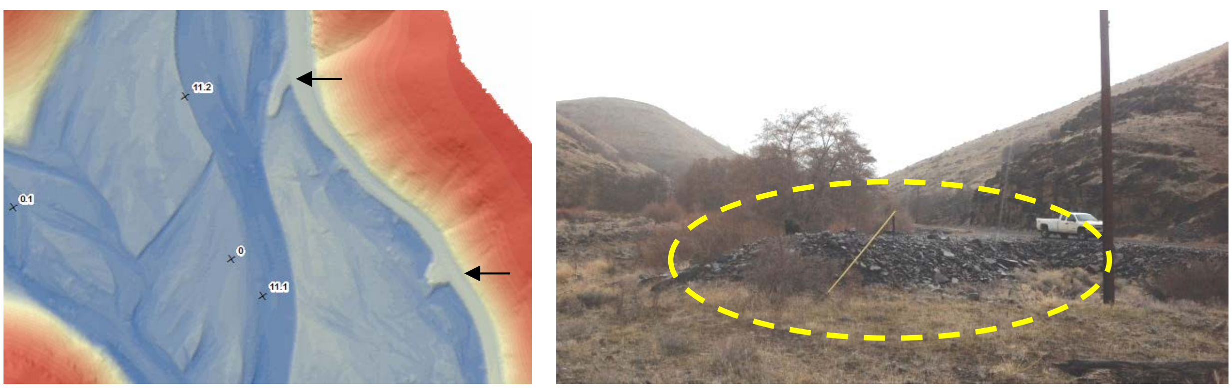


Figure 28. Rock barbs to protect road and utility pole.

Valley-spanning embankments occur in a limited number of locations, but have the greatest hydraulic effects. Most notable are the road embankments at Imrie Road (Figure 29) and Old Highway 8. Both are hydraulically under-sized and backwater some flood flows. The local decrease in water surface slope (as a proxy for the energy line) upstream of the crossings contributes to deposition of bed materials, resulting in multi-thread channel patterns with flanking behavior immediately upstream (Figure 30). Signs of scour and fill and historic damage were observed at both locations. The bridge's upstream right wingwall is missing and apparently torn from the right abutment at Imrie Road and has been repaired with large riprap (Figure 29). The right abutment footing at the Highway 8 bridge was visible in the bottom of the pool. Both locations appear to stage gravels and small cobbles during low-frequency events (e.g. ≥ Q5 or Q10) which get re-worked at more frequent discharges (≤ Q5).

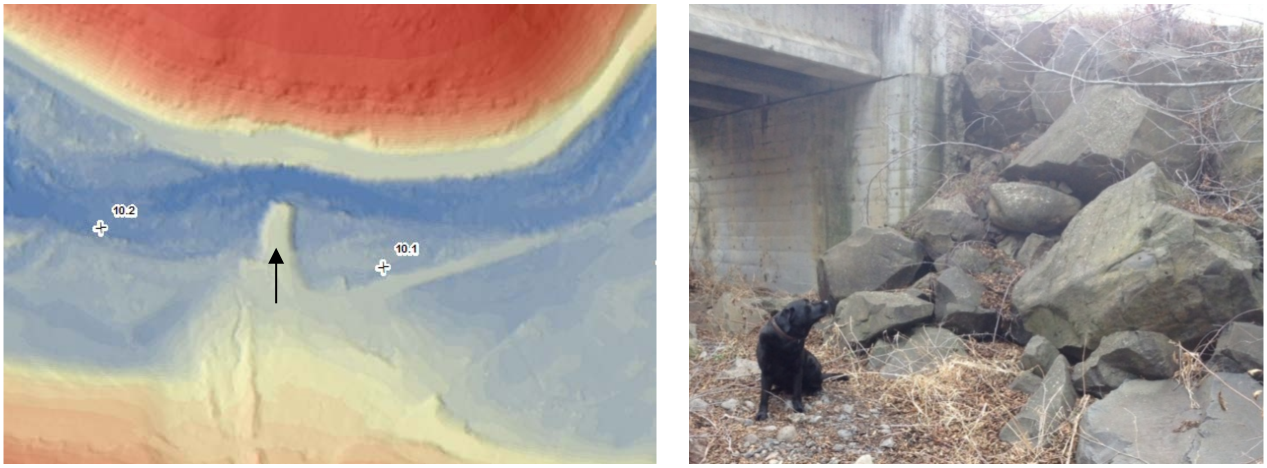


Figure 29. Undersized bridge at Imrie Road (~VM 10.1) is missing the right-upstream wingwall. Riprap repair likely indicate historic flood damage.

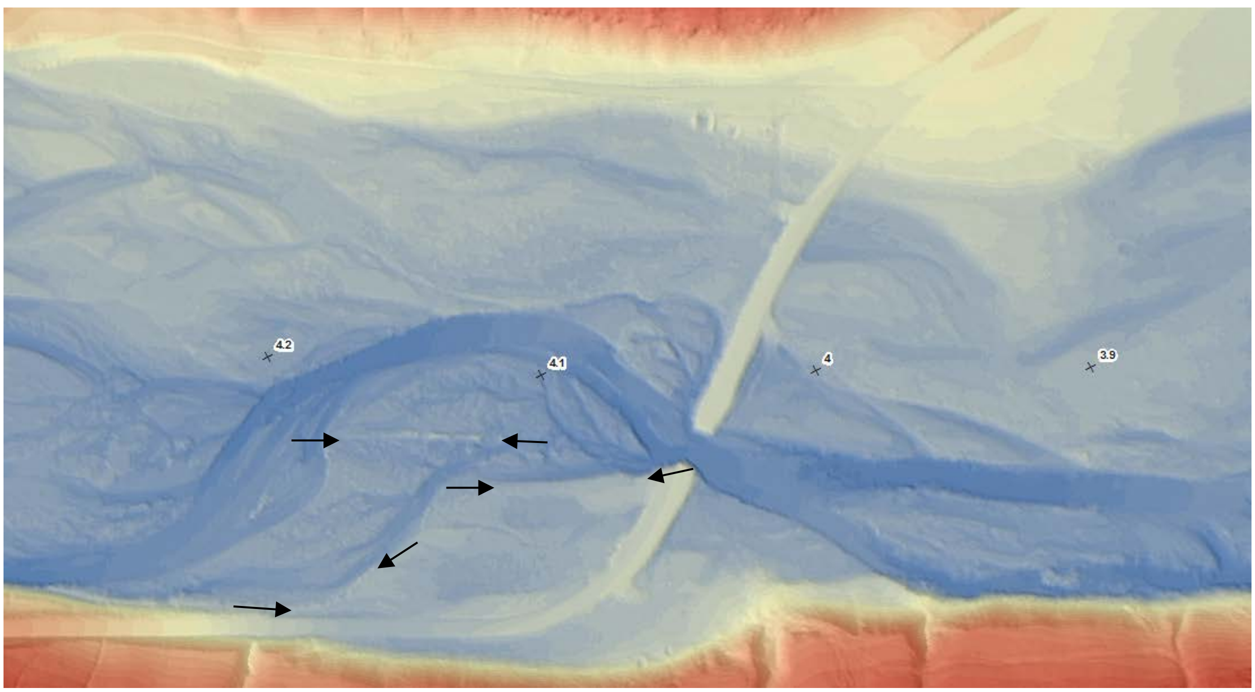


Figure 30. Braiding and flanking upstream of cross-valley embankment at Old Hwy 8; arrows indicate historic attempts to address channel response to undersized crossing.

A previously undersized bridge at the Bickleton Highway crossing of Rock Creek was replaced sometime between 2008 and 2013. Though embankment materials still occupy historic floodplain, there now appears to be sufficient cross-sectional area to easily accommodate a Q100 event.

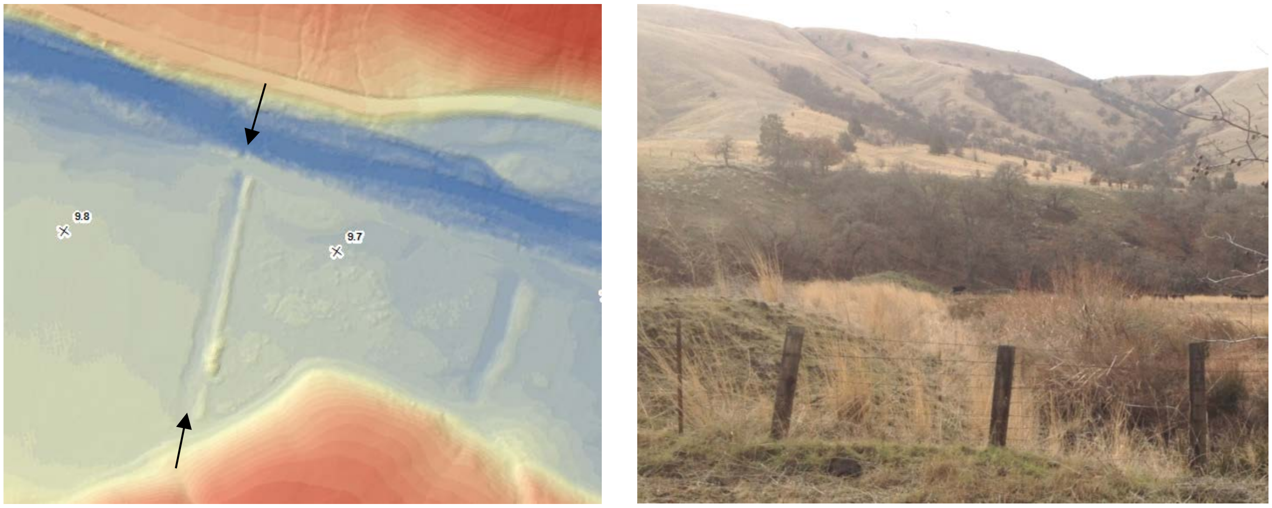


Figure 31. Drain with low, cross-valley levee vicinity (~VM 9.7).

Drains constitute the fourth common type of hydromodification and usually have companion cross-valley (but not valley-spanning) levees (Figure 31). Drains typically occur in areas of richer valley-bottom soils associated with springs. These areas appear particularly productive for forage/hay production and/or pasturing livestock. The levees are likely by-products of drain excavation and some hydraulic effect can be expected during low-frequency events. The effect of the drain itself constitutes a more routine, hydrologic modification by drawing down the water table and reducing soil-water storage. While drains could conceivably contribute to late-summer and early-fall streamflows, it is also possible that they could reduce instream flows during the same period due to lost storage capacity. Their specific effect on streamflow is unknown and seasonal variation in spring discharge would need to be evaluated.

Woody Debris

Woody debris is defined as any dead, woody plant material, including logs, branches, down and dead trees, and root wads. The scientific literature has an array of definitions of large woody debris (LWD), but for the purposes of this study, LWD is considered to be any woody debris at least 6.6 feet long with a 4 inch diameter at the small end.


Figure 32. Small, single pieces of woody debris in the wetted (left) and active (right) channels are not uncommon, but rarely form persistent habitat.

Woody debris is abundant in Rock Creek, but is generally of small diameter and length and contributes little to habitat formation. In the reaches surveyed, alders provide the primary source of woody debris. Single pieces within the wetted and active channels are generally not in configurations expected to persist through a single water-year (Figure 32). Buried woody debris was notably absent in bank facies throughout the 14 mile field survey, except for two isolated locations in the lower six miles.


Figure 33. Same location on 1/7/14 during prolonged low-flow (left) and on 2/26/14 following small (<<Q1.01) freshet. Note redistribution of mid-channel woody debris.

Wind and icing events tend to be the input mechanism for these smaller woody debris pieces (inclusive of small branches) which move during the first freshet (Figure 33). Though transient, these features were observed providing primary habitat collect leaf litter which increases water depth of some glides and pools up to 0.4 additional feet (Figure 34).

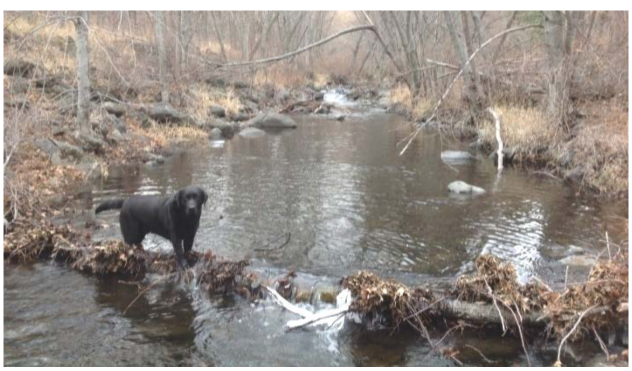



Figure 34. Transient pool habitat created by single LWD trapping hardwood leaf litter and increasing upstream water depth.

Persistent woody debris accumulations are composed of generally small diameter (<6-8 inch), short (<10 ft) materials. They generally have minimal active channel exposure and are usually configured in one of four forms:

- *rafts* – usually occur in overbank areas on the tops of bars (Figure 35) and floodplains (Figure 36) as well as down-valley extents of diagonal and transverse bars. Rafts form where flow becomes too shallow to maintain transport or by accretion into previous raft and may be dispersed and re-distributed by large events. In some instances, rafts may be reinforced by mature alders at distil end of medial bars where side channel orientation is cross-wise or oblique to valley-axis.

- *fences* – generally parallel the active channel. Occur in re-entrant areas where perched, overbank flow re-enters the primary or secondary channel and woody debris becomes racked into the off-channel side/face of riparian vegetation (Figure 37).
- *mini-apex* – occur where smaller debris is racked into the upstream face of standing riparian vegetation and splits flow (Figure 38 and Figure 39), in-particular where mature alders occur within the active channel. Likely ephemeral, dispersed, and re-formed at high-frequency floods (<Q10).
- *spurs* – occur on channel margins and are oriented perpendicular to active channel, racked into upstream face of riparian vegetation with one end tied into topography so flow only occurs around one side or over the top (Figure 40 and Figure 41). May be over-topped during large (> Q5 or Q10) events. Spurs often have larger wood pieces (10-14 inch diameter) and appeared most likely to be habitat-forming (though infrequent).

Figure 35. Examples of woody debris 'rafts'; many exhibit signs of accretion (right) with younger material deposited by recent events near bar apex in flow separation zones.

Figure 36. Floodplain woody debris 'rafts' deposited by the March 2012 peakflow event (Q3).

Figure 37. Woody debris "fences" occur in areas where perched floodplain flow re-enters a channel.

Figure 38. Example of alder growing within active channel and recruiting woody debris in "mini-apex" form during 2012 event (Q3).


Figure 39. 'Mini-apex' forms of woody debris accumulation on edge of active channel with adjacent floodplain lacking roughness (left) and along margins of diagonal bar where flow splits into multiple chutes (right).

Figure 40. Woody debris ‘spur’ oriented perpendicular to channel with no flow path around the off-channel end.

Figure 41. Example of woody debris spurs; racked into riparian trees, oriented perpendicular to channel, with one end butted into a higher topographic surface.

Though, not as common as alder, flood-deposited black walnuts trees (*Juglans nigra*) are common on the highest active floodplain surfaces where they were deposited by the 1964, 1974, and/or 1996 peakflow events. Sounding of numerous specimens indicated most of the older flood-deposited walnut trees to be surprisingly solid and able to bear their own weight, often with much of their primary branching structure still intact.

Figure 42. Example of a modest (16” diameter) walnut tree that was transported and deposited overbank by the 1996 (or earlier) peakflow event. Note degree of rootmass and portion of branching structure still intact.

This stands in stark contrast to the native alders, which are quite brittle even when live and deteriorate quickly. As more walnut trees are recruited in the fluvial system over time, their increased resistance to weathering and fluvial transport (via greater specific gravity, persistent length, and form complexity) has potential to alter the nature of stream processes and habitat formation. The ecological implications of walnut trees are discussed further in the "Vegetation Patterns" sub-section.

Coniferous LWD of sufficient size to individually generate a response in channel morphology or primary habitat was rarely observed during field surveys. This is likely due to availability of source material. Upstream of the Quartz Creek confluence both streams have topwidths of about 20-25' or less (Figure 43). Upstream of the confluence, both streams flow through confined, generally bedrock-controlled, higher gradient (> 0.05 average) canyons, each four to five miles long with multiple choke-points. The likelihood of upstream sources to contribute LWD of appreciable size to reaches downstream of the Rock-Quartz confluence is very low.

Figure 43. Rock Creek upstream of Quartz Creek confluence (~VM 16.9).

Downstream of the Rock-Quartz confluence, local recruitment appears the most likely potential source. Scattered individuals, mostly ponderosa pine (*Pinus ponderosa*) up to 30" DBH, were observed growing on high floodplains, terraces and hillsides downstream of Quartz Creek. This occurred with some frequency to about VM 12, but not always in proximity (tree-length or less) of the active channel. Downstream of VM 12 (between Badger and Luna creeks) pine occurrence declines precipitously. Conifer distribution is discussed further in the "Vegetation Patterns" sub-section.

Based on high-resolution topography and aerial photography, woody debris appears to become morphologically significant in Quartz Creek upstream of VM 5.3 and especially so upstream of VM 7.4 (~2,800 feet). In Rock Creek, woody debris appears to have a morphological influence upstream of VM 21 (~2,350 feet). Remote detection of woody debris within confined segments of both streams is hampered in some reaches due to topographic and canopy shadowing.

Vegetation Patterns

A variety of interesting vegetation patterns were encountered during field surveys along Rock Creek including: distinct alder (*Alnus* spp) cohorts, active channel colonization and persistent woody hydrophytes, size and distribution of black walnut trees, and active floodplain occupation by mature big sagebrush (*Artemisia tridentata*).

Alder is the most common riparian tree along stream banks within the surveyed area. Using trunk diameter as a proxy for age, four to five cohorts were observed. The youngest cohort was typically less than 2 inches basal diameter. This group was old enough to have survived at least several winter peak flow and summer low-flow cycles and seemed to be consistently rooted in a narrow, linear band between 0.5 and 1.5 vertical feet above channel control. This narrow, linear pattern of colonization is reflected in the persistence of larger cohorts which, roughly, group into 4-8", 8-12" 12-16", and greater than 16" diameter at breast height (DBH), though there were local variations along the profile. It was not uncommon to have different cohorts on opposite banks in some hydraulic units. Alders greater than 16 and even 20 inches were not uncommon. It should be noted that at least two different species of alder are documented in the Rock Creek watershed which have different growth habits which may complicate interpretation for smaller-diameter (<~8-10" diameter) single-stem cohorts, particularly given field visits during dormancy.

Collections of *Alnus rhombifolia* ("white" alder) and *A. incana* ("gray" or "thinleaf" alder) have been documented within the Rock Creek watershed (UW 2014). White alder typically grows as a tree with a single-stem and may reach 45 feet or more in height. Thinleaf alder typically has a multi-stem (shrub) habit, but may grow as a small tree (single-stem) less than 25 feet tall (USDA 2014). There have been a couple of isolated reports of *A. viridis* and *A. rubra* in the subbasin, but UW herbarium collections for those species are not mapped in Rock Creek.

Figure 44. Alder cohorts on active channel margins.

The narrow width of alder bands is most likely driven by subsurface moisture conditions during seedling germination and establishment (spring and early summer). A hydrograph that is already well into recession during seedling establishment, poor water holding capacity of granular substrates, and arid summer conditions combine to challenge hydrophyte establishment and typically dictate that successful establishment occurs within the active channel. This pattern is commonly observed in tributaries of the lower Klickitat River subbasin. Alder cohorts are “thinned” or removed based on the random occurrence of discharge events that generate enough shear stress to uproot, abrade, or otherwise cause lethal damage.

Perennial vegetation within the active channel occurs throughout surveyed reaches (Figure 45). Alder bands were most widespread and often associated with compound active channels consisting of an inset wetted channel and a slightly higher ledge surface (Figure 46).

Figure 45. Mature in-channel coyote willow copse (left) and in-channel alders recruit woody debris (right).

Figure 46. Young alder cohort persists in narrow band within compound active channel.

Willow copses were also observed growing within the active channel, though these tended to occur in proximity to reaches or channel units where surface flow is seasonal. While leaders were often young, rootstocks indicated long-term (probably > 10 years) persistence (Figure 47). Though low-density in nature, woody hydrophytes were observed even in some of driest summertime reaches such as in proximity of the Luna Creek confluence (Figure 48). Coyote willow (*Salix exigua*) was the most common species observed in such areas. The presence of a few well-established and vigorous individuals suggests establishment and early colonization as the limiting period, with successful recruitment classes potentially highly dependent on summer flow duration. Once mature coyote willow rootstocks are established, they seem to tolerate and resprout from routine disturbances (e.g. beaver browse and flood abrasion) quite well.

Figure 47. Older coyote willow root (>4" diameter) within active channel, re-sprouting with young, vigorous leaders.

Figure 48. Mature coyote willow colony with incrementally younger suckering radiating upstream (to right).

The largest alders in each area may not be on the margins of the active channel. Often, the largest individuals occupy off-channel areas that are usually re-entry points of historic channel alignments. Mostly these areas are hyporheically-fed and receive surface inflow only during the largest events. These features are present in air photos pre-dating the 1964 floods. They also challenge primary channel delineation from older aerial photography in reaches where the primary channel dries-up seasonally. Establishment is presumed to have occurred when they were adjacent to primary channel alignments, as new recruits in these areas were not often observed. Mature alders were frequently observed in areas where seedling establishment would not be expected under current channel conditions. In particular, they are common in actively eroding areas such as the crest and chutes associated with the downstream facies of diagonal bars (Figure 49).

Figure 49. Older alders established under different channel conditions now occupy (and influence) chute dissection of diagonal bar. Lower channel (left) is a "seam" resulting from headward channel extension.

Figure 50. Woody debris deposited during 2012 event (Q3) amongst mature big sagebrush.

The position and juxtaposition of shrubs not typically considered as occupants of active floodplains was also intriguing. A variety of indicators left by the 2012 peak flow event (Q3) were observed throughout areas occupied by big sagebrush (Figure 50 and Figure 51) and rabbitbrush (*Chrysothamnus* spp, Figure 52) including woody debris and gravel sheets.

Figure 51. Woody debris (left) and gravel sheet (right) deposits associated with Q3 event adjacent to big sagebrush.

Figure 52. Mature rabbitbrush with downstream lean, woody debris, and gravel from the 2012 (Q3) event.

Aside from the apparently high inundation frequency of surfaces occupied by plant species usually not associated with active floodplains, some very interesting plant associations were observed suggesting the 2012 event was not an aberration. Big sagebrush was observed growing coincident with black cottonwood and willows in multiple locations. Such occurrences often indicate trend toward wetter or drier because either the wetter or drier species show signs of stress and/or will not be recruiting younger individuals. However, age structure and vigor of young cohorts of all three species was notable in some locations along Rock Creek.

Figure 53 illustrates an example of a site where black cottonwood, big sagebrush, and an unidentified species of willow are all vigorous and actively recruiting new individuals or expanding colonies on the same floodplain surface. Establishment in these areas may be driven by interannual hydroperiod variability. Wet years with extended streamflow recession likely favor cottonwood and willow establishment. Sagebrush may be favored by years with good winter moisture in the absence of major inundation events. Dry years may preclude establishment by any species. Persistence of species with a wide array of moisture tolerance in such areas is likely due to a water table with sufficiently short duration of near-surface saturation, but a September water table within accessible depth of the hydrophytes' roots.

Figure 53. Black cottonwood, big sagebrush, and willow occupy and actively recruiting on same surface.

A variety of invasive plant species were observed throughout Rock Creek including, but not limited to: several different knapweeds (*Centaurea* spp), Canada thistle (*Cirsium arvense*), star thistle (*Centaurea solstitalis*), and medusahead (*Taeniatherum caput-medusae*). Reed canary grass (*Phalaris arundinacea*) and Himalayan blackberry (*Rubus armeniacus*) were abundant throughout the riparian corridor and floodplain (Figure 54). Reed canary grass was mostly observed in the lower 10 miles of Rock Creek, generally growing within the primary channel where it did not appear to be displacing native species. It was also observed in secondary and off-channel areas where it was likely displacing native plants. Himalayan blackberry was widespread, aggressive, generally expanding, and in some cases choking out native plants.

Black walnut trees (*Juglans nigra*) were introduced to the area by homesteaders and have naturalized in some portions of the watershed, lower Squaw Creek and Rock Creek downstream of Squaw Creek in particular. Naturalization reportedly began several miles up Squaw Creek (Blaine personal communication 2014). This seems to be supported by larger size frequency and general abundance of walnut trees along Squaw Creek (including individuals exceeding 48" diameter; Figure 55) versus those observed along Rock Creek. Most walnut tree occurrence along Rock Creek upstream of Squaw Creek is within the first half-mile (only individuals of small to modest size (<18") were observed). Size classes of walnut trees along Rock Creek downstream of the Squaw Creek confluence appeared to be generally larger than those along Rock Creek upstream of the confluence. The geographic distribution of walnut tree size classes may be indicative of fluvial transport of reproductively-viable walnut tree materials as a primary distribution vector and, potentially, animals (inclusive of humans) as a secondary vector.

Figure 54. Invasive species such as Himalayan blackberry (left) and reed canary grass (right) become increasingly common downstream of VM 13.

Figure 55. Very large black walnut tree in Squaw Creek floodplain (~VM 1.2).

In the Rock Creek watershed, walnut trees appear to occupy an ecological niche between Oregon white oak (*Quercus garryana*) and alder that intrudes and displaces both species on the margins of their respective niches. Walnut trees seem to be thriving in mid-elevation floodplains with higher fines (silt) content, and intermediately drained substrates. From these areas, they extend somewhat into higher floodplain surfaces and displace oaks on the lower/wetter end of their distribution. They also extend into somewhat lower elevation surfaces (that still have higher fines content) and displace alder on the upper elevation (more mesic) range of its distribution. Alders seems to out-compete walnut trees in granular substrates.

Having an exotic, but naturalized population of walnut trees creates an intriguing dilemma. They are the dominant canopy species along many portions of lower Squaw and Rock creeks. Given concerns over water temperatures (and related TMDL), any amount of shade provided by riparian vegetation is likely important.

However, walnut trees could effectively be re-engineering the fluvial system for the reaches in which they occur in lower Rock and Squaw creeks. While alive, they are longer-lived than native alders so any given individual that becomes established increases the duration of their effect as floodplain roughness. The largest live trees of any species observed during field work were all walnut trees, with numerous individuals exceeding 3 to 4 feet diameter. Given the extent of their root network they would appear to be less vulnerable to scour.

As woody debris, they are more structurally sound than the native tree species creating more resistance and persisting longer in a portion of the system that has generally low availability of large trees (see "Woody Debris" sub-section). Their greater density, individual volume, tendency to retain length, and shape complexity (rootwads and branching) make fluvial transport less likely than native trees. Collectively, these characteristics likely decrease transit distance and should increase overall hydraulic resistance. Their apparent slower decomposition rate should effectively increase the duration of whatever effect they have. The above characteristics support expectations for walnut trees to contribute to more complex hydraulic environments than alders. For low-gradient alluvial streams, increased hydraulic complexity translates to increased habitat complexity which is generally more favorable to salmonids. However, there are also risks.

Expected benefits of increased shade and prospects for instream habitat formation by walnut trees have potential trade-offs. Black walnut is allelopathic; that is, it produces a toxin that inhibits or prevents growth of other plants in its proximity (USDA 2014). Walnut tree monocultures where native vegetation has been displaced were observed in several locations (Figure 56) and seem to be an increasing in distribution.

Figure 56. Walnut grove monocultures along Rock Creek floodplain in vicinity of VM4 (left) and VM 8 (right).

Finally, walnut trees could have both unit and bulk effects on the fluvial system's water balance. Given that black walnut as a species evolved in more humid climates, any individual walnut tree may have greater evapotranspirative demands than any individual alder or oak (this could also be normalized as a function of leaf area). To the degree that walnut trees contribute to an overall expansion of floodplain canopy, there is potential for increased bulk evapotranspirative demand. Either or both effects could potentially reduce streamflows at a time of year that already limits steelhead habitat. Finally, depending on quantity and configuration, too much channel and floodplain roughness introduced to systems that already appear capacity-limited (Figure 57) could encourage aggradation. An increase in the thickness of valley fill above whatever subsurface controls exist on hyporheic flow (and assuming no increases in streamflow inputs) distribution and cumulative length of perennial reaches could diminish.

Figure 57. Apex jam contributing to upstream bar development on Squaw Creek.

Field visits and air photo interpretation indicate coniferous cover is infrequent below approximately 2,100 feet ASL. Coniferous stands begin to appear at that elevation where topographic shading is favorable. MAP in this zone is 17.5 to 18.5 inches and seems to be the lower end of suitability for stand development. Scattered ponderosa pines were observed growing on high floodplains and terraces along Rock Creek valley bottoms between VM 17 (slightly upstream of Quartz Creek confluence) and ~VM 12 (between Badger and Luna confluences). Ponderosa pine becomes very rare along lower elevation stream reaches. Live and dead pines up to 24-30 inch diameter were observed as far downstream as ~VM 6, though no appreciable recruitment was noted. MAP at VM 12 is about 14.5 inches 10.6 inches at VM 6. It seems probable that previous pine establishment in this zone occurred under cooler and wetter climatic conditions.

Beaver

Fifty-eight instances of beaver activity were noted while walking the lower 17 miles of Rock Creek (Figure 58). All observations but one were in reaches where stream gradient is less than 0.02 and downstream of VM 12.2, with most observations, including all fresh signs, downstream of Luna Creek. Age of signs ranged from days or weeks old to over a decade or more (Figure 58). Channel-spanning beaver dam construction was infrequent and generally composed of smaller materials (e.g. coyote willow) less likely to survive significant peakflow events. However, ballasting with cobble was observed and the general low-head character of dams (all of which had less than a 1.0 foot of water surface differential) likely increases their chances of persistence.

Review of high resolution topography and air photos suggests beaver may have had historic valley bottom influence in Quartz Creek upstream of VM 7.9. It is also possible that White Creek upstream of VM 0.7 may have also supported beaver, though strong influence of tributary alluvial fans complicates remote interpretation.

Figure 58. Freshly chewed sticks (left) and historic stumps (middle) were not uncommon during field surveys along Rock Creek. Channel-spanning beaver dams (right) were less frequent, but noted in several locations in the lower 10 miles.

Alluvial Sediments

Character, supply, organization, and transport of alluvial sediments are some of the most intriguing elements in Rock Creek. Sediment dynamics also present the greatest challenge for any potential in-channel treatments.

Character

Field observations indicate bed surface material was dominated by cobbles and small-boulders for almost the entirety of VM 17 to VM 3 walked along Rock Creek. Localized exceptions exist where the particle distributions are finer (e.g. due to backwatering from undersized road crossings or beavers). Surface fine sediment was noticeably low with very little embeddedness. There appeared to be a downstream trend of increasing surface fines, (i.e. more active-channel surface fines downstream of Old Hwy 8 than vicinity of Bickleton Hwy) though the effect was subtle. Quantitative sediment data is generally scarce, though two studies have characterized surface sediments.

Environ (2013) conducted the most geographically widespread surface sediment data set and presents pebble count results for thirteen sites. Cumulative frequency curves indicate generally high proportions of fine sediment (7 sites had 30-50% fines) and D84 values between 80-150 mm. Pebble counts were performed “across the full range of the cross-section” and so likely include bank sediments and potentially floodplain sediments, though the extent of cross-sections is unspecified. Cross-sections were near major tributary confluences. Data presented appear to indicate a finer distribution than generally appears along active channel profile of Rock Creek. This difference is most likely a result of site selection (e.g. backwatering and deposition that occurs in vicinity of confluences) as well as sampling across sediment populations (e.g. channel bottom, bank, and possibly floodplain). Pebble count results are also sensitive to observer effects, though experience was not noted.

Harvey (2014) presents pebble count data for three different locations in the basin. This study targeted spawning areas, so it is presumed the sampled channel environment was active channel bottom in pool tail-outs in vicinity of riffle-crests. The ACOE site shows the finest distribution (D84 ~100 mm), but is presumed to be intermittently affected by backwaters of the John Day pool and is excluded from further consideration in this report. The Rock Creek RM 13 (Bickleton Highway) and Squaw Creek RM 1 sites both had D84 values in the 200-250 mm (large cobble) range and appear more consistent to what was observed during the field component of this study.

Six general populations of alluvial surface sediment (with numerous nuances) were observed during field work for this study: armored bed, high-relief bedforms, low-relief bedforms, channel fills, floodplains, and relic fines.

1) The *coarse, well-packed armor layer* is often only visible in the bottom of pools and glides. This was particularly interesting as, in other streams, these pools often exhibit a disproportionately high frequency of bed surface fines. Small boulders are frequent (D50 to D84) though large cobbles are typically a greater proportion of the surface distribution. Relative particle relief is low and visible portions of particles tend to be rounded.
2) *High-relief bedforms and channel controls* (Figure 59) occur mainly as diagonal and transverse bars composed of large-gravels to large-cobbles. Most are well-packed, except on the distil/downstream facies where steeper local gradients at higher-frequency peak discharges result in ongoing re-working. The chutes and seams that dissect these areas often have particles with greater relative relief and are less well-packed. These features are interpreted to be sediment slugs deposited by high-magnitude peakflow events (Q25 or greater) that were transported over the armor layer and dissected by subsequent flows following deposition. “Perched” water surfaces at relatively low flows likely indicate a greater subsurface fines component.
3) *Low-relief bedforms* and channel controls (Figure 60) tend to be gravel-dominated, but many include cobbles. They are largely inset features (lateral bars, medial bars, and low-gradient riffles) within longer plane-bed features, may act as a hydraulic control at lower discharges, and are interspersed within high-relief bedforms. Particles associated with these features tend to be somewhat smaller, rounded, not particularly well-packed and likely associated with higher frequency sediment transport. Their deposition and formation may be associated with localized backwatering and ineffective flow areas within the active channel.

Figure 59. High-relief bedforms; post-dissection (left) with larger residual clasts and active-dissection (right).

4) *Channel fills* (Figure 60) tend to be sandy gravels and occupy former channel alignments where active channel "switching" or modest flow into overbank channels has occurred. They are granular and unpacked. These are highly localized and infrequent. Until they are stabilized by vegetation, their erodibility facilitates reoccupation of old channel alignments during low-frequency peaks.

Figure 60. Low-relief features (low-gradient riffle and lateral bar; left) and channel fill (right).

5) *Floodplain sediments* are generally poorly- to moderately-sorted, often weakly clast-supported, and have a comparatively high component of fines (<2mm) with modest cohesive properties (mainly silts). Larger clasts tend to be sub-rounded to sub-angular cobbles and small boulders. Many of these deposits are in the process of being re-worked via stripping or lateral erosion by the active channel. Sorting apparent in bank facies suggests turbulent depositional conditions and is interpreted to be largely associated with large magnitude, low-frequency events. Characterization of some floodplain surfaces is locally complicated by sand or gravel sheets (recent deposition).

Figure 61. Bank facies reveal poorly sorted floodplain sediments.

6) The *relic fines* group (Figure 62 and Figure 63) consists of deposits of generally high silt content, displays cohesive properties, and generally thickly-bedded (3-8’). This group of sediments generally only appears in erosional banks and was not observed in areas of recent deposition or bank construction. This group of sediments appear to be more laterally extensive downstream of VM 10. A few localized occurrences in bank facies were observed between VM 10 and 13 with little surficial indication of horizontal extent, but they are generally uncommon. All observed instances occur below 1050’ elevation which is within the maximum Missoula Flood stage modeled (~1,115’) by Benito and O’Connor (2003) for the Columbia River at the mouth of Rock Creek. This could be geologic coincidence as the deposits were not often observed to have distinctive bedding or laminations and many bank facies appeared massive. However, they could be the result of upstream re-working of slackwater fines and subsequent redeposition. “Relic fines” units often occupy more central portions of the valley floor unlike units showing laminations which tend to occupy only valley margins, frequently as terraces. They appear to be representative of depositional environments that do not currently exist in Rock Creek, possibly secondary deposition due to downstream obstructions (e.g. beaver dams or tributary alluvial fans that temporarily dammed the valley). Hand-texturing suggests they may also have slightly higher clay content than terrace materials.

Figure 62. Eroding facies of fine-textured sediments.


Figure 63. Thicker deposits of 'relic fines' in the valley floor.

Supply

The primary source for materials mobilized, transported, and deposited by more frequent peakflow events seems to be redistribution of active channel boundary sediments in alluvial reaches. Most of the recruitment seems to result from:

- ongoing dissection of high-relief bedforms - Bar dissection seems to occur during higher frequency peakflows Q1.01 to Q10 when free-overflow of the riffle crests and steep local water surface gradients on the downstream faces prevail. "Hot Spots" in stream power graphics on maps in Appendix B are indicative of such gradients (Figure 59).
- lateral erosion of banks with lower resistance and consolidation – This occurs generally as a function of low density of woody riparian plants and is moderated by content of cohesive fines as well as self-armoring by cobbles and small boulders as the generally poorly sorted floodplain materials are reworked (Figure 64 and Figure 65).


Figure 64. Poorly-sorted, unreinforced banks eroded (left) leaving larger clasts behind (right).

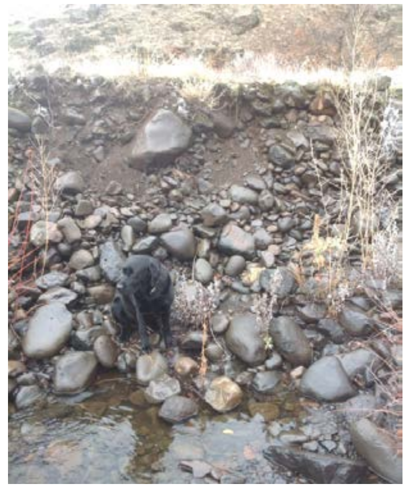



Figure 65. Self-armoring of bank toe as lateral erosion re-works poorly-sorted floodplain sediments.

Unnamed tributaries to Rock Creek between VM 14.1 and 17.0 appear largely decoupled in terms of sediment supply except during very low-frequency events. Where bed-sized materials were observed exiting these drainages, they were generally intercepted by floodplains and terraces (Figure 66). Some alluvial sediment continuity was observed for both named and unnamed tributaries at VM 12.0 and 14.0. However, throughout much of the lower mainstem of Rock Creek, fluvial sediments from most unnamed tributaries are intercepted by terraces or floodplains and provide generally few routine contributions to the active channel of Rock Creek.


Figure 66. High terraces between Bickleton Hwy and Quartz Creek often intercept many colluvial particles as well alluvial sediments from smaller, unnamed tributaries.

Sediment recruitment was noted from a variety of more consolidated materials (though at much slower rates), including terraces (Figure 67 and Figure 68), re-working of alluvial and debris flow fans (Figure 69), and cutting into indurated layers (Figure 70). The latter includes a location at ~VM 8.75 that was the only location noted where the bed was composed of and channel actively cutting into indurated sediments. Stripping of unconsolidated floodplain surface sediments (Figure 71) was also observed as a sediment source.

Some of the most noticeable landforms in lower Rock Creek are high terraces composed of pale silts along the valley margins (Figure 67). Though most apparent downstream of VM 5.5 in Rock Creek and VM 1.5 in Squaw Creek, similar features occur upstream but are subtler and diminish in relief. Some of the features appear on soil maps USDA (2013) as “loess”. Examinations of eroded facies at two locations upstream of Squaw Creek reveal thin bedding. Animal burrows are common in vertical faces as well as the upper surface and investigation of castings produces very few clasts, none of which were larger than about 30 mm in size. Terrace relief above the valley floor decreases in the up-valley direction and degree of dissection appears to increase. Thick silt deposits on valley margins were found as far upstream as the vicinity of the Luna Gulch confluence. Relatively little active toe erosion of these terraces was observed as they generally overly other clastic sediments (e.g. alluvial fans), or have self-armored from past erosion, or benches of toe ravel have been colonized and somewhat stabilized by woody hydrophytes. Peakflows exceeding the Q5 to Q10 seem necessary to engage these sediments.

Figure 67. Fine sediment (loess) sources from direct channel contact (left) are infrequent. Concentrated road runoff (right) drains onto fines overlying alluvial fan deposits.

Terrace treads slope downstream at approximately the same slope as the valley bottom. They also slope toward valley centerline. Due to slope toward valley centerline and differential degrees of lateral re-working (intrusion) by adjacent streams, down-valley slope is difficult to measure precisely. Based on a 3.28 ft LiDAR-derived DEM, down-valley slope was estimated as 2.0%, 1.9% and 1.7% in the vicinity of Squaw Creek VM 1.0, Rock Creek VM 5.1, and Rock Cr VM 3.0, respectively. Measurements along both corridors yielded estimates as high as 4.2%, though those are assumed to reflect some degree of bi-axial pitch. These features were first noted by Allison (1933) and are known to have been inundated multiple times by slackwaters of late-Pleistocene outburst floods (Benito and O’Connor 2003). Inundation from these events would have extended up the Rock and Squaw creek valleys to approximately Badger Gulch and Harrison Creek, respectively.

Figure 68. Re-working of poorly-sorted terraces with high cohesion. Terrace on left appears to have surficial armor layer from period of pre-incision re-working. Terrace on right is composed largely of matrix-supported materials (possibly from debris flow).

Figure 69. Re-working of historic alluvial and debris fan toes.

Figure 70. Exposures of indurated sediments were observed locally throughout the field-surveyed area, generally exhibiting greater erosion resistance and frequently associated with groundwater expression.

Figure 71. Floodplain stripping, most recently active during March 30, 2012 (~Q3).

Though most eroding channel boundaries appeared to have been active for some time, previous work (Glass 2009) noted that stream inventory field crews observed that “stream bank erosion is not widespread”. It is possible that the Q3 event in 2012 and/or other intervening events reactivated facies that had been less active for some years prior. It is also possible that reaches sampled in the 2009 study simply didn’t occur in eroding areas.

Supply of bed-sized particles from the upper watershed (upper Rock and Quartz creeks) was not notably abundant during field surveys. Gravel and cobble bars within the active channel were infrequent (Figure 72).

Figure 72. Active medial (left) and lateral (right) bars are infrequent upstream of ~VM 14 along Rock Creek.

Bed Organization

Bed particles in Rock Creek have several different scales of organization. This discussion focuses on 1) bedforms acting as hydraulic controls and 2) grain-scale organization.

As noted earlier, bedform hydraulic controls in alluvial reaches occur as “high relief” and “low relief” types.

- High-relief types most frequently have at least five feet of profile relief, but range from three to eight feet, and have the greatest profile influence through alluvial reaches. They result from sediment slugs deposited during very high magnitude peakflows (e.g. >Q25) such as the 1964, 1974, or 1996 events. These deposits get subsequently re-worked into (typically) one of two forms, both of which are usually actively eroding (during some portion of a year):
    - Diagonal bars (Figure 73) – all dissection (chute development) favors one side of primary channel centerline and usually cross into a "seam" channel that cuts headward along a resistant boundary. Most high-relief bedforms are some variation of a diagonal bar.
    - Transverse bars (Figure 73) – dissection results in chute development on both sides of a projected centerline of the primary channel, though there may be preferential flow to one side. The preferred side may switch through time. Transverse bars are less common and may be more of a temporary state as upstream/approach channel alignment is shifting.

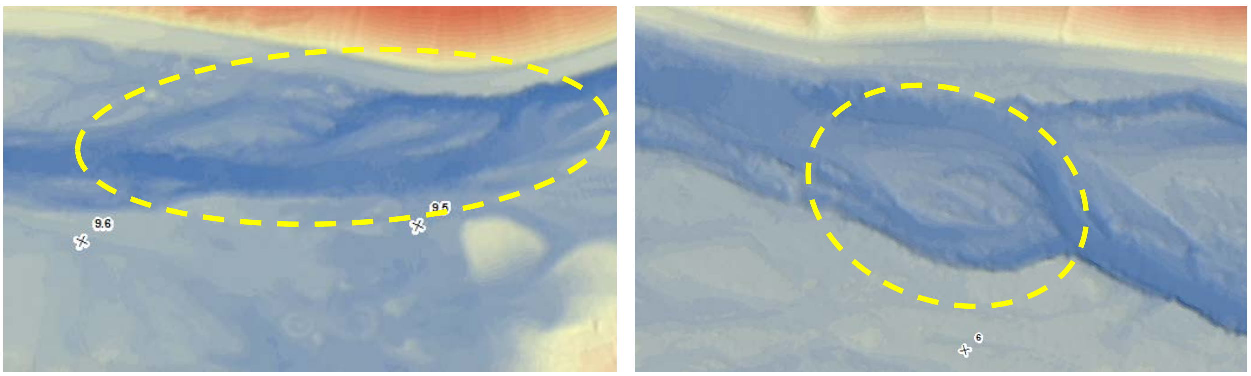


Figure 73. High-relief bedforms; diagonal bar (left) and transverse bar (right).

- Low-relief types have less than three feet of profile relief, usually less than 1.5 feet. These are generally inset features that only serve as hydraulic controls under average daily winter conditions and drowned-out by most freshets. They take a variety of forms, but most commonly:
    - Diagonal bars (Figure 74) – all dissection (chute development) favors one side of primary channel centerline and usually cross into a "seam" channel that cuts headward, usually along a resistant boundary.
    - Low-gradient riffles (Figure 74) – Interpreted as being fairly stable on average. Generally, a result of sorting downstream from localized bed scour. Likely somewhat spatially ephemeral depending on magnitude of discharge events.

Figure 75 illustrates the mechanism by which dissection of high-relief diagonal bars in Rock Creek is likely occurring. Sediments deposited initially as a unit (e.g. "slug" or "wedge") during a large, infrequent peakflow event are re-worked incrementally through time, driven by local gradient. Crossover flow concentrates into a "seam" channel which incises, usually along a resistant boundary. As the seam channel migrates headward, local gradients steepen, capture crossover flow, and eventually form channelized "chutes". The youngest chutes are upstream (e.g. Chute 5) and the oldest are downstream (e.g. Chute 1) and become abandoned or require increasing discharge for activation as younger chutes upstream mature and capture more flow. This process may occur over decades.

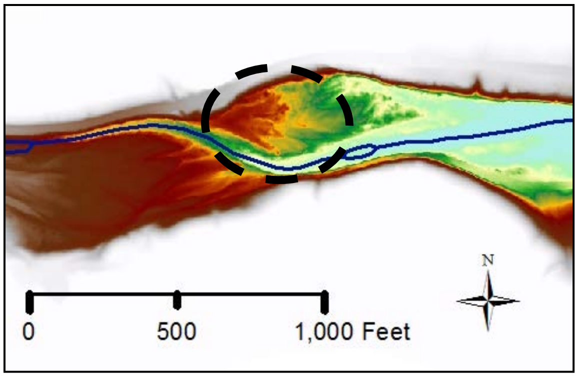
The persistent geomorphic influence of the 1964, 1974, and 1996 peakflows on channel forms and processes in Rock Creek is consistent with Church et al. (1998) who noted that bed structure of gravel bed channels may reflect the history of dominant flows rather than more recent flows. Review of aerial photographs for the subbasin indicates the greatest degree of change in channel alignments occurred between the 1960 and 1969 photos. This is interpreted as being a result of the 1964 peakflow event which appears to have been a signature event.

Figure 74. Low-relief bedforms: diagonal bar (left) and low-gradient riffle (right).

Figure 75. Schematic showing development of high-relief diagonal bar (left) and upstream view of chutes (right).

Given the magnitude and extent of disturbance and generally low stream-power nature of Rock Creek in most years, combined reaction and relaxation time is sufficiently long (given the system is still adjusting 50-years post flood) and disturbance recurrence sufficiently short (50 years or less), the status quo for Rock Creek may be a constant state of channel adjustment.

Though not an active-channel bedform per se, another manifestation of this routine, unsteady state are very large (valley-scale) lobate features visible in a number of locations throughout the system (Figure 76) that, like high-relief bedforms, persist on decadal or longer timescales.



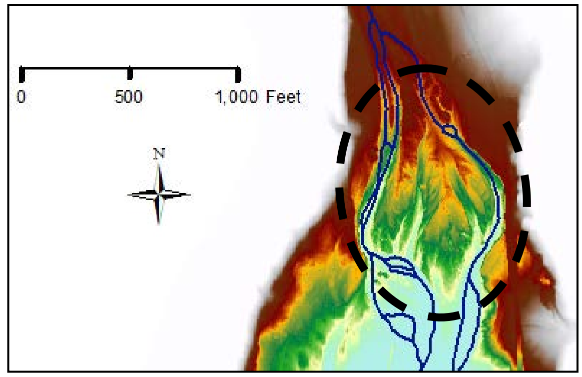


Figure 76. Valley-scale, lobate features located within (left, ~VM 9.3) and at downstream end of (right, ~VM 5.5) of entrenched reaches.

Several different grain-scale organizations pertinent to mobility and transport conditions were observed throughout field surveys. Imbrication and clustering of cobbles to small boulders was common (Figure 77). Ribs were also fairly common and typically composed of large cobble to medium boulders (Figure 78). Clusters can generally increase boundary roughness and influence hydraulics, sediment dynamics, and bed stability (Wohl 2010) by delaying incipient motion (Brayshaw 1984) and increasing critical shear stress above that required to mobilize isolated particles (Papanicolaou and Ely 2005). The upshot is that they can substantially reduce availability of sediment for transport (Brayshaw 1984, Tribe and Church 1999).


Figure 77. Clustering (left) and imbrication (right) of larger clasts is frequent along the mainstem of Rock Creek.


Figure 78. "Ribs" (left and right) are commonly observed in plane-bed and low-gradient riffles, sometimes associated with clusters (right).

Mobility and Transport

As far as mobility of bed particles is concerned, the active channel invert is generally well-armored and resistant to motion except where re-working of sediment slugs by bar dissection occurs. This process is driven by steep local gradients. Andrews and Smith (1992) proposed a two-phase transport model for streams with armored beds. Phase 1 (marginal) transport (also noted by Carling, 1987) occurs where a well-developed armor layer exists and transported materials pass over a stable, coarser bed.

This has been observed occurring in Rock Creek associated with the Q3 event in 2012 (Figure 79) which deposited two vertical feet of gravel and cobble over the PIT tag antennas immediately upstream of the mouth of Squaw Creek. These deposits were re-worked within several months following the event until the bed was almost back to its original elevation by early summer (B. Allen personal communication). Gravel sheets on floodplain (Figure 51) may create similar, phased transport regime in overbank areas.

Figure 79. PIT-tag array near mouth of Squaw Cr before (left) and immediately after (right, buried) 2012 peak flow (~Q3). Photos courtesy of B. Allen, USGS.

Phase 2 transport (when armor layer breached) is infrequent and when channel morphology changes can take place. In Rock Creek, Phase 2 transport probably requires at least a Q10 to Q25 or greater magnitude discharge. The well-packed boulder sub-pavement that appears periodically in runs and pools through the surveyed profile is likely immobile with most human timeframes.

Combined with dramatic range between peak and base flow magnitudes, sediment dynamics would be one of the biggest challenges to performing instream habitat work in Rock Creek.

Channel Gradient, Pattern, and Behavior

Nearly all reaches in the study area have average gradients less than 0.06 (Figure 80). One notable exception is on Luna Creek at approximately VM 4.7 at a fault intersection, but even there, average gradient is still less than 0.07. Rock Creek downstream of Quartz Creek is less than 0.025 in its entirety and decreases to less than 0.02 downstream of Luna Creek, and less than 0.016 downstream of Squaw Creek. Only one short (<700 lineal foot) reach (on Rock Cr immediately downstream of Squaw Cr) in the entire study area was under 0.01. Excepting the faulted area mentioned previously, most of Luna Creek is between 0.02 and 0.03. Squaw Creek is between 0.015 and 0.03. White Creek has two reaches between 0.04 and 0.05 near the mouth, then diminishes to 0.02 to 0.03. Harrison Creek is 0.03 to 0.04 with the uppermost reach 0.044. Upper Rock Creek (upstream of Quartz Creek confluence) is 0.035 to 0.06. Downstream of Box Canyon, Quartz Creek is mostly 0.025 to 0.03, while upstream of Box Canyon, Quartz Creek is 0.04 to 0.056. Profiles (Figure 81) show prevalence of bedrock control on Rock and Quartz creeks.

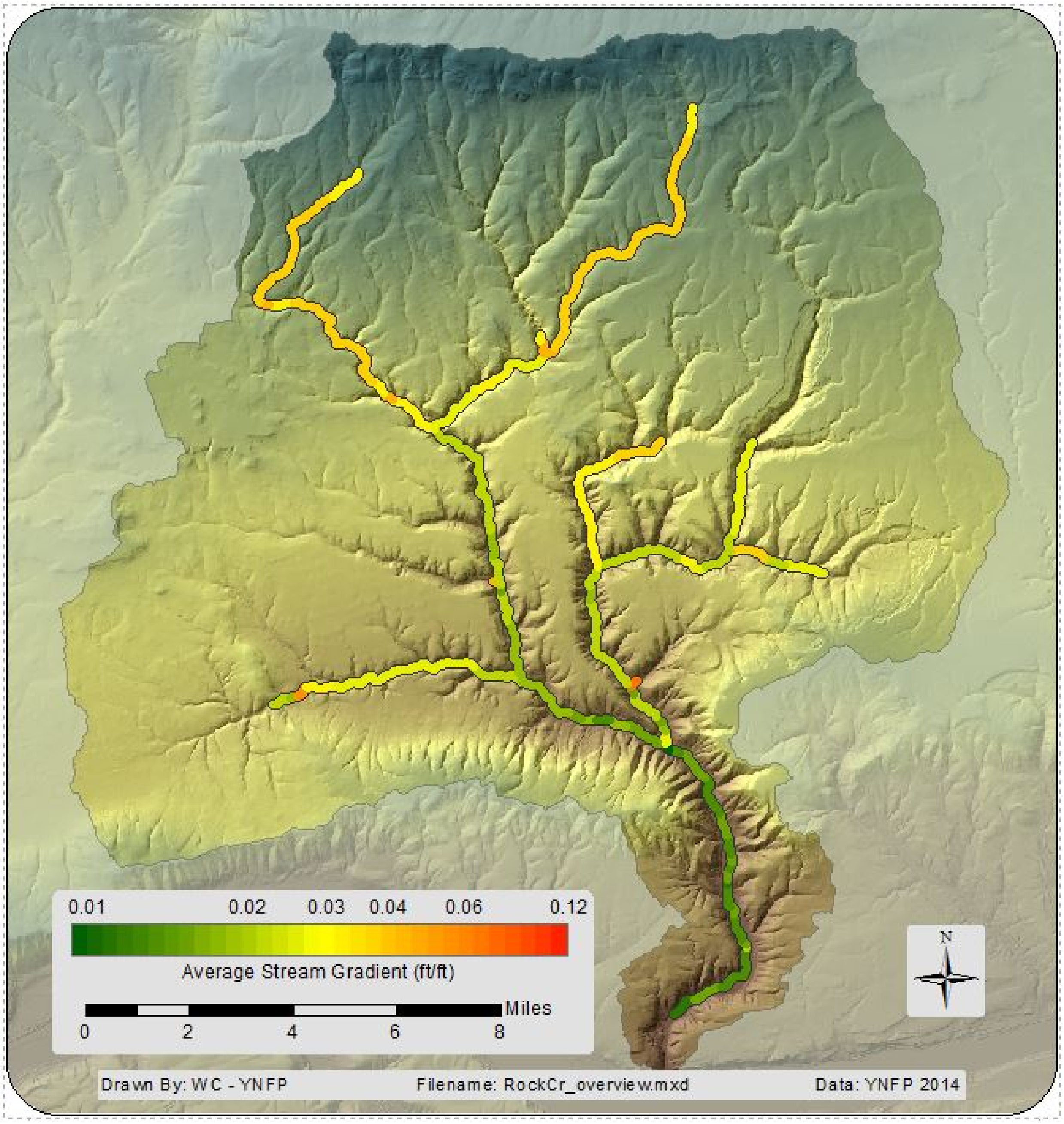


Figure 80. Average stream gradient (LiDAR-based) map for reaches within the study area.

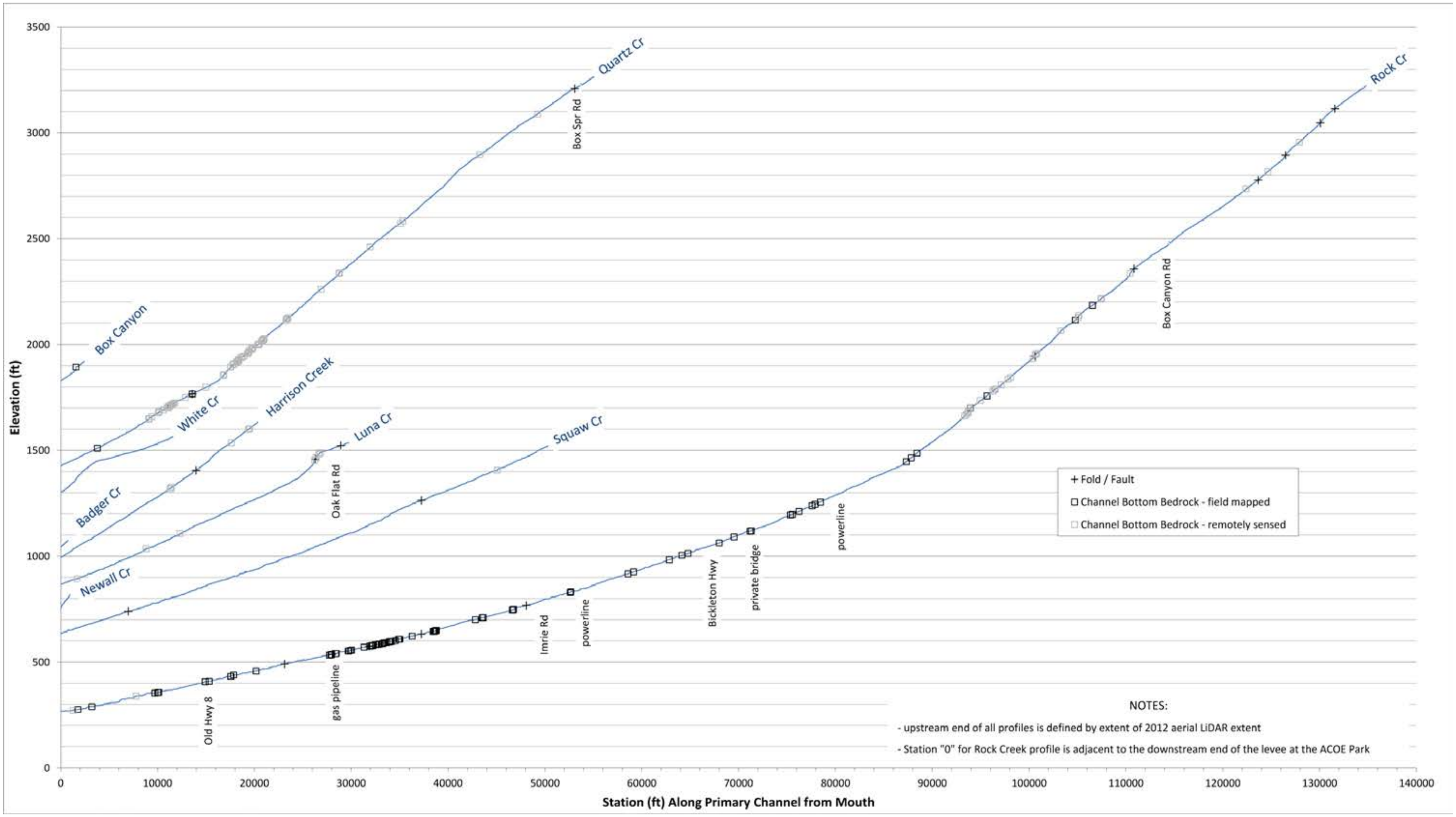


Figure 81. LiDAR-derived profiles for stream reaches and geologic control within study area (a larger format version is also presented in Appendix C).

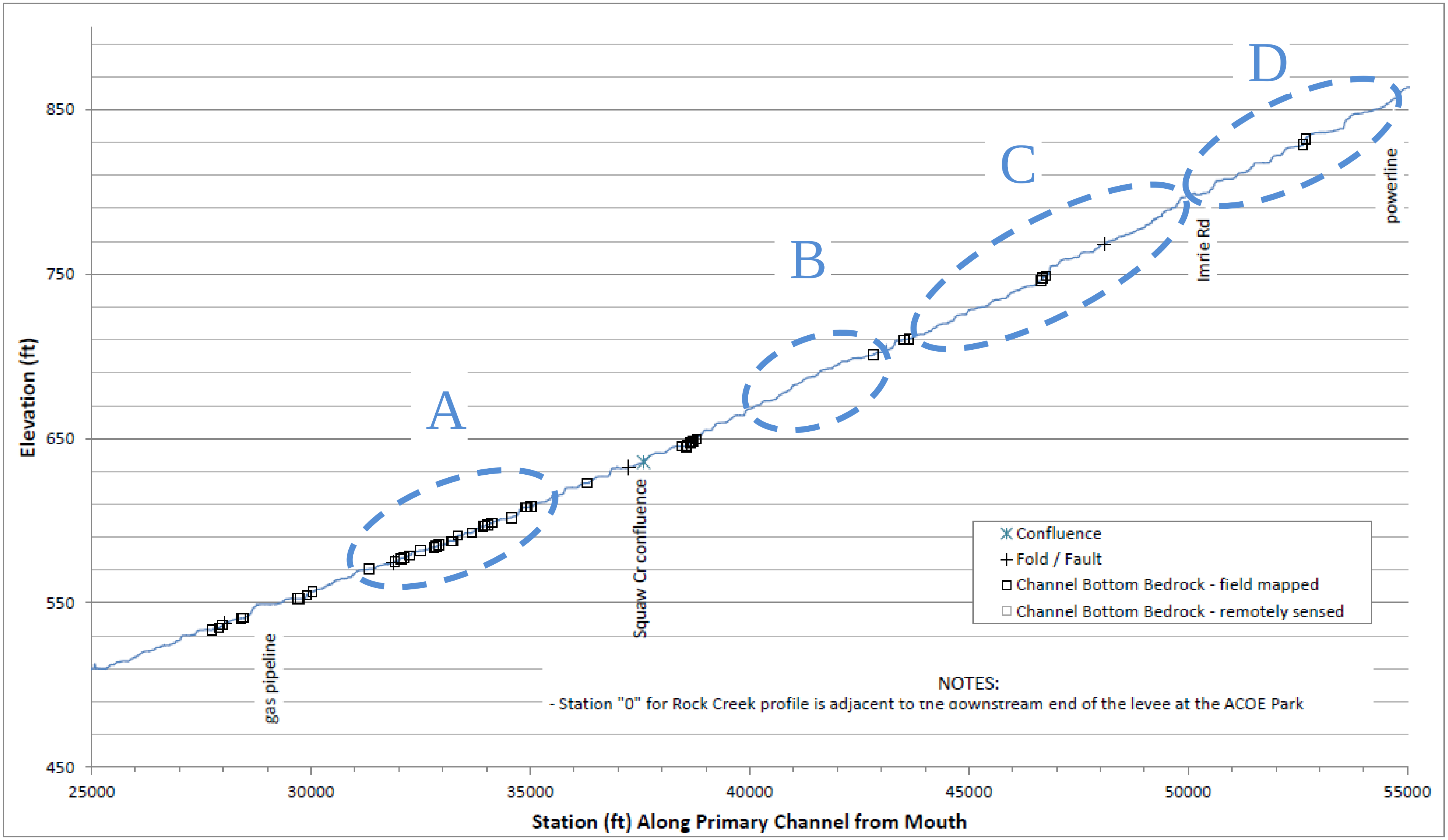


Figure 82. Rock Creek profile ~VM 5.2 to VM 10.8.

Stream profiles generally have a concave shape, though convexities can occur in areas of geologic control and/or sediment deposition. Remote-sensing of bedrock was particularly challenging in forested areas and likely resulted in under-mapping of channel bottom bedrock contacts. Figure 82 focuses on an interesting segment of Rock Creek and includes annotations for reference purposes. "A" is the largely bedrock-controlled reach where Rock Creek crosses several folds and the main axis of the Goodnoe Hills. "B" is a profile convexity where Rock Creek enters a wider valley bottom and exits a somewhat entrenched reach. Historic aggradation of alluvial sediments is likely, though the current trend is unclear. "C" is a region where the upstream and downstream portions of the profile are vertically offset. In this case, the downstream portion of the profile may represent segment through which headward incision has already passed, possibly due to historic channel excavation near station 43,000 (Figure 83). The apparent knickpoint at station ~47,000 is a high-relief diagonal bar (the bedrock in the vicinity is located near the toe) which, like most of the other high-relief diagonal bars is being dissected incrementally. This stream segment is also interesting because of the near-absence of bedrock surface exposures, yet the reach is mostly perennial. This is likely due to increases in discharge due to springflow in the area. "D" is a portion of the profile that provides a nice example of the influence of a sequence of high-relief bed controls.

Figure 83. Alder rooted near top of bank indicates 5-6 feet of incision has occurred fairly recently (likely <50 years).

The segment noted in "C" is one of several largely perennial reaches documented by the USGS and YN during low-flow habitat surveys. Many of these largely perennial reaches are somewhat more entrenched within adjacent valley fill than seasonal reaches upstream or downstream. Figure 84 shows an example of a sequence that appears in multiple segments of Squaw and Rock creeks where a perennial reach is interspersed with unentrenched, seasonal reaches immediately upstream and downstream. The perennial condition could be a function of spring/seep additions to flow, a decrease in subsurface hydraulic conductivity (e.g. bedrock), and/or a local reduction in evapotranspiration. However, given multiple occurrences of this sequence, a subtler relationship should be considered: greater wetted perimeter for a common discharge may generate more infiltration within unentrenched reaches. Thus, the dry reaches that don't appear to provide a habitat function during baseflow conditions may be important recharge areas for the unconfined aquifer that helps sustain flow within entrenched reaches. This is not proposed as a universal explanation as some entrenched reaches are seasonal.

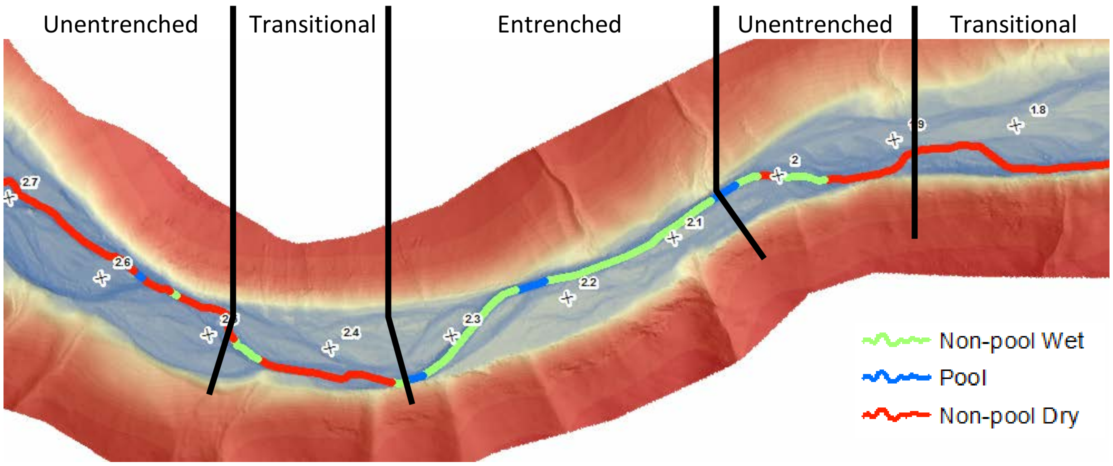


Figure 84. Example of relation between entrenchment and perennial habitat. Note whitish floodplain areas adjacent to "pool" and "non-pool wet" habitat units and bluish valley bottom adjacent to "non-pool dry" units. Whitish color indicates higher elevation relative to blue.

As discussed in the "Bed Organization" sub-section, the combined duration of the system's post-disturbance reaction and relaxation times relative to the expected recurrence of such events, it seems likely that Rock Creek is in a near continuous state of adjustment. Indicators of local aggradation, primarily alders (either live or stumps), were noted in several locations (Figure 85 and Figure 86). In general, indicators of incision were more abundant and widespread. Though most were subtle and indicated less than a foot or two of incision (Figure 87), some indicate more significant vertical and/or horizontal channel movements (Figure 88).

Figure 85. Emergent, live alders where bed has recently aggraded.

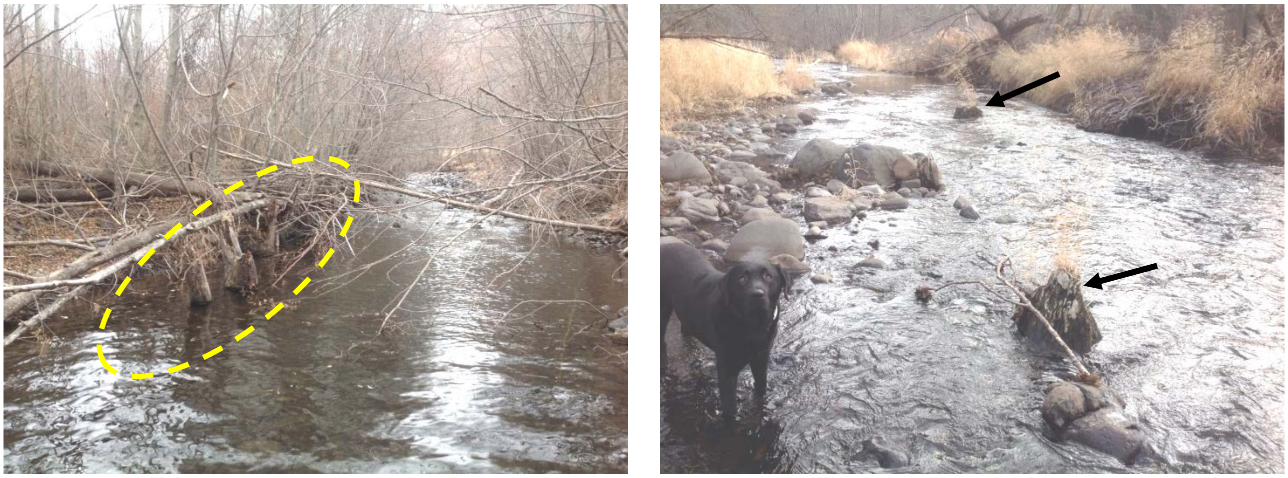


Figure 86. Emergent stumps in areas where bed has previously aggraded.

Figure 87. Alders suggest modest incision has occurred based on position of root crown relative to water surface and growth form of roots.

Figure 88. Pedestalling of mature alders where channel has incised and laterally migrated.

The most common and widespread channel adjustment in the subbasin appears to be re-working/dissection of sediment slugs into (primarily) diagonal bars. The process, described and illustrated in the “Bed Organization” sub-section specific to high relief bars, is observed on low-relief bars as well. In all cases, the “seam” channel (Figure 89) appears to be the driver as it incises in the upstream direction approximately parallel with the valley axis. Chutes form to connect the original channel (now perched) to the seam. Older/downstream chutes become less active (requiring greater discharge to activate) as new chutes form as the sequence progresses headward (Figure 90).

Figure 89. Looking upstream at mouth of mature diagonal bar "seam" channel (right).

Figure 90. Downstream view at early stages of “seam” development at future head of diagonal bar.

Given the narrow ecological margins for alder establishment and survival, they typically form lineal cohorts on the margins (sometimes within) the active channel. Once established they can often persist even if the channel moves away, but there is often a spatial gap between cohorts.

Gaps may be twenty or more feet wide and effectively alleys of lower hydraulic resistance that concentrate flow in narrow zones of the floodplain or old channel alignments (Figure 91). This can increase shear in a narrow zone and stimulate channel development (Figure 92). In time, the primary channel may "switch" back and forth between two or more alignments.

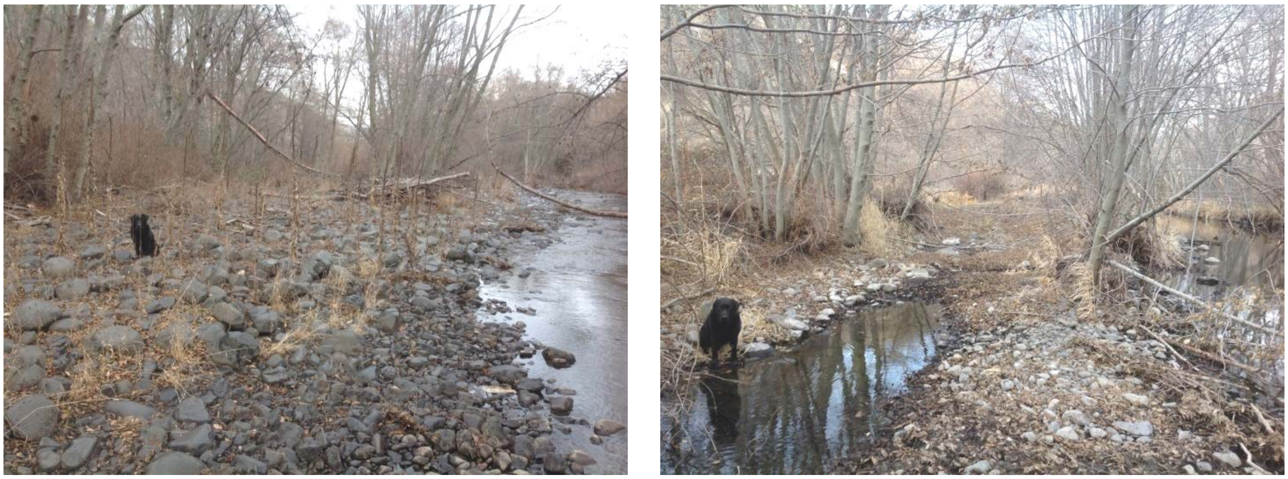


Figure 91. Hydraulic "alleys" between narrow, linear bands of early seral riparian vegetation.

Figure 92. Cross-over flow through strip of alders converts floodplain (that may have previously been a channel) into active channel.

Peakflow Stage Indicators

Field observations between valley miles 3 and 17 of Rock Creek in December 2013 and January 2014 found field indicators of historic flood stages to be ubiquitous. Relatively fresh mineral and organic deposits along banks and floodplains occurred throughout the surveyed area (Figure 93 and Figure 94) consistently at 4.5 to 5.0 vertical feet above bed controls. A few localized exceptions were as low as 4.0 and high as 5.5 feet. This elevation was also correlated with the top of accumulations of woody debris racked into riparian vegetation. Channel-margin and floodplain sand deposits still mostly unvegetated but showing early colonization by grasses were correlated at similar relative elevations. Recent tree scars (Figure 95) on streamside trees is correlated with the same stage. Given that water-year (WY) 2013 and early WY2014 lacked significant peak events, finer organic debris, uncolonized / barely colonized sand deposits, and fresh tree scars were interpreted to result from the March 30, 2012 event (Q3).

Figure 93. Recent sand deposits (left) on floodplain correlate with elevation of top of debris line (right, arrows) 4.5 to 5 vertical feet above channel controls; likely resulting from 3/30/2012 event.

Figure 94. Floodplain depositional features indicating minimum high water surface and/or inundation: band of detritus (left, circled) and gravel sheet with detritus patches (right).

Figure 95. Scarring on the upstream faces of bank alders. Light scarring (left, circle) from 2012 event correlated with debris accumulation (left, arrow). Scarring from multiple events (right).

Robust indicators from past, higher magnitude peakflow events are widespread and include: scoured roots of non-riparian tree species (Figure 96 and Figure 97), scarring of tree trunks (Figure 98), fluvially transported debris (Figure 98, Figure 99, and Figure 100), altered growth forms (Figure 101), and translocated and/or partially buried human debris in alluvial deposits (Figure 102, Figure 103, Figure 104, and Figure 105).

Figure 96. Scouring of oak trees rooted on the margin of high floodplain surfaces.

Though outside the scope of this study, dendrochronological (e.g. for woody vegetation) or archeological (e.g. for buried human debris) dating techniques could be used to more precisely date various geomorphic surfaces.

Figure 97. Buttressing and scour of oak tree roots along margin of high floodplain.

Figure 98. Modern high-stage indicators include scarring of upstream faces of trees. Rooted on high floodplain surfaces (left) and lower-lying areas with racked debris (right).

Figure 99. Woody debris 'raft' on high floodplain upstream of ponderosa pines, buried by years of needle-cast (left). Individual debris pieces visible with removal of needle cover (right).

Figure 100. Fluvially transported and/or re-worked walnut trees on highest portion of floodplain (~VM 7.7).

Figure 101. Riparian (left) and floodplain (right) trees with down-valley lean/sweep rooted on high floodplain surfaces.

Figure 102. Bridge (left) that was washed off its piling foundation 1500 lineal feet upstream (right) and deposited by the 1964 flood on a high floodplain surface (~VM 10.1).

Figure 103. Remnants of bridge (left) washed-out and deposited by the 1964 flood on a high floodplain surface 1900 lineal feet down-valley (~VM 8.6). Note sediment wedge (circled) to right/upstream of bridge debris. Surface clasts wedge have dense lichen cover (right).

Figure 104. Bridge timber (left) and pile (right) deposited on high floodplain surfaces.

Figure 105. Wheel (left, at arrow) and old pickup truck (right) partly buried in alluvial sediments on high floodplain surfaces.

Hydraulic Model Review

Hydraulic models can be highly valuable tools in assessing both geomorphic form and process. Given the high potential for utility related to this report, an uncalibrated HEC-RAS model produced by Environ (2013) was reviewed for suitability in assisting field indicator interpretation.

Relative stationing (e.g. horizontal distance from an arbitrary point) is a commonly accepted technique for locating cross-sections in hydraulic models and was used by Environ (2013) in their HEC-RAS model. Since their datum was not reported, it was difficult to locate the sections in absolute space making detailed, localized review difficult. A map (Figure 3 in Environ 2013) at approximately 1:85,000 scale was used to identify unlabeled cross-sections based on a sequence from known points (e.g. upstream or downstream of tributary confluences). Map annotations and field surveys for "Badger Gulch" where an unnamed tributary meets Rock Creek (~1 mile upstream of the Badger Creek confluence) created some uncertainty while reviewing the upstream portion of the HEC-RAS model. This author's local topographic knowledge from field surveys and LiDAR was used to select HEC-RAS output plots presented in Appendix B of the Environ (2013) report for comparison to field indicators observed in this study.

A high-degree of valley relief (50-200 feet) in the published cross-sections (Appendix B in Environ 2013) made it difficult to differentiate the ten water surface elevations (WSEs) which occurred over a range of about seven feet (Figure 106). Fortunately, resolution of the electronic version of the Environ (2013) report facilitated zooming to a scale where some of the WSEs could be differentiated (Figure 107 and Figure 108). Comparison of zoomed graphics from Environ (2013) to field indicators observed by this study suggest the modeled Q100 water surface under-predicts field indicators (e.g. tree scars), typically by 5 vertical feet or more. Lower magnitude events were difficult to distinguish graphically because of scale, so tabular results (Appendix C in Environ 2013) were used.

One potential contributor to the difference between the field stage indicators observed by this study and modeled WSE could be a change in hydraulic boundary conditions. In other words, it is possible that channel geometry or vegetation could have changed between when the highest stage indicators were created in 1964, 1974, and/or 1996 and when topographic data used in the model were collected (e.g. LiDAR in 2012). Lack of historic topographic data precludes a direct comparison to surveyed topography.

However, evaluation of modeled WSEs with more recent indicators established under known comparable boundary conditions facilitates a more controlled comparison. Field indicators from the 2012 event which occurred approximately three weeks prior to the LiDAR flight were utilized. Field surveys associated with this report note 2012 WSE indicators were typically 4.5 to 5 vertical feet above channel controls along the entire 14 miles of Rock Creek surveyed in 2014.

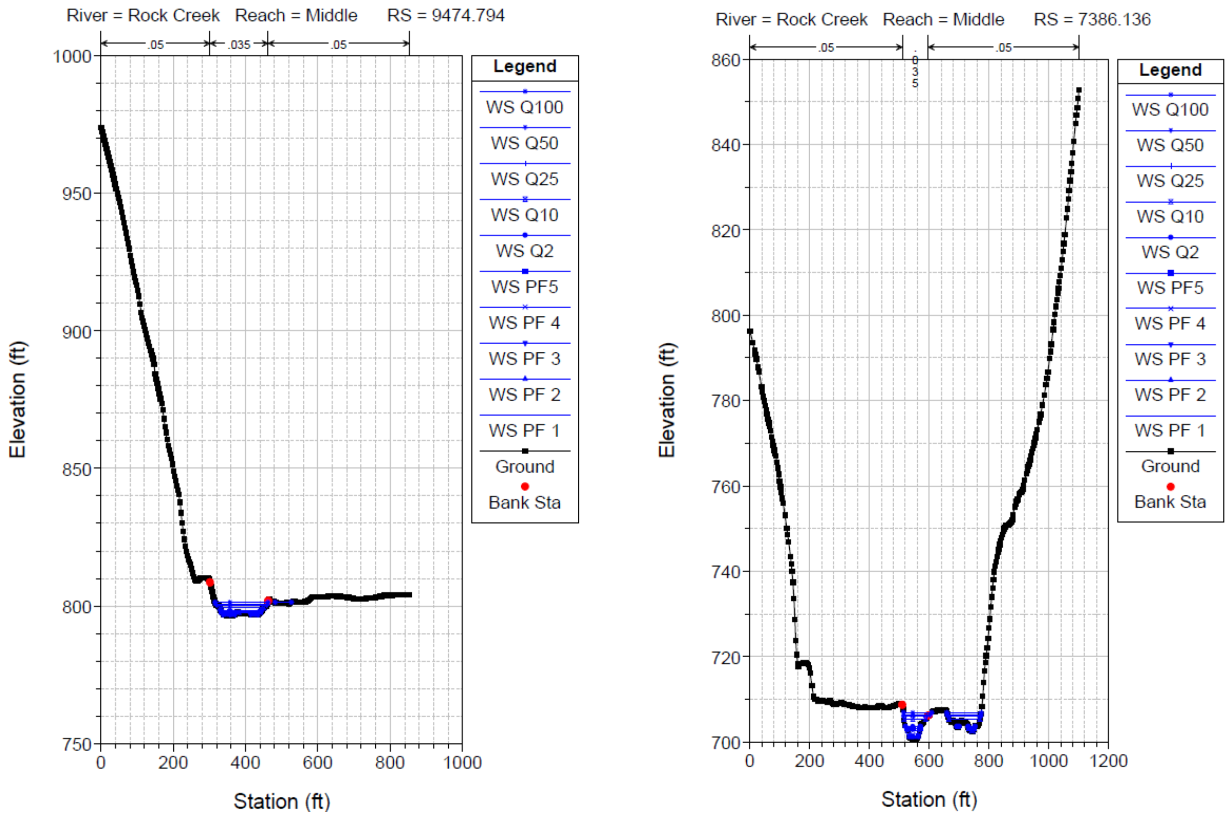


Figure 106. Actual published size of cross-section outputs (Environ 2013).

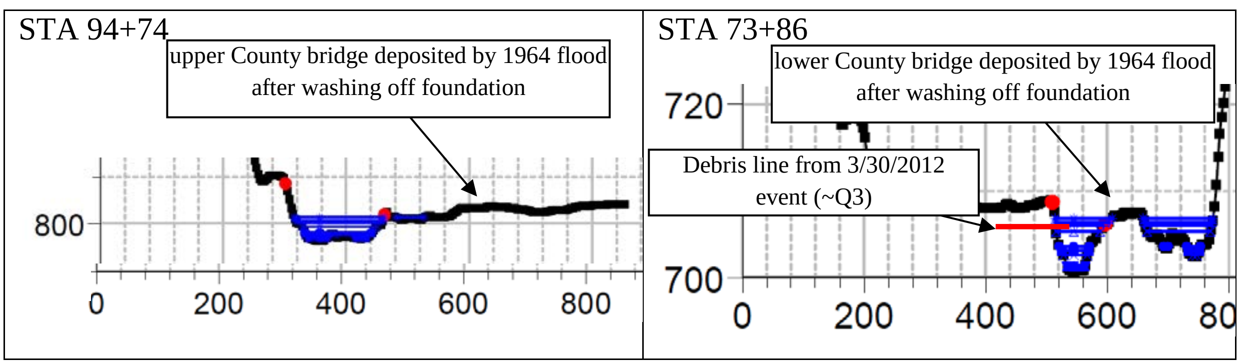


Figure 107. Close-ups of two Rock Cr ("Middle" reach) cross-sections modeled by Environ (2013) with YN field-observed stage indicators superimposed; uppermost horizontal blue line is the 100-yr modeled water surface.

The 2012 peakflow event is correlated with a Q3 recurrence (see "Peak Flow Hydrology" section of this report). Since Q3 hydrology was not modeled, 2012 field indicators are compared to the Q2 WSE from the HEC-RAS model. Tabular data presented in Appendix C (Environ 2013) were used to provide greater precision than what could be derived from cross-section graphics (Appendix B in Environ 2013).

In the absence of specific discussion to the contrary, it is assumed that cross-section bathymetry for HEC–RAS inputs was also LiDAR generated. This would not be unreasonable since LiDAR can penetrate shallow water, and flow conditions at time of LiDAR collection would not have been very deep. The effect of aerially-derived bathymetry was not evaluated, but could affect hydraulic model results.

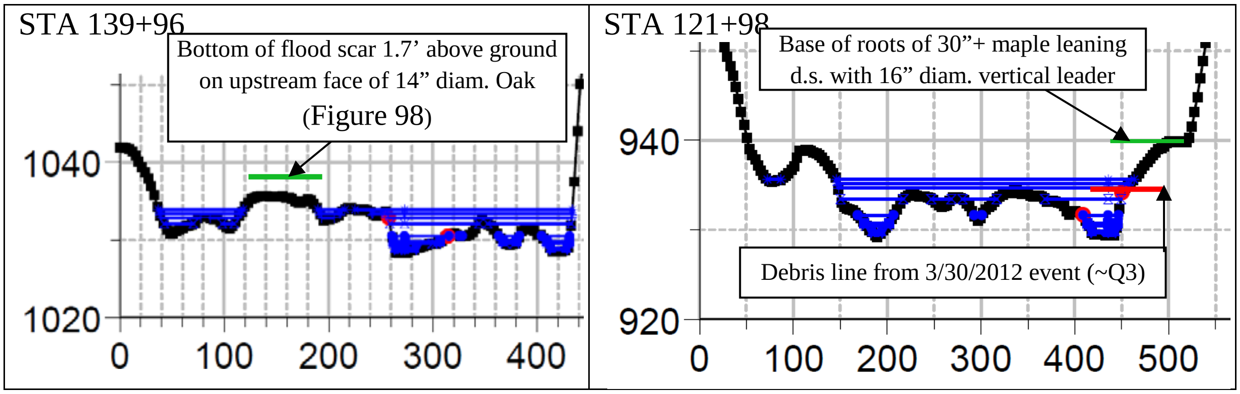


Figure 108. Close-ups of two Rock Cr ("Below Badger" reach) cross-sections from hydraulic model (Environ 2013) with YN field-observed stage indicators superimposed; uppermost horizontal blue line is the 100-yr modeled water surface.

Given generally wide toe widths (>40 feet), WSE (Appendix C in Environ 2013) for the lowest modeled discharges (0.7 to 2 cfs) was assumed to be the bed elevation. Using the lowest modeled WSE as a datum, modeled Q2 WSE for Rock Creek has a typical stage of approximately 2 to 3 feet. Modeled Q100 stage along Rock Creek typically ranges between 4.5 and 6 vertical feet, with a few cross-sections up to 7 feet.

Field indicators observed in this study suggest the HEC-RAS model under predicts the Q2 WSE by about 2 to 3 feet. Given this, it seems reasonable to attribute much of the 5 to 6 foot difference between Q100 model results and field indicators to the model inputs (as opposed to on-the-ground changes in boundary conditions).

Factors likely contributing to differences between model results and field indicators include large cross-section spacing, low resistance (n) values, and errors in hydrologic model inputs.

Station-values reported in Environ (2013) indicate moderately coarse (~200-500') cross-section spacing. While not ideal, this is sometime adequate for large channels with simple planform and profile where cross-sections are located at the crests of hydraulic controls. However, reaches in the Rock Creek HEC-RAS model generally have complex channel patterns. Field observations in this study suggest that hydraulic controls change with discharge. Thus, accuracy of future 1D modeling might be improved by partitioning hydrology based on objective (e.g. low-flow, Q2-Q5, and Q25-100) into separate model simulations. Environ (2013) does not discuss criteria for selecting modeled cross-section locations, so suitability of their cross-section locations is not evaluated herein.

Transverse and diagonal bars are a significant hydraulic influence throughout the lower 13 miles of Rock Creek with many having 4-8 vertical feet of profile relief. These features have multiple chute channels and, frequently, perennial vegetation growing within the active channel (Figure 109).

Figure 109. Upstream view of multiple chutes and perennial vegetation within active channel at crest of transverse bar.

Model inputs for resistance values reported by Environ (2013) are generally low and seem to reflect grain roughness only. Pebble counts are noted multiple times, but there is no mention of resistance due to in-channel vegetation and channel form. Field observations in this study indicated vegetation and channel form are significant hydraulic influences in Rock Creek and tributaries. Examples of multi-thread reaches modeled with single cross-sections and low roughness values are presented in Figure 110.

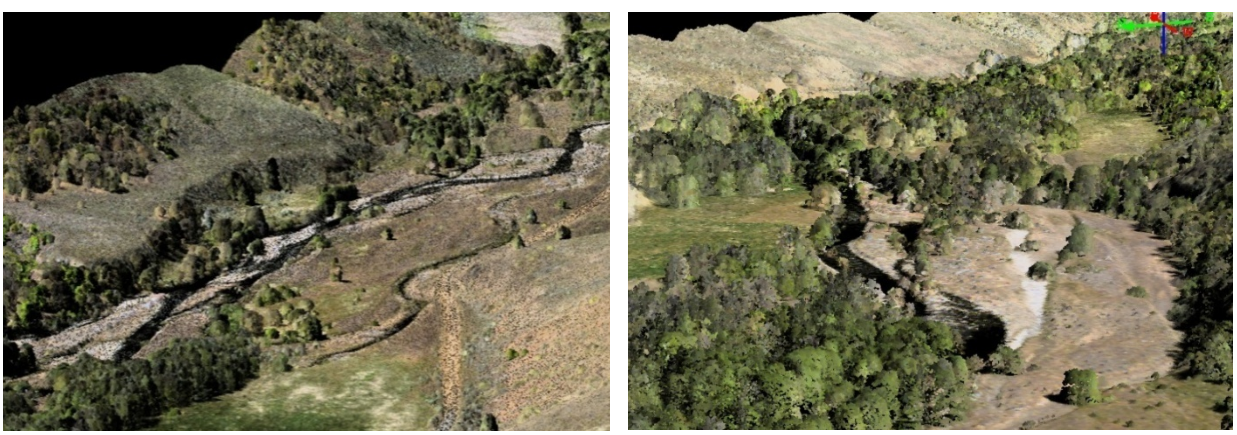


Figure 110. Oblique views of selected multi-thread reaches of Rock Creek with low roughness values. Left, looking upstream at station 66+54 (~VM 8.1 this report) where channel n = 0.035 and floodplain n = 0.05. Right, looking downstream at station 52+67(~VM 7.6 this report) where entire section was modeled with n = 0.035.

Vegetation growing within the active channel occurs throughout reaches in the Rock Creek HEC-RAS model. It is frequently associated with transverse and diagonal bedforms (Figure 111) where mature alders of patchy distribution prevail and frequently trap woody debris. Modeling complex bed features and vegetation relationships as exist in lower Rock and Squaw creeks with a 1-dimensional model (e.g. HEC-RAS) and wide cross-section spacing requires some tenuous assumptions and is a challenging endeavor at-best.

In some reaches, this study observed woody vegetation encroaching aggressively and almost spanning the active channel (Figure 112). The hydraulic influence of woody vegetation rooted nearly continuously across the channel is particularly notable downstream of the Luna Gulch confluence (~VM 10.8-11.0), upstream and downstream of Imrie Road (~VM 9.8-10.3), upstream of the Squaw Creek confluence (~VM 7.8 – 8.0), and downstream of the Longhouse (~VM 3.2).   The active channel in these areas is often dominated by shrubs and/or smaller alders (<4” basal diameter). Coyote willow is particularly robust and persistent in these reaches, often with basal diameters greater than 2 inches. Based on low-flow data (Allen et al. 2014), it seems many of these reaches dry seasonally, but must have somewhat shallow summer water tables.

Figure 111. Downstream view of multiple chutes and perennial vegetation within active channel at crest of diagonal bar. Mid-stream trees recruited woody debris during recent freshet (<$Q_{1.01}$).

Figure 112. Examples of perennial vegetation growing within and crowding active channel.

A cursory review of model input hydrology revealed inconsistencies between modeled values used to populate the HEC-RAS model (Appendix C in Environ 2013) and those published in the body of the report (Table 10 in Environ 2013). Q10 and Q100 values were selected for specific comparison (Table 9 this report).

Table 9. Calculated peak flows for 10 and 100-year recurrence events; "Table 10" values are from the body of the Environ (2013) report and "Appendix C" values are from HEC-RAS tables in Environ (2013) and represent model input hydrology.

	Q10		Q100	
	Environ 2013 Table 10	**Environ 2013 Appendix C**	**Environ 2013 Table 10**	**Environ 2013 Appendix C**
Rock / Squaw Confluence				
Rock Cr above Squaw Cr	2,176	2,257	5,424	5,625
Squaw Cr	1,524	1,070	3,799	1,968
Rock Cr below Squaw Cr	3,207	3,211	7,993	5,904
Rock / Luna Confluence				
Rock Cr above Luna Cr	1,582	1,909	3,942	4,760
Luna Cr		1,128		2,812
Rock Cr below Luna Cr	2,176	2,257	5,424	5,625
Rock / Badger Confluence				
Rock Cr above Badger Cr		1,273		3,173
Badger Cr		636		1,587
Rock Cr below Badger Cr	1,582	1,909	3,942	4,760
Squaw / Glass Canyon (White Cr)				
Squaw Cr above White Cr	681	681	1,698	1,698
White Cr	503	503	1,253	1,253
Squaw Cr below White Cr	999	999	2,491	2,491

Values presented in the body of the Environ report ("Table 10" columns, in Table 9 above) were reasonably close to values calculated using Sumioka et al. (1998) for this report, with differences small enough to be explained by methodological differences in drainage area and/or mean annual precipitation determination. HEC-RAS input values ("Appendix C" columns, in Table 9 above) generally differ from Table 10 (Environ 2013) values, quite significantly in some cases:

- Squaw Cr and Glass Canyon (White Cr) confluence: all values are identical.
- Squaw Creek at the Rock Creek confluence: Q10 and Q100 model inputs (Appendix C in Environ 2013) are 30% and 48% lower, respectively, than Table 10 (Environ 2013) values.
- Rock Creek downstream of Squaw Creek: Q100 model input (Appendix C in Environ 2013) is 26% lower than Table 10 (Environ 2013) values.
- Rock Creek between Badger and Luna creeks: Q10 and Q100 model inputs (Appendix C in Environ 2013) are 21% greater than Table 10 (Environ 2013) values.

- Rock Creek between Luna and Squaw creeks: Q10 and Q100 model inputs (Appendix C in Environ 2013) are higher, but close (+3%) than Table 10 (Environ 2013).

As noted in the "Peak Flow Hydrology" section of this report, regional equations (Sumioka et al. 1998) under-predict Q2 and Q100 discharges based on the local regression equation by 114% and 71%, respectively. Hydrology inputs into the HEC-RAS model (Environ 2013) based on regional equations seems a likely contributor to differences between model WSE results and field indicators observed in this study. Inconsistency in model inputs (differences between Table 10 and Appendix C, Environ 2013) obscures our ability to evaluate the effect. Refinement of hydrology inputs to better simulate field conditions is a suggested area for future model development.

Increased incorporation of field-based data is another area for future model refinement. Environ (2013) notes that 18 cross-sections were field surveyed using a total station and then localized using GPS (of unspecified make/model) and Google Earth. It is unclear if these data were incorporated into the hydraulic model and, if so, how datum issues were resolved with LiDAR data. Model results in the Appendices B and C of Environ (2013) have a 1:1 occurrence with LiDAR-based sections in their map (Figure 3, Environ 2013), suggesting ground-based cross-sections were not used in their HEC-RAS model. That said, field-based surveys are excellent opportunities to verify remotely-sensed conditions, particularly bathymetry and changes in roughness. Additionally, elevations of the many WSE indicators can be collected.

HEC-RAS results (Environ 2013) were not used in this report due to the magnitude of differences between their model results and our field-observed indicators coupled with concerns about model quality-control. Sediment model results (Environ 2013) were similarly disregarded in this report given their dependency on hydraulic model results. Based on this review, results of the existing HEC-RAS hydraulic and sediment model are not suitable for predictive or design purposes.

MANAGEMENT CHALLENGES AND UNCERTAINTIES

There are several "big picture" influences and developing trends that affect future hydrologic and steelhead habitat trajectories including water quantity, climate change, water quality, and the composition of the steelhead run itself. These subjects provide context for subsequent discussion of need and potential benefits of habitat protection, restoration, and enhancement actions.

Water Quantity

A watershed planning effort by state and county governments for WRIA 31 (inclusive Rock Creek) in the 2000s decided not to include an instream flow component within its assessment scope. However, one of the reports produced as part of the WRIA 31 watershed planning process (Aspect 2004) included a review of surface water rights in the Rock Creek subbasin and indicated surface water use was minimal. While low surface water consumption bodes well for habitat, groundwater trends warrant further investigation. The current effect on discharge to Rock Creek or tributaries, if any, is unclear. However, a 50-year trend of increasing groundwater use (Figure 113) provides pause given groundwater dependency of perennial stream reaches.

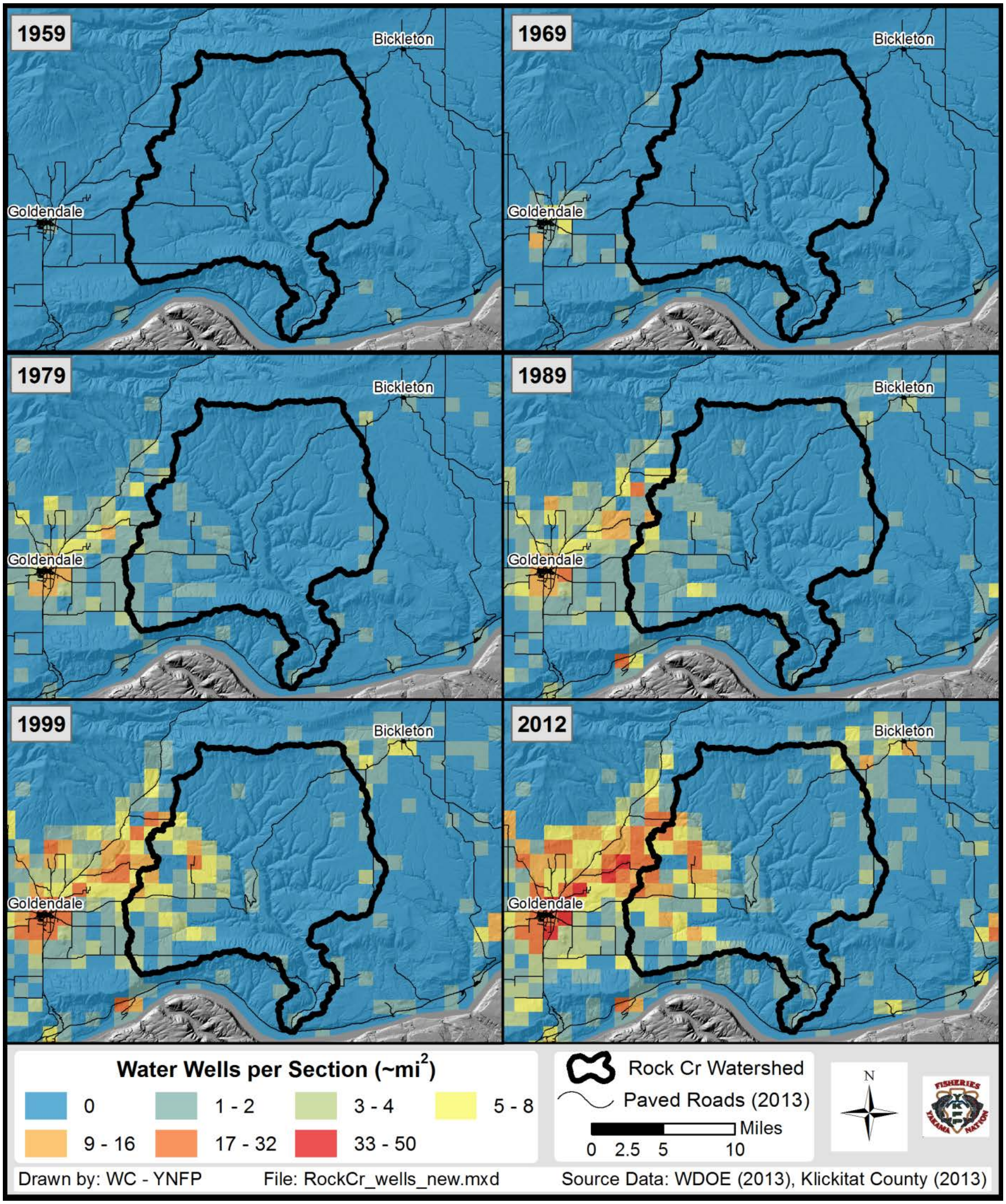


Figure 113. Water well abundance and distribution through time, Rock Creek vicinity.

With only 16.6 inches of mean annual precipitation and lacking summer precipitation, lakes, large wetlands, glaciers, and permanent snowfields, Rock Creek has some fundamental summer flow limitations. In a climate zone that does not receive appreciable summer rain, perennial reaches of Rock Creek and its tributaries are sustained by infiltration of winter moisture and groundwater discharge through the summer and early fall. Seasonally low streamflows and drying of some reaches are noted in GLO survey notes from the late-1800s (Aspect 2004), though it is unclear if the present geographic distribution or duration of dry reaches differs from pre-development conditions. Increasing groundwater withdrawal indefinitely will eventually have adverse effects on flow conditions in Rock Creek and tributaries. Given the small magnitude of current baseflows, small interruptions in continuity due to human surface and/or groundwater use could be highly significant to long-term distribution of summer and fall habitats and persistence of aquatic species, particularly considering climate change projections.

Climate Change

A variety of climate patterns are known to influence Pacific Northwest watersheds at interannual (e.g. El Niño / La Niña) and decadal (e.g. Pacific Decadal Oscillation) timescales. In recent years, longer-term climate models are becoming down-scaled to where they can inform strategic-level decision-making at sub-regional scales. Several variables that affect salmonid habitat conditions are reviewed here as indicators of probable trend, not for their outright magnitude.

The NASA NEX-DCP-30 dataset model was chosen to illustrate trends for Rock Creek because 1) it has been downscaled to 800m cells and 2) it is publicly accessible and easily accessed via the National Climate Change Viewer (USGS 2015). The down-scaled resolution is what allows analysis at the spatial level of Middle Columbia-Lake Walulla sub-region, of which Rock Creek is a part. Maximum temperature (Figure 114), average precipitation (Figure 115), runoff (Figure 116), soil water storage (Figure 117), and evaporative deficit by season (Figure 118) time series are presented.

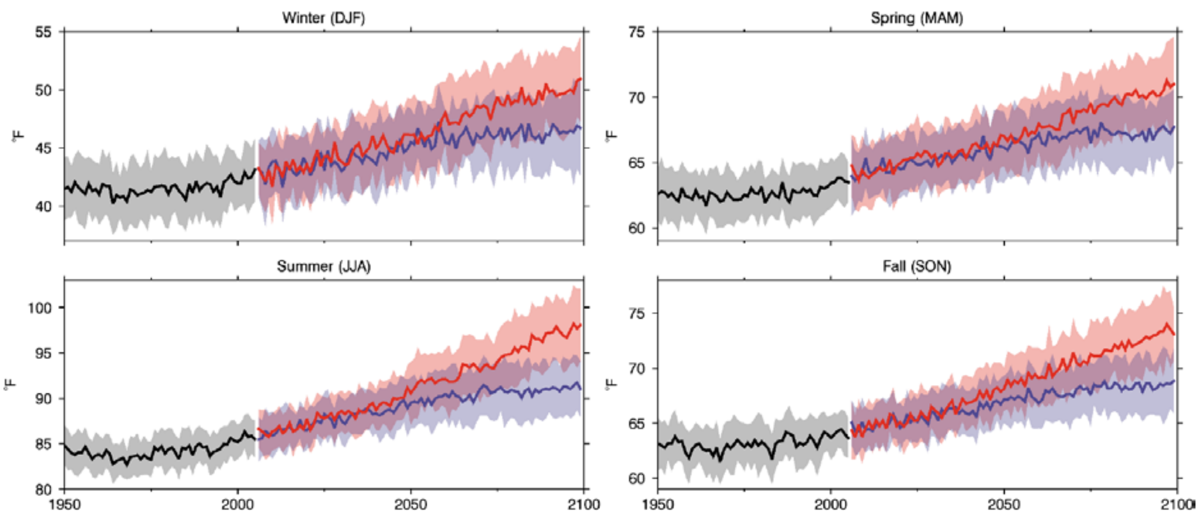


Figure 114. Maximum historic (black) and projected 2 m air temperature for two future scenarios (RCP4.5 blue, RCP8.5 red) by season in the Mid-Columbia-Lake Walulla area (USGS 2014a).

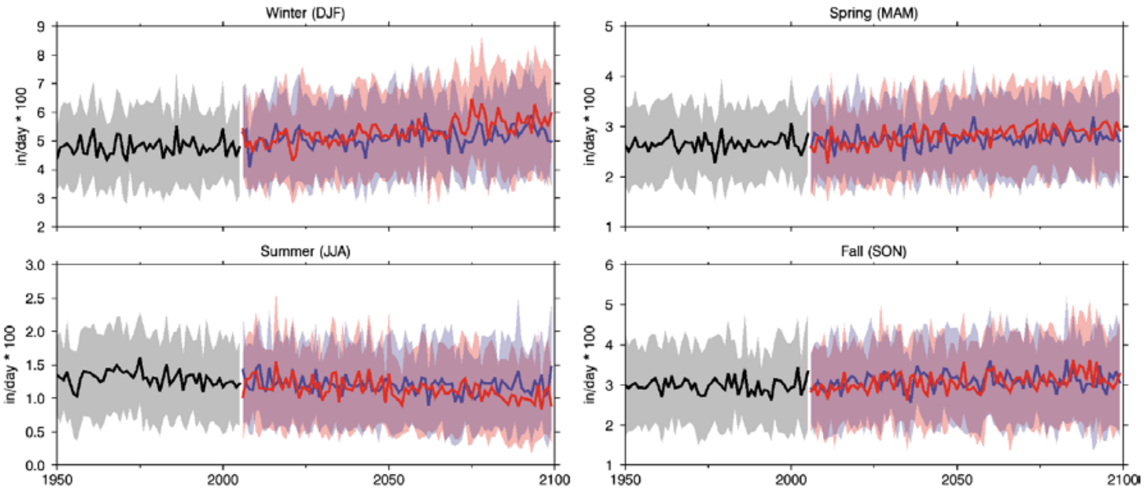


Figure 115. Average historic (black) and projected precipitation for two future scenarios (RCP4.5 blue, RCP8.5 red) by season in the Mid-Columbia-Lake Walulla area (USGS 2014a).

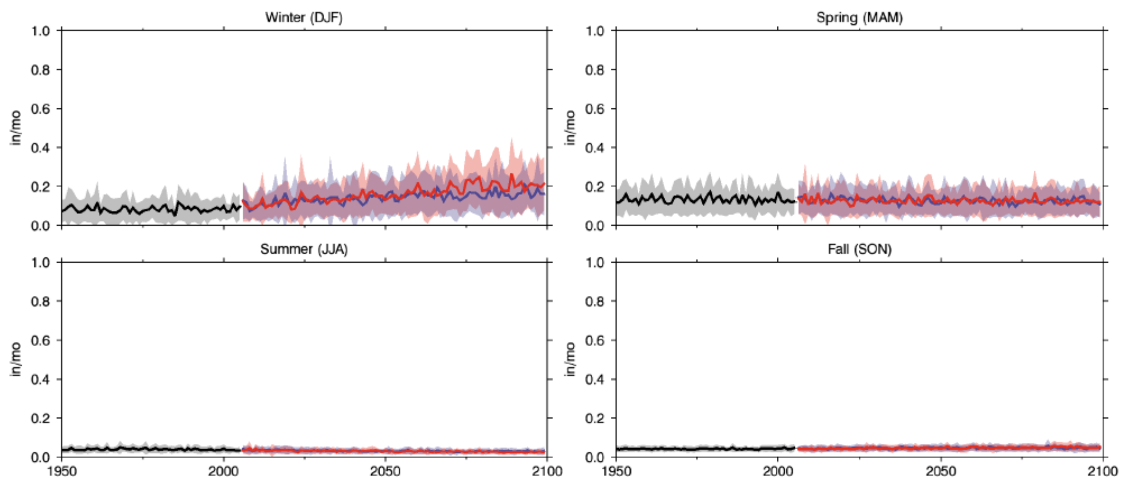


Figure 116. Average historic (black) and projected runoff for two future scenarios (RCP4.5 blue, RCP8.5 red) by season in the Mid-Columbia-Lake Walulla area (USGS 2014a).

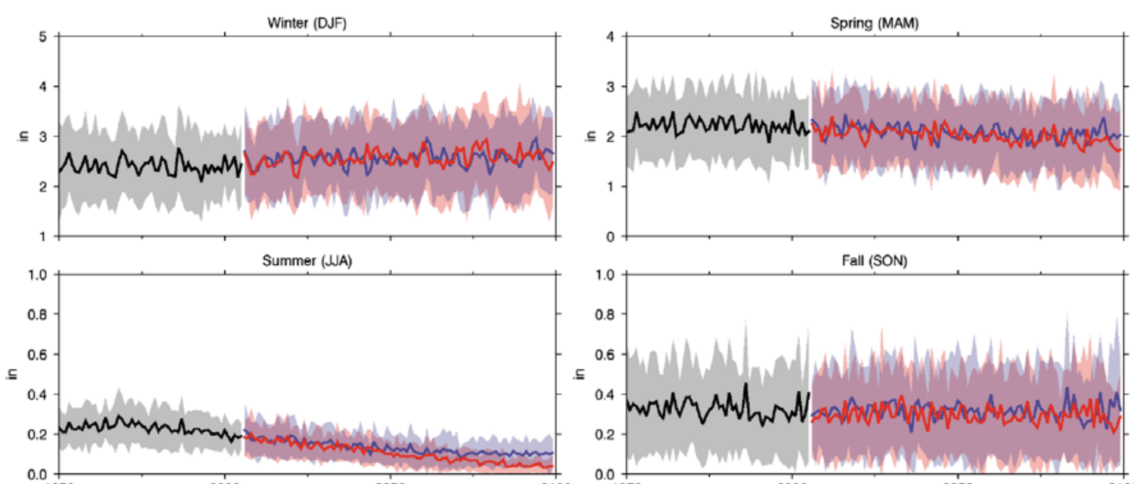


Figure 117. Average historic (black) and projected soil water storage for two future scenarios (RCP4.5 blue, RCP8.5 red) by season in the Mid-Columbia-Lake Walulla area (USGS 2014a).

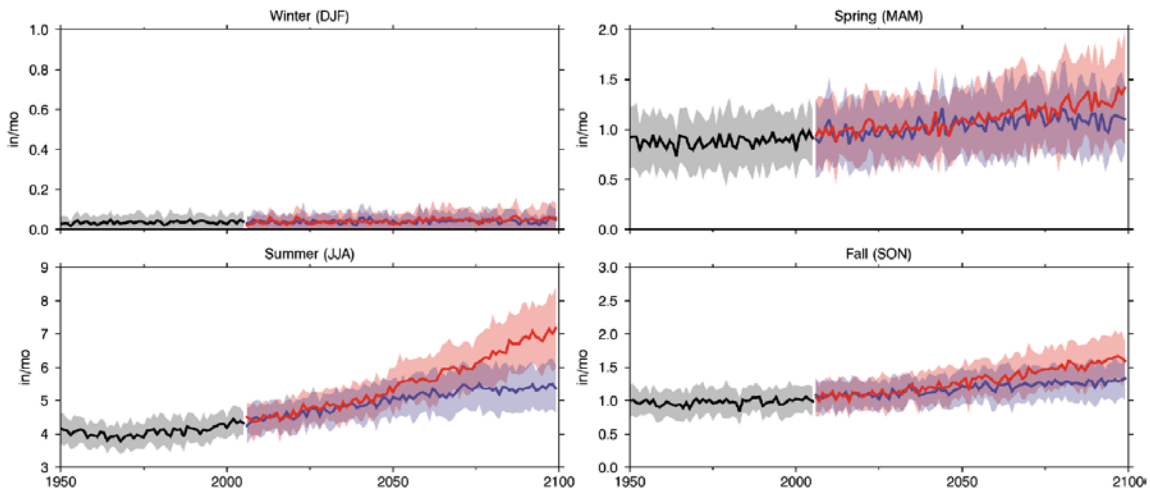


Figure 118. Average historic (black) and projected evaporative deficit for two future scenarios (RCP4.5 blue, RCP8.5 red) by season in the Mid-Columbia-Lake Walulla area (USGS 2014a).

The "RCP4.5" projections assume that atmospheric greenhouse gas concentrations are stabilized not to exceed a 4.5W/m radiative equivalent after the year 2099. "RCP8.5" projections represent a scenario where greenhouse gas emissions continue to rise unchecked through the end of the century resulting in radiative equivalent of 8.5 W/m. Expressed in terms of CO_2 concentration, the global average is currently about 400 ppm, the RCP4.5 scenario is about a 650 ppm equivalent, and the RCP8.5 scenario is about 1,370 ppm equivalent (USGS 2014b).

The consequences of hotter summer maximum temperatures and reduced summer precipitation for cold-water fish are self-evident. Increased winter precipitation and runoff could result in even more dynamic stream channel behaviors than historically observed.

Monthly averages forecast in 25-year increments from 2025 through the end of the century help visualize intra-annual shifts. Maximum temperature gets warmer for every month, with disproportionately greater summer warming (Figure 119). Relative timing remains about the same.

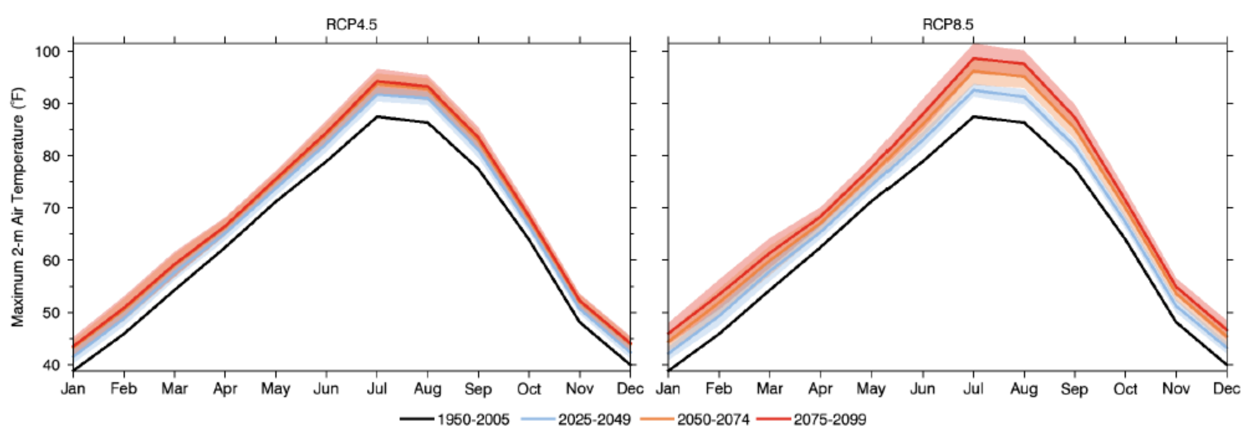


Figure 119. Monthly average maximum temperature for four different time periods for two different greenhouse gas scenarios (USGS 2014a).

Winter precipitation likely increases to a greater degree than summer precipitation decreases (Figure 120). Winter runoff likely increases substantially and arrives earlier while spring runoff declines and enters recession earlier (Figure 121).

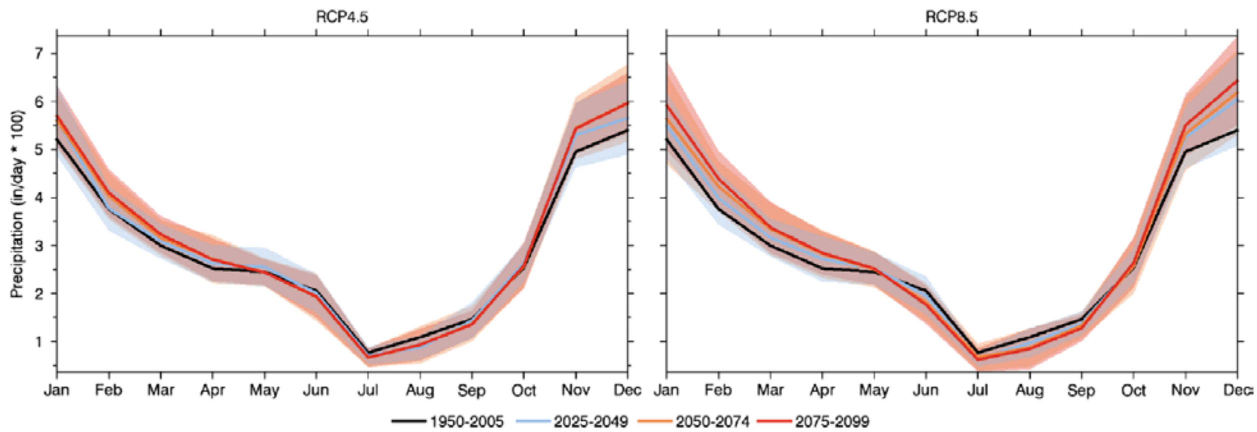


Figure 120. Monthly average precipitation for four different time periods for two different greenhouse gas scenarios (USGS 2014a).

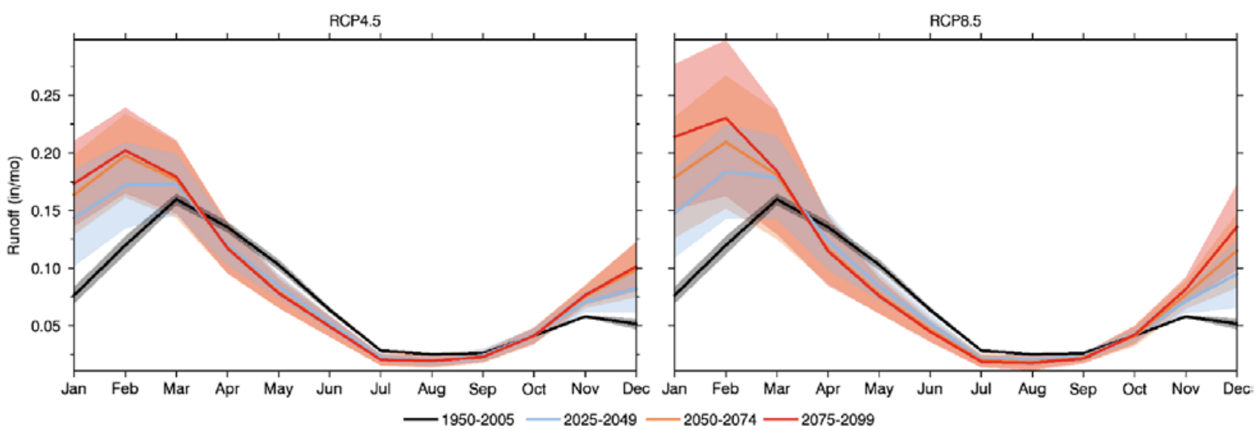


Figure 121. Monthly average runoff for four different time periods for two different greenhouse gas scenarios (USGS 2014a).

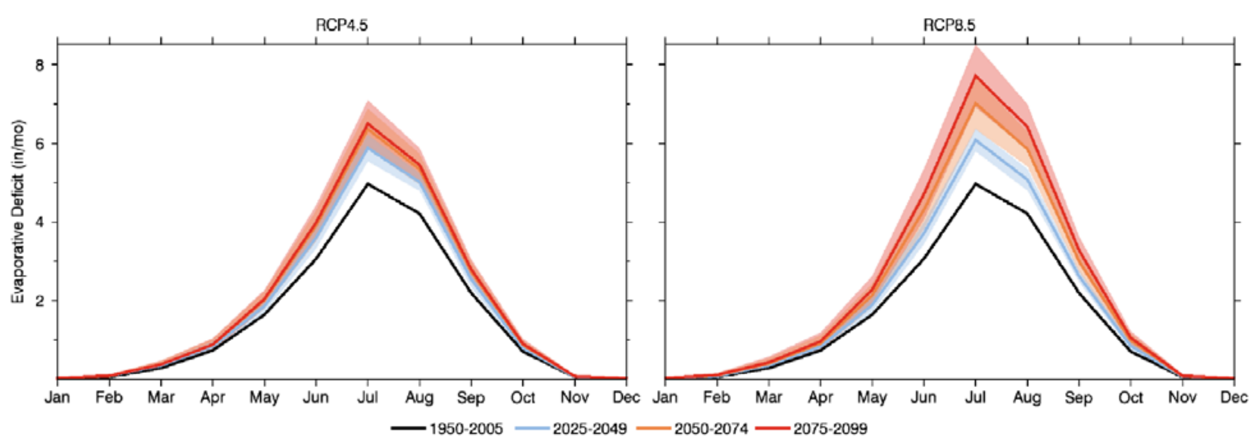


Figure 122. Monthly average evaporative deficit for four different time periods for two different greenhouse gas scenarios (USGS 2014a).

Summer soil water storage and evaporative deficit (Figure 122) are particularly of interest for riparian vegetation dynamics. Lower storage and greater deficit translates to greater stress on hydrophytes that will likely increase demand on hyporheic water and may result in changes in distribution and abundance of riparian vegetation. This may result in a more limited distribution of perennial aquatic habitats and/or changes in channel behaviors as boundary resistance changes. These conditions will also affect upland vegetation and contribute to changes in species composition and/or ground cover that could increase unit runoff and increase slope erodibility.

Surface-water modeling by Mantua et al. (2010) suggests future peakflow magnitude-frequency relationships (as indicated by 20-year recurrence event) and magnitude of the 2-yr, 7-day low flow will be similar to present. However, if increased summer moisture stress were to change riparian composition in a way that reduced root reinforcement of banks and/or increased growth within the active channel, the interaction with greater overall winter runoff seems likely to result in dynamic channel behaviors that generally result in lower quantity and lower quality salmonid habitats.

At the Washington State scale (i.e. less specificity due to greater averaging), as a function of winter precipitation changes, annual runoff is expected to decrease 0.1-2.0% by the 2020s, increase 2.2-2.7% by the 2040s, and increase 4.2-6.4% by the 2080s, though the extremes of modeled variability ranged from -9% in the 2020s to +21% in the 2080s (Elsner et al. 2010). Seasonal shifts are expected with October-March precipitation and runoff expected to increase and April-September precipitation and runoff expected to decrease (Elsner et al 2010) consistent with patterns observed in the NASA data above. The length of the summer low-flow period is expected to increase throughout interior Columbia River watersheds (Mantua et al. 2010) with an estimated one- to two-month earlier arrival of the low-flow period in Rock Creek (Beechie et al. 2012).

Water Quality

A coarse-scale (1-km) water temperature model for the Columbia Basin (USFS 2014) was developed by the Rocky Mountain Research Station. Based on an empirical stream temperature database with over 15,000 sites and coupled with climate models, stream temperatures for the years 2010, 2040, and 2080 were estimated. Rock Creek was modeled as part of the mid-Columbia unit (Figure 123).

Temperatures projected for 2080 are already observed in the Rock Creek basin, particularly in the lower 10 miles of Rock Creek and lower Squaw Creek (Aspect 2005, Harvey 2014). As such, results are not introduced here as an outright representation of future magnitude. Results are presented to indicate anticipated trajectory of climatic and stream temperature pressures exerted at the subbasin scale. In other words, given changes in driving atmospheric conditions, streams like Rock Creek appear likely to be less hospitable in the future given current knowledge of salmonid physiology.

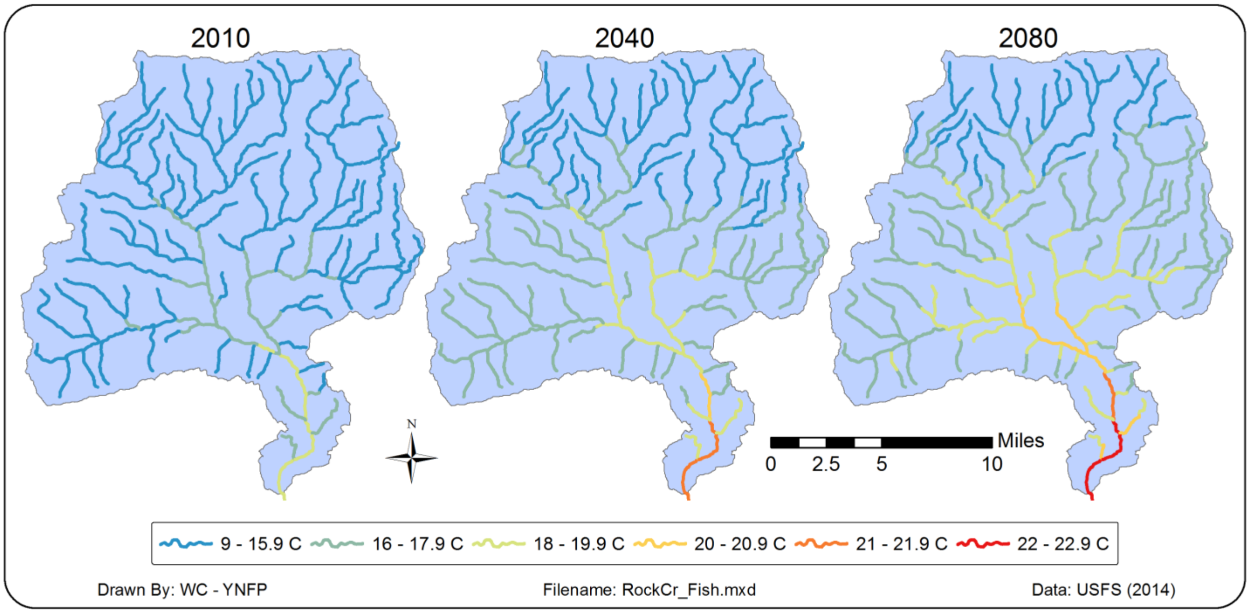


Figure 123. Multi-decadal 1-km summer stream temperature projections for Rock Creek.

Because the model is a stochastic model, it is trained on the data itself and does not make assumptions about the physics of continuity, heat transfer, etc. This works well for indicator purposes as a physical temperature model for Rock Creek would be challenged with changes in surface continuity. For example, it's conceivable that flow intermittency could slow the rate of future warming, particularly in reaches without riparian canopy.

Additional temperature data can be found in Allen et al. (2014a). Dissolved oxygen and pH data can be found in Harvey (2014, Report B). Nutrients and aquatic insect information can be found in Harvey (2014, Report C). Table 5 in Lindley and Conley (2013) provides an index of other studies (prior to June 2013) in Rock Creek that have addressed water quality metrics.

Fisheries Conservation

A literature review (Lindley and Conley 2013) found few reports that quantitatively investigated fisheries status. Of those, only a joint effort by the Yakama Nation Fisheries Program (YNFP) and USGS occurred across multiple years, included field work during flow-limited times of the year (September and early October), and occurred at spatial scales sufficient to characterize patchy habitat distribution. A 5-year synopsis published in September 2014 (Harvey 2014) compiles several reports and provides the most comprehensive perspective on *O. mykiss* status for the Rock Creek subbasin to date.

Allen et al. (2104a) documents repeat visits over several years and found habitat typically fully seeded with age-0 *O. mykiss* in the spring. Despite wide variation in age-0 spring populations between 2011 and 2012, fall populations were similar, suggesting summer rearing habitat is limiting. They concluded that lack of water, rather than temperature was the primary cause of mortality. Summer growth rates were generally positive, despite temperatures >20°C, low streamflow, and increased competition. Overall, they found Rock Creek to be a seasonally intermittent stream able to successfully rear steelhead and coho to the smolt life stage.

Results of spawner surveys conducted from 2009 through 2013 are presented in Table 10. PIT-tagging and detections at in-basin fixed PIT-tag detection arrays suggest smolt production was about 1,545 smolts in 2012 and 2,785 smolts in 2011 (Harvey 2014).

An average of 2,165 smolts for 2011 and 2012 and an average of 373 estimated adults (based on observed redds and an ODFW (2013) equation for winter steelhead) over the three years of greatest survey effort (2011-2013) suggests a smolt-to-adult ratio (SAR) of 17.2%. This value was cross-checked with an equation for summer steelhead (Miller et al 2014) that produced slightly lower adult estimates (average of 2011 -2013 is 348 spawners), though produces an overall comparable SAR estimate of 16.1%.

Table 10. Steelhead spawner survey results for Rock Creek and tributaries (2009-2013) based on data published in Harvey (2014).

	Live Adults		Redds		Miles Surveyed		Redds/Mile		Estimated Adults	
Year	Rock Cr	Tribs	Rock Cr	Tribs	Rock Cr	Tribs	Rock Cr	Tribs	ODFW[a]	WDFW[b]
2009	7	30	12	33	5.0	7.5	2.4	4.4	81	73
2010	84	20	89	38	9.2	5.5	9.7	6.9	220	204
2011	73	81	187	100	20.8	6.0	9.0	16.7	492	461
2012	38	21	159	99	29.8	27.1	5.3	3.7	443	414
2013	36	6	84	22	20.8	22.0	4.0	1.0	184	170

[a] based on [(1.70* total redds) + 3.74] per ODFW (2013) [b] based on 1.603 fish per redd (Miller et al. 2014)

SAR is the metric (= adults/smolts * 100%) typically used to relate freshwater outmigration to returning adults. For native steelhead populations, values of 2% to 3% are considered adequate for sustainability or replacement. The 16.1% and 17.2% SAR values observed in Rock Creek would be unprecedented if purely a function of natural production.

A component of the YNFP/USGS fisheries assessment effort included the use of PIT-tagging to track individual fish through space and time. Three fixed PIT-tag antenna arrays were installed in Rock Creek capable of detecting juveniles tagged within Rock Creek as well as adults returning from the ocean (irrespective of origin). Where juvenile origin was known, eighty-five percent of the unique adult detections were individuals that originated in the Snake River basin (Allen et al. 2014a). Of these, 55% were known to have been transported downstream by barge as juveniles (Allen et al. 2014a).

Genetic analysis of tissue collections from Rock Creek *O. mykiss* (Matala 2014) reinforce PIT-tag detection results (Allen et al. 2014). Expected genetic groupings, showing closer relation of Rock Creek *O. mykiss* to Klickitat and John Day *O. mykiss* only occurred for fish sampled in upper Quartz (RM 7.45) and upper Rock (RM 18.1) creeks. Both collection sites were upstream of high gradient reaches where geologic features that partly obstruct upstream fish passage. Not only were the upper Rock and Quartz creek *O. mykiss* populations different from other collections in the subbasin, they were different from each other (Figure 124).

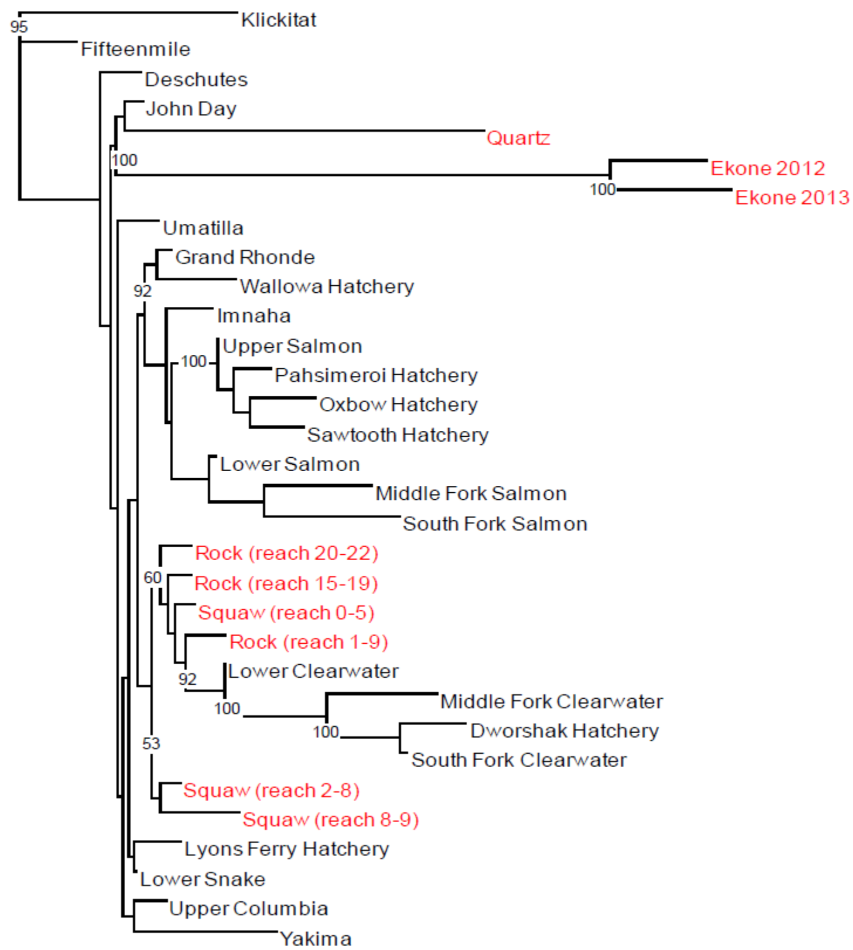


Figure 124. Neighbor joining tree showing Nei's genetic distance between *O. mykiss* from the Rock Creek Subbasin (by river reach) and primary out-of-basin stocks of inland lineage *O. mykiss* from throughout the Columbia River Basin (reprinted from Matala 2014).

The remainder of Rock Creek *O. mykiss*, including those from portions of Rock and Squaw creeks where steelhead adults are regularly observed, group with Snake River *O. mykiss* (Figure 124). While four individuals (out of 550) collected from Squaw and Rock (<RM 18.1) grouped with Quartz and upper Rock creek groups, Matala (2014) concludes that *O. mykiss* collected from reaches where adult steelhead are most commonly observed appear "highly (and generally uniformly) introgressed with out-of-basin sources".

Straying by adult Snake River steelhead into the Deschutes and John Day rivers has been frequently documented with disproportionately high rates for those that were transported by barge as juveniles (Carmichael and Taylor 2010). Based on literature review and modeling, Keefer and Caudill (2012) concluded that Snake River strays could numerically overwhelm small recipient populations, though they had yet to document such an instance. Rock Creek could be such a case.

Keefer and Caudill (2012) noted that successful establishment of out-of-basin fish would depend on successful breeding rates by strays for most recipient populations and fitness and population-level effects. While large numbers of steelhead spawners are observed in Rock Creek, neither parentage, nor productivity have been determined.

The National Marine Fisheries Service recovery plan for Rock Creek (NMFS 2009) identifies an overall biological recovery goal for Rock Creek steelhead to contribute to recovery of the Mid-Columbia DPS by reaching a moderate risk status. The NMFS recovery plan also identifies geographic subgroups (Major Population Groups or “MPG”) of the Mid-Columbia DPS and establishes goals for four “viable salmonid population” (VSP) criteria that include abundance, productivity, spatial structure, and diversity.

In terms of MPG, Rock Creek is grouped with the Cascades Eastern Slope Tributaries MPG which includes the Klickitat, White Salmon, Deschutes, and Fifteenmile subbasins (NMFS 2009a). VSP goals for Rock Creek are:

1) *Abundance* - Mean minimum abundance threshold of 500 naturally-produced spawning adults.
2) *Productivity* – Should exceed >1.56 returning adults per spawner.
3) *Spatial Structure and Diversity* – have two (combined) goals:
    a. *Maintaining natural rates and levels of spatially mediated processes*: Maintain natural rates of recolonization within the population and between populations.
    b. *Maintaining natural patterns of variation*. Ensure that populations can withstand environmental variation in the short and long-terms. The Rock Creek population has a relatively simple population structure, containing a single major spawning area (MaSA).

Abundance/ Productivity Risk	Spatial Structure/Diversity Risk: Very Low	Low	Moderate	High
Very Low (<1%)	**HV**	**HV**	**V**	**M**
Low (1-5%)	**V**	**V**	**V**	**M**
Moderate (6 – 25%)	**M**	**M**	**M**	**HR**
High (>25%)	**HR**	**HR**	**HR Rock Creek***	**HR**

Figure 125. Overall/integrated risk rating for the Rock Creek steelhead population (NMFS 2009). HV – Highly Viable; V – Viable; M – Moderate/Maintained; HR – High Risk; * = Candidate for Maintained; Shaded cells – does not meet viability criteria.

Run composition and uncertainty regarding Rock Creek's steelhead population viability raise several questions regarding relevance of potential habitat actions. Section 5.4 of the NMFS (2009) recovery plan considers and discusses a range of "Out-of-Basin Limiting Factors and Threats", though doesn't address straying or swamping by other Distinct Population Segments.

The YNFP/USGS PIT-tagging effort is ongoing, and steelhead adults tagged as juveniles within Rock Creek began returning in 2014. With a few more years of data, it should become apparent if steelhead in Rock Creek are a viable naturalized Snake River DPS subpopulation or sustained by an annual influx of stray steelhead originating from the Snake River. Determination of whether the watershed is a meta-population "sink" will be important to ensuring that habitat actions are potentially effective (Cooper and Mangel 1999).

In the event Rock Creek's present steelhead population is a self-sustaining run of Snake River steelhead, a bit of a conservation biology quandary develops. Can habitat actions that support an exogenous population be considered "restoration", particularly if they don't replicate historic physical conditions? Should restoration of a Mid-Columbia DPS population be attempted?

SYNOPSIS AND MANAGEMENT IMPLICATIONS

Rock Creek has a cobble bed with a high frequency of small and medium boulders in the lower 17 miles. Physical channel conditions in Rock Creek are largely a function of infrequent, high magnitude flow events. Boulder pavements are common in the active channel and, in at least some cases, are likely naturally-occurring. For example, bed armor in Rock Creek between Quartz Creek and the Bickleton Highway is largely a long-term product of residual clasts from fluvial reworking of debris flow runout terraces (Figures 14, 66, and 68). In downstream alluvial reaches, particle arrangement, bedforms, and floodplain/bank stratigraphy indicate high-energy, turbulent conditions, though the frequency of such conditions appears low (likely >Q25 or Q50).

Overall, physical channel and floodplain conditions seem largely a function of high magnitude, low-frequency events and subsequent re-working by more routine flows. Peak discharge events (~Q100) have generated unit-discharges greater than 85 cfs/mi^2. The combination of bedrock and boulder sub-armors and absence of resisting elements, long, shallow, linear hydraulic units result and persist with some development of minor bedforms interspersed between ones with high profile relief. Active channel cross-sections are frequently planar and alluvial channel behavior can be characterized as wandering or switching. True meandering and braided behaviors are generally absent.

Infrequent, but high magnitude events mobilize and rearrange large quantities of sediments, particularly in lower-gradient (<2%) reaches. Higher frequency events seem to contribute little bed-sized material from the watershed, but tend to laterally re-work poorly-sorted floodplain deposits and the downstream faces of sediment slugs. Dissection of high-relief bars, and lateral erosion seem to generate most of the sediment associated with smaller, more frequent peakflow events, though floodplain stripping was also observed.

While the prevailing channel profile of Rock Creek is largely defined by bedrock, superimposed sediment slugs are common in wider valley segments and punctuate the profile. Alder cohorts suggest a cyclical process of burial and exhumation. As high-relief bedforms get reworked, the location of the hydraulic control they exert changes through time.

Field observations noted a surprisingly high frequency with which quality pools did not occur in places they would normally be expected to form. In particular, combinations of woody debris, tree roots, resistant banks, boulders, bedrock, and geomorphic position (e.g. outside of a bend, channel re-entry points) often did not produce deeper habitats. This appeared to be largely due to bed armoring at least some of which is believed to be of natural origin.

The degree to which human management may have influenced physical habitat and fluvial processes in Rock Creek has not previously been evaluated with sufficient rigor to provide meaningful management insights. However, initial indications from this reconnaissance suggest that natural processes impose significant limitations on salmonid habitat in Rock Creek. More-so than temperature, low streamflow continues to be a primary limitation on fish populations. Low late-summer and early-fall streamflows (September and early-October) were observed at the outset of European colonization of the area. Though it is unclear how the current spatial distribution of seasonally dry reaches compares to pre-settlement conditions. Intrinsic climate and basin characteristics including low mean annual precipitation, slow infiltration rates, low watershed elevation, general lack of storage, and watershed shape contribute to “flashy” winter behaviors and harsh baseflow salmonid habitat conditions.

Perennial reaches downstream of VM 13 tend to be entrenched and alternate with unentrenched, multi-thread reaches that dry seasonally. This pattern is probably a combination of valley controls imposed during low-frequency, high magnitude peakflow events and a function of where sediments stall whenever a transport event runs out of energy. Shallow, multi-thread forms with intermittent flow duration frequently occur in wide valley segments downstream of more confined valley segments. High-relief diagonal bars are common in moderate and less-confined segments and may be a function of sediment stalling.

Though appearing inhospitable to aquatic life during the summer and early fall, the seasonally dry, multi-thread reaches may increase shallow aquifer recharge during the rainy season as a function of greater wetted perimeter. Thus, unentrenched reaches could very well be an important contributor to prolonged hydroperiod observed in entrenched reaches downstream.

Climate and human development trends seem likely to add increased future stress to already challenging basin conditions. Climate-based streamflow models predict an increase in the duration of low-flow periods. Increased evaporative deficit seems likely to alter riparian hyporheic demands and species composition with cascading effects of altered distribution and abundance of perennial aquatic habitats and even more dynamic active channel behavior possible. Increasing human demands on groundwater in and near Rock Creek have potential to reduce perennial hydroperiod and distribution in the future.

Despite routine observation of large numbers of spawning steelhead, PIT-tag and genetic analyses suggest the vast majority were out-of-basin strays and the population is highly introgressed with the Snake River DPS. Consequences of this are unclear at this time pending determination of productivity and self-sustainability by ongoing PIT-tagging work by fisheries investigators.

Potential instream habitat actions in Rock Creek are better-characterized as “enhancement” than “restoration” and will be challenged by the system’s fundamental behaviors, particularly sediment dynamics. Prior reports have recommended against major channel construction such as conversion to a single-thread channel (Aspect 2005) or woody debris installation in “wide channel areas subject to frequent meandering or aggradation” (Environ 2013). Despite disagreement with some underlying findings of these reports, this report concurs with those recommendations.

Environ (2013) notes that “engineered log jams [ELJs] could be installed in narrower channel reaches that are nestled between steep channel banks,” but stops short of recommending such treatments. While it is unclear specifically to which reaches they refer, ELJs within some entrenched alluvial reaches could be expected to have a greater functional life expectancy than in multi-thread reaches. However, the primary stream channel planform wanders even in some entrenched reaches, albeit within a narrower belt which could shorten effectiveness duration if intended to enhance baseflow habitat. As previously noted, entrenched reaches in moderate confined valley segments are also subject to influxes of sediment slugs.

Given risks and uncertainties associated with channel behaviors, ongoing and expected watershed changes, lack of protection of instream flows, and unresolved benefits to Mid-Columbia DPS steelhead, high unit-cost treatments such as ELJs do not seem warranted. More distributed, lower unit-cost treatments may be anticipated to have some short-term success, but their effectiveness will depend on instream flow protections and proper identification of meta-population relationships. Figure 126 provides a decision-tree for habitat actions intended to increase steelhead population viability. Within the context of the decision-tree, previous genetics work suggests the answer to box number one is “no”. Ongoing PIT-tagging work should answer the question in box number two.

Ultimately, habitat actions should adhere to two principles:

1) do no harm, and
2) be objective-driven

Given channel behaviors and low baseflow, there is high potential for habitat actions to do unintended harm. For example, improperly-placed woody debris could attract fish into areas that dry up seasonally. Pool excavation that pierces a seal in bed material (indurated sediment layers were observed to perch shallow groundwater in a number of bank profiles and similar layers may be unseen below bed materials) and could unintentionally create a drain. Given general uncertainties and narrow margins for habitat treatment errors in Rock Creek, if habitat enhancement is to occur, passive approaches are preferable given their lower expense and lower likelihood to cause harm.

While awaiting determination of current population status, physical habitat management objectives for the basin could be developed concurrently as contingencies. If the decision process in Figure 126 arrives at Box #7, the basic hierarchy presented in Roni et al (2008) provides a sound, strategic hierarchy (Figure 127).

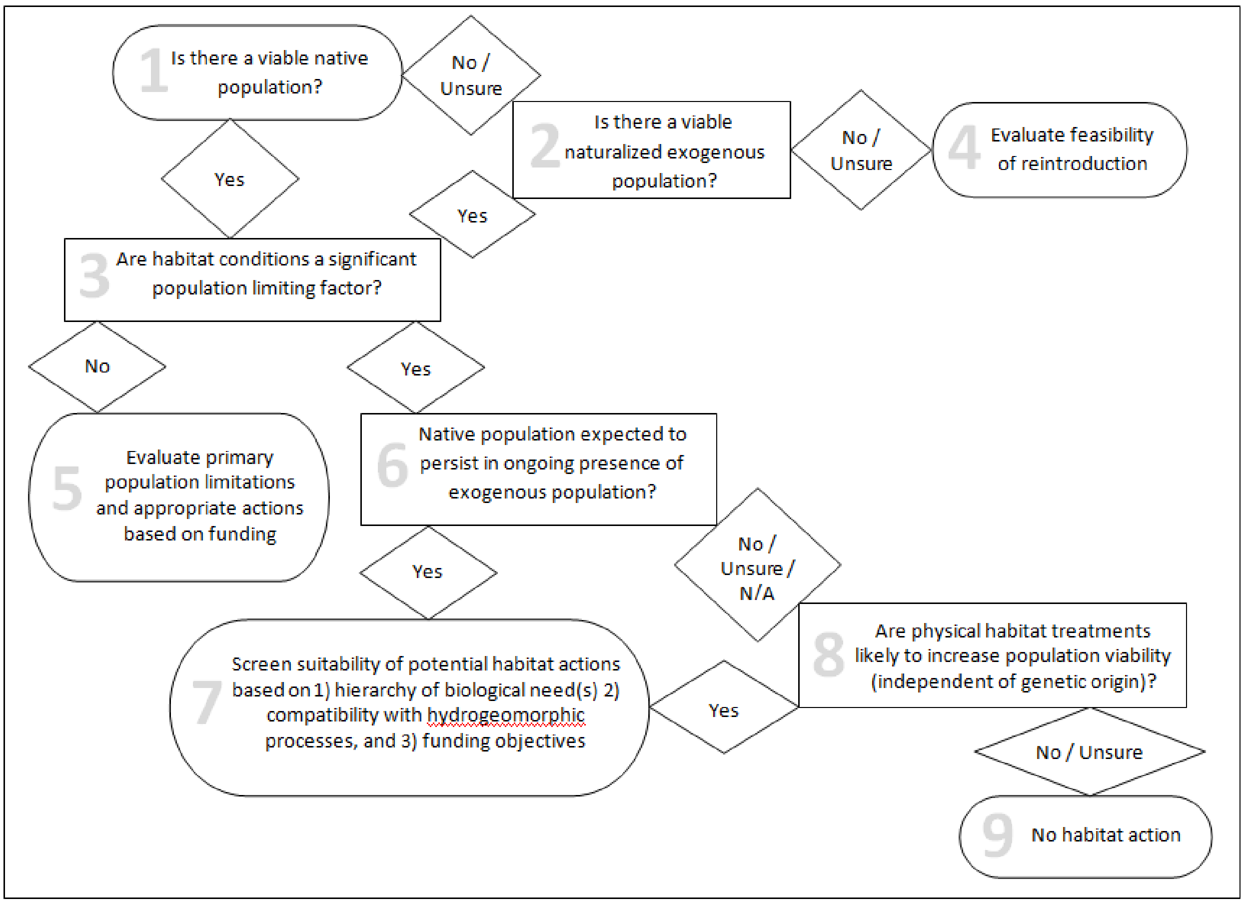


Figure 126. Decision-tree for evaluating context/relevance of habitat actions intended to increase viability of a fish population.

Habitat Protection

Within the context of actions to benefit steelhead in Rock Creek, protection of perennial streamflows offers the greatest certainty. A variety of strategies and mechanisms exist to accomplish this, but instream flow water rights provide the greatest certainty. Engaging in meaningful planning processes and/or zoning that encourages land uses that are less water-intensive and are less likely to intercept water otherwise bound for stream channels is another critical strategy. Put simply, if there is less (or no) water, then physical habitat enhancement is unlikely to provide a population benefit. In this regard, agricultural uses such as dry-land cropping or rangeland grazing will likely be more compatible than irrigated agriculture or residential development. While land acquisitions and/or easements may also indirectly address this priority, benefit certainty to target populations are ultimately dependent on specific protections for instream flows themselves. The terms and conditions of allowable uses along with monitoring and enforcement thereof are also critical elements in determining whether habitat benefits are realized by easements and acquisitions.

Geographic Priorities

Protection activities should target perennial reaches identified in Table 8. Passive actions can occur virtually anywhere in Rock Creek and produce benefits of varying magnitude for steelhead. At this point in time, active instream investment in habitat actions for steelhead in Rock Creek seems premature. Realistic habitat goals and objectives that account for intrinsic watershed constraints and address the proper hierarchy of population controls should be developed. For example, if the steelhead run is exogenous and sustained purely by annual influx of out-of-basin adults, efforts to enhance rearing or spawning habitat may be superfluous.

An EDT model for the basin suggests actions in reaches lower in the system have greatest potential benefit (Harvey 2014). However, locations closer to the mouth (particularly downstream of Old Hwy 8) will be most susceptible to adverse complications associated with high water temperatures, climate change, and intrusion by exotic predators from the John Day pool. Given evidence of groundwater influx, general habitat quantity and quality, Rock Creek between VM 6.4 and 7.4 (where it passes through the Goodnoe Hills) should be the highest priority.

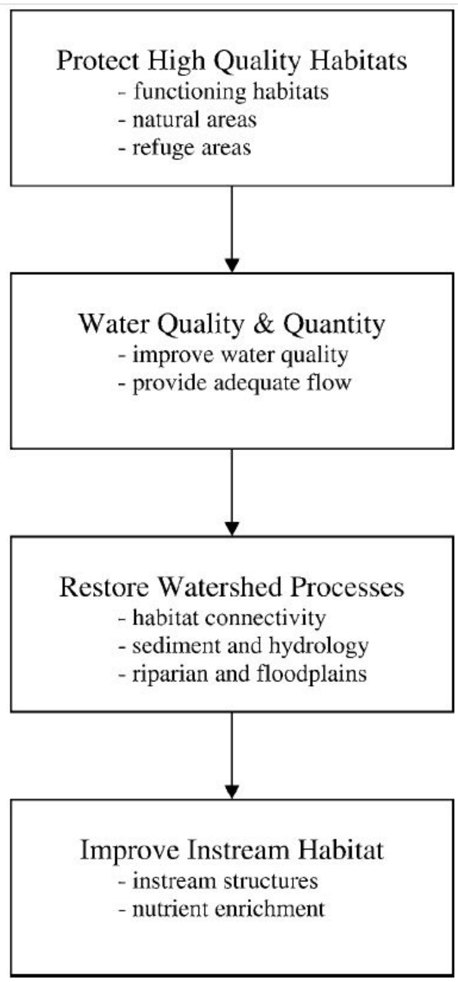


Figure 127. Suggested strategic hierarchy for stream rehabilitation (Roni et al. 2008).

Passive Enhancement Strategies

Passive activities that contribute to instream habitat quality are good candidates for habitat actions. These include not interrupting beaver activities (e.g. not trapping them or removing dams) and/or managing livestock (e.g. season of use, reducing intensity and/or duration of grazing) in ways that improve abundance, density, and/or composition of native riparian plants.

The generally lower expense of passive actions is also more commensurate with the significant management and fishery uncertainties.

Active Enhancement Strategies

Allen et al. (2104a) note that enhancing habitat complexity in perennial pools could increase carrying capacity for age-0 and age-1 fish. Should decision-process (Figure 126) warrant active treatment, this study concurs that increased pool cover would provide high benefit to juvenile salmonids.

Potential for 1) harm caused by improperly-executed physical habitat treatments and 2) short service life due to geomorphic dynamics necessitates a well-informed, measured approach to active enhancement. Where consistent with management objectives and informed by data, such physical treatments should be implemented in a pilot approach and monitored to evaluate effects before proceeding to the next implementation.

Appropriate "active" implementations include small footprint embellishments of existing channel morphologies, locations of which should meet the following criteria:

- known to be perennial based on multiple years of base-flow (mid- to late-September) observation
- existing pools or glides

Table E1 (APPENDIX E) presents locations that have been preliminarily screened for the above criteria through combined historic aerial photo interpretation and review of low-flow habitat data collected in 2012.

Intensive construction on either site or reach-based scales will generally be inappropriate in Rock Creek. Major excavations or earth moving activities are not warranted given generally low likelihood of persistence and/or risk of adverse morphological response, the small magnitude of likely population response, and potential for negative fishery response. Examples include constructed riffles, channelization, and channel-spanning structures. Complex woody debris jams (ELJs) have some prospects in entrenched, perennial reaches, but cost:benefit of less-intensive treatments is likely better.

Conceptual Example of an Active Enhancement Approach

To increase summer rearing capacity in existing pools by increasing underwater cover while minimizing cost and effort, conduct site visits (generally in mid-September to early-October) to one or more of the following reaches and confirm perennial pool locations:

<u>Rock Cr</u>:
- VM 5.8 to 6.6
- VM 6.6 to 7.8
- VM 9.4 to 10.3
- VM12.25 to 13.55

<u>Squaw Cr</u>:
- VM 0.1 to 0.4
- VM 0.65 to 0.95
- VM 1.25 to 1.5

In the adjacent riparian zone, collect branching woody debris that can be manually manipulated. Complex alder branches and tops from frost damage and/or windthrow are abundant and would make suitable material. Time in-channel placement for once flows have diminished to when debris won't simply float to the tail-out, likely July. If need be, place multiple layers on top of one another to be self-ballasting through low-flow period and minimize wind drift of debris. Expected duration of the treatment would be until fall rains arrive and surface flow continuity resumes. Monitor effectiveness with a Before-After-Control-Impact (BACI) design using PIT-tags and mark-recapture for survival, abundance, and growth estimates to determine if treatment in expanded geographic area and/or future years is warranted.

Future Considerations for Active Enhancement Approaches

Once it is determined if a viable steelhead population exists or can exist (i.e. if answer to question #2 in Figure 126 is "yes") and what the composition of that population should be, active interventions of greater intensity than described above may become warranted. Suitable examples, in order of increasing cost include:

1. Untreated wood posts manually driven into streambed to trap debris
    - posts driven by hydraulic post-driver
    - smaller logs and slash from riparian zone racked into posts and banks
    - more info can be found in Wheaton et al. (2012)
2. Boulder placement
    - placed by machinery, or rolled off adjacent hillside
    - place with high reveal (relative roughness)
    - would need to be very large (>4-5' median axis)
    - cluster near channel margin to encourage scour and break-up bed armor
3. Small woody debris jams or individual logs with rootwads keyed into banks or anchored to bedrock
    - placement by winching or machinery
    - anchored via trenching, weaving into riparian trees, or mechanical means into bedrock
    - revetments over extended distances not appropriate

The use of posts (#1, above) to trap and retain small woody debris within the active channel has the best prospects as a) small woody debris is abundantly available, b) cross-sectional reshaping by inducing deposition of sediments mobilized during Type 1 transport conditions is a feasible approach to increasing salmonid habitat suitability, and c) there is potential for alder colonization to increase duration. Though increasing pool depth by scour is unlikely in many locations due to armoring and net gain will likely come from lateral bar deposition and tail-out inflation, some net gain due to scour may be locally feasible.

A greater degree of design would be required to achieve the greater duration effect reasonably expected of higher intensity / cost treatments. As habitat treatments increase in cost or effort, they should be restricted to locations with a high degree of channel planform fidelity through time (APPENDIX E), in particular, locations within entrenched and/or moderately confined reaches. "Typical" designs could be appropriate, if position along the profile, amount of projection into channel, spacing, and horizontal and vertical configuration are specified and an experienced field designer is on-site during construction.

Effectiveness Monitoring

Effectiveness monitoring is a key part of treatment, both for documentation of effect as well as lessons-learned. Because of the potential to inadvertently make survival conditions worse, starting with a small, measured scope and robust study design to monitor fish survival and growth would be imperative. A BACI design with mark-recapture efforts to evaluate fish response at the habitat unit level could be implemented and provide direction on whether further treatment is warranted.

Information Needs

Habitat objectives and priorities for areas of known steelhead use are dependent on 1) determinations of population viability and 2) if viable, effects of repeated out-of-basin influence. As such, these should be considered the highest priority information needs. Pending determination of the above, a variety of information development can assist in increasing the physical habitat knowledge base (Table 11).

Reaches with "5" generally indicate the information already exists and doesn't need to be collected again at this point in time. Reaches with "1" values generally indicate filling a need for which little or no current information exists. Reaches with "2" values indicate either areas where information exists, but there is high value in having repeated annual data sets or the information does not exist and is a slightly lower priority than other gaps.

Knowledge of surface-water / groundwater interaction should be a high priority as well as increased documentation of baseflow habitats. Field surveys that census wetted habitats are highly valuable and should be considered for reaches not yet surveyed. Repeat surveys should also be considered to document range of variability. Upstream and downstream ends of perennial habitat units should be marked via high-resolution (3-foot) GPS. Mid-September to early October will generally be the best time to document such conditions.

The naturalized population of black walnut trees creates an intriguing dilemma and information need. Walnut trees are likely re-engineering the reaches in which they occur in lower Rock and Squaw creeks. They are the dominant canopy species along many portions of lower Squaw and Rock creeks where any amount of shade is likely important. However, they form monocultures and displace native vegetation. They are larger and longer-lived than native riparian trees and persist longer in the environment once dead with greater density and more complex forms that should be more suitable to salmonid habitat formation. However, they may have greater evapotranspirative demands than native riparian trees which could negatively affect hyporheic water balance and perennial habitat distribution.

Table 11. Information priorities for Rock Creek to fill gaps in identifying and prioritizing locations for habitat actions to support *O. mykiss* conservation at the subbasin scale.

Stream	Downstream End (valley mile)	Upstream End (valley mile)	Priority (1 = high, 5 = low)			
			Base Flow Habitat	Base Flow Fish Presence / Absence	LiDAR	Fish Passage
Rock Cr	1.1	13.2	2	5	5	5
Rock Cr	13.2	16.7	1	5	5	4
Rock Cr	16.7	21.0	3	5	5	2
Rock Cr	21.0	25.0	1	5	5	2
Rock Cr	25.0	headwaters	1	2	5	2
Squaw Cr	0.0	5.05	2	5	5	5
Squaw Cr	5.05	6.05	1	2	5	1
Squaw Cr	6.05	9.0	3	2	5	3
Squaw Cr	9.0	9.7	3	2	3	3
Squaw Cr	9.7	12.6	2	2	3	1
Squaw Cr	12.6	headwaters	2	2	3	2
Harrison Cr	0.0	3.5	3	3	5	4
Harrison Cr	3.5	headwaters	4	4	4	4
Spring Cr	0.0	headwaters	2	2	3	2
White Cr	0.0	0.8	2	3	5	1
White Cr	0.8	2.0	2	2	5	2
White Cr	2.0	4.6	2	2	3	2
Luna Cr	0.0	4.5	1	1	5	1
Luna Cr	4.5	4.8	3	3	5	2
Luna Cr	4.8	headwaters	2	2	3	3
Badger Cr	0.0	headwaters	2	2	3	2
Quartz Creek	0.0	2.95	1	1	5	2
Quartz Creek	3.0	7.4	4	2	5	2
Quartz Creek	7.4	9.7	1	2	2	2
Quartz Creek	9.7	headwaters	1	2	2	2
Box Cyn	0.0	0.3	1	3	5	5
Box Cyn	0.3	headwaters	1	2	3	3
Dairy Cr	0.0	headwaters	1	2	3	3

O. mykiss habitat usage has focused on the active channel but several locations were observed that have potential for enhancement as off-channel refugia:

- A blind network of floodplain channels drains valley-bottom silt deposits that have some cattail patches in the vicinity of VM 8.0.
- An old primary channel alignment on the right side of the valley is spring-fed in the vicinity of VM 8.6 that likely only has surface connectivity to the main channel network a few days a year.
- A topographically-low area on the left side of the valley in the vicinity of VM10.4 has one of the most extensive and densest blackberry infestations observed, but may also be spring-fed and have extended hydroperiod.

Findings of the literature review (Lindley and Conley, 2013) indicated existing information generally lacked primary data, precise method documentation, sufficient geographic and/or temporal resolution, and/or focus to guide on-the-ground stream protection, restoration and/or enhancement decision-making. The state of knowledge and certainty of analyses will be greatly improved by increased documentation and metadata for all information gathering and data creation.

Other Areas for Investigation

A broader conservation view beyond anadromous fish presents a variety of ecological restoration opportunities. While addressing the below provide little direct benefit to anadromous salmonids, there are potential benefits to a whole suite of resident fish, wildlife and native plants as well as range management, related to:

- Exotic plant control: A variety of invasive plants were observed in the subbasin, mostly downstream of Bickleton Highway. Knapweeds (*Centaurea* spp), Canada thistle (*Cirsium arvense*), star thistle (*Centaurea solstitalis*), reed canary grass (*Phalaris arundinacea*), and medusahead (*Taeniatherum caput-medusae*) were observed, amongst others. Himalayan blackberry (*Rubus armeniacus*) was the most frequently observed and single largest displacer of native vegetation. Black walnut is discussed in previous section.
- Headwater *O. mykiss* populations: Genetic analysis of collections from upper Rock and Quartz creeks identified likely endemic *O. mykiss* populations (Matala 2014). While believed to have largely resident life histories, several individuals were identified from downstream tissue collections that classified with these groups. Further work could include evaluation of population status, habitat conditions, and enhancement opportunities. Additionally, Harrison, White, Luna, and upper Squaw Creeks have not been sampled.
- Overwinter habitat: While summer and early-fall habitat conditions are generally limiting and receive most of the attention, winter (December-January) habitat conditions may be worth investigating. Field work conducted for this study occurred on the tail-end of an extended hard-freeze. Lower Rock Creek through the Goodnoe Hills had frozen-over and a few dead frye were observed in shallower habitats (glide-riffle transitions) where ice had anchored to bed particles. The segment between Quartz Creek and the Bickleton Highway froze particularly hard and was very slow to break-up due to topographic shading. Very few pools were observed in this segment with sufficient overwintering depth (>2.5’). Deeper pools observed had small surface area and often very high densities of parr to trout-sized individuals. As previously noted, potential for natural pool development and increased scour in this segment is limited due to (likely natural) armored bed conditions. However, there may be other reaches or segments (e.g. Rock Creek upstream of VM 21.0 and Quartz Creek upstream of VM 6.0) that experience similar icing conditions, but have greater potential for pool development.

- Bridgelip suckers (*Catostomus columbianus*): While less charismatic than salmon or steelhead, suckers are both native to the Rock Creek watershed and culturally important as a First Food. Further work could include evaluation of population status, habitat conditions, and restoration opportunities.
- Erosion-control along valley-bottom pastures: From a pasture perspective, the most productive valley bottom areas seem to have deep (<3') silty soils and are at least partly naturally sub-irrigated by springs or seeps. However, the foreslope of these soils is generally poorly vegetated and subject to lateral erosion during over-bank streamflow events (some as low as Q3). Valley-bottom fencing is not a good solution given channel dynamics. However, establishment of dense shrub cover could be effective. Mesic to slightly hydric native shrubs, perhaps rose (*Rosa* spp) or hawthorne (*Crataegus douglasii*) along the toe and with more drought-tolerant species along the face might be appropriate and assist in stabilizing these areas somewhat and help minimize livestock traffic on the perimeter. The vicinity of VM 8.9-9.0 on both sides of the valley is one place to evaluate for such planting. It should be noted that, to some degree, erosion is probably an ongoing process in the aftermath of the Missoula Floods, however, desirability of these areas from an agricultural perspective may warrant action to reduce erosion rates.

CONCLUSIONS

Rock Creek has challenging hydrogeomorphic conditions which are largely a product of intrinsic watershed characteristics, specifically: south-facing facing aspect, equant shape, low elevation (83% below 3,000 feet), moderately-high relief, low mean annual precipitation (MAP, 16.6 inches), and no lakes, permanent snowfields, glaciers, or appreciable wetlands.

The general lack of watershed storage contributes to very low baseflow hydrology that includes high degree of spatial discontinuity for extended periods of time. It also increases sensitivity to climate change and increases the importance of groundwater contributions. Climate modeling projects earlier runoff and a one to two month extended baseflow period and suggests greater hyporheic demand by riparian vegetation by the end of the century.

The 1964 peakflow was a signature event with significant changes in channel alignments and riparian vegetation. Similar, but less dramatic changes are observed following large magnitude flow events in 1974 and 1996. Many reaches are still responding to geomorphic effects from one or more these events. The duration of post-disturbance channel response combined with expected recurrence frequency of similar perturbances, suggest many of Rock Creek's alluvial reaches can be expected to be in a nearly continual state of adjustment.

Low streamflows are the primary factor currently limiting steelhead production. Long, shallow, linear habitat features with planar cross-sections prevail. Pool structure is infrequent, shallow, and lacking cover. Underwater cover limited juvenile survival during summer baseflow in all years of YN/USGS surveys. Though smolt production is low, steelhead spawners are abundant and immigration appears a likely cause of very high SAR values (16-17%). Fisheries investigations by others indicate juvenile steelhead from Squaw Creek and most of Rock Creek are predominantly of Snake River genetic origin, and 85% of adult PIT-tag detections with known juvenile origin were Snake River origin. Further evaluation of the fishery is critical to determining population viability and need for habitat enhancement.

Other key observations and findings:

- Analysis of results produced by indirect regional magnitude-frequency peakflow equations indicates 55 to 63% under-prediction of flood peaks fit to local data.
- Active channel mapping based solely on high-resolution (6 inch pixels) color aerial photography alone undermapped secondary channels and 27% of total length for all active channels compared to mapping supported by LiDAR and field confirmation.
- Perennial channel units within alluvial valley segments tend occur in more entrenched reaches and often downstream of shallow, seasonal, multi-thread reaches. The latter may provide an unconfined aquifer recharge function during periods of flow.
- Plane-bed channel conditions generally prevail with abundant long, linear, simple habitat features. Pool structure is generally infrequent, shallow, and lacking cover.
- Better quality salmonid habitats tend to be hydraulically-forced.
- Rock Creek's prevailing profile is bedrock-controlled. A boulder pavement routinely appears at the channel surface between Quartz Creek and the ACOE park, particularly in pools and runs. This appears to be a natural condition for some reaches and limits potential to enhance pools by scouring.
- Less-confined valley segments have accumulated sediments which are generally poorly-sorted and frequently have a cohesive matrix. Tributary input of coarse sediments appears very limited in space and time. Most of the routine sediment supply seems to be from re-worked floodplain deposits, alluvial fan toes, and terraces.
- Alluvial reaches primarily exhibit wandering or switching active channel behaviors with planform occupation (and reoccupation) strongly influenced by resistant features such as bedrock and cohesive valley margins, alluvial/debris fan toes, and mature riparian forest.
- Though multi-thread channel forms are common, true braided behaviors are rare.
- Density and spatial extent of human groundwater development has steadily increased with considerable entry into the Rock Creek watershed since the mid-1990s.
- Large woody debris is generally absent from the low-flow channel and not a habitat forming agent. However, transient habitat associated with accumulations of smaller wood pieces and leaf-litter may have greater value than typically recognized in other systems.
- Cursory review of available aerial imagery indicates considerable variation across years. USDA orthoimagery appears generally consistent within and between years. However, horizontal errors of 150 to 200 feet were observed for some valley-bottom locations for 1938 and 1969 imagery which would be highly consequential for any quantitative study of channel migration.

- Timing of data collection to limiting periods affects utility and better informs analysis.
- Existing hydraulic models are unsuitable for geomorphic assessment or design

Once population status is determined and placed within a meta-population context, it will be more feasible to determine whether habitat actions will contribute to population viability. For example, if the steelhead run is exogenous and sustained purely by annual influx of out-of-basin adults, efforts to enhance rearing or spawning habitat may be superfluous. If viable, a conservation biology and ESA recovery planning dilemma of whether there’s a benefit to enhancing an exogenous population. If potential exists for habitat enhancements to improve viability of a specified target population, habitat goals and objectives that account for intrinsic constraints and geomorphic behavior of the watershed and address a hierarchy of population controls should be developed.

Prescription development should address habitat objectives and emphasize passive approaches. A bias toward active instream enhancement in Rock Creek and tributaries should generally be avoided at this time. There may be some value in ongoing protection efforts, but only if instream flow rights are secured and population viability is determined. Active, instream work in Rock Creek and its tributaries has a high potential to inadvertently cause harm and don’t necessarily provide greater certainty than some passive treatments. Lower-intensity active treatments may be appropriate on a measured and localized basis. A reevaluation of the above approach should be conducted once current steelhead population status questions have been addressed.

Instream treatments often dogmatically pursue “stability”, yet habitat transience may be more of the natural condition and part of what encourages anadromous life histories in systems like Rock Creek. Given enough physical space and intact processes, a hands-off approach may be appropriate. Hydrogeomorphic observations along Rock Creek suggests a strategy that combines habitat and instream flow protections with passive activities would have less risk and greater certainty than active enhancement treatments alone.

Substantial planform and/or profile shifts combined with very low baseflow constrain habitat action effectiveness prospects and make the risk of unintended, negative consequences high. Improperly implemented actions have medium to high potential to convert perennial units to intermittent flow duration or entice and strand salmonids into existing intermittent habitats. Pending population-level determinations, appropriate “active” implementations include small footprint embellishments of existing channel morphologies, locations of which should be existing pools or glides and known to be perennial based on multiple years of base-flow (mid- to late-September) observation.

Regardless of approach, efforts should be strategic, objective-driven, and coordinated. Succumbing to the temptation to avoid difficult, but critical issues (e.g. instream flow) and focus on action- or task-level projects (e.g. LWD additions) is likely to result in “feel-good” projects that deliver little or no persistent benefit to the target population.

(THIS PAGE INTENTIONALLY LEFT BLANK)

DATA CITED

Allen, B., C. Munz, and E. Harvey. 2012. Tabular data (Excel) for spatially continuous low-flow habitat surveys in 2010, 2011, and 2012. Received from B. Allen, March 2013.

Beechie, T. 2013. Shapefile for channels >25' width. Received from T. Beechie, July 2014. See Literature Cited for "Beechie, T. and H. Imaki. 2013."

CRITFC. 2013. Polyline shapefile of YNFP/USGS 2011 low-flow habitat survey. Received from E. Harvey, YNFP, December 2013. No metadata.

CRITFC. 2014. Polyline shapefile of YNFP/USGS 2012 low-flow habitat survey. Received from E. Harvey, YNFP, February 2014. No metadata.

NAIP. 2006. Color digital orthophotography mosaic received from Klickitat County Planning Department via L. Meagher, EKCCD, June 2013. 1.5 ft pixels.

NAIP. 2009. Color digital orthophotography mosaic received from Klickitat County Planning Department via L. Meagher, EKCCD, June 2013. 1m pixels.

National Water Information System (NWIS). 2014. Historic peak flow data and gage information from USGS-operated gages. http://nwis.waterdata.usgs.gov/wa/nwis/peak

O'Connor, J. 2014. Tabular data (Excel) of modeled step-backwater surfaces of maximum Missoula floods. Received from J. O'Connor, February 2014. See Literature Cited for "Benito, G. and J. O'Connor. 2003."

PRISM. 2014. 800m GRIDS of 30-year normals for Mean Annual Precipitation and Mean January Minimum Temperature. Downloaded by Will Conley, February 18, 2014. http://prism.nacse.org/

University of Washington (UW). 2015. UW Herbarium Vascular Plant Collection Map. http://biology.burke.washington.edu/herbarium/resources/wtustatemap.html

Unknown. 1938. Black-and-white aerial photography tiles. Scanned and georeferenced by Aspect Consulting. Received from S. Germiat, March 2014. 1m pixels. No metadata.

Unknown. 1969. Black-and-white aerial photography tiles. Scanned and georeferenced by Aspect Consulting. Received from S. Germiat, March 2014. 1m pixels. No metadata.

USDA. 1960. Black-and-white digital orthophotography mosaic received from L. Meagher, EKCCD, June 2013. 1m pixels. No metadata provided.

USDA. 1981. Black-and-white digital orthophotography mosaic received from L. Meagher, EKCCD, June 2013. 1m pixels. No metadata provided.

USDA. 1990. Black-and-white digital orthophotography mosaic received from L. Meagher, EKCCD, June 2013. 1m pixels. No metadata provided.

USDA. 2013. File geodatabase of soils data for Washington State Soil Survey Area 639. SSURGO. Downloaded August 2013 by W. Conley.

USDA. 2014. PLANTS Database. http://plants.usda.gov/java/

USFS. 2013. Stream temperature scenarios for "Mid-Columbia" Processing Unit. 1-km shapefile. Rocky Mountain Research Station; Air, Water, and Aquatic Environments Program (AWAE). http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html Downloaded April 2014 by W. Conley.

USGS. 2013. National Elevation Dataset, 1/3 arc-second. Downloaded August 2013 by W. Conley. http://earthexplorer.usgs.gov/

USGS. 2014. Streamstats in Washington State. Interactive map: http://water.usgs.gov/osw/streamstats/Washington.html

USGS. 2015. National Climate Change Viewer. NASA NEX-DCP-30 dataset. Mid-Columbia – Lake Walulla. http://www.usgs.gov/climate_landuse/clu_rd/apps/nccv_viewer.asp

Watershed Sciences, Inc (WSI). 2012. LiDAR-based topography and color aerial photography tiles. 0.5 ft pixels. Received from L. Meagher, EKCCD, June 2013. Report included.

Washington Department of Ecology (WDOE). 2013. Water well logs 1:100,000. Shapefile dated 1/10/13. Downloaded by W. Conley August 2013. http://www.ecy.wa.gov/services/gis/data/data.htm

Washington Department of Natural Resources (WDNR). 2013. Surface Geology 1:100,000. File geodatabase. Downloaded by W. Conley August 2013. http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/gis_data.aspx

LITERATURE CITED

Allen, B., C. Munz, and E. Harvey. 2014a. Fish Distribution and Population Dynamics in Rock Creek, Klickitat County, Washington: November 2009 – November 2013. Report A *in* Harvey, E., ed., Rock Creek Fish and Habitat Assessment for Prioritization of Restoration and Protection Actions: July 1, 2008 – May 31, 2013. Prepared for Bonneville Power Administration, Portland, OR. Project # 2007-156-00.

Allen, B., C. Munz, and E. Harvey. 2014b. Adult fish and habitat assessments. Report B *in* Harvey, E., ed., Rock Creek Fish and Habitat Assessment for Prioritization of Restoration and Protection Actions: July 1, 2008 – May 31, 2013. Prepared for Bonneville Power Administration, Portland, OR. Project # 2007-156-00.

Allison, I. 1933. New Version of the Spokane Flood. Bulletin of the Geol. Soc. Am. 44:675-722.

Andrews, E. and J. Smith. 1992. A theoretical model for calculating marginal bed load transport rates of gravel *in* Billi, P., R. Hey, C. Thorne, and P. Tacconi (eds), Dynamics of gravel-bed rivers. Chichester, Wiley. 41-52.

Aquatic Informatics, Inc. 2014. Aquarius v3.4.153. Vancouver, B.C., Canada.

Army Corps of Engineers (ACOE). 2010. HEC-SSP. Version 2.0. Davis, CA.

Aspect Consulting. 2005. Rock Creek Water Quality Report: Water Resource Inventory Area 31. Prepared for the WRIA 31 Planning Unit. Project #030009-001-01. Grant # G0400370.

Aspect Consulting and Environ International. 2012. Straight to Implementation Plan for Water Quality Improvement: Rock-Glade Watershed (WRIA 31). March 2012.

Aspect Consulting and Watershed Professionals Network. 2004. Level 1 Watershed Assessment WRIA 31 (Rock and Glade Watersheds). Prepared for the WRIA 31 Planning Unit. Project #030009-001-01. Bainbridge Island, WA.

Beechie, T. and H. Imaki. 2013 Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research 50: 1-19. doi:10.1002/2013WR013629, 2014

Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua. 2012. Restoring Salmon Habitat for a Changing Climate. River Research and Applications 29:939-960.

Benito, G. and J. O'Connor. 2003. Number and size of last-glacial Missoula floods in the Columbia River valley between the Pasco Basin, Washington and Portland, Oregon. GSA Bulletin 115(5):624-638.

Berg, L (ed.). 2001. Rock Creek Subbasin Summary. Prepared for Northwest Power Planning Council. Portland, OR. 44p.

Blaine, J. 2014. Personal communication. Local resident/rancher.

Brayshaw, A.C. 1984. Characteristics and origin of cluster bedforms in coarse-gained alluvial channels in *Sedimentology of Gravels and Conglomerates*. E.H. Koster and R.J. Steel. Can. Soc. Petrol. Geol., Mem.10:77-85.

Brierley, G.J. and K.A. Fryirs. 2005. Geomorphology and River Management. Blackwell Publishing. Malden, MA. 398p.

Carling, P. 1987. Bed stability in gravel streams, with reference to stream regulation and ecology. *in* K.S. Richards (ed.), River channels: Environment and Process. Oxford, Blackwell. 321-347.

Carmichael, R. and B. Taylor. 2010. Conservation and Recovery Plan for Oregon Steelhead Populations in the Middle Columbia River Steelhead Distinct Population Segment. Oregon Department of Fish and Wildlife, LaGrande, OR. 797 pages.

Christensen, H. 2014. Personal Communication. Email regarding Rock Creek nr Roosevelt peak magnitude for March 30, 2012 event. Washington Department of Ecology.

Church, M., M.A. Hassan, and J.F. Wolcott. 1998. Stabilizing self-organized structures in gravel bed stream channels: Field and experimental observations. Water Resources Res. 34:3169-3179.

Cooper, A.B. and M. Mangel. 1999. The dangers of ignoring metapopulation structure for the conservation of salmonids. Fish. Bull. 97:213-226.

Cooper, R.M. 2006. Estimation of Peak Discharges for Rural, Unregulated Streams in Eastern Oregon. State of Oregon, Water Resources Department. Salem, OR. Open File Report SW 06-001.

Dilts, T. 2011. Polygon Centerline to Polyline tool for ArcInfo. Downloaded by W. Conley from http://www.cabnr.unr.edu/weisberg/downloads/

Dilts, T. 2013. Riparian Topography Tools v10.0 for ArcInfo. Downloaded by W. Conley from: http://www.cabnr.unr.edu/weisberg/downloads/

Ehinger, W. 1996. Evaluation of High Temperature in Rock Creek (Klickitat County), Ecology Report No. 96-308. February 1996.

Elsner, M., L. Cuo, N. Voisin, J. Deems, A. Hamlet, J. Vano, K. Mickelson, S. Lee, and D. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. Clim. Change doi:10.1007/s10584-010-9855-0.

Environ International Corporation. 2013. Canopy Closure and Channel Morphology Study for Rock Creek, WRIA 31. Prepared for WRIA 31 Watershed Planning and Advisory Committee, Klickitat County, and the Eastern Klickitat County Conservation District. Project # 3025134A.

Environmental Protection Agency (EPA). 2010. Level III and IV Ecoregions of Washington. http://www.epa.gov/wed/pages/ecoregions/wa_eco.htm#Please%20note:

Environmental Systems Research Institute (ESRI). 2012. ArcGIS Desktop: Release 10.0.4.4000. ArcINFO, Spatial Analyst, and 3D Analyst licenses. Environmental Systems Research Institute Redlands, CA.

Espirito, E. 2009. Rock Creek Fish and Habitat Assessment for the Prioritization and Protection – 2008. Annual Report, BPA Project No. 1997-156-00, August 2009.

Espirito, E. 2010. An Evaluation of Steelhead Habitat Conditions of the Rock Creek Subbasin, A Thesis. Presented to the Graduate Faculty Central Washington University, May 2010.

Espirito, E. 2011. Rock Creek Fish and Habitat Assessment for the Prioritization and Protection – 2009. Annual Report, BPA Project No. 1997-156-00, September 2011.

Espirito, E. 2013. Rock Creek Fish and Habitat Assessment for the Prioritization and Protection – 2010. Annual Report, BPA Project No. 1997-156-00, February 2013.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management. 10: 199-214.

Glass, D. WRIA 31 Instream Habitat Assessment. Prepared for Klickitat County and Washington Department of Ecology. Grant # G0900072. 61p with Appendices.

Harris, D.D. and L.E. Hubbard. 1983. Magnitude and Frequency of Floods in Eastern Oregon. USGS Water Resource Investigations Report 82-4078. Portland, OR. 39p.

Harvey, E. 2014. Assessment of the Rock Creek Watershed Using Ecosystem Diagnosis and Treatment Model. Report C *in* Harvey, E., ed., Rock Creek Fish and Habitat Assessment for Prioritization of Restoration and Protection Actions: July 1, 2008 – May 31, 2013. Prepared for Bonneville Power Administration, Portland, OR. Project # 2007-156-00.

Keefer, M.L. and C.C. Caudill. 2012. A Review of Adult Salmon and Steelhead Straying with an Emphasis on Columbia River Populations. Prepared for: US Army Corps of Engineers, Walla Walla District. Technical Report 2012-6. 86 pages.

Kellerhals, R., M. Church, and D.I. Bray. 1976. Classification and analysis of river processes. Journal of the Hydraulics Division, Proc. Of Am. Soc. Civil Eng. 102(HY7): 813-829.

Knighton, D. 1998. Fluvial Forms and Processes. Oxford Univ. Press, New York. 383p.

Lindley, D. and W. Conley. 2013. A Literature Review of Anadromous Salmonid Habitat, Rock Creek, Klickitat County, WA. Appendix B in Harvey (2014). Prepared for Bonneville Power Administration, Portland, OR. Project # 2007-156-00.

Mantua, N, I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102: 187-223.

Matala, A. 2014. Genetic evaluation of steelhead trout (*Oncorhynchus mykiss*) in the Rock Creek watershed of the middle Columbia River Basin. Report D *in* Harvey, E., ed., Rock Creek Fish and Habitat Assessment for Prioritization of Restoration and Protection Actions: July 1, 2008 – May 31, 2013. Prepared for Bonneville Power Administration, Portland, OR. Project # 2007-156-00.

Meagher, L. 2013. Personal communication, December 2013. Eastern Klickitat Conservation District.

Microsoft Corp. 2007b. Microsoft Office Access 2007. v12.0.6606.10000. SP3. Redmond, WA.

Microsoft Corp. 2007b. Microsoft Office Excel 2007. v12.0.6683.5002. SP3. Redmond, WA.

Miller, B.F., J.L. Miller, D.T. Hathaway, and J.A. Arterburn. 2014. 2013 Okanogan Subbasin Steelhead Escapement and Spawning Distribution. Prepared for Bonneville Power Administration, Project #2003-022-00. Colville Confederated Tribes, Omak, WA.

Neuendorf, K., J. Mehl, and J. Jackson. 2005. Glossary of Geology. American Geological Institute. Alexandria, VA. 779p.

National Marine Fisheries Service (NMFS). 2009a. Recovery Plan for the Rock Creek Population of the Middle Columbia River Steelhead Distinct Population Segment. October 2009. 137p.

Oregon Department of Fish and Wildlife (ODFW). 2013. Winter Steelhead Redd to Fish Conversions, Spawning Ground Survey Data. Corvallis Research Office, Corvallis, OR. http://oregonstate.edu/dept/ODFW/spawn/pdf%20files/reports/Winter%20Steelhead%20Redd%20to%20Fish%20conversions%20-%20Final.pdf

Osterkamp, W. 2008. Annotated Definitions of Selected Geomorphic Terms and Related Terms of Hydrology, Sedimentology, Soil Science, and Ecology. Reston, VA. Open File Report 2008-1217. 49p.

Papanicolaou, T. and L. Ely. 2005. Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams. State of Washington Water Research Report WRR-21. College of Engineering, Univ. of Iowa. 47p.

Pierson, T. 2005. Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds. USGS Fact Sheet 2004-3142. 4p.

Pleus, A., D. Schuett-Hames, and L. Bullchild. 1999. Method Manual for the Habitat Unit Survey. Prepared for the Washington State Department of Natural Resources under the

Timber, Fish, and Wildlife Agreement. TFW-AM9-99-003. DNR #105. Northwest Indian Fish Commission, Olympia, WA. 31p with appendices.

Roni, P., K. Hanson, and T. Beechie. 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. N. Am. J. of Fish. Mgt. 2:856-890.

Sumioka, S.S., D.L. Kresch, and K.D. Kasnick. 1998. Magnitude and Frequency of Floods in Washington. USGS Water-Resources Investigations Report 97-4277. 91p.

Tribe, S. and M. Church. 1999. Simulations of cobble structure on a gravel streambed. Water Resources Research 35:311-318.

USGS. 2014a. National Climate Change Viewer: Summary of Middle Columbia – Lake Walulla. Oregon, Washington. (17070101).

USGS. 2014b. National Climate Change Viewer: Tutorial and Documentation.

Waananen, A., D. Harris, and R. Williams. 1971. Floods of December 1964 and January 1965 in the Far Western States: Part 1 – Description. USGS Water Supply Paper 1866-A. 265p.

Washington State university (WSU). 2014. http://www.pnwplants.wsu.edu/PlantDisplay.aspx?PlantID=247

Watershed Sciences, Inc. (WSI) 2012. LiDAR Remote Sensing: Rock Creek Drainage, Washington. Prepared for Eastern Klickitat Conservation District. June 25, 2012. Corvallis, OR. 22p.

Watters, T.R. 1989. Periodically spaced anticlines of the Columbia Plateau *in* Reidel, S.P. and Hooper P.R., eds., Volcanism and tectonism on the Columbia River flood-basalt province: Boulder, Colorado, Geological Society of America, Special Paper 239, Pages 283-292.

Wheaton J, Bennett S, Bouwes N, and Camp R. 2012. Asotin Creek Intensively Monitored Watershed: Restoration Plan for North Fork Asotin, South Fork Asotin and Charlie Creeks, Eco Logical Research, Inc., Prepared for Snake River Salmon Recovery Board. Logan, UT, 125 pp.

Wohl, E.E. 2010. Mountain rivers Revisited. American Geophysical Union. Wash, D.C. 573p.

WRIA 31 Planning Unit, 2008, Watershed Management Plan, Rock-Glade Watershed (WRIA 31), Prepared with assistance of Aspect Consulting and Watershed Professional Network, January 2008.