Black Canyon Hydroelectric Project
FERC Project No. P-14110
Geomorphology, Large Wood, and Sediment Transport Study Report
February 2014

Prepared for
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1 EXECUTIVE SUMMARY

Black Canyon Hydro, LLC (BCH) plans to file an application with the Federal Energy Regulatory Commission (FERC) for an original license for the Black Canyon Hydroelectric Project (Project), FERC Project Number P-14110, and associated facilities on the North Fork Snoqualmie River approximately 4 miles northeast of North Bend, King County, Washington. As required by the Integrated Licensing Project of FERC, BCH filed Proposed Study Plans to evaluate a wide range of potential impacts associated with the Project.

Confluence Environmental Company (Confluence) conducted a study of geomorphology, large wood, and sediment transport within a segment of the North Fork Snoqualmie River that would be affected by the proposed Project. This portion of the river, which extends from approximately river mile (RM) 5.3 to RM 2.6), is referred to as the Project Reach. This document presents the study results as part of the overall program of studies evaluating how flow-dependent resources may be affected by the BCH Project operations and informing how Project goals can be achieved.

The geomorphic analysis evaluates potential changes in geomorphic processes related to sediment transport and transport of large woody debris (LWD) resulting from changes in river flow associated with operation of the proposed Project. The proposed operation would withdraw water up to a total volume of 900 cubic feet per second (cfs) from the river based on the volume of flow available. Flow availability is based in part on a requirement to maintain no less than the minimum instream flow volume needed to support fish use within the affected river reach. At the time of this study, the instream flow requirement has not yet been determined. During periods of low flow below the minimum, water withdrawals would not occur. Project operation would have the most notable effect on flow in the river during periods of moderate flow. For flows up to 1,800 cfs, the maximum withdrawal of 900 cfs would be a large fraction of the total flow. As flow volume increases beyond 1,800 cfs, the withdrawal has a diminishing effect on channel hydraulics and the geomorphic processes driven by flow.

The primary analytical element of the geomorphic study focuses on establishing a relation between river flow volume, hydraulic forces, and mobilization thresholds for different size classes of the gravel, cobbles, and boulders that make up the river bed. The analytical results are then interpreted to determine how thresholds of sediment movement would change in response to changes in river flow. Reducing flows by water withdrawal during low and moderate flows would diminish or inactivate transport of gravel for part of the time during periods of river flow less than a few thousand cfs. Coarser material (coarse gravel, cobbles, boulders) begins moving at higher flows at which sediment transport is less sensitive to a water withdrawal up to 900 cfs.

During August 2013, Confluence conducted a reconnaissance of the river within the study area to observe the geomorphology of the channel and riparian corridor. Following the reconnaissance, Confluence surveyed six channel cross sections at selected representative locations throughout the Project reach and reference reaches upstream and downstream. At each cross section location, Confluence also surveyed the slope of the river bed along the approximate channel centerline and qualitatively documented the river bed composition and presence of LWD within and adjacent to the channel.

For each surveyed cross section, Confluence developed a stage discharge relation using Manning's equation. Bed shear stress (the force applied by flowing water to the river bed) was determined for selected river flows ranging from a low flow of 100 cfs up to the 100-year flow of 21,554 and corresponding to notable recurrence interval flow events within that range. Bed shear stress provided a basis for identifying the size of river bed material mobilized at each selected flow.

In addition to the potential impact analysis, Confluence also evaluated mobility of the cobbles and boulders within the river reach that would be located directly upstream of the proposed water intake for the facility. This part of the analysis focused on evaluating the movement of large boulders and debris that could damage the proposed infrastructure.

Key observations and findings of the geomorphic analysis are summarized below:

- The river can be divided into three geomorphic reaches within the study area based on changes in topographic confinement and channel gradient. The upper reach and lower reach are moderate gradient and moderately confined. The middle reach corresponds to Black Canyon, and it has a steep gradient and is highly confined.

- Proposed water withdrawals up to 900 cfs would have the most notable effect on sediment dynamics at low and moderate flows up to about 1,800 cfs. For such flows, the water withdrawals would remove 50% or more of the flow within the Project Reach. Geomorphic processes at work during such flows are limited to reworking and winnowing of sand and gravel bars formed during less frequent higher flows.

- Macro-scale channel formation including primary depositional features (e.g., bars and bed forms) occurs at flows higher than 1,800 cfs. Such flows occur less frequently, and the proposed water withdrawal would have a small or negligible effect on those processes.

- LWD is scarce within the Project Reach. Confluence observed a few intact logs along the channel margins or suspended above the channel on bedrock or extremely large boulders. The few pieces of LWD that showed signs of transport were heavily worn and ground up. Channel margins are stable for the vast majority of the Project Reach, and LWD recruitment is limited to wind throw, tree mortality, and a few areas of bank erosion. The river channel dimensions and range of flows indicate that all observed LWD and any candidate trees from the riparian zone would be mobile during high-flow events.

- The upstream approach reach at the proposed water intake location has a wider channel that is relatively low gradient and moderately confined compared to the Project Reach. These factors reduce sediment mobility at this location. Analytical results of this study indicate that at the 100-year flow of 21,554 cfs, material on the river bed up to approximately 1.5 feet median diameter is mobilized by the average bed shear stress under steady flow conditions. During high flows, bed shear stress varies with time and across the channel as a result of channel irregularity and turbulent eddies. Larger boulders can be moved by localized short bursts of higher shear stress, but their movement will also be limited to hopping, sliding, or rolling only a short distance until the localized short-term shear stress increase subsides.

2 INTRODUCTION

2.1 Overview

Black Canyon Hydro, LLC, (BCH) ultimately plans to file an application for an original license for the Black Canyon Hydroelectric Project (Project), FERC Project Number P-14110, and associated facilities on the North Fork Snoqualmie River (North Fork), approximately 4-miles northeast of North Bend in King County, Washington. The Project has a proposed generating capacity of 25-megawatts (MW) and would be located predominantly on private lands. The combined maximum hydraulic capacity of the four project turbines would be 900 cubic feet per second (cfs). The run-of-river Project would divert water from an approximately 2.7-mile-section of the North Fork. This reach is referred to as the Project Reach.

As required by the Integrated Licensing Process of FERC, BCH conducted several studies to evaluate a wide range of potential impacts associated with the Project. BCH will incorporate the information provided by these studies into ongoing Project design and operations planning. BCH conducted an environmental flows study within the segment of the North Fork that would be affected by the proposed Project. This portion of the river, which extends from approximately river mile (RM) 5.3 to RM 2.6, is referred to as the Project Reach. This document presents the study results as part of the overall program of studies evaluating how flow-dependent resources may be affected by the Project operations and informing how Project goals can be achieved.

The location of the Project is illustrated on Figure 1, and the Study Reach is identified in Figure 2.

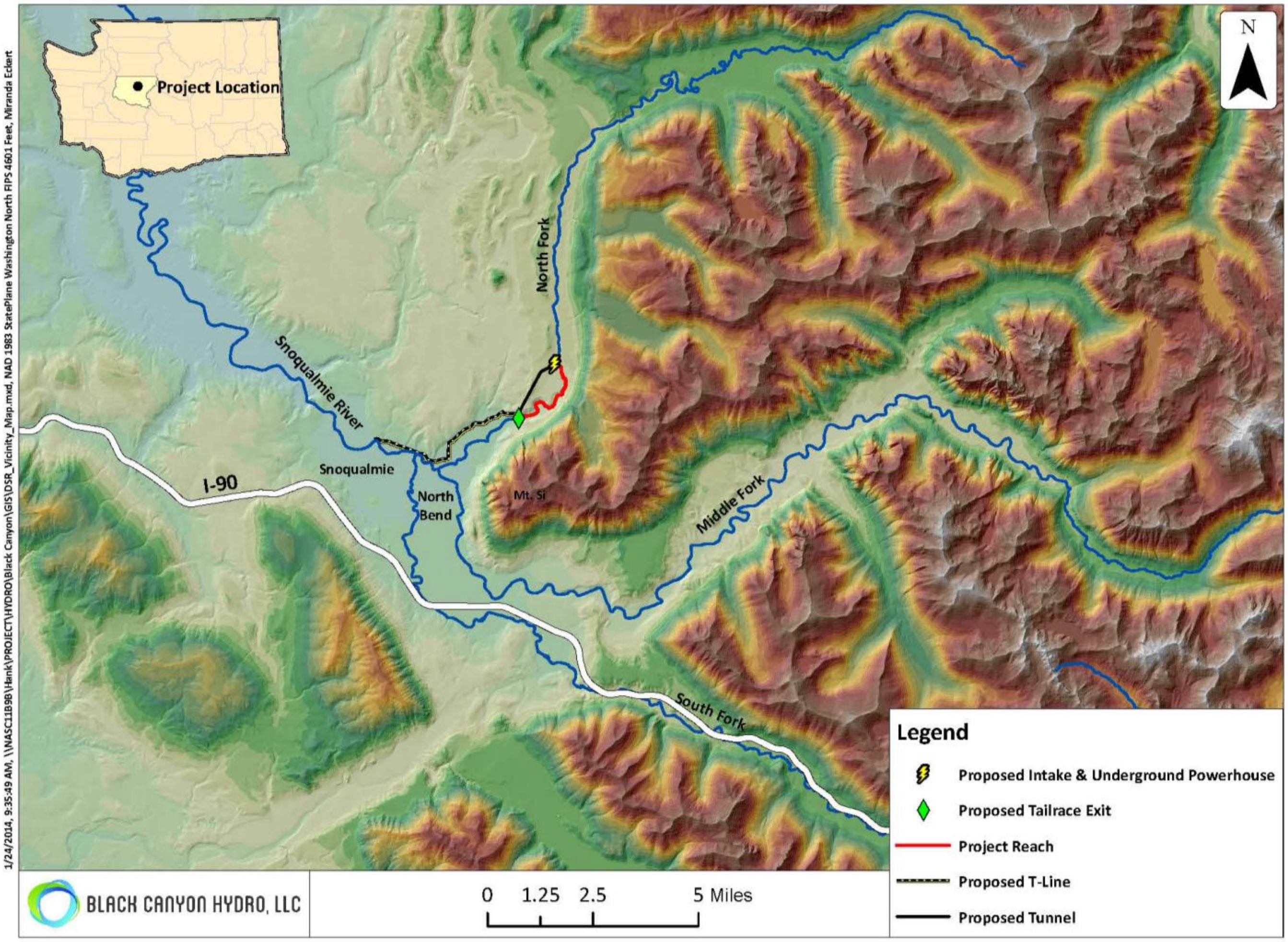


Figure 1. Project Vicinity and Project Reach
King County, Washington

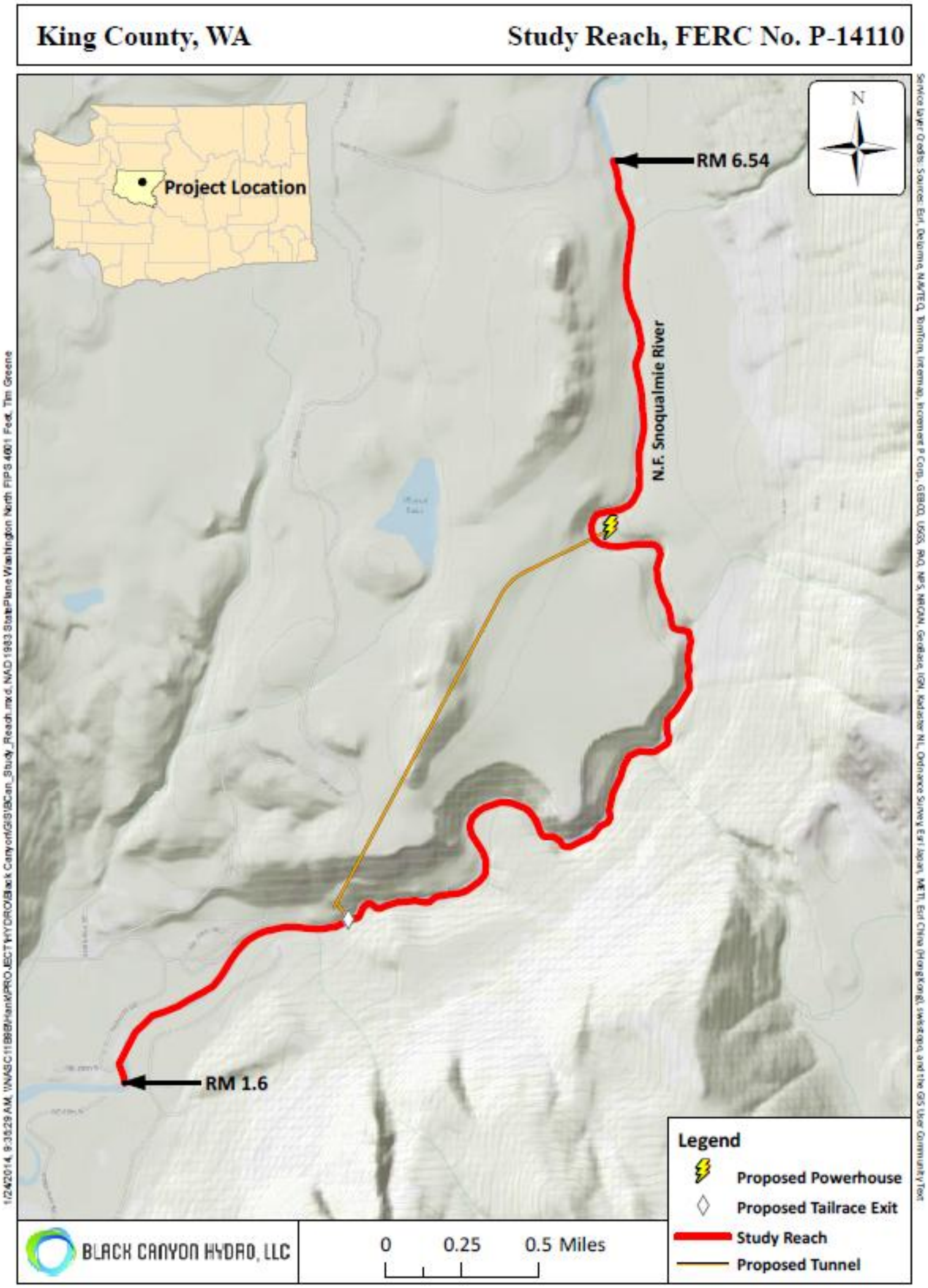


Figure 2. Study Reach, FERC No. P-14110
King County, WA

2.2 Project design

2.2.1 Intake

The following description of intake features reflects an evolution in Project design since the filing of the Pre-Application Document (PAD) through scoping, stakeholder comment, and study results. As a result of completing relevant studies, two possible design alternatives have been developed for the intake. These Alternatives are called Alternative C and D. Both alternatives involve bulk water screening located at approximately RM 5.3, on the same river bend and point-bar as Alternative A. Alternative C uses a vertical plate screening system, and Alternative D uses a horizontal plate screening system.

Both alternatives would have a (1) control sill to control the normal water surface elevation and maintain a consistent river bed elevation for a side channel bulk-water intake. The control sill would consist of a concrete weir with boulders inset on the surface over top of a sheet pile cutoff wall to capture hyporheic flow. The sill would be at the newly established grade of the river bed and would allow uninterrupted flow through a natural looking re-profiled river as a roughened channel series of step pools, riffles, and boulder weirs. (2) An intake structure with a coarse trashrack, jib crane, and radial gate with sluiceway located on the east bank of the river. Diverted water would be conveyed through; (3) an open channel to a; (4) head gate control structure and into a; (5) fish and debris screening structure. (6) Fish and debris would be screened and bypassed back into the river. Screened water would then flow through a power conduit to the underground powerhouse. (7) Access to the intake site would use an existing logging road and approximately 400 feet of new roadway extending to the intake site.

2.2.2 Powerhouse

The powerhouse location would be located underground beneath the selected intake site. This would include a (1) 450-feet tall, 30-foot diameter vertical shaft to allow space for the power penstock(s), elevator, stairs, ducting, mechanical, and electrical chases. Screened water from the intake screen system would be delivered down a (2) vertical power penstock(s) to the powerhouse. The powerhouse would (3) use four Pelton Turbines each rated at 6.25-MW, as well as appurtenant facilities. The (4) powerhouse substation and (5) elevator building would be located near the intake structure.

2.2.3 Tailrace

The tailrace will be an approximately (1) 8,600 foot long 12 foot diameter tunnel, and is anticipated to be constructed primarily in bedrock. The tailrace water return to the North Fork would be located at approximately the same location as proposed in the PAD at approximately RM 2.6.

2.2.4 Transmission

Transmission would consist of a 34.5-kilovolt (kV) underground transmission line and overhead transmission that transmits project power to the regional grid. The transmission line would be sited predominantly on an existing power line corridor. The transmission line would originate at the powerhouse substation located at the intake site at RM 5.3. Subsurface transmission would follow the vertical shaft to the underground powerhouse, and down the 1.6 mile long tunnel. After exiting the tunnel the transmission would travel underground 1.0 miles on new and existing roads then 4.2 miles as 34.5- kV overhead transmission line predominantly following an existing power line corridor to the point of interconnection. The point of interconnection is located at an existing overhead transmission line near the intersection of 396th Drive SE and SE Reinig Road approximately 0.4 miles from the City of Snoqualmie. A new switch and substation would be added at the point of interconnection to transform voltage from 34.5-kV to 115-kV.

3 DESCRIPTION OF STUDY

In accordance with 18 CFR §5.11(d)(1), this section describes the goals and objectives of the study and the information that was obtained.

Several participants in the Black Canyon Hydro Licensing process have commented on the key role that sediment and LWD play in maintaining desirable habitat for fish and wildlife in the North Fork. The diversion will create a minor pool and hydraulic conditions that promote sediment deposition. Streamflows that would normally mobilize and transport coarse sediment (bedload) downstream in the North Fork could be reduced in magnitude by diversion at the intake (up to a maximum of 900 cfs). Lower flows could become more common in the Project Reach, and moderate flows that would normally transport significant quantities of bedload could occur less frequently. High flows (i.e., those that significantly exceed the intake capacity), although infrequent and diminished in magnitude, will continue to occur on a regular basis, resulting in the mobilization and downstream transport of coarse sediment and LWD. A major question is whether the modified flow regime will affect the amount of sediment and wood delivered, stored, and transported in the Project Reach. Due to the anticipated reduction in the frequency of moderate flows in the Project Reach, there could be a change in sediment and wood delivery in the Project Reach relative to historical patterns.

The objectives of this study were to use flow duration data to assess stream-power duration in the study area, the expected yield of sediment and LWD from upstream, and expected changes in timing of transport and deposition of sediment and LWD in the study area. This information would be used to address concerns raised by stakeholders about the potential effects of the project on fish habitat in the Project Reach and downstream areas.

The North Fork in the study area is moderately steep. Gravel suitable for fish spawning is transported through the reach by high flows but does not generally accumulate in large volumes before being remobilized, although deep pools often retain gravel. The natural pattern of gravel movement and accumulation may be disrupted to varying degrees depending on methods of construction and operational protocol of the diversion. The altered flow regime will include longer periods of low-flow volumes that are interrupted by sporadic high-flow events. The alterations in the natural flow regime may lead to changes in the amount and distribution of gravel habitat throughout the Project Reach. The current channel geomorphology, distribution of LWD, and sediment transport processes associated with the natural flow regime was assessed to better understand project impacts and to establish baseline data for monitoring and mitigation.

The study was designed to achieve the following specific goals:

- Goal 1: Identify suitable sites for field assessment of geomorphology and distribution of sediment and LWD in the upstream and downstream control reaches and, to the extent safe access is possible, in the Project Reach.
- Goal 2: Obtain existing, available information on streamflow and topography and earlier studies of geomorphology, LWD, and sediment transport in the study area.
- Goal 3: Conduct a geomorphic assessment of the structure and bed material type of the Project Reach and the upstream and downstream control reaches.
- Goal 4: Characterize and rank the relative importance of mechanisms for sediment and LWD delivery to the Project Reach and transport of that sediment and LWD through the Project Reach.
- Goal 5: Characterize how seasonal variations in the duration of flows in the Project Reach each impact the timing and quantity of sediment and LWD movement into and through the Project Reach.
- Goal 6: Assess how project design and operational alternatives may impact flow duration, stream power, and resulting channel forming processes, including the abundance, distribution, and transport of sediment and LWD and issues of how flow returns and mixing might affect potential scour and riverbank erosion near the point of return from timing of reduced sediment in the return flow.
- Goal 7: Define potential scenarios for sediment and LWD transport to affect project infrastructure, including the diversion and inlet screens.
- Goal 8: Coordinate geomorphic assessments with other technical studies affected by the results of this study.

The geomorphology, LWD, and sediment transport study includes assessment of yields from upstream of sediment and LWD but does not evaluate upstream or downstream factors and sources outside the control of BCH or the proposed hydroelectric generation project.

This study was conducted in close cooperation with other studies undertaken at the same time and that are informed by this study. This study received considerable input on flow duration statistics and projected trends developed with the Hydrology Study. Other complementary studies that use results from this study include the Instream Flow; Wildlife, Vegetation, and Sensitive Habitats; Fish Passage; Aquatic Resources; Water Quality studies; and to a lesser degree the Aesthetics; Recreation Resources and Whitewater Boating studies.

4 METHODS

In accordance with 18 CFR §5.11(d)(1) and §5.11(d)(5), this section provides a detailed description of the study methodology, including data collection and analysis techniques, objectively quantified information, sampling strategy, and a schedule including appropriate field season(s) and the duration (see "Schedule" heading below).

The Geomorphology, Large Wood, and Sediment Transport Study was conducted in close conjunction with other concurrent studies. Flow duration curves developed as part of the Hydrology Study were used to evaluate river bed shear stress for a range of flow conditions. The duration curves represent alternate operational scenarios for the proposed Black Canyon Hydroelectric Project. These were used to compare sediment transport capacity in the Project Reach and upstream and downstream control reaches occurring under each scenario and existing conditions. By relating these alternative operational flow duration curves to transport capacity and to the available yield of sediment and LWD from upstream flows, this study provides a technical basis for quantifying the potential effects of construction and operation of the proposed facilities on instream sediment and wood.

The Geomorphology, Large Wood, and Sediment Transport Study includes the following study elements:

- Literature review. Existing relevant literature and data sources were identified, compiled, and reviewed to provide context and inform the analysis.

- Geomorphology summary. A geomorphology summary was prepared, distilling and synthesizing results of the Hydrology Study and this study.

The following sections identify specific methods used to address each study goal identified in Section 3.

4.1 Identify Suitable Sites for Field Assessment

The field assessment combined a broad reconnaissance with focused data collection at six representative study sites located within the Project Reach and the within the North Fork Snoqualmie River upstream and downstream of the Project Reach. Study sites were selected to represent a range of geomorphic conditions within the river. Prior studies, including an earlier Instream Flow study (R.W. Beck & Associates 1985), topography, and aerial photographs, informed the focus of the initial reconnaissance. The initial reconnaissance validated the distinct geomorphic reaches within the study area. All this information was applied to identify and select representative locations for field assessment in the control reaches upstream and downstream of the Project Reach and within the Project Reach. Access to the river was achieved via locations with written permission from property owners.

4.2 Obtain Existing Available Information

Available information regarding river flow and watershed hydrology was obtained in coordination with the Hydrology Study team. Coordination ensured that the flow analyses conducted as part of that study are suitable to support the geomorphic assessments conducted as part of this study.

The study included obtaining and reviewing additional information, including historical and current aerial photography and ground elevation data based on LiDAR.

Additional information sources including previous river and watershed studies identified by Project stakeholders were obtained and reviewed.

4.3 Conduct a Geomorphic Assessment of the Structure and Bed Material Type

Data collected at the six study sites included a survey of channel cross section and longitudinal slope using standard surveying equipment (i.e., transit, rod, tape). Surveyed cross sections were used to characterize local bathymetry and provide information necessary to calculate local bed shear stress over a range of flow conditions. At each study site, additional observations included characterizing river bed material, identifying the presence and extent of depositional features, evaluating the presence of an armor layer, and identifying the presence and nature of LWD.

4.4 Characterize and Rank the Relative Importance of Mechanisms for Sediment and Large Wood Delivery and Transport

Mechanisms for sediment and LWD delivery and transport were identified based on observations made during the field reconnaissance and the data collected at each of the six study sites. Evidence of transport mechanisms (e.g., deposition features, spatial variations in bed material composition, LWD accumulations) were documented and compared to the results of the hydraulic analysis (e.g., flow depth, velocity, and shear stress). A literature review of sediment transport studies conducted in similar geologic and hydrologic regimes provided broader validation of the transport mechanisms identified.

4.4.1 Sediment Mobility Analysis

Sediment mobility thresholds define the flow conditions in the river under which different sediment sizes begin to move along the river bed and change the shape and composition of the channel bed. The river bed includes diverse sediment material ranging from sand up to boulders larger than 10 ft in diameter. The sediment mobility analysis used well-established techniques to analyze the potential sediment transport in the river. For each cross section, Manning's Equation was used to develop a relation between flow and water surface elevation. Bed shear stress was calculated based on flow depth and water surface slope. Sediment mobility was determined for a range of flows using a Shields equation analysis.

4.4.1.1 Choice of Friction (Manning's n) Value

An initial estimate of n=0.070 was chosen to be the representative Manning's parameter for all six reaches surveyed for the geomorphic study, based on tables of n for open channels developed by Chow (1959) and our observations of the reach characteristics.

Manning's n parameters can be difficult to specify.

- Friction is a function of the amount of flow in the river. As the flow rises, the friction effects at the river bed are less significant to the overall flow.
- There is wide variety in the river substrate. We consistently observed sediment ranging from sand grains to boulders larger than 10 feet diameter at the surveyed cross sections.

4.4.1.2 Development of stage-discharge relationships

Manning's Equation can be solved numerically to determine flow:

$$Q = \frac{K_n}{n} A R_H{}^{2/3} S^{1/2}$$

Where Q is flow rate in cfs, Kn = 1.49 for US Customary units, n is Manning's parameter of roughness, and A is the wetted area.

Stage-discharge relationships were developed by solving Manning's equation for flow at a series of water depths for each cross section.

4.4.1.3 Determining the relationship between shear stress and particle size at the threshold of motion

Shear stress in a river can be represented as:

$$\tau_o = \gamma R_H S$$

Where γ is the product of density and gravity, R is the hydraulic radius (defined as cross sectional area divided by wetted perimeter), and S is the reach slope.

The dimensionless shear parameter is defined as:

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma)d_s}$$

Where ds is the particle size.

Rearranging, we can relate the shear stress (τ_o) to its dimensionless analog (τ_*):

$$\tau_o = \tau_* \, (\gamma_s - \gamma)d_s$$

At the threshold of motion, we have critical shear stress:

$$\tau_{oc} = \tau_{*c} \, (\gamma_s - \gamma)d_s = \tau_{*c} \, \rho g(S - 1)d_s$$

Where S = 2.65, ρ= 1.94 slugs/ft^2, g=32.2 ft/s^2.

Dimensionless critical shear stress for turbulent flows is constant.

$$\tau_{*c} = 0.055$$

Plugging this into the previous equation, we arrive at:

$$\tau_{oc} = (0.055)(1.94\frac{slug}{ft^3})(32.2\,\frac{ft}{s^2})(2.65 - 1)d_s$$
$$\tau_{oc} = (5.669\frac{lb\,ft}{s^2}\frac{1}{ft^3})d_s$$

Where d_s is sediment size in feet. The units are included to show that this checks out dimensionally (as a force per unit area). This relationship between critical shear stress and particle diameter can be used to determine the maximum size particle that can be mobilized by a specific river flows.

This approach assumes fully turbulent flow and uniform bed roughness. Actual conditions in the river bed are not uniform, but uncertainty associated with the approximation is acceptable for the application of this analysis. Non-uniform bed roughness would tend to increase energy loss in association with larger stationary boulders, and the approach would tend to higher than actual mobility.

4.4.2 Qualitative Evidence of Sediment Transport Dynamics

The study included observations of instream depositional features, overall abundance of mobile sediment, and spatial variations in dominant sediment size class. Qualitative evidence of sediment transport processes were used to determine the various mechanisms of sediment transport and deposition at work within the river bed.

4.5 Characterize if and how Seasonal Variations in the Duration of Flows in the Project Reach Impact Timing and Quantity of Sediment and Large Wood Flux into and Through the Project Reach

Flow frequency, magnitude, and duration data provided by the Hydrology Study illustrate seasonal variations in flow conditions within the project reach. These variations drive the transport of sediment and LWD. The study included a review of variable flow conditions and an assessment of the relation between flow and initiation of sediment transport for sediment size classes over the range of available bed material observed in the river. The analysis of sediment mass balance focused on determining whether the river has the capacity to transport the material delivered from upstream through the Project Reach and the degree to which changes in flow frequency and magnitude could alter transport capacity resulting in net deposition or temporary delay of transport.

4.6 Assess if and how Project Design and Operation Alternatives may Impact Flow Duration, Stream Power, and resulting Channel Forming Processes

The Hydrology Study provided information on the effects of Project design and operation alternatives on flow conditions including changes in flow magnitude, duration, and timing. The six surveyed cross sections were used to evaluate changes in stream power associated with altered flow conditions and assess the results in terms of changes in sediment mobility and resulting channel forming processes.

4.7 Define Potential Scenarios for Sediment and Large Wood Transport to Affect Project Infrastructure

Whitewater Engineering provided a description and illustration of Project infrastructure that would interact directly with the river. One of the six study sites including a surveyed cross section was located immediately upstream of the proposed water intake structure. This provided a basis to conduct a detailed analysis of sediment mobility within the approach reach upstream of the proposed structure. Additional data were collected within this reach to characterize the larger size classes of bed material (e.g., cobbles and boulders) and inform an analysis focused on determining the flows at which extremely large material was mobilized and directed toward the proposed infrastructure. Sediment mobility analysis also provided a basis for evaluating potential aggradation and degradation of the streambed in the vicinity of the proposed infrastructure.

4.8 Coordinate Geomorphic Assessments with Other Technical Studies

The geomorphic assessment was conducted in close coordination with the Instream Flow Study, the Hydrologic Study, and field data collection to characterize fish habitat and fish use within the study area. Field data collection efforts were scheduled to put scientists from multiple teams on site together to coordinate field data collection and to transfer field observations and data across multiple studies. Contact with the Hydrology Study team was maintained throughout the effort so that hydrologic data developed as part of the Hydrology Study supported this Geomorphology study.

5 RESULTS

The results of the study are presented using the same study elements as those defined in the previous methods discussion.

5.1 Identify Suitable Sites for Field Assessment

The field assessment combined a broad reconnaissance with focused data collection at six representative study sites located within the Project Reach and the within the North Fork Snoqualmie River upstream and downstream of the Project Reach. Figure 3 shows the location of the six study sites within the bounds of the Project study area. Appendix A includes photographs of the study sites and their vicinity.

Three of the study sites are located within the Project Reach, one study site is located within the upstream and downstream control reaches, and one study site is located in the approach reach immediately upstream of the proposed water intake structure.

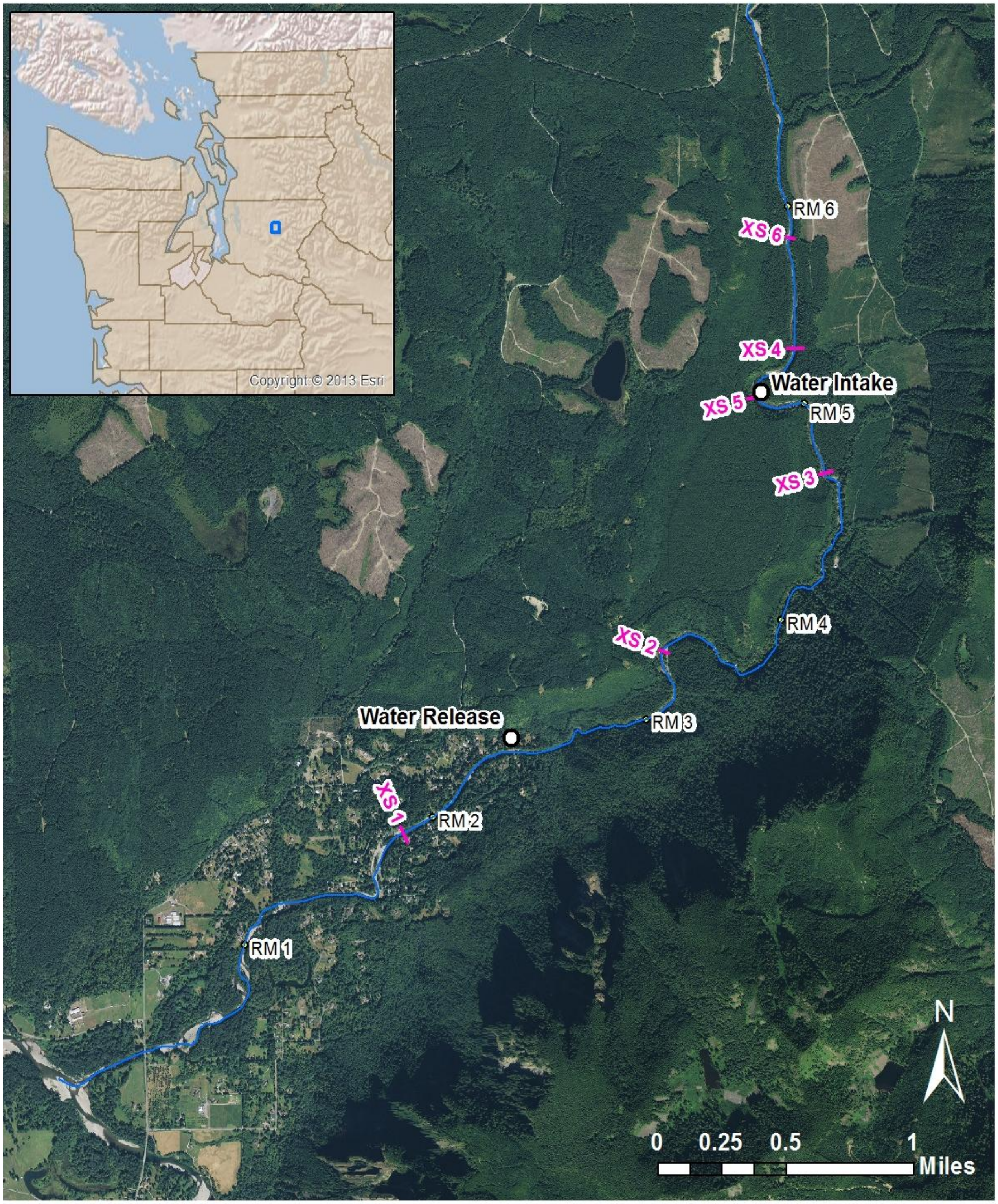


Figure 3. **Study Site Locations**
Data collected by CEC in August 2013

Study sites were selected to represent a range of geomorphic conditions within the river. Prior studies, including an earlier Instream Flow study (R.W. Beck & Associates 1985), topography, and aerial photographs, informed the focus of the initial reconnaissance. The initial reconnaissance validated the distinct geomorphic reaches within the study area. All this information was applied to identify and select representative locations for field assessment in the control reaches upstream and downstream of the Project Reach and within the Project Reach. Access to the river was achieved via locations with written permission from property owners.

5.2 Obtain Existing Available Information

Available existing information was obtained from published literature, publicly available flow data, publicly available imagery (e.g., aerial photos, LiDAR), and parallel technical studies performed for this project. Relevant data and study findings were incorporated throughout the analysis.

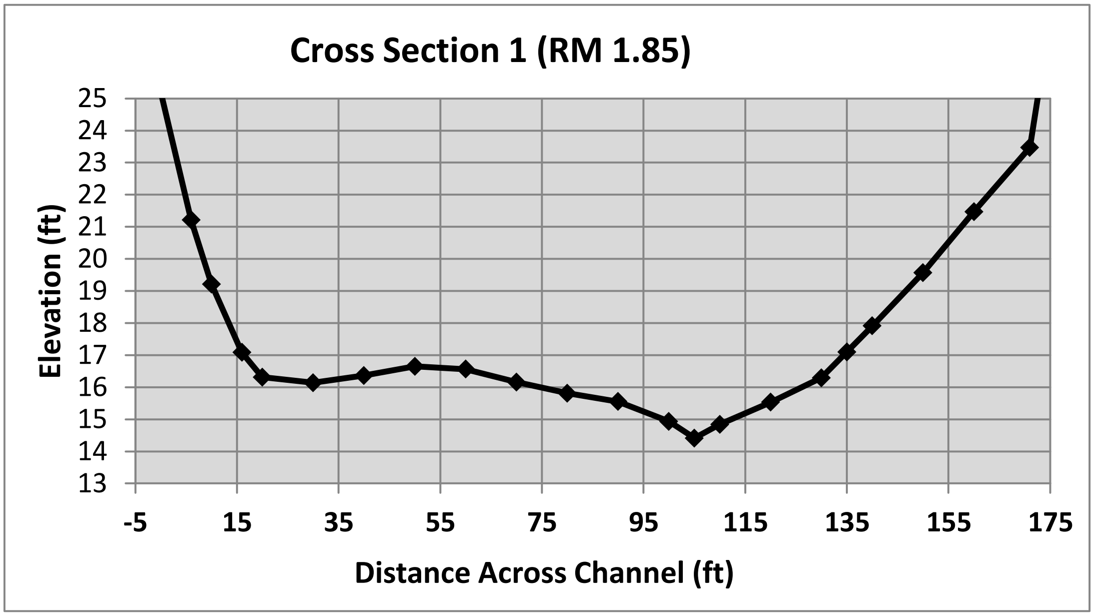
5.3 Conduct a Geomorphic Assessment of the Structure and Bed Material Type

A description of how data was collected at the six study sites can be found above in Section 4.3. Surveyed cross sections for each of the study sites are shown in Figures 4, 5, and 6. The set of cross section plots illustrate the variability in cross section shape. Bed material characteristics for each cross section are provided in Table 1.

The Project Reach includes the narrow, steep canyon reach as well as control reaches both upstream and downstream that are less steep and less confined in comparison to the canyon. Throughout the study area the riverbed is dominated by boulders and cobbles with pockets of gravel and sand common along the channel margins and in areas protected by boulders or bedrock structure. The Project Reach is dominated by chutes, drops, and pools with occasional riffles and pools in short sections that are less steep and less confined. The upstream and downstream control reaches exhibit riffle pool sequences with plane bed morphology. Pools are formed by bedrock and boulders in most instances with river bends contributing to pool formation in a few locations.

LWD place no notable role in channel forming processes. The LWD observed within the reach is very sparse and small in size. Individual pieces that had been transported were heavily worn.

Notable bank erosion was observed in only two locations within the project reach. There is little sediment recruitment within the project reach, and the sediment moving through is dominated by material delivered from upstream. The scarcity of mobile sediment within the reach suggests that the supply of sediment from upstream is far less than the capacity of the river to transport it. Mobile sediment observed within the river bed is located in sheltered places. Large scale depositional features are composed of large cobbles and boulders that are only mobilized at rare high flow events. The river has the power to transport and deposit these materials, but that does not occur from year to year during modest frequent flows.



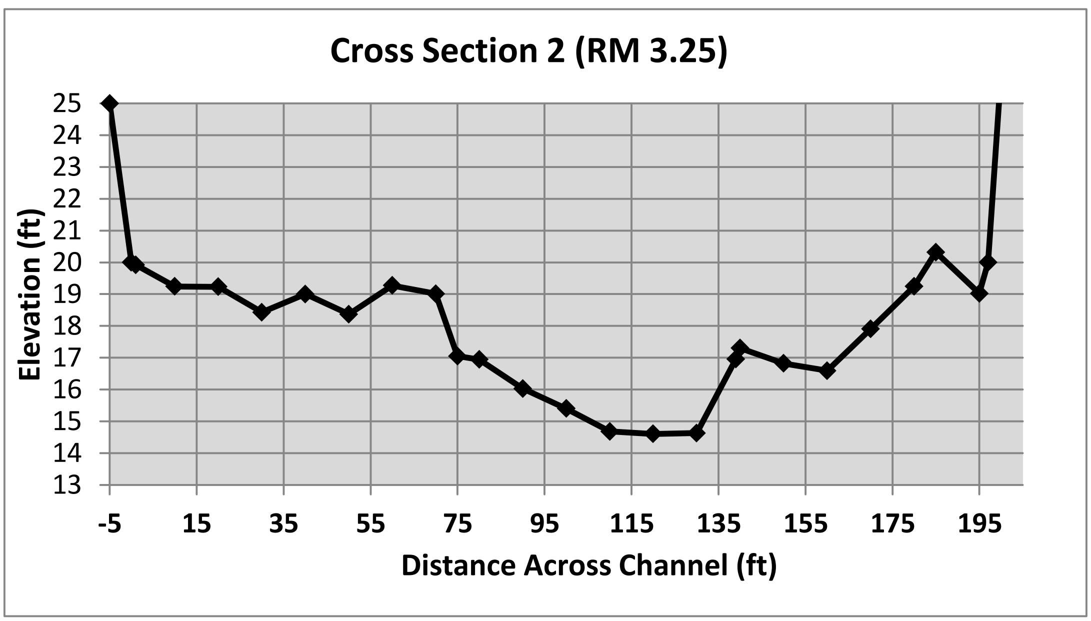
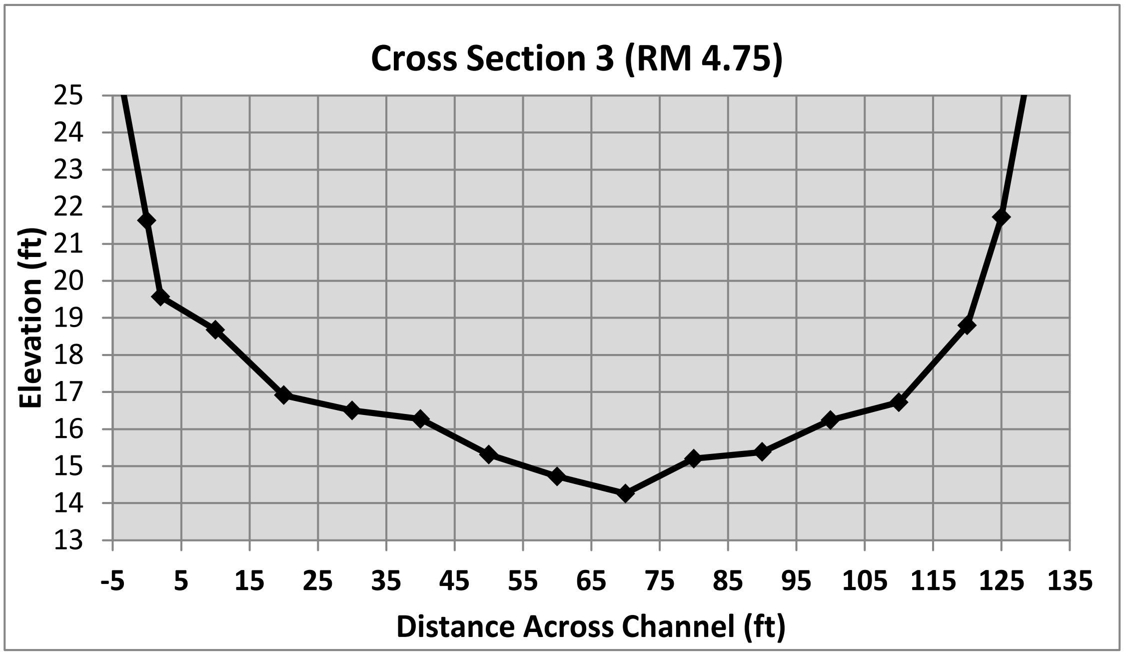


Figure 4. Cross Sections 1 & 2

Data collected by CEC in August 2013. Elevations are not referenced to vertical control



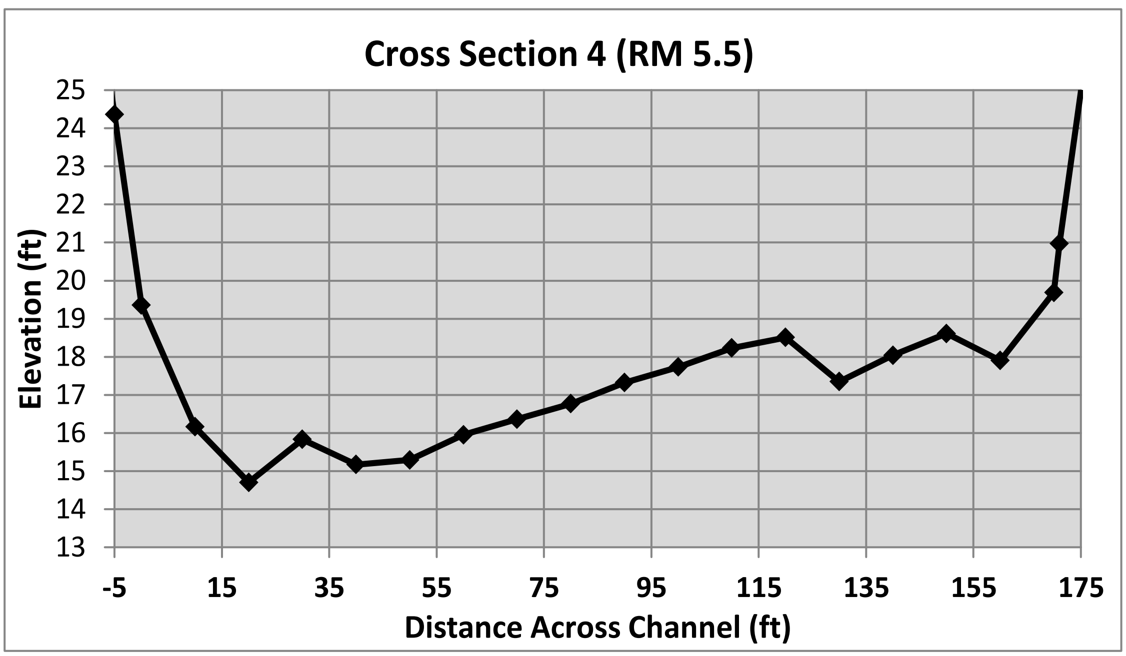
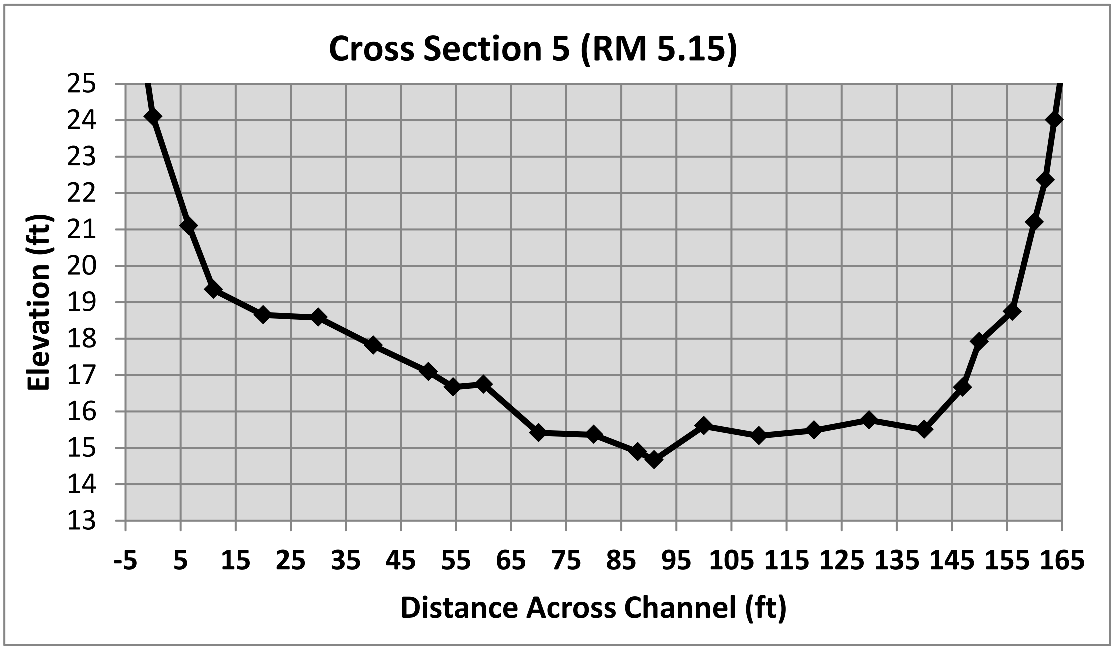


Figure 5. Cross Sections 3 & 4

Data collected by CEC in August 2013. Elevations are not referenced to vertical control



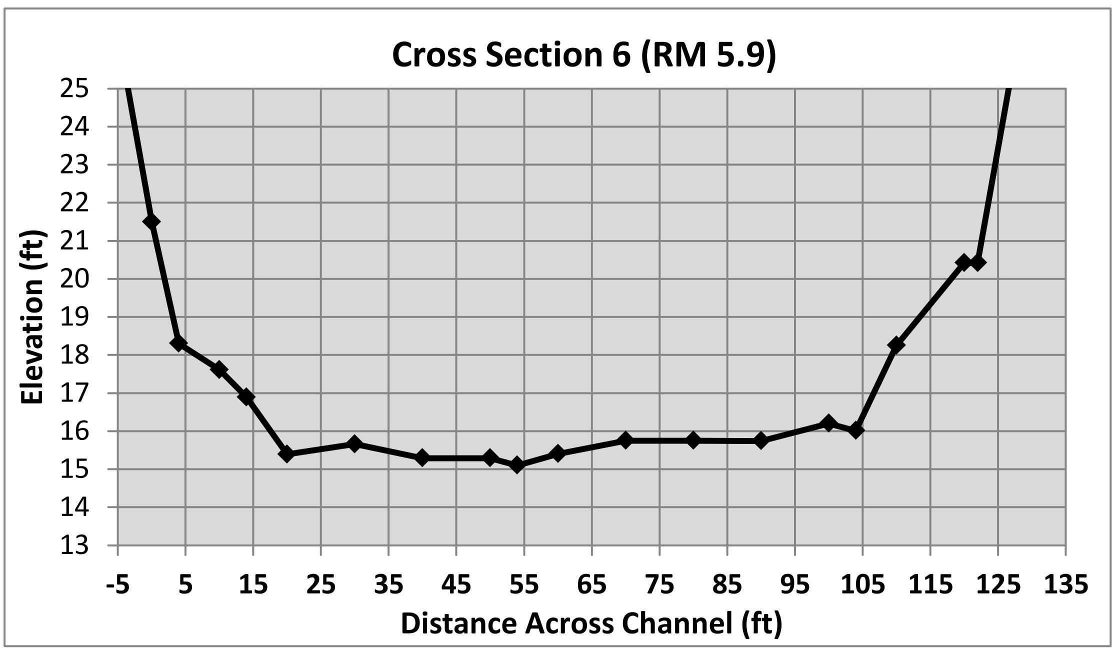


Figure 6. **Cross Sections 5 & 6**

Data collected by CEC in August 2013. Elevations are not referenced to vertical control

Table 1. Bed Material Characteristics

Study Site	Dominant Bed Material	Largest Observed	Description
1	Cobble/Boulder	3.5 feet diameter	Cobble/boulder dominant with sand and gravel 1-3 inch diameter common in pockets and along the margins. Bed armoring apparent.
2	Boulder/Cobble	8 x 12 feet boulder	Boulder/cobble dominant with clasts strongly interlocking and armored. Boulders 4 feet diameter common. Gravel bars in pockets and on channel margin. Pool bottoms lined with cobbles.
3	Boulder	8 feet diameter	Boulder dominant with cobbles and sparse gravel. Boulders 1 -3 feet diameter common.
4	Boulder/Cobble	8 x 5 x 10 feet boulder	Boulder dominant with cobbles. Large boulder/cobble bar along right bank facing downstream. Gravel and sand deposits in pockets and along channel margins. Boulders 1 - 2 feet diameter common.
5	Boulder/Cobble	5 feet diameter	Cobble/boulder dominant with maximum diameter 1.5 feet on the bar. Sand and gravel 1-3 inch diameter common in pockets and along the margins. Bed armoring apparent.
6	Boulder/Cobble	10 feet diameter	Boulders common throughout in both riffles and pools. Point bar composed of cobbles up to 2 feet diameter. Pockets of sand and gravel common. Point bar ends abruptly at downstream end.

5.4 Characterize and Rank the Relative Importance of Mechanisms for Sediment and Large Wood Delivery and Transport

Refer to Section 4.4 for methods to analyze mechanisms for sediment and LWD delivery and transport.

5.4.1 Sediment Mobility Analysis

The analysis of sediment mobility focused on identifying thresholds of movement for different sediment size classes at each of the six Study Sites. The analysis identifies the maximum sediment size that can be transported by the river over a range of progressively larger flow events. As flow volume (discharge measured in cfs) increases, the stream power increases and applies a greater force to the river bed. This force is called “bed shear stress”. Fine material (e.g. sand and gravel) is easily mobilized at modest bed shear stress values that occur several times each year. Cobbles and boulders become mobile with higher bed shear stress that occurs more rarely. The analysis identifies sediment mobility as the largest mobile sediment size for each of the six surveyed cross sections at a range of flow events up to the 100-year recurrence interval flow. Table 2 summarizes the results.

Table 2. Sediment Mobility Summary Table

Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
Cross Section 1 (RM 1.85)					
N/A	100	0.97	2.37	0.14	0.025
N/A	200	1.28	2.85	0.21	0.036
2 yr	7297	8.11	11.20	1.32	0.23
5 yr	10539	10.11	13.22	1.64	0.29
10 yr	12911	11.23	14.65	1.82	0.32
20 yr	15353	12.26	15.98	1.99	0.35
50 yr	18777	13.83	17.57	2.24	0.40
100 yr	21554	15.03	18.77	2.44	0.43
Cross Section 2 (RM 3.25)					
Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
N/A	100	1.04	1.27	1.26	0.22
N/A	200	1.23	1.70	1.67	0.29
2 yr	7297	3.86	6.84	5.66	0.92
5 yr	10539	4.81	7.82	7.05	1.14
10 yr	12911	5.43	8.46	7.97	1.29
20 yr	15353	6.03	9.07	8.84	1.43
50 yr	18777	6.80	9.86	9.97	1.61
100 yr	21554	7.28	10.46	10.68	1.73
Cross Section 3 (RM 4.75)					
Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
N/A	100	0.76	1.48	1.34	0.24
N/A	200	1.13	1.84	2.03	0.36
2 yr	7297	4.80	6.88	9.38	1.52
5 yr	10539	5.75	8.18	11.23	1.82
10 yr	12911	6.49	8.96	12.68	2.05
20 yr	15353	7.21	9.70	14.07	2.28
50 yr	18777	8.13	10.63	15.88	2.57
100 yr	21554	8.83	11.33	17.25	2.79
Cross Section 4 (RM 5.5)					
Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
N/A	100	0.87	1.81	0.43	0.08
N/A	200	1.24	2.32	0.60	0.11
2 yr	7297	5.75	8.26	2.94	0.48
5 yr	10539	7.05	9.70	3.61	0.58
10 yr	12911	7.96	10.61	4.07	0.66
20 yr	15353	8.69	11.58	4.44	0.72
50 yr	18777	9.80	12.73	5.02	0.81
100 yr	21554	10.65	13.60	5.45	0.88

Cross Section 5 (RM 5.2)					
Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
N/A	100	0.94	1.61	0.36	0.06
N/A	200	1.16	2.07	0.48	0.09
2 yr	7297	6.39	8.66	2.79	0.45
5 yr	10539	7.71	10.34	3.37	0.55
10 yr	12911	8.71	11.37	3.80	0.62
20 yr	15353	9.66	12.33	4.22	0.68
50 yr	18777	10.90	13.57	4.76	0.77
100 yr	21554	11.44	14.71	5.00	0.81
Cross Section 6 (RM 5.9)					
Return Period	Flow rate (cfs)	Average water depth (ft)	Maximum water depth (ft)	Shear stress (lb/ft^2)	Maximum mobile sediment size (ft)
N/A	100	0.66	1.09	0.67	0.12
N/A	200	0.90	1.40	1.02	0.18
2 yr	7297	5.39	6.91	6.56	1.06
5 yr	10539	6.72	8.27	8.18	1.32
10 yr	12911	7.59	9.14	9.24	1.50
20 yr	15353	8.42	9.97	10.25	1.66
50 yr	18777	9.29	11.20	11.30	1.83
100 yr	21554	9.86	12.07	12.00	1.94

Stream power increases in proportion to flow with the highest bed shear stress values occurring during the highest flows. Bed shear stress also increases in proportion to stream gradient. Steeper river reaches produce higher velocities and shear stresses compared to flatter reaches. Channel confinement can also strongly affect bed shear stress. A narrow deep channel produces a higher shear stress than a wide shallow channel. In summary, the steep, narrow, deep canyon reach of the river within the project reach has a much larger shear stress than the flatter, wider river reaches located both upstream and downstream of the project reach. Logically, the project reach would have the ability to transport everything that is delivered by the river from upstream. This hypothesis is demonstrated by the mobility analysis.

At the 100-year recurrence interval, the largest mobile bed sediment size ranges from small cobbles (0.43 feet diameter) at study site #1 up to boulders (2.79 feet diameter) at study site #3. These findings are consistent with the observations of boulder/cobble composition of the depositional features (e.g. point bars, lateral bars) throughout the study area. Association of these sediment sizes with the 100-year recurrence interval flow suggests that the cobble/boulder bars are formed and modified at rare flow events while smaller cobbles, gravel, and sand are mobilized more frequently. From year to year, the active portion of the river bed is reflected in the pockets and small bars composed of sand and gravel.

5.4.2 Qualitative Evidence of Sediment Transport Dynamics

The river bed composition is widely variable within the Project Reach ranging from sandy gravel up to individual boulders larger than 10 feet diameter. The largest size class observed on a depositional feature within the channel was large cobbles and small boulders ranging from 1 – 2 feet diameter. Smaller bars occupying pockets behind boulders and along the channel margins were composed of finer gravel and sand material (e.g. sandy 2-inch minus).

Cobble bars were observed in the vicinity of each of the six study sites. The extent of these bars ranged from 30 – 200 feet length along the channel, and they occupied up to half the width of the bank full channel. Cobble and gravel made up the surface of these bars with scattered larger boulders. Gravel and sand occur below the cobbles and were observed when cobbles were moved to explore the subsurface by hand. Clusters of cobbles and imbrication (i.e. cobbles that group together like a row of fallen dominoes) provide evidence that cobbles move and are arranged by flows. The prevalence of an armor layer throughout the project reach and the scarcity of depositional features within the project reach suggest that the available sediment load is much smaller than the capacity of the channel to transport sediment.

Extremely large boulders (e.g. diameter greater than 4 feet and sometimes exceeding 10 feet) were observed in the channel throughout the study area. In contrast to the cobbles, which were clean and well rounded, all boulders greater than 4 feet diameter were covered with moss and small plants. All observed boulders within the river bed were also partially buried. Small patches of sand and gravel deposited on top of two large boulders were observed within the project reach near study site #3. These observations suggest that the boulders have not recently been moved by the river.

5.4.3 Large Wood Delivery and Transport

LWD is scarce within the Project Reach. Confluence observed a few intact logs along the channel margins or suspended above the channel on bedrock or extremely large boulders. The few pieces of LWD that showed signs of transport were heavily worn and ground up. Channel margins are stable for the vast majority of the Project Reach, and LWD recruitment is limited to wind throw, tree mortality, and two observed areas of bank erosion. The river channel dimensions and range of flows indicate that all observed LWD and any candidate trees from the riparian zone would be mobile during high-flow events. Observations of LWD within the Study Area were consistent with previous observations reported in a separate study (WDFW 2011).

5.5 Characterize if and how Seasonal Variations in the Duration of Flows in the Project Reach Impact the Timing and Quantity of Sediment and Large Wood Flux into and Through the Project Reach

Refer to Section 4.5 for a description of methods used to assess the relation between flow variations and transport of sediment and LWD.

Figure 7 shows exceedance probability and recurrence intervals for peak stream flow events. Table 3 shows flow values for each recurrence interval ranging from the 2-year up to the 100-year recurrence event flow values. Figure 8 shows the annual flow duration curve at the proposed flow diversion structure.

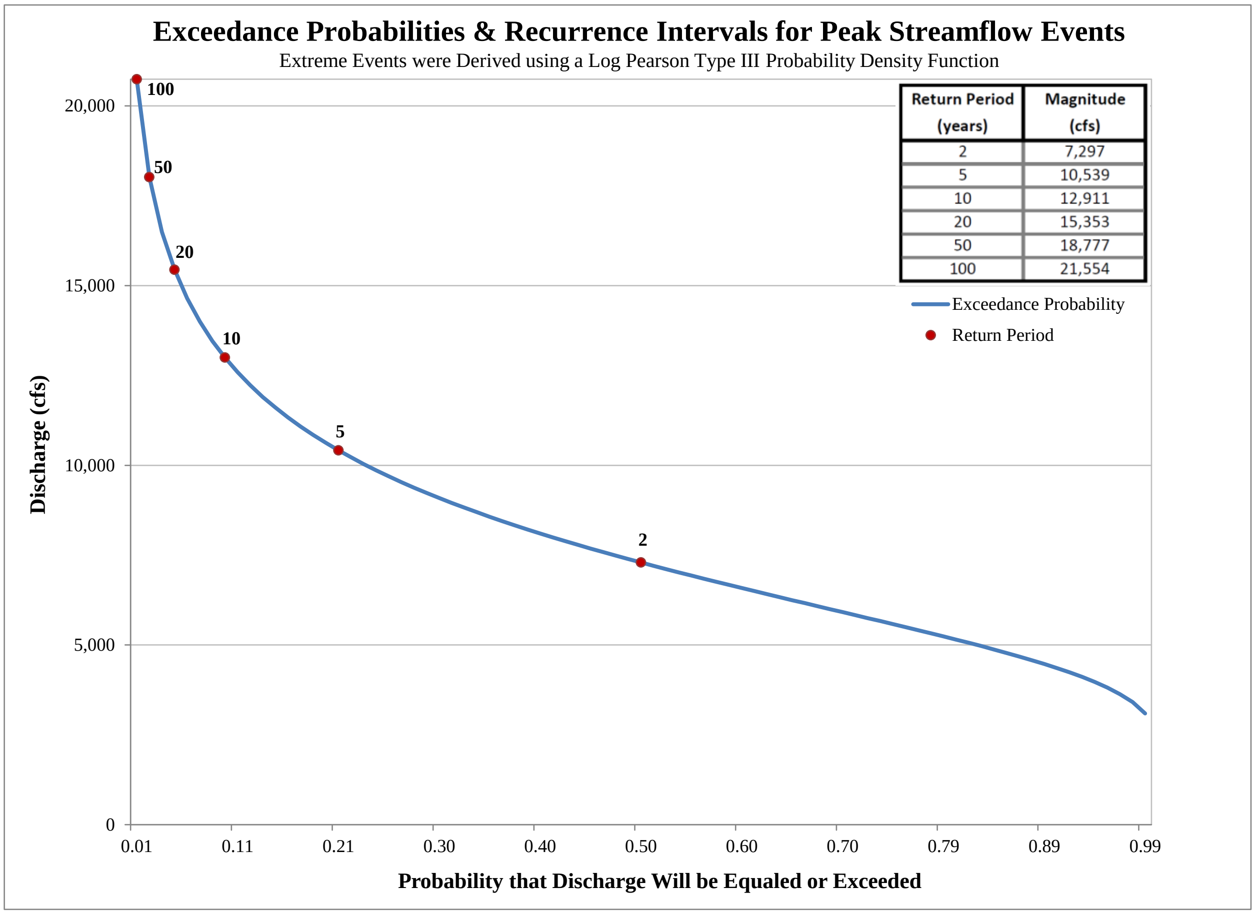


Figure 7. Exceedance probabilities and recurrence intervals for peak stream flow events.
Provided by Whitewater Engineering

Table 3. Recurrence Interval Flow Values

Recurrence Interval	Flow Value (cfs)
2-year	7,297
5-year	10,539
10-year	12,911
20-year	15,353
50-year	18,777
100-year	21,554
*Values provided by Whitewater Engineering.	

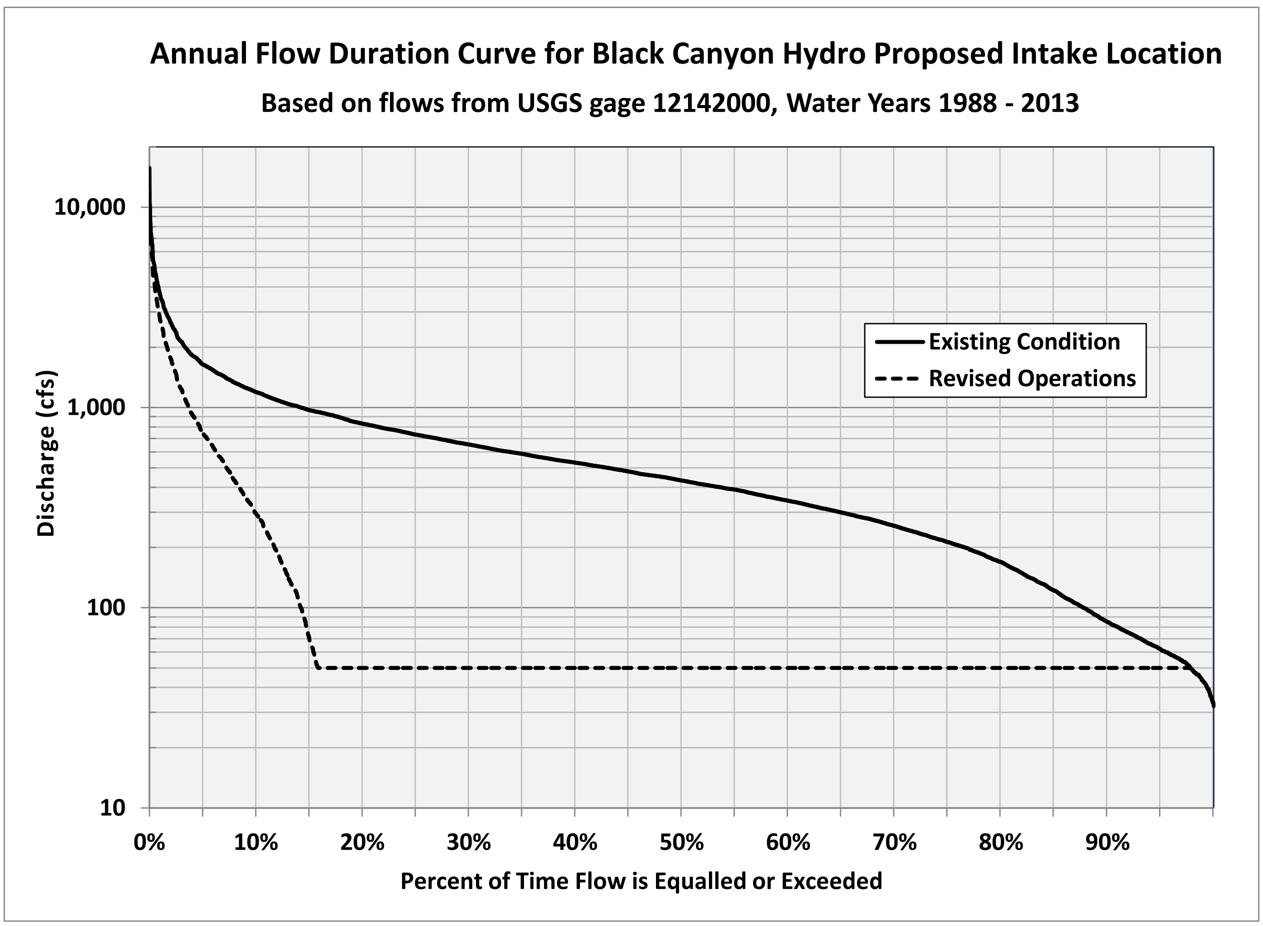


Figure 8. Annual Flow Duration Curve, for Proposed Intake Location

The sediment mobility analysis demonstrated that cobbles and boulders making up the large scale depositional features observed in the river bed are only mobilized and actively transported during rare high flow events. The finer material (i.e. sand and gravel) observed in the river bed only occurs in pockets and along channel margins in small quantities. Sediment recruitment into the project reach is dominated by delivery from upstream within the river. Little sediment recruitment was observed within the project reach due to stable channel margins. The river maintains a capacity to transport sediment far in excess of the available sediment load.

5.6 Assess if and How Project Design and Operation Alternatives may Impact Flow Duration, Stream Power, and Resulting Channel Forming Processes

The Hydrology Study provided information on the effects of project design and operation alternatives on flow conditions including changes in flow magnitude, duration, and timing. The six surveyed cross sections were used to evaluate changes in stream power associated with altered flow conditions and assess the results in terms of changes in sediment mobility and resulting channel forming processes.

Figure 7 shows the existing annual flow duration curve at the proposed intake location along with the anticipated change in the flow duration curve associated with project operation. For this analysis, we assumed the minimum instream flow requirement of 50 cfs and a maximum flow diversion of 900 cfs.

The sediment mobility analysis considering the existing flow regime indicated that portions of the sediment bed composed of material finer than 4 inch diameter cobbles and gravel would be mobilized multiple times every year, and the 2-year recurrence interval flow event would mobilize cobbles approximately 0.5 – 1.5 ft diameter depending on the local riverbed gradient and resulting bed shear stress. At the proposed intake location, the 2-year recurrence interval flow of 7,297 cfs would mobilize gravel and cobbles up to 0.48 ft diameter. River bed mobilization of material finer than 4 inch diameter would still occur several times per year under the modified flow regime that would be in effect under project operation. The operation would most notably modify flows at the low end of the flow magnitude range. These flows do the least work in modifying the channel bed, and alterations to these flows would have a much smaller effect on dominant channel modifying flows leaving channel forming processes intact.

5.7 Define Potential Scenarios for Sediment and Large Wood Transport to Affect Project Infrastructure

Refer to Section 4.7 for methods to determine how transport of sediment and LWD would affect project infrastructure.

Observations throughout the Project Reach and overall study area indicated that LWD is scarce within the system. Every observed piece of LWD was small enough to be easily transported at flows greater than 4 ft average depth. The size and scarcity of LWD suggest that LWD accumulation on the proposed infrastructure would be very unlikely. Additionally, the impact of LWD hitting the structure could be minimized by thoughtful orientation and location of the structural elements relative to the direction of flow and local plan form of the channel. The proposed lateral intake along a river bend would be suitable for minimizing encounters with LWD in transport.

The sediment mobility analysis of Study Site #4 identifies the relation between flow and mobilization of gravel, cobbles, and boulders. The results of the analysis indicate that at the 100-year recurrence flow event, all bed material up to 0.88 ft diameter would be mobilized. At the 2-year recurrence interval, all bed material up to 0.48 ft diameter would be mobilized. These calculations are consistent with the observed cobble boulder composition of the river bed. Cobbles and boulders in this size range were common. Extremely large boulders were present in this reach ranging from 5 – 10 ft diameter. The evaluation considered whether those extremely large boulders could be mobilized by flow.

Alternative mechanisms for moving large boulders were considered, but no clear evidence for any of these mechanisms was observed during the reconnaissance beyond the presence of boulders larger than 5 ft diameter in the river bed. Such other mechanisms include the following:

- **Leverage by LWD** – During periods of modest flow in which the largest boulders are just covered over by the water surface, LWD floating along the surface could jam against a boulder. The force of the initial impact as well as the additional force of flow on the LWD could lever the boulder into motion. While possible, this transport mechanism would be rare due to the scarcity of LWD in the system and the limited water depth range in which such encounters would be possible. Additionally, the transport distance for a single boulder would be on the scale of several feet since transport would likely free the LWD piece from its short-term attachment to the boulder.

- **Scour and rolling -** Large boulders create a hydraulic shadow downstream and have the potential to form a small scour pool downstream of the boulder. As flow increased, it is possible for flow to scour a hole downstream of a boulder and eventually roll the boulder into the hole. Many of the boulders observed at Study Site #4 were partially buried suggesting that this transport mechanism may be at work in this location. Transport distances are limited to approximately the diameter of the boulder.

- **Short-term localized variations in shear stress -** The mobility analysis considers average shear stress applied to the river bed in determining the maximum mobile sediment size. In fact, local shear stress varies widely across the channel and along the channel over short distances. The local shear stress could be twice the average value. As a result, much larger boulders could be moved, but only for a short distance within the local zone in which shear stress is greater. Boulders moved by short-term small-scale increase in shear stress would be moved a short distance for a short time at the same scale as the deviation from average.

While extremely large boulders are likely mobilized during extreme flow events, they remain barely mobile at the100-year recurrence event flow. Transport mechanisms are limited to short distances and short times and would occur rarely. Within the approach reach upstream of the proposed flow diversion structure, cobbles and boulders up to 0.88 ft diameter are mobilized between the 2-year and 100-year recurrence interval flow events. The proposed structure should account for potential aggradation of such material.

5.8 Coordinate Geomorphic Assessments with other Technical Studies

As described in Section 4.8, the geomorphic assessment was conducted in close coordination with the Instream Flow Study, the Hydrologic Study, and field data collection to characterize fish habitat and fish use within the study area.

6 CONCLUSIONS

- The river can be divided into three geomorphic reaches within the study area based on changes in topographic confinement and channel gradient. The upper reach and lower reach are moderate gradient and moderately confined. The middle reach corresponds to Black Canyon, and it has a steep gradient and is highly confined.

- Proposed water withdrawals up to 900 cfs would have the most notable effect on sediment dynamics at low and moderate flows up to about 1,800 cfs. For such flows, the water withdrawals would remove 50% or more of the flow within the Project Reach. Geomorphic processes at work during such flows are limited to reworking and winnowing of gravel bars formed during less frequent higher flows.

- Macro-scale channel formation including primary depositional features (e.g., bars and bed forms) occurs at flows higher than 1,800 cfs. Such flows occur less frequently, and the proposed water withdrawal would have a small or negligible effect on those processes.

- LWD is scarce within the Project Reach. Confluence observed a few intact logs along the channel margins or suspended above the channel on bedrock or extremely large boulders. The few pieces of LWD that showed signs of transport were heavily worn and ground up. Channel margins are stable for the vast majority of the Project Reach, and LWD recruitment is limited to wind throw, tree mortality, and a few areas of bank erosion. The river channel dimensions and range of flows indicate that all observed LWD and any candidate trees from the riparian zone would be mobile during high-flow events.

- The upstream approach reach at the proposed water intake location has a wider channel that is relatively low gradient and moderately confined compared to the Project Reach. These factors reduce sediment mobility at this location. Analytical results of this study indicate that at the 100-year flow event, material on the river bed up to approximately 1.5 feet median diameter is mobilized by the average bed shear stress under steady flow conditions. During high flows, bed shear stress varies with time and across the channel as a result of channel irregularity and turbulent eddies. Larger boulders can be moved by localized short bursts of higher shear stress, but their movement will also be limited to hopping, sliding, or rolling only a short distance until the localized short-term shear stress increase subsides.

7 REFERENCES

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Chow, V.T. 1959. Open-channel Hydraulics. McGraw Hill. New York, NY.

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Appendix A – Project Site Photographs

Photo 1 – Geomorphology survey site #1, Ernie’s Grove.

Photo 2 – Geomorphology survey site #1, Ernie’s Grove.

Photo 3 – Geomorphology survey site #2, Canyon Springs Reach.

Photo 4 – Geomorphology survey site #2, Canyon Springs Reach.

Photo 5 – Geomorphology survey site #3, Upper Canyon Reach.

Photo 6 – Geomorphology survey site #3, Upper Canyon Reach.

Photo 7 – Geomorphology survey site #4, Hancock Reach.

Photo 8 – Geomorphology survey site #4, Hancock Reach.

Photo 9 – Geomorphology survey site #5, Upper Project Reach.

Photo 10 – Geomorphology survey site #5, Upper Project Reach.

Photo 11 – Geomorphology survey site #6, Hancock Reach.

Photo 12 – Geomorphology survey site #6, Hancock Reach.