Sediment Impact Assessment of Columbia River System Operations

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Extended Abstract

A 2020 Environmental Impact Statement (EIS) was completed to review and update management of the Columbia River System (CRS) comprised of fourteen federal water regulation projects in Idaho, Montana, Oregon, and Washington. The CRS includes both storage and run-of-river regulation projects in four major subbasins. In support of the EIS alternatives analysis, a suite of river mechanics metrics were developed to assess potential response within the CRS. Spatiotemporal distributions of hydraulics and sediment metrics were computed using daily timeseries representing a standardized suite of 5000-year stochastic hydroperiods to quantify baseline conditions and assess potential change within 82 sub-reaches under multiple EIS alternatives. This presentation summarizes two sediment impact metrics of interest in the run-of-river reaches: the potential for changes in sediment passing reservoirs and reaches, and the potential for changes in bed material.

Introduction

A river mechanics assessment was completed in support of the Columbia River System Operations (CRSO) Environmental Impact Statement (EIS) (Corps, 2020). The general approach for evaluating the river mechanics response was to leverage baseline and alternative stochastic forcing conditions across the CRS system of fourteen federal hydroregulation projects as inputs to a suite of quantitative river mechanics metrics. Discrete metrics were developed for both storage projects and run-of-river reaches (including both non-storage reservoirs and free-flowing reaches). This presentation summarizes the modeling approach and calculations of critical grain size, sediment suspension thresholds, and sediment transport capacity that were used to assess the potential for relative change in both bed material composition and sediment passing reservoirs and reaches across the CRS.

Area of Analysis

For the river mechanics assessment, the area of analysis was the CRS project reservoirs, and the river reaches downstream that are within the borders of the United States. The CRS is organized into four physiographic regions lettered A through D which extend from the basin headwaters to the Pacific Ocean (Figure 1).

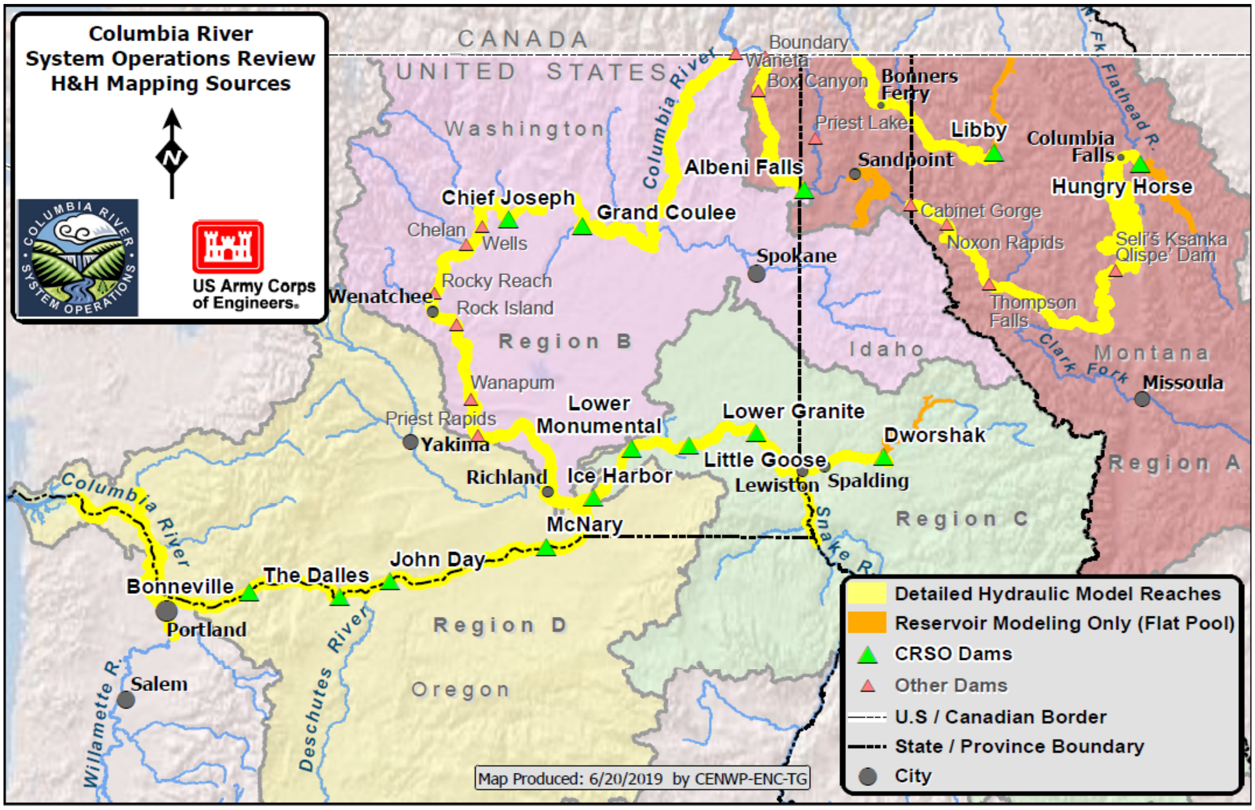

Figure 1. Overview Map of CRS Study Area Regions

Region A is the basin headwaters within the U.S., and includes the Kootenai, Flathead, and Pend Oreille Basins each with a respective large storage project (Libby, Hungry Horse, and Albeni Falls). There are nine hydroregulation projects located within Region A, three of which are CRS projects operated for storage, and a remaining six run of river projects that are not part of the CRS but were included in the modeling framework.

Region B includes the middle Columbia River Basin as it enters the United States from Canada. The middle Columbia River Basin analysis reach spans approximately 413 river miles from the U.S.- Canada border upstream in northeastern Washington to Richland, Washington, downstream near the Yakima River confluence. The downstream extent of this major reach ends at the transition from the free-flowing Hanford Reach to the backwatered McNary Reservoir. There are seven hydroregulation projects located within Region B, only one of which Grand Coulee is part of the CRS and is operated for storage. The remaining six projects are all run-of-river projects.

Region C includes the Clearwater and lower Snake River Basins in western Idaho and eastern Washington. There are five CRS hydroregulation projects located within Region C that have modified operational measures under the EIS. Only one of the projects (Dworshak) is operated for storage, while the remaining four on the lower Snake River below Lewiston, Idaho are run-of-river projects.

Region D includes the Columbia River below Richland, Washington. The upstream extent of Region D begins at the downstream extent of Region B. The lower Columbia River reach extends over 300 river miles from the mouth of the Columbia River near Astoria, Oregon to the confluence with the Snake and Yakima Rivers. There are four hydroregulation projects located within Region D that have modified operational measures under the EIS.

To capture the complex interactions across the heavily regulated CRS, the approach for the river mechanics assessment required integrating a large quantity of data. Detailed simulations for hydrologic forcing, and hydraulic/sediment response were considered to establish baseline conditions and assess multiple objective alternatives for changing project operations and/or configuration.

Hydrologic Models

Regional boundary conditions for the river mechanics assessment were computed by the CRSO hydrology team using a hydroregulation model of the CRS. A standardized inflow dataset was developed using the 2010 Level Modified Streamflows (Bonneville 2011) as the widely accepted eighty-year regional baseline for the 1929 to 2008 hydroperiod. This was then complemented with several other datasets to interpolate data gaps and extend the hindcast record to include historical floods as detailed in Appendix B-4 of the CRSO EIS (Corps, 2020).

The hydroregulation planning model was developed using the Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) model and integrated across the basin using the Watershed Assessment Tool (HEC-WAT). This framework was used to model the multipurpose operations of CRS projects and applied a Monte Carlo scheme to incorporate hydrologic uncertainties into the simulations. The general approach randomly sampled hydrologic inputs from the event record compared to the forecast volume and flow to evaluate uncertainty and synthesize daily timeseries of flow and stage over a 5,000-year hydroregulation period. This approach was used to represent the stochastic variability of watershed forcing for a discrete hydroregulation scenario (i.e. baseline or alternative) and is discussed in detail in Appendix B-3 of the CRSO EIS (Corps, 2020). Stochastic daily timeseries outputs from the hydrologic models were generated at 67 common computation points (CCPs) and used as quasi-unsteady boundary conditions for the CRS hydraulic models and ratings.

Hydraulic Models

In 2012, USACE developed a modernized set of Columbia River Basin reach-scale hydraulic models intended for multiple purposes to support a future assessment of the current level of flood risk and the flood risk impacts of the future changes in the Columbia River Basin. These Iteration-1 models refactored historical data with updated bathymetric, terrain, and calibration data into an integrated model set, and were incrementally updated to Iteration-4 by 2016 to reduce error and improve stability. The models were developed using the one-dimensional solver of the Hydrologic Engineering Center River Analysis System (HEC-RAS) and integrated across the CRS basin using HEC-WAT as detailed in Appendix B-2 of the CRSO EIS (Corps, 2020).

Major river systems within the CRS were discretized into approximately thirty major river reaches that spanned ~1,613 river miles (Figure 2). The major reach model domains were typically set between CRS projects (i.e. from upstream project tailwater to downstream project forebay) which allowed for integration with the ResSim hydroregulation models. To account for interactions at key river junctions, the 30 major reaches were consolidated into 27 production models that included ~4,500 cross-sections.

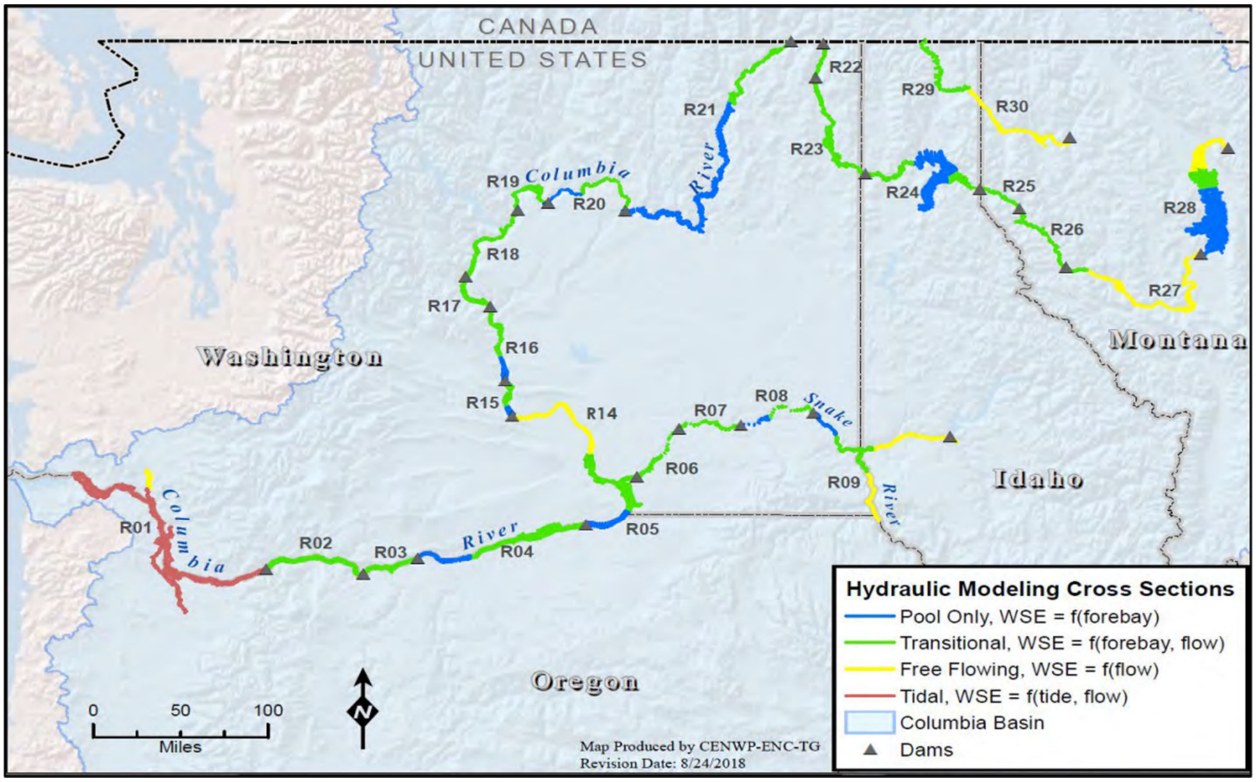

Figure 2. Overview Map of CRS Hydraulic Reaches

The CRSO hydraulics team used HEC-WAT to complete hydraulic model simulations for a deterministic hydrology set that included the period of record 80-year level modified streamflow (BPA, 2011) plus 26 synthetic years. The deterministic model runs were subsequently used to train a k-NN ratings model that provided a means for rapid flow/stage transformation across the CRS directly in the WAT, without the subsequent need to run HEC-RAS. These flow/stage pairs were output at 67 CCPs and used as inputs to subsequent hydraulic ratings as detailed below.

For the river mechanics assessment, additional hydraulic model results including velocity, energy grade slope, and bed shear stress were needed to compute the sediment metrics of interest over each 5,000-year hydroperiod in the study. As such, a second set of transformation ratings were needed, that could represent both the upstream and downstream effects on hydraulic response across the CRS.

To develop the hydraulic rating inputs, each of the 27 hydraulic models within the CRS was simulated over a wide range of potential forcing conditions that spanned the full domain of upstream flow loading and downstream stage regulation (where applicable) and bounded the deterministic hydrology set. The extent of downstream stage spanned from historical normal depth conditions to regulated full pool. The hydraulic response from these model runs was then used as inputs to compute subsequent sediment metrics at each of the ~4,500 cross sections within the CRS and build hydraulic ratings as detailed below.

Sediment Metrics

The hydraulic simulation results were used as inputs to three deterministic calculations of sediment response: critical grain size, sediment suspension thresholds, and sediment transport capacity. The variables were then used to assess the potential for change in bed material composition and sediment passing reservoirs and reaches. Additional sediment metrics were developed for the storage reservoir projects and run-of-river reaches as detailed in CRSO Appendix C (Corps, 2020) and are not discussed herein.

Critical Grain Size

The first metric, critical grain size is a widely used competence-based approach whereby the response in grain mobility is a balance between applied and resisting forces. It was considered for grain size classes representing bed material load coarser than very fine sand (62.5 um). The computation utilized the seminal work of Shields (1936), and Einstein (1950) to iteratively partition grain shear stress from the cross-section bed shear stress and compute a critical grain size over a range of dimensionless critical shear stress (τ_c^*) from 0.03 to 0.06. While the critical grain size is a threshold, the shape and range of its distribution has been shown to correlate with the distribution of sampled bed material at the sub-reach scale.

Sediment Suspension Thresholds

Water flowing in nature is predominately turbulent with chaotic changes in flow intensity and direction occurring at many scales internal to the overall downstream movement of the water. These turbulent forces can be strong enough to hold small sediment grains in suspension and vary as a concentration gradient within the water column. For gradually varying flow in a wide channel, most of the sediment is concentrated near the bed with hydraulic turbulence effectively diffusing sediment from this deeper zone of high concentration toward a lower concentration zone near the water surface. The more energetic the turbulent forces, the larger the grain size that can be suspended at a discrete horizontal reference within the water column.

The second metric, sediment suspension thresholds estimated the size of material that can be held in suspension in the water column at a cross-section for a specific set of hydraulic conditions. It represents the hydraulic capacity to suspend a discrete sediment grain size at a concentration threshold under equilibrium conditions.

The metric was considered for applicable grain size classes depending on the CRS reach. In the lower to mid basin, suspended sediment can be generally categorized as fine silts and clays (<62.5um) that travels as washload, transitioning towards the finer subset of bed material load (which is typically sands <1mm) in the mid basin where valley slopes steepen slightly. In the upper CRS basin headwaters without downstream backwater effects, suspended sediment can at times be as large as coarse gravels (<32mm) or small cobble (<64mm) during the spring freshet, although this suspension of coarser grain sizes would be expected to manifest as a short-term saltation.

For the sediment suspension threshold metric, a competence-based approach was applied according to the general Rouse equation (Rouse, 1937) whereby particle suspension is an assumed function of flow stratification that scales with the Rouse number -- a ratio between sediment grain settling and grain shear velocity, a hydraulic surrogate of turbulence acting on the channel bed. Nominal grain settling velocities were computed using Ferguson and Church 2004. With the suspended sediment concentration being continuously distributed through the water column, suspended grain size thresholds were evaluated for Rouse numbers between 0.8 and 7.5.

Sediment Transport Capacity

A third metric, equilibrium sediment transport capacity was also evaluated by grain size class at each cross section within the CRS for a given set of hydraulic conditions. Similar to critical grain size, equilibrium conditions assumes that there is sufficient supply available of transportable grain size classes. The equilibrium transport capacity was formulated as two dimensionless components, one for coarse bedload fractions and another for the finer suspended load fractions. It was computed across a range of discrete 1ψ size classes for bed material load spanning from very fine sand (62.5um) to large cobble (128mm). The bedload transport fraction was computed using the Meyer-Peter-Muller equation with revised coefficients (Wong & Parker, 2006). The suspended load transport fraction was computed as the depth-integrated product of the Rouse concentration profile and the logarithmic velocity profile (Einstein, 1950) at each cross section for a discrete set of hydraulic conditions.

Hydraulic and Sediment Ratings

A suite of hydraulic and sediment metric ratings were developed for each of the ~4,500 cross sections within the CRS (Figure 3). Due to the large spatial extent of the CRS hydraulic models, in order to develop representative ratings of hydraulic response, it was necessary to further discretize each CRS major reach model into minor reaches, and sub-reaches. Minor hydraulic reach breaks were selected to account for logical breaks between stream network segments and accommodate additional forcing from lateral tributary inflows; sub-reaches represent the finest resolution and were selected based on localized details including valley type and gradient, tributary interactions and geomorphic context. The sub-reach boundary conditions from the hydroregulation models were used to develop a discrete hydraulic and sediment rating response at each cross-section.

Transient backwater effects from downstream hydroregulation can influence hydraulic response within the lower and mid-basin CRS projects including: lower Columbia (R01-R05), Lower Snake (R06 – R09), mid-Columbia (R15-R21), and Pend Oreille (R22-R24). Ratings within those reaches were developed as a function of two parameters (upstream flow and downstream stage). In fully free flowing headwaters reaches including portions of the Clearwater (R10), upper Flathead (R28), and upper Kootenai (R30), single parameter ratings as a function of discharge and normal depth were used.

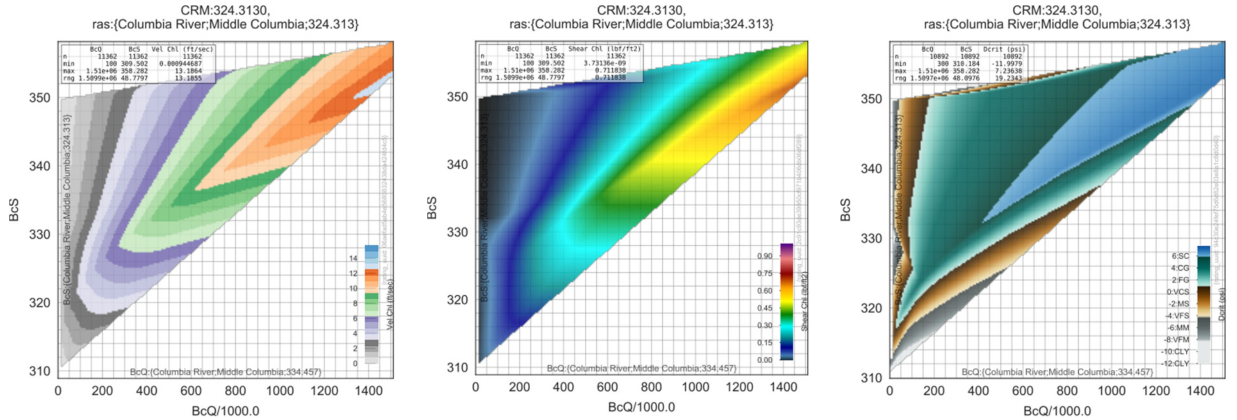

Figure 3. Example hydraulic ratings for velocity, shear stress, and critical particle size at a discrete cross section as a function of the subreach inflow (BcQ in kcfs) and the downstream stage (BcS in feet). Color magnitude represents the hydraulic response for velocity (left), shear stress (middle), and critical grain size (right).

System Response

Distributions of the system hydraulic response and corresponding sediment variables for a given hydroregulation set (i.e. baseline or alternative) were computed by applying the 5,000-year stochastic timeseries outputs from a representative hydroregulation model to each of the ~4,500 cross-section ratings in the CRS. Within each of the 82 CRS sub-reaches, stochastic hydrologic timeseries of upstream flow and downstream stage at bounding CCPs were transformed through select hydraulic ratings to develop a daily response timeseries at each sub-reach cross-section (Figure 4). The 5,000-year stochastic timeseries of the hydraulic and sediment response at each cross section were then used to compute river-length weighted sub-reach distributions to inform the alternatives analysis (Figure 5).

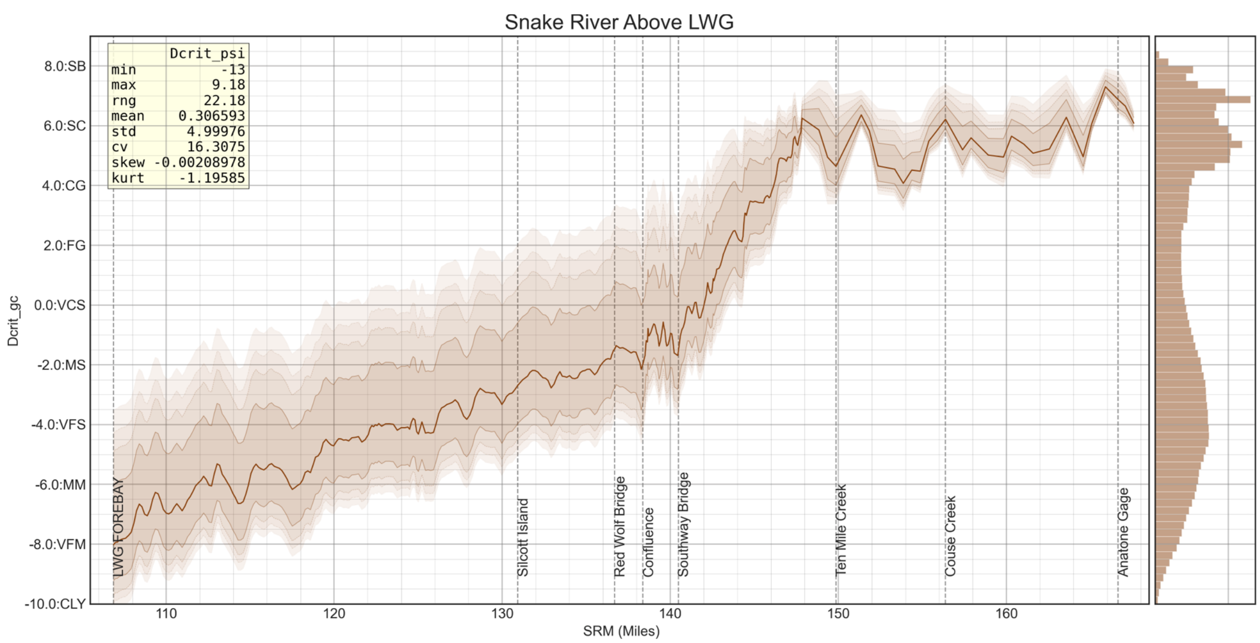

Figure 4. Example longitudinal quantiles for baseline critical grain size. The solid line represents the median (50th percentile), bounded by the shaded inner quartile range (25th to 75th percentiles). The outer shading regions are paired quantiles (15th/85th, 10th/90th, and 5th/95th).

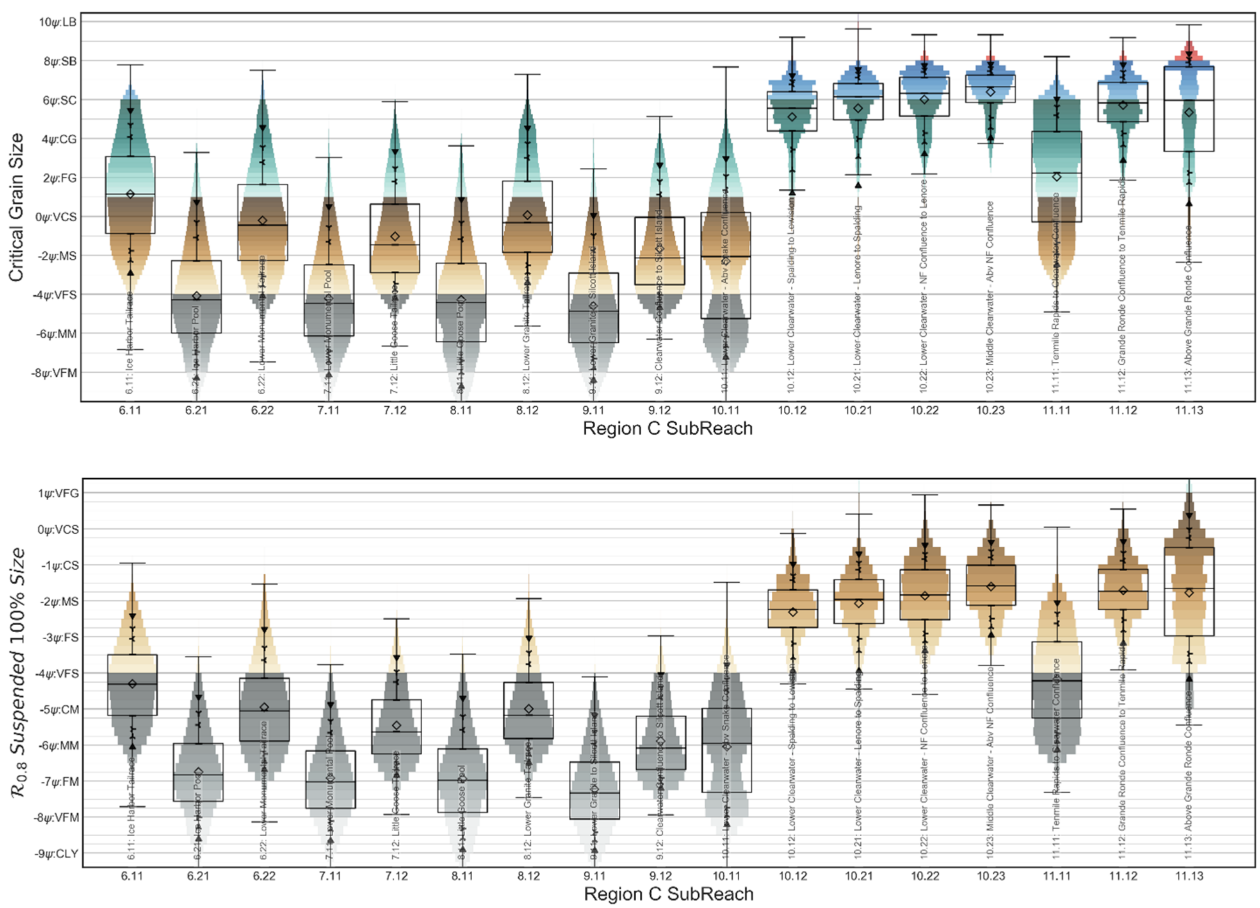

Figure 5. Example distributions for baseline critical (top) and suspended (bottom) grain size grouped by subreach. Histograms colored by grain size group: silt (gray), sand (brown), gravel (green), cobble(blue), and boulders (red).

Alternative Comparisons

Multiple objective alternatives (MOA) were developed for the larger EIS to meet a wide range of authorized purposes across the CRS. Sediment metric timeseries and distributions were developed for baseline conditions and each MOA. Various comparisons were made at the sub-reach level between sediment metric distributions of each MOA and baseline conditions to quantify departure and assess sediment impact thresholds. The sediment impact thresholds developed were specific to each metric and organized into a standard five-category change detection framework (no effect, negligible, moderate, and major). Example comparison plots are shown in Figures 6 through 9. Details of the alternative comparisons are presented in CRSO Chapter 3 and Appendix C (Corps, 2020)

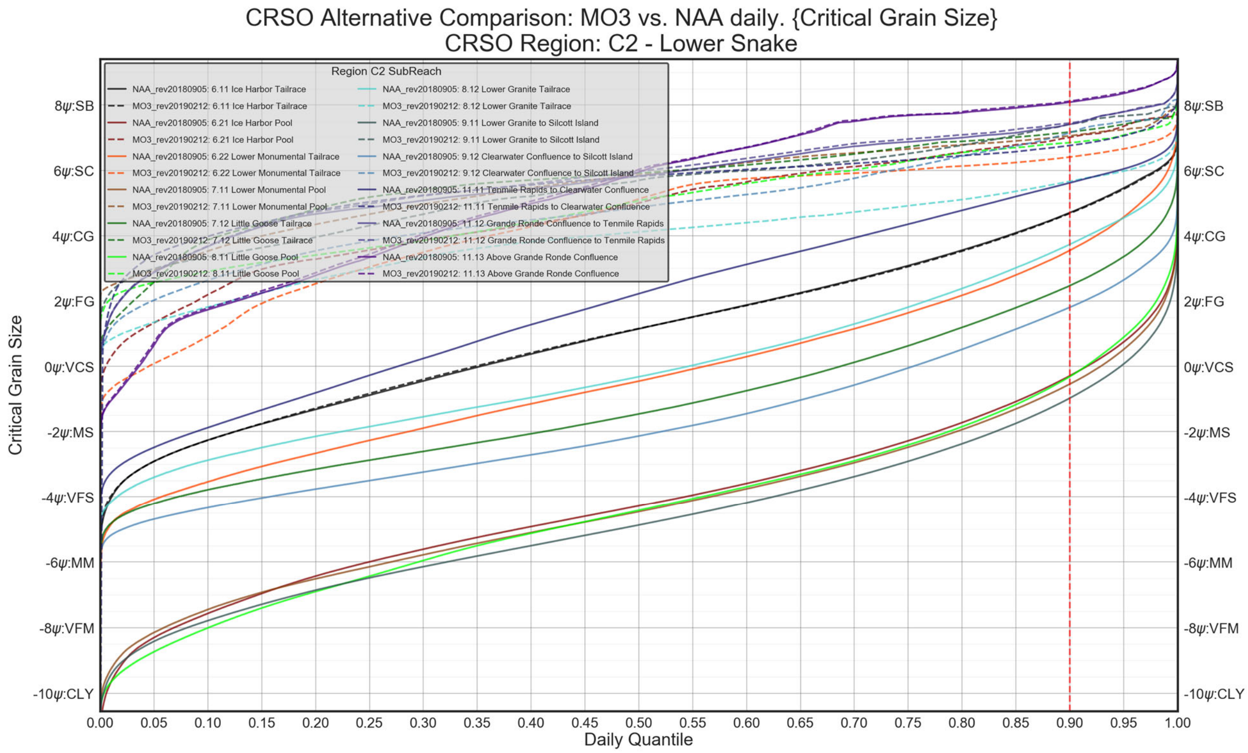

Figure 7. Example Region C2 comparisons between critical grain size distributions colored by subreach. Solid lines represent the No-Action-Alternative, and dashed lines represent the MO3 alternative.

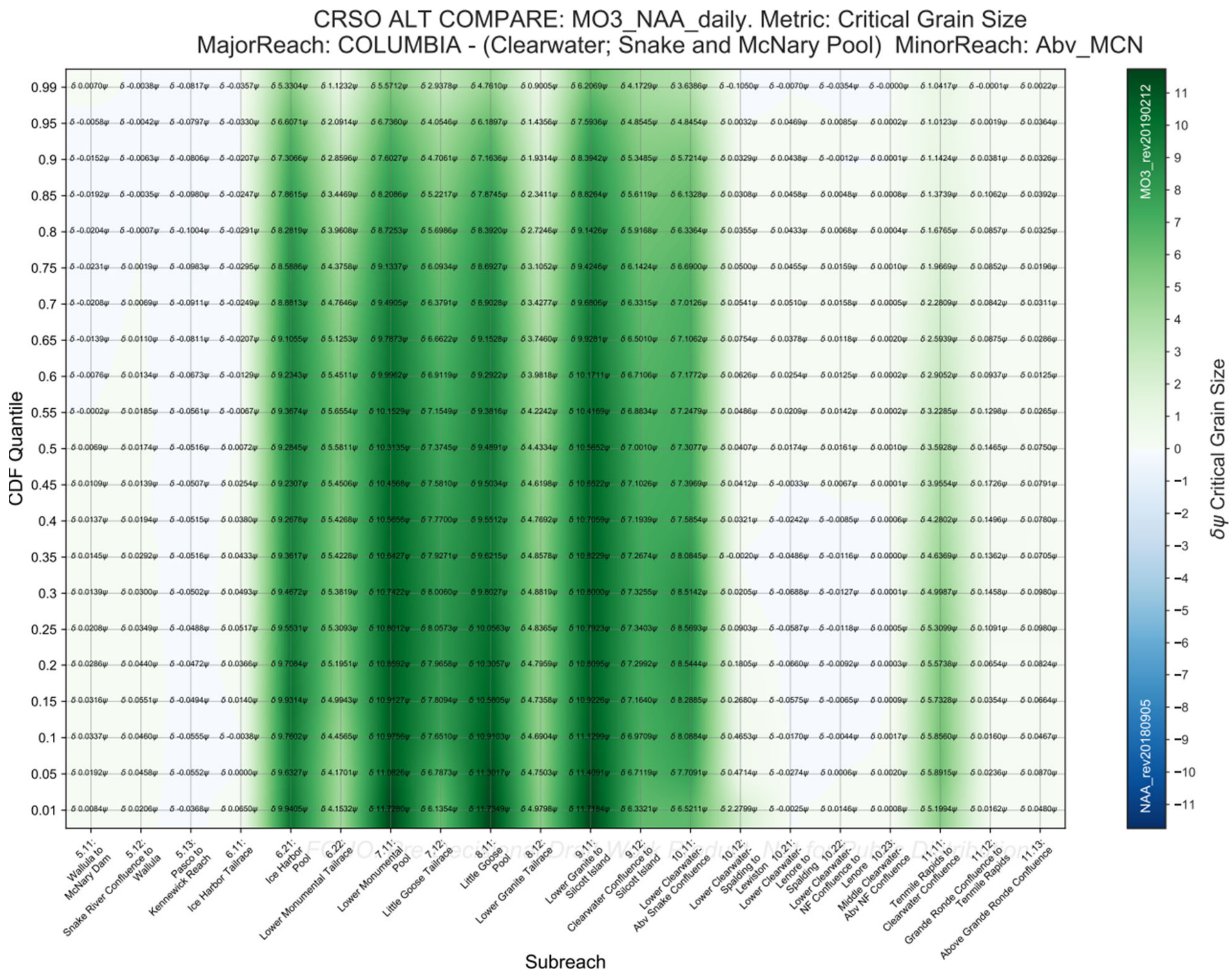

Figure 8. Example regional heatmap depicting differences between critical grain size distributions grouped by subreach (x-axis) for alternative MO3 minus the No-Action-Alternative.

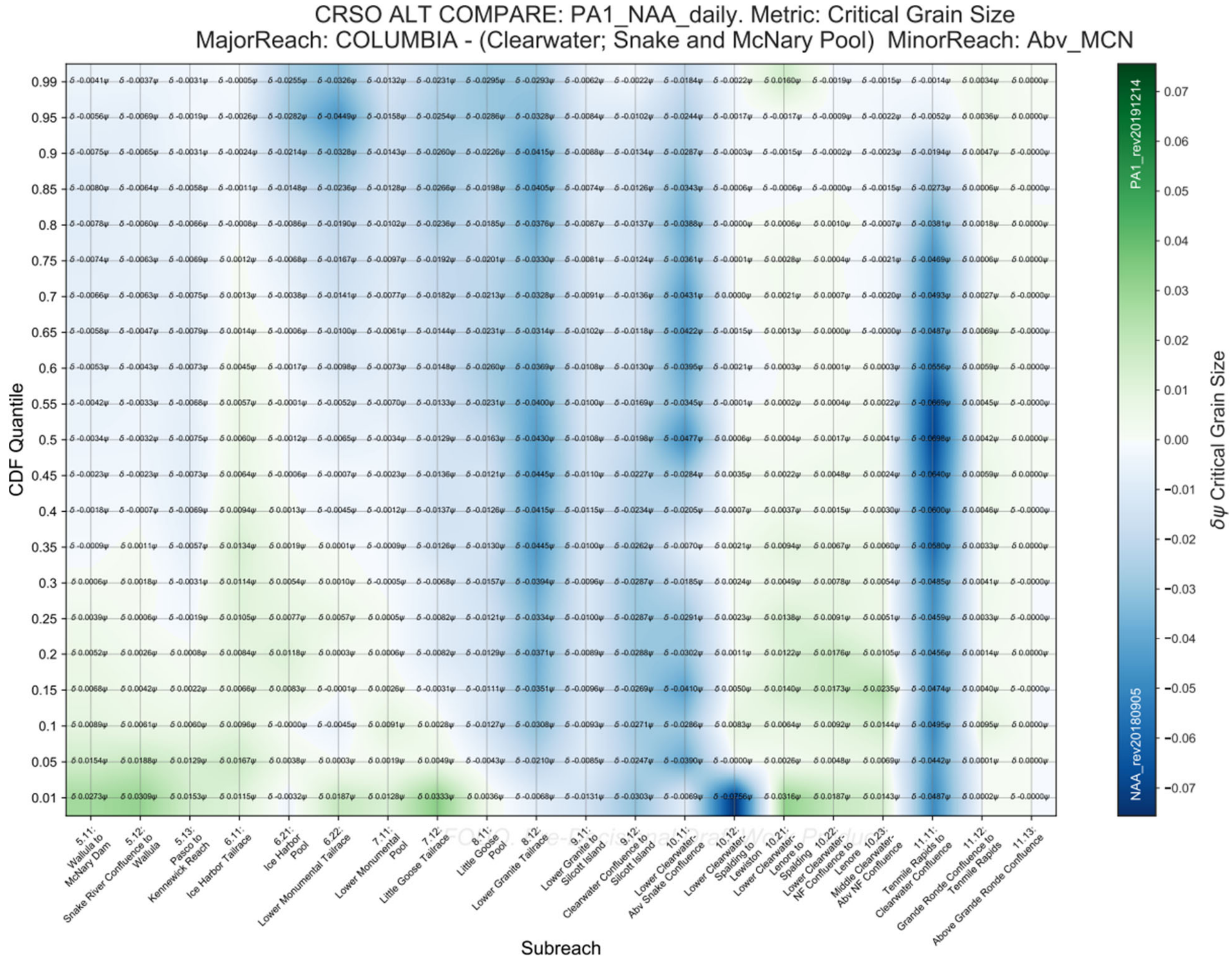

Figure 9. Example regional heatmap depicting differences between critical grain size distributions grouped by subreach (x-axis) for alternative PA1 minus the No-Action-Alternative.

References

Bonneville (Bonneville Power Administration). 2011. 2010 Level Modified Streamflows. Portland, OR.

Corps (U.S. Army Corps of Engineers). 1989. Sedimentation Investigations of Rivers and Reservoirs. EM 1110-2-4000.

Corps (U.S. Army Corps of Engineers). 2020. Columbia River System Operations Environmental Impact Statement.

Einstein, H. A. 1950. The Bedload Function for Sediment Transport in Open Channel Flows. Technical Bulletin 1026. U.S. Department of Agriculture, Soil Conservation Service. Washington, D,C.

Ferguson, R.I. and Church, M. 2004. A Simple Universal Equation for Grain Settling Velocity. Journal of Sedimentary Research. Vol 74. No 6. P 933-937

Garcia, M. H. 2007. ASCE Manual of Practice 110-Sedimentation Engineering: Processes, Measurements, Modeling, and Practice.

Rouse, H. 1937. “Modern Conceptions of Mechanics of Fluid Turbulence.” Transactions of the American Society of Civil Engineers 102(1):463¬–505. http://cedb.asce.org/CEDBsearch/record.jsp?dockey=0288088.

Shields, A. F. 1936. Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegun, Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau, 26, 26, 1936. (uuid:61a19716-a994-4942-9906-f680eb9952d6). English translation by W. P. Ott and J. C. van Uchelen. U.S. Department of Agriculture, Soil Conservation Service Cooperative Laboratory, California Institute of Technology. Pasadena, CA.

Vanoni, V. A. 2006. Sedimentation Engineering. ASCE Manual of Practice No. 54. Reston, VA.

Whipple, K. 2004. “IV. Essentials of Sediment Transport.” 12.163/12.463 Surface Processes and Landscape Evolution: Course Notes. MIT Open Courseware.

Wong, M. and Parker, G. (2006). "Reanalysis and Correction of Bed-Load Relation of Meyer-Peter and Müller Using Their Own Database." J. Hydraulic Engineering, 132(11), 1159–1168.