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A GIS investigation into basin scale sediment transport potential post dam removal

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Abstract

The Klamath River of Oregon and California is impacted by four dams that are planned to be removed in 2021, with the goal of expanding salmon habitat and improving water quality in the downstream river system. The unpresented scope of this dam removal and river restoration project invites questions and concerns about the effects of such a discrete disturbance on the environment and nearby infrastructure. Of particular concern is fate of the entrapped reservoir sediments. Sediment transport modeling can help predict responses to the proposed removal and inform design decisions to mitigate harmful effects. When detailed data are not available, stream power can be an informative metric to map along a river reach to determine sediment transport potential. In this exercise, stream power is used to delineate reaches along the Klamath River that may be susceptible to erosion and deposition, and thus warrant further modeling.

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Introduction

Reach-scale trends in sediment transport potential can be a valuable first step in assessing bed stability and depositional trends in an area of concern. However, sediment transport can be difficult to predict, as there is often considerable uncertainty in sediment properties. By ignoring sediment properties and quantifying the remaining transport drivers of sediment transport, slope and discharge, a qualitative estimate of transport probability can be made. A simple GIS procedure to estimate these trends is to map stream power over a reach of the river. Stream power has various definitions, but essentially is the product of the river slope and discharge. Low stream power indicates a reach prone to deposition, and high stream power conversely suggests possible erosion. By creating a longitudinal profile of a river reach, stream power can be calculated along its length, and thus regions of high or low stream power can be easily distinguished.

Stream power calculations are a useful preliminary calculation in a thorough geomorphic evaluation, such as evaluating potential morphology near critical habitat or infrastructure under changed sediment supply conditions. In this case, stream power will be used to model potential sediment transport and deposition downstream from a dam removal event.

Site Description

The Klamath River of Oregon and California is unique, in that it is an "upside down" river, as it begins in a low-relief, agricultural area and flows through more mountainous terrain on its way to the Pacific Ocean. The watershed encompasses many diverse environments, with varying vegetation, climate, geology, and land use. The total watershed of over 40,000 km^2 is split fairly distinctly into an upper basin, characterized by flat, high elevation agricultural valleys with an igneous lithology, a middle reach through the aged metamorphic rocks of the Klamath Mountains, and finally traversing the wet, younger coastal range (Gathard Engineering, 2006).

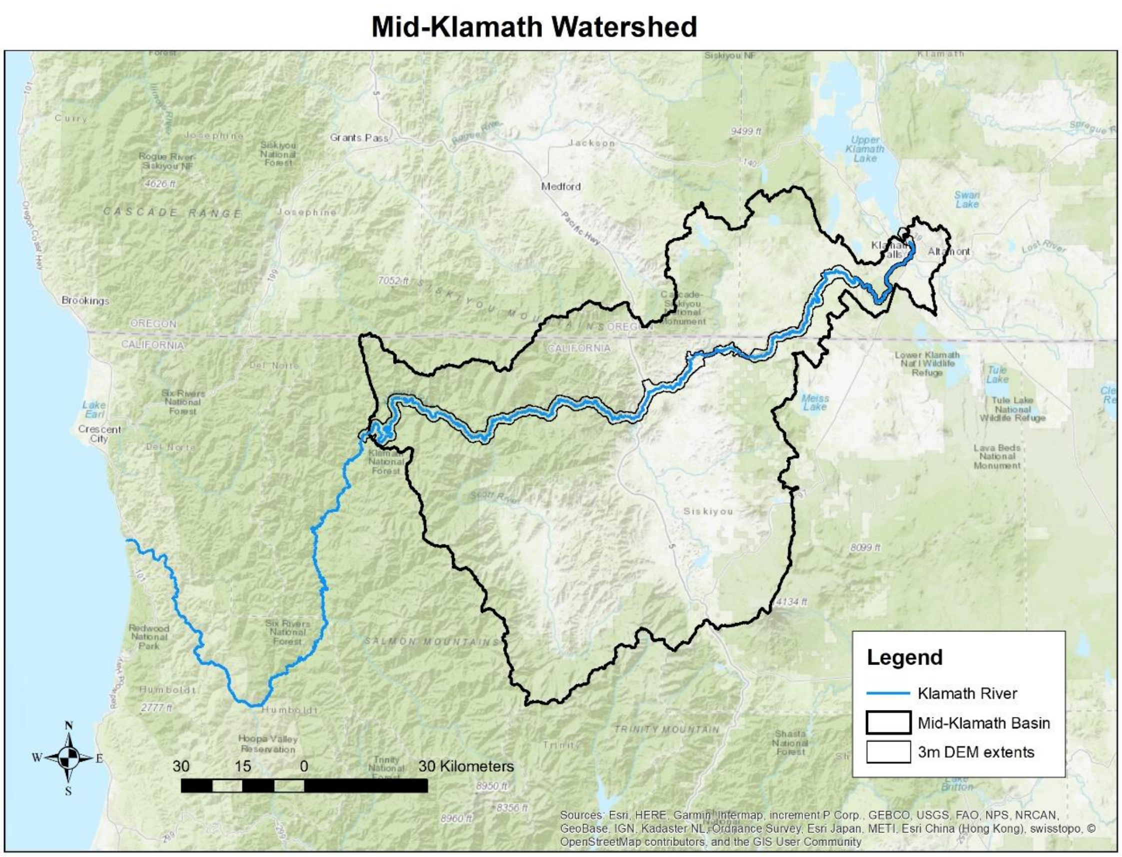

Figure 1: Mid-Klamath Basin location on the Klamath River

Although the watershed is sparsely populated, humans have nevertheless had a significant impact on the Klamath River and its ecosystem. Human intervention in the affairs of the Klamath watershed began in the 1800's, as the Upper Basin was dammed and flows diverted for irrigation. It was not until 1922 that a dam was built on the main stretch of the Klamath below the basin. The final dam, Irongate, was finished in 1964. These four dams, JC Boyle, Copco 1, Copco 2, and Iron Gate, now owned by PacifiCorp, were built primarily for hydropower, and provide minimal storage or flood protection (KRRC, 2018).

Slope map

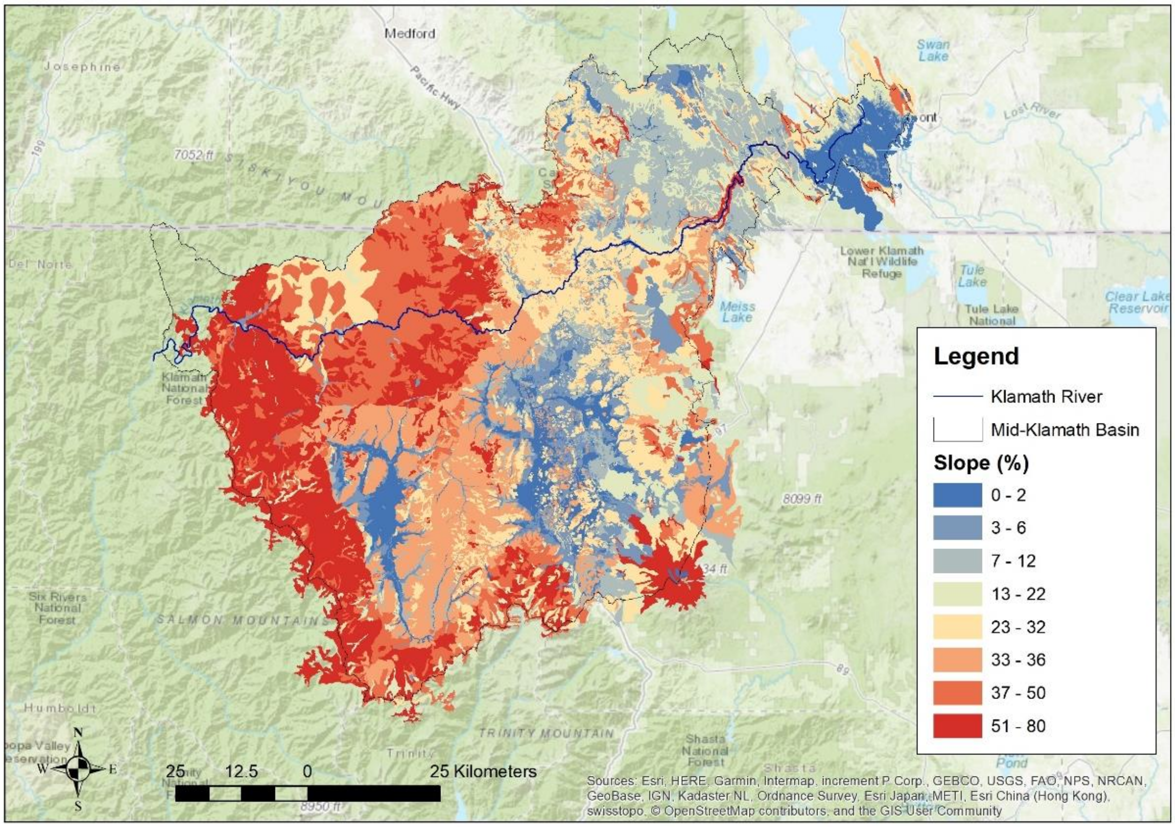

Figure 2: Map showing mid Klamath Basin split between the upstream valleys and downstream mountains

Few anthropogenic activities impact a watershed as much as major river obstructions. In the most basic sense, a dam breaks the continuity of a watershed. Ecologically, they separate habitat for fishes and other aquatic organisms, preventing passage. Further affecting these biota, dams can change annual flow patterns, raise water temperatures and otherwise degrade water quality. Physically, they halt the natural movement of sediment, starving the river downstream of the dam while the sediment accumulates in the reservoir. These impacts can only be fully mitigated by removal. However, dam removal itself is no easy task. A dammed river has adapted to its altered constraints, and it can be uncertain to what extent a river will attempt to return to its pre-dammed, natural state (Major et al., 2017). The dam may be adjacent to critical human infrastructure or vulnerable wildlife habitat, which imposes further constraints on the restoration project. Communities have often built themselves around these reservoirs, which only raises the stakes higher. The agencies removing these dams are challenged to meet many conflicting demands, and often have little historical precedent as backup (Tullos et al., 2016).

By virtue of the agricultural runoff from the Upper Klamath basin, the water in the Klamath River is especially vulnerable to retention behind dams. This nutrient-laden water leads to significant algae blooms in the Klamath reservoirs. In addition, the lack of sediment delivery in the Upper Klamath River has caused significant changes to the stream bed composition, which has been blamed for hurting fish populations by facilitating the propagation of deadly parasites in the reach of the Klamath below Iron Gate Dam (Holmquist-Johnson, 2010) (Beeman et al., 2012).

The proposed dam removal project would remove these four run-of-river dams. The plan involves using the diversion tunnels from the dam construction to dewater the two biggest reservoirs, Copco and Iron Gate (KRRC, 2018) (Stillwater Sciences, 2008). The dams would be removed simultaneously after drawdown was completed, starting January 2021. The dams retain significant sediment – over 15 million cubic meters, with 85% fines (US Dept of the Interior, 2012). The fate of this sediment is of primary concern, and regardless of modeling efforts, will remain one of the largest sources of uncertainty in this dam removal project.

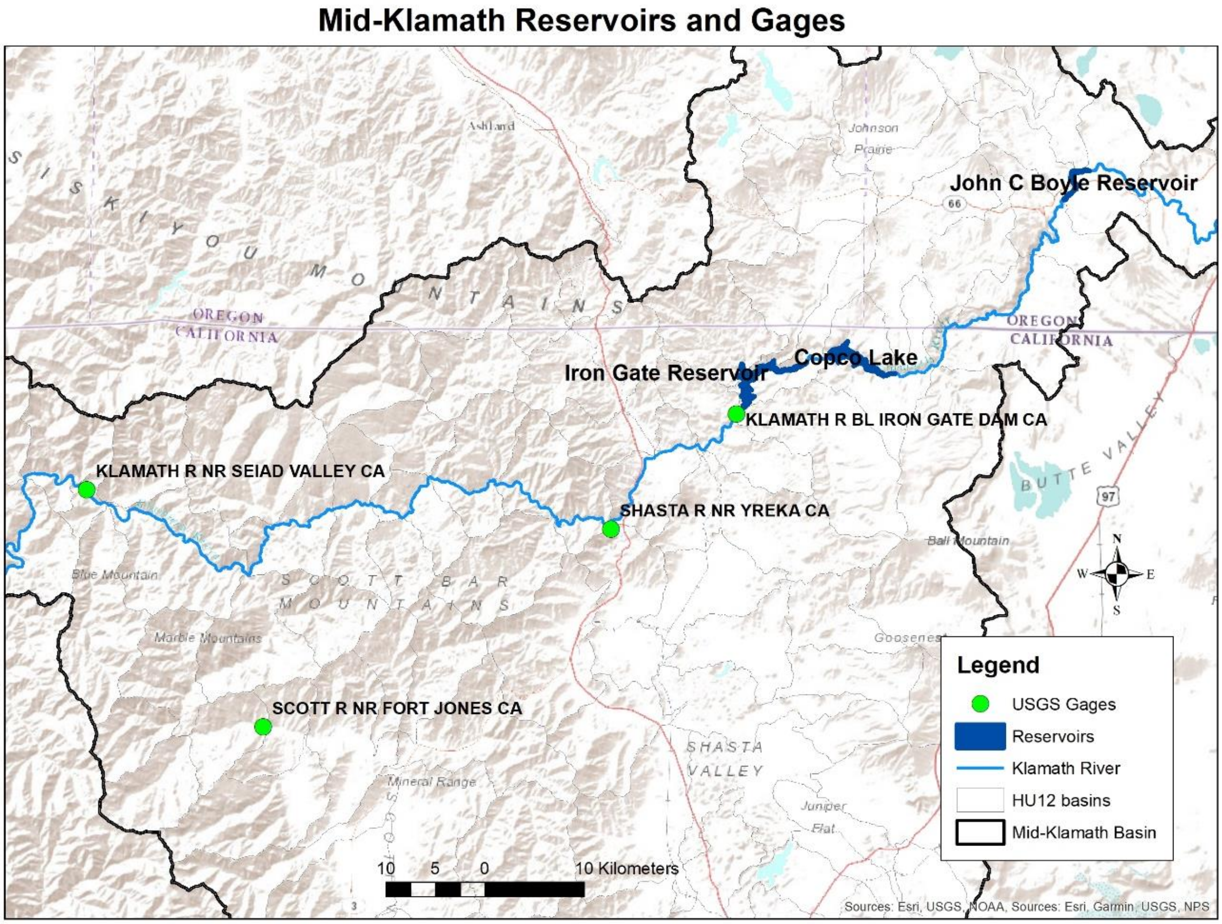

Figure 3: Reservoirs and gages of concern on the Mid-Klamath River

Data

Spatial data for this project was acquired from the National Hydrography Database (NHD). Stream power calculations require a Digital Elevation Model (DEM) raster and vector shapefiles for the river and watershed boundaries. In this case, a high resolution 3m DEM was used,

GIS Methods

The following GIS process was used to build the stream power map. The NHD vector and raster data was downloaded from the national map web interface for the area of interest, in this case the Upper Klamath Basin. All data was brought into ArcGIS and projected to the California State Plane, Region 1 projection (Lambert Conformal). The individual DEM rasters were then combined using the "mosaic" tool and clipped to the region of interest. The Klamath River was selected from NHD river layer and exported as a new layer. The river layer was then clipped using a polygon of the DEM extent. Finally, the river was dissolved into a single polyline. Now the 3D analyst "Stack Profile" tool could be used to add the underlying elevation data from the DEM to the river polyline, creating a 3D polyline. This data was then exported to Excel for visualization.

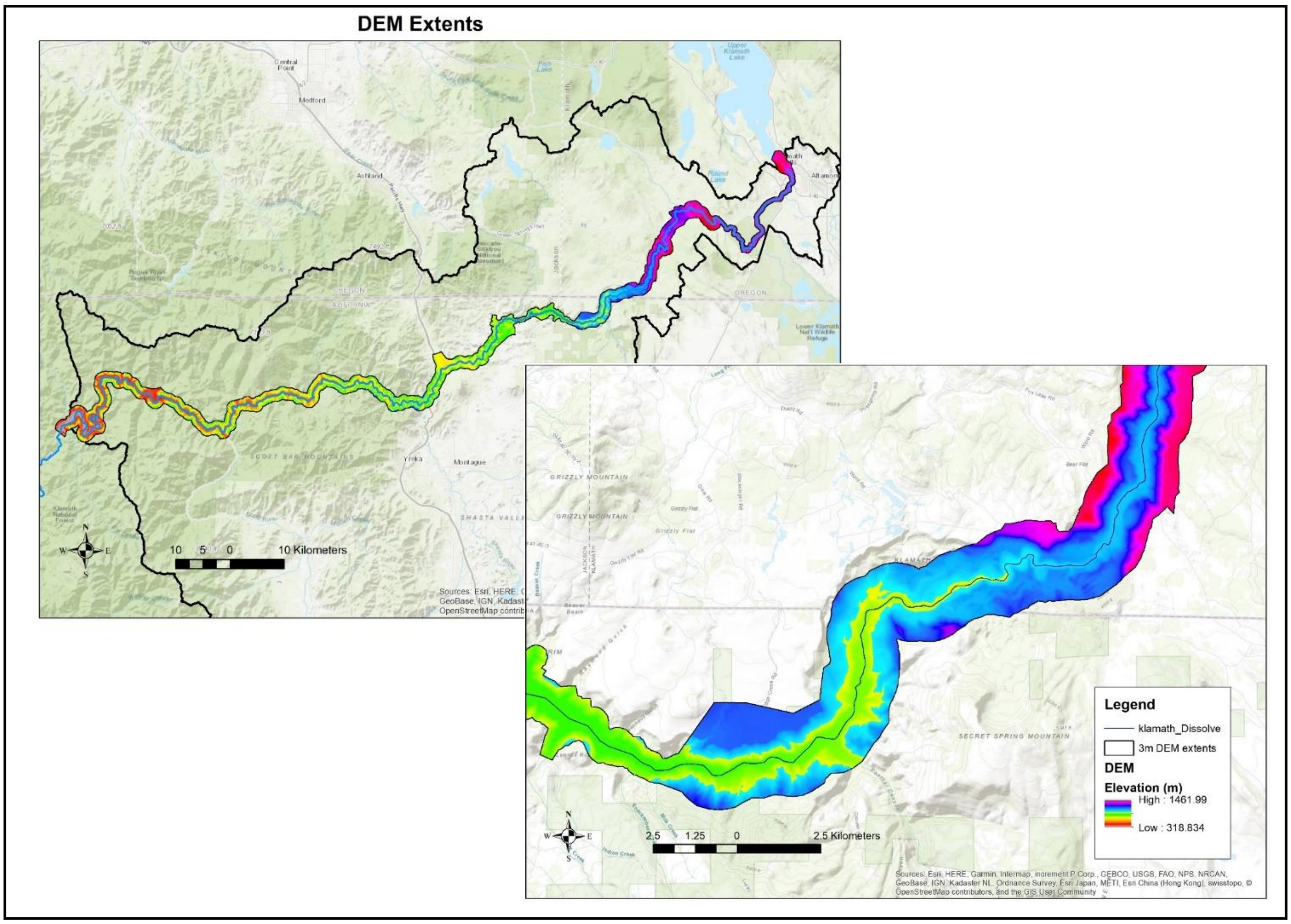

Figure 4: Extent of DEM data in mid Klamath River

Flow chart of GIS processing tools used in the creation of the river longitudinal profile

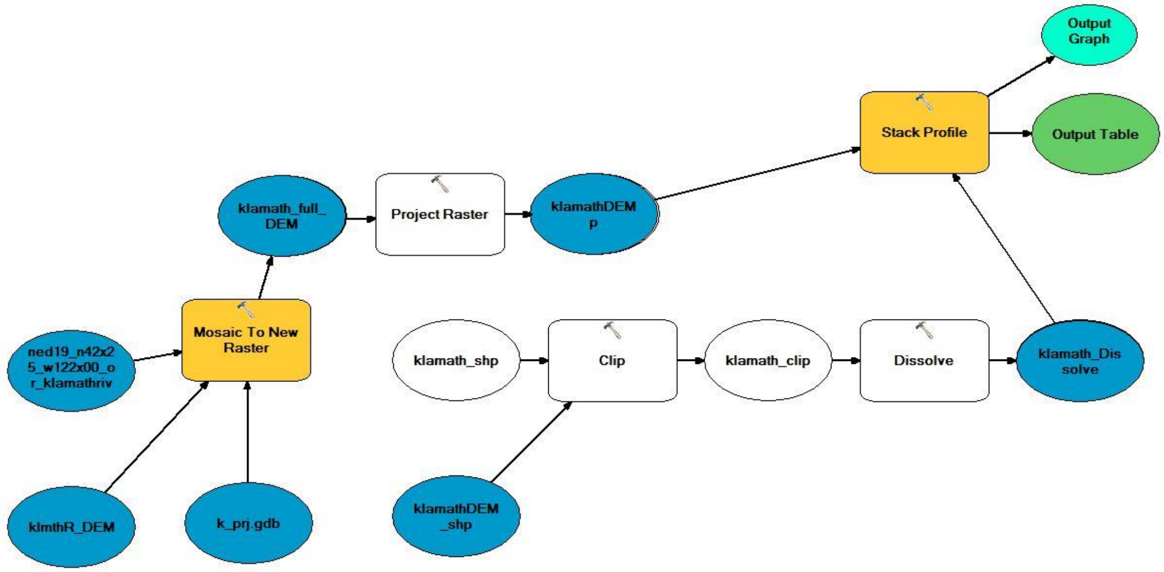

Figure 6: GIS processing flow chart

Figure 5: Klamath River DEM data extents

Given the longitudinal profile data exported from ArcGIS, a plot was easily reproduced using Excel. To calculate stream power, the raw water surface slope was first averaged over 200 meter reaches. This average slope was used as the average energy slope, assuming steady flow conditions. A representative discharge of 4000 CFS was chosen after consulting recent studies supporting dam removal plans (USBR 2011). This flow represents a conservative average annual peak flow. Using the following equation, Eq. 6-16 from NRCS (2007),

$$\Omega = \gamma Q S_f$$

where:

γ = unit weight of water (lb/ft^3)

Q = discharge (ft^3/s)

S_f = energy slope (ft/ft)

stream power estimates are obtained for each position along the river. Stream power is then plotted along with longitudinal slope [Figure 8]. Longitudinal profile and stream power are plotted both pre- and post-dam removal, for which the dams and reservoirs were removed from the profile and replaced with a reach-averaged bed slope. This adjustment considerably reduces the peak stream power spikes that occur at each dam site, and raises the stream power from zero in the previous reservoirs to an average value for that reach. Of note is the widely varying nature of the stream power calculations. Even averaged over 200m reaches, stream power still encompass a wide range of values, from zero to over five times the reach average. This is representative of the pool-riffle morphology of the Klamath River, and is important in considering sediment transport ramifications. As a river descends a rapid or riffle, the fast moving water will scour away smaller sediments and keep them suspended. When the river slows in pools, suspended sediments may have time to drop out of the water column and settle on the bed, and bed transport will halted, as the drop in stream power suggests. This means that, although there may be minimal deposition along the entire reach, these isolated slow moving pools may exhibit significant deposition.

To gain a clearer understanding of stream power trends over the mid Klamath River, the stream power was plotted using box diagrams, to further declutter the spikes at major river drops. In this graph, a sharp distinction is clearly seen between a lower and upper section, making this transition right at Irongate Dam. This agrees with the linear trend line that was fitted in the original stream power plot, which showed an average increase in power in the upstream direction. These two reaches with different stream power potential are highlighted in Figure 7.

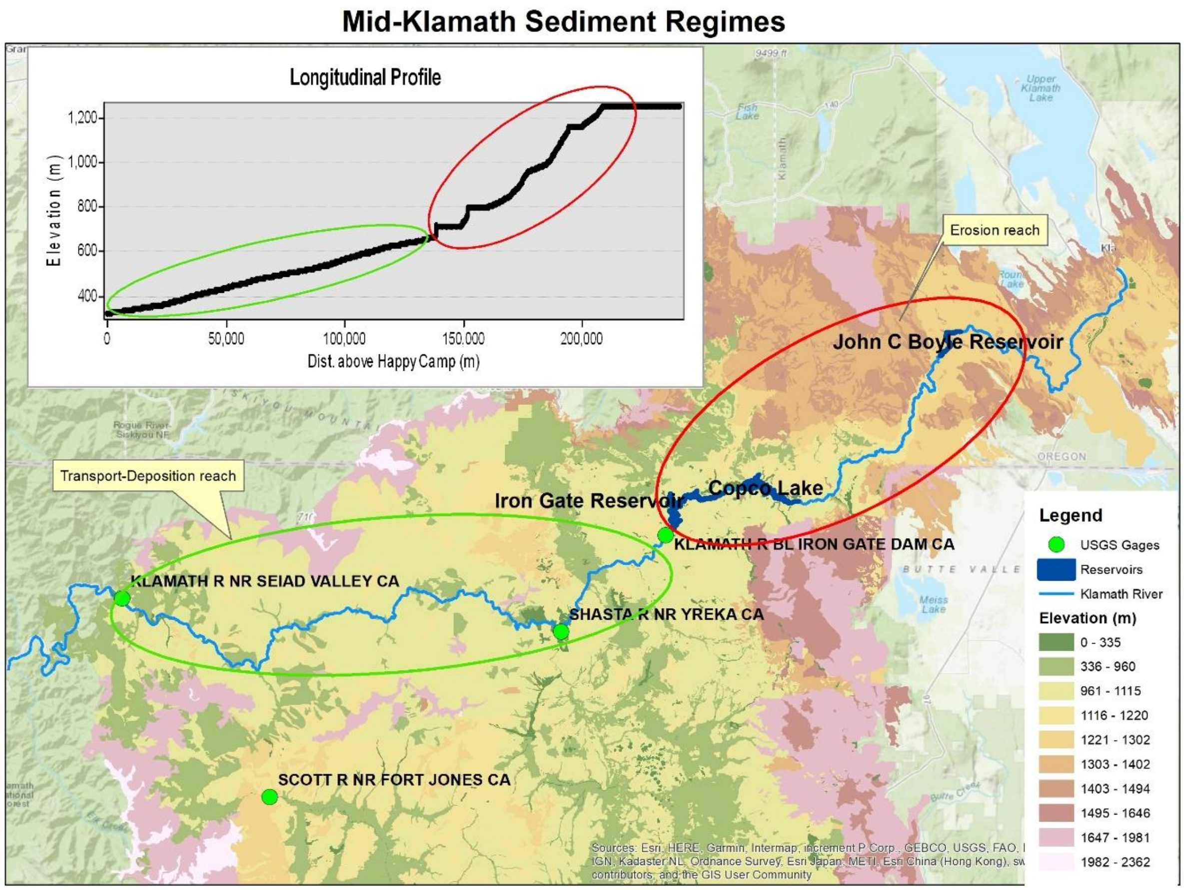

Figure 7: ArcGIS Stack Profile tool output, labeled with reach sediment transport regimes

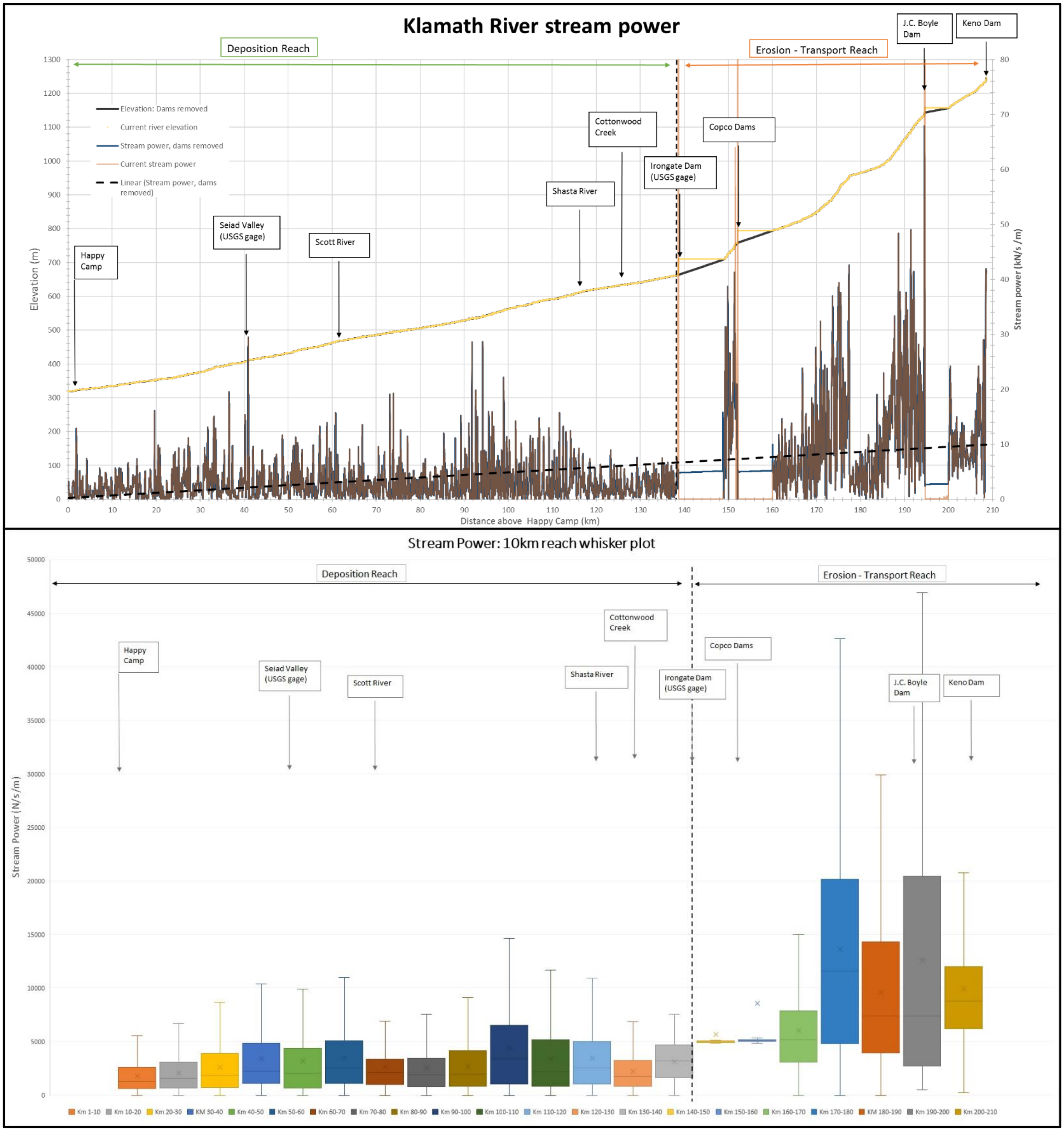

Figure 8: Longitudinal profile and stream power of the Mid-Klamath River

Conclusion

Stream power can be a simple but powerful way to visualize sediment transport potential in streams and easily communicate trends to other parties. In this example, we gain valuable insight into the behavior of the middle Klamath River after a significant dam removal event and subsequent influx of sediment. We see that the sediment retained behind the dams lies in a steep, high-power reach, which suggests ample opportunity for these sediments to be mobilized and transported downstream. Below the lowest dam, we see a significant decrease in bed slope and drop in stream power. We can anticipate slower transport potential in this reach, and there could be significant deposition of these sediments in low velocity areas, such as pools and on the stream margins. Though this process ignores sediment properties and does not provide numbers for sediment volumes or bed changes, there is value in visualizing relative behavior. This exercise successfully highlights areas that may be prone to fluvial morphological processes, which then are worthy of a more intensive modeling effort. Uncertainty in sediment behavior in river systems is unavoidable and perpetually vexing. This uncertainty can be very expensive to reduce, requiring extensive data collection and modeling efforts. This stream power method is an important, easy tool which can help chisel one of the first bits of that uncertainty away.

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