Estimating fluvial sediment mass flux in the lower Klamath River basin prior to removal of four hydroelectric dams, California

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Introduction

The transport and deposition of fluvial sediment following dam removal can affect river function, including geomorphic processes and alterations to riverine biota, and has many implications for river management. Although many dam removal projects have examined river response to sediment transport following dam removal, few have had the ability to examine pre-dam removal sediment transport to characterize baseline conditions. Four hydroelectric dams are currently scheduled for removal on the Klamath River in Oregon and California, beginning in winter of 2024. This project constitutes the largest dam removal project in U.S. history. Sediment stored behind the four dams is estimated at approximately 10 million cubic meters (m^3) and is primarily comprised of fine-grained material (particle size <= 0.075 mm) and high moisture content (Reclamation, 2011). The transport of these reservoir sediments may have far-reaching effects to the 312-km river corridor downstream of the lowermost dam, including the Klamath River estuary. In anticipation of this large dam removal project, data were collected to compute fluvial sediment flux at six mainstem locations within the river reaches in the hydroelectric reach where the dams are located, and downstream of the dam removal sites.

The Klamath Basin is large (~31,000 km^2) and is often referred to as an "upside-down" basin (Oliver et al., 2014) . The Upper Klamath Basin (described herein as the portion of the basin upstream of Keno Dam, figure 1), has generally flat topography and has more agricultural activities compared to the lower portion of the basin. The upper basin contains large lake-wetland complexes including Upper Klamath Lake, which is the primary habitat for two species of endangered suckers and is the primary source of irrigation water for the Klamath Reclamation Project, managed by the U.S. Bureau of Reclamation. The Klamath Reclamation Project delivers water to ~900 km^2 of agricultural lands for crop cultivation and livestock grazing in the upper Klamath Basin. Water is diverted from Upper Klamath Lake for irrigation just upstream of Link River Dam, which will not be removed. Keno Dam, approximately 37 km downstream of Link River Dam, will also remain in place. The dams that will be removed are located within the hydroelectric reach starting with JC Boyle Dam, and includes a total of four dams: JC Boyle, Copco 1, Copco 2, and Iron Gate (figure 1). The river downstream of Iron Gate Dam (hereafter, “lower Klamath River”) spans 312 km and will be directly affected by sediment transport during and following dam removal. The Klamath River below Iron Gate dam is a coarse-grained and semi-alluvial river that has much higher gradients than the upper basin and in some areas is narrow, incised, and constrained by rock outcrops (Curtis et al., 2021). The lower Klamath River contains endangered Coho Salmon, and a recent petition to the National Marine Fisheries Service (NMFS) has resulted in Chinook salmon being considered for endangered status as well (NMFS, 2022).

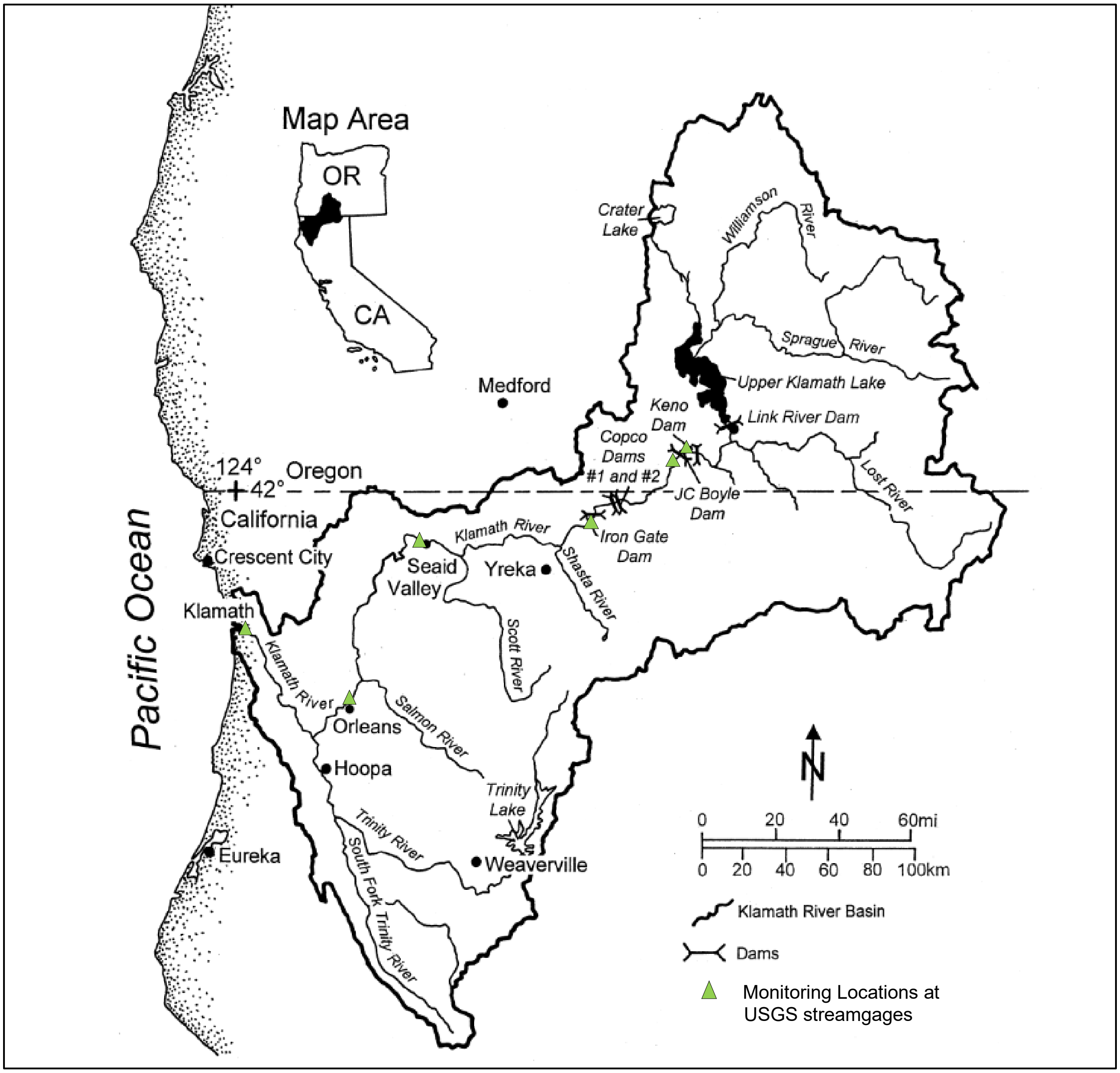

Figure 1. Area map of the Klamath basin, modified from Bartholow, 2004

Data Collection

In anticipation of this large dam removal project, suspended-sediment samples and turbidity data have been collected since water year 2019 at six mainstem USGS river gages by staff from the Karuk and Yurok Tribes and USGS to characterize pre-dam removal conditions. Three of the sites are located below dams in the hydroelectric reach: Keno (USGS site ID 11509500), JC Boyle (USGS site ID 11510700), and Iron Gate (USGS site ID 11516530). And three are in the lower Klamath Basin downstream of Iron Gate Dam: Seaid (USGS site ID 11520500), Orleans (USGS site ID 11523000), and Klamath (USGS site ID 11530500)). Turbidity sensors measuring in Formazin Nephelometric Units (FNU) every 15 minutes were deployed at all monitoring sites and suspended-sediment concentration (SSC) samples were collected using one of two methods: 1) point samples collected with an ISCO automated sampler, and 2) cross-sectional SSC samples collected using the Equal Discharge Increment (EDI) method as described in (Edwards and Glysson, 1999). Correction coefficients were calculated to adjust the pump sample concentrations to cross section EDI samples when adequate EDI samples were collected (Edwards and Glysson, 1999). All samples were analyzed for SSC (in milligrams per liter [mg/L]) and percent finer than 63 microns (% fines) at the USGS Santa Cruz sediment laboratory in California or the USGS Cascades Volcano Observatory sediment laboratory in Washington. A subset of the ISCO samples were analyzed for loss on ignition (LOI) at the Keno and JC Boyle sites, to determine the amount of organic material in the samples. Each discrete SSC sample was assigned a temporally adjacent turbidity and streamflow (in cubic feet per second [cfs]) value from the continuously monitored in-stream data. The resulting datasets were used to calibrate regression models at each site. All streamflow, turbidity, and SSC data are stored on the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2023).

Data Analysis

Model development followed USGS guidelines outlined in Rasmussen and others (2009). Site-specific regression models were developed from paired discrete turbidity, streamflow, and SSC data. Log10-transformed and untransformed turbidity and streamflow data were used to create both simple and multiple linear regression models which were evaluated based on residual plots and summary statistics. The preferred models were used to compute continuous (15-minute) SSC for each of the sites. Continuous suspended-sediment loads were computed from time series of SSC and streamflow. Surrogate regression models using turbidity as an independent variable were used to estimate time-series of suspended-sediment concentration (SSC) at all sites for years when data were collected, and these models were extrapolated to time periods where there were few or no observations. SSC were combined with time-series streamflow data to compute mass flux of fluvial sediment for four water years (2019-2022). For some of the sites, there were large gaps of time without observations to validate the regression models, which added to model uncertainty.

Results

Comparisons of sediment flux between mainstem gages show relatively smaller suspended sediment loads in the hydroelectric reach downstream of three of the dams scheduled for removal (Keno, JC Boyle, and Iron Gate, figure 2), which reflects the capture of sediment by these impoundments. Samples from sites Keno and JC Boyle contain algal material due to the large algal blooms from the hypereutrophic Upper Klamath Lake and the Klamath River downstream of Link River Dam. A subset of these samples was analyzed for loss on ignition (LOI), measured in mg/L, and calculated as a percent of the total SSC value. Samples were collected at Keno and JC Boyle mainly during elevated streamflow that occurs in the spring months (typically April) as part of managed flows in the Klamath River intended to mitigate fish disease below Iron Gate Dam. Results suggest that approximately 18% of the samples are comprised of organic material during these elevated flows, with the rest of the samples containing inorganic sediment.

Below Iron Gate Dam, sediment loads gradually increase downstream, with the highest suspended sediment loads reported at the Klamath site, which is the furthest monitoring location below Iron Gate Dam. Multiple large tributaries contribute sediment and streamflow to the mainstem Klamath downstream of Iron Gate Dam, increasing the sediment loads in a downstream direction. Past studies have shown that the Trinity River contributes a large amount of sediment to the mainstem Klamath River upstream of the Klamath site (Reclamation, 2011). WY2019 load results at Klamath and Orleans show the highest suspended sediment loads of the four years evaluated, likely due in part to the high mean annual streamflow in that year. The large suspended-sediment loads at Seiad in 2022 may have been the result of debris flows from the McKinney wildfire, which burned within the river corridor upstream of Seiad Valley in the summer of 2022. The Yurok tribe and researchers at Cal Poly-Humboldt are currently investigating the effects of the debris flow on sediment transport in this reach.

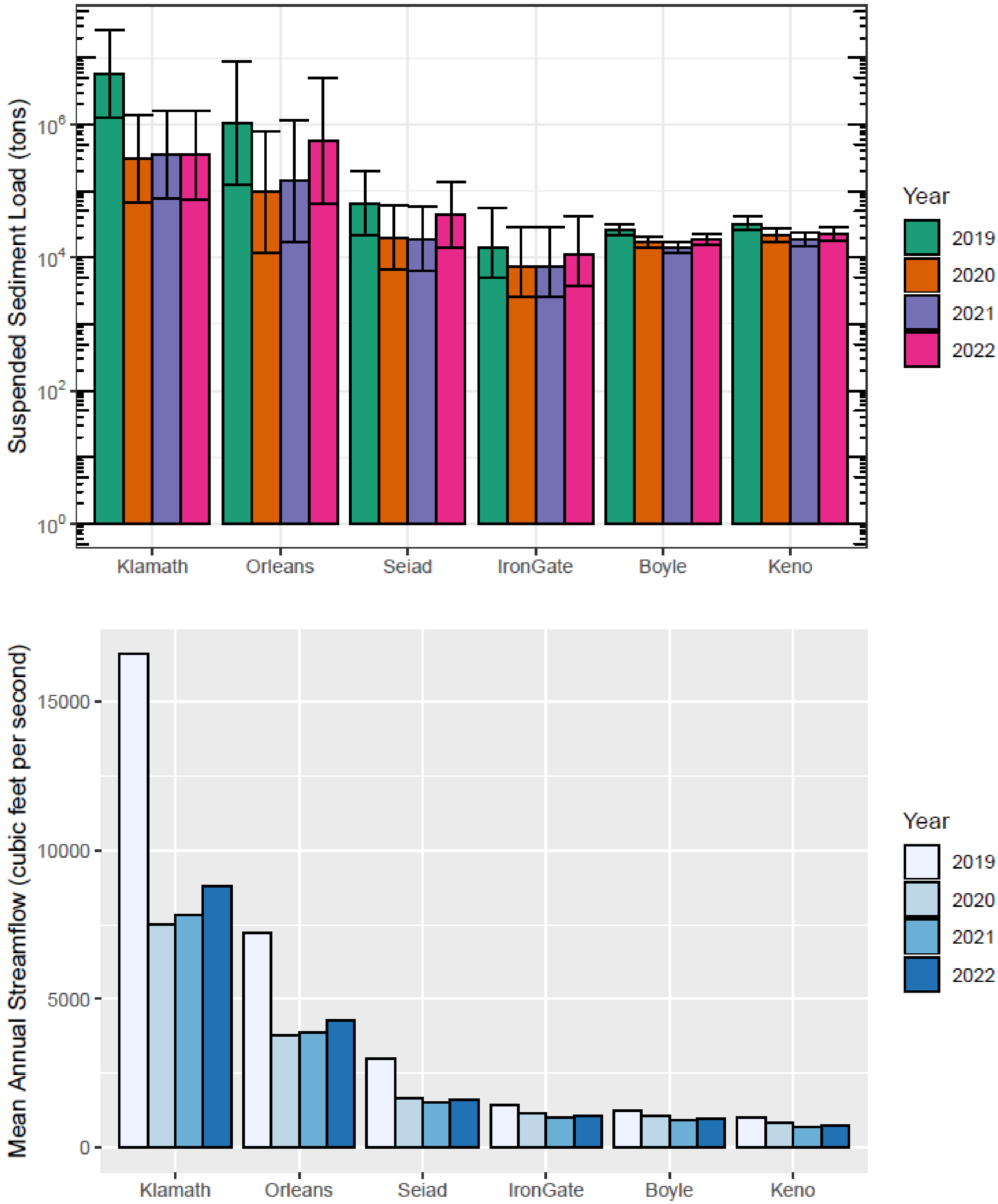

Figure 2. Suspended-sediment loads and mean annual streamflow during water years 2019-2022 at six monitoring locations along the Klamath River. Error bars on suspended sediment loads represent 90 percent prediction intervals. (Provisional data, do not cite or distribute).

Summary

Sediment flux pre-dam removal shows relatively low suspended sediment flux in the upstream reaches of the Klamath River directly affected by the dams compared to tributary and mainstem-influenced sediment flux in the downstream reaches of the Klamath River. Suspended sediment flux dynamics are expected to change drastically during and following dam removal with sediment transport changing from supply-limited to transport-limited directly below the dams. As such, the regression models used in this pre-dam removal time period will not be applied to during-and post-dam removal periods since the character of the suspended sediment is expected to be different from pre-dam removal conditions. These regressions will be evaluated against dam-removal sediment in an ongoing process while the dams are being removed. Geomorphic studies have identified a depositional reach between Iron Gate Dam and Cottonwood Creek, and studies on channel morphology will determine how the armored reaches of the lower Klamath River will respond to the large influx of fine-grained sediment. Suspended-sediment monitoring and flux estimates will continue in the coming years to determine not only the quantity of suspended-sediment transported during and following dam removal, but also the fate of fine sediment throughout the river corridor.

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