Five Years of Sedimentation behind Two Large Run-of-River Dams in the Brazilian Amazon

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Extended Abstract

Sedimentation behind run-of-river (ROR) dams is expected to be limited and quickly stabilized, because of the preserved energy gradient available to move sediment through these systems. However, this depositional expectation may not hold behind reservoirs along large, tropical rivers with high sediment loads. Estimations of sedimentation for environmental licensing and design for the Madeira Hydroelectric Complex (MHC) in the Brazilian Amazon was done following standard engineering practices. These studies used empirical and one-dimensional sediment retention and transport models to determine relatively uniform sedimentation along the reservoirs, with wedge shaped sedimentation at the foot of the dams, and no upstream delta (Furnas 2005). Environmental and operational licenses were granted, and dam designs were finalized based on the conclusion that after 20 years, reservoir sediment retention would discontinue (Furnas 2005). On-going monitoring reports, required to maintain dam operation, have been made public through the Brazilian Institute of Environment and Renewable Resource Natural Resources (IBAMA, acronym from Portuguese). Since the construction of the dams, monitoring of established control cross-sections show the predicted sedimentation at the foot of the dam, but sedimentation has not been horizontally uniform along the reservoir. Major sedimentation in the now flooded, pre-dam floodplains (as high as 10-15m) has blocked off passage of smaller tributaries. While the environmental and design studies did acknowledge the shortcomings of the initial methodologies used (including the use of one-dimensional sedimentation modeling that did not capture the observed non-uniform horizontal deposition), third party reviews concluded that estimates also lacked a rigorous uncertainty analysis and attention to unsteady flow conditions (Dunne 2007; Molina et al 2008). Moreover, these studies also do not take into account non-stationary climate and upstream anthropogenic activities. The above justifies a non-stationary and uncertainty bounded quantification of sedimentation behind the MHC.

The above-mentioned monitoring reports are rich with additional information that has yet to be synthesized to aid in estimating sedimentation under a non-stationary future. Here we synthesize and validate monitoring data with independent measurements taken by our research group in May of 2018. We first present the study reach and findings from the MHC Environmental Impact Assessment (EIA), design documents, and monitoring programs. We then report on preliminary results of our field-based data collection to validate and complement the EIA and monitoring data. Finally, a two dimensional modeling framework is proposed as future work to model the cumulative effects of changing climate and upstream development on the life expectancy to the MHC reservoirs.

Study Reach

Figure 1 shows the reach of the Madeira River where the MHC was constructed. The MHC is comprised of two large, ROR dams - Jirau (commissioned in 2013-2016) and Santo Antonio (2012) - with a combined installed potential of >7000MW. The Madeira River carries 430 MT of sediment per year (Vauchel et al, 2017) - nearly 50% of the Amazon’s total sediment flux - with suspended concentrations ranging between 120 - 3500 mg/l (PCE 2005). Of the yearly total sediment load, it is estimated that 94.3% is transported as suspended sediment (PCE 2005).

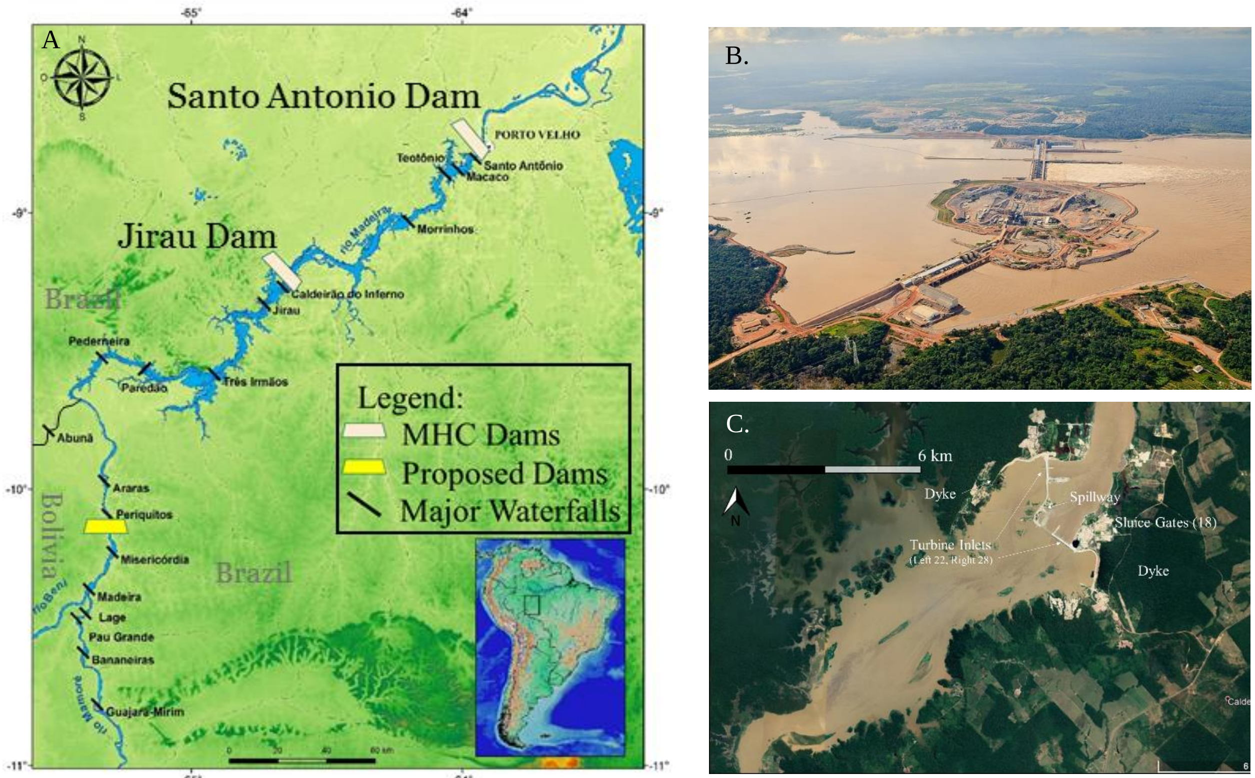

Figure 1. A. Santo Antonio and Jirau dam locations along the Madeira River in Rondonia, Brazil (Modified from Cella-Ribeiro et al 2013); B. Santo Antonio Dam under construction (skyscrapercity.com); C. Jirau Dam with major components and scale for reference (Google Earth).

Combined, the reservoir is greater than 200 km long, with a surface area greater than 500km^2, and a total storage volume > 4km^3. The EIA analysis concluded that sedimentation would reach an equilibrium after about 22 years and result in the loss of about half of the combined reservoir capacity due to trapping of approximately 2.06 km^3 of sediment. Monitoring and 3D computer and a physical models now show that sedimentation will stabilize in just six to seven years, rather than the 20 years predicted in the EIA, implying the reservoirs have almost stopped long-term deposition as of 2018, due to the concentration of flow toward the main channel as floodplains fill with sediment. These conclusions, however, were made without including the extensive upstream dam development plans, increasing land use cover change, or changes in climate change (Forsberg et al. 2017).

Preliminary Results from 2018 Survey

Explicit comparisons of 2018 cross-sections to pre-dam surveys show that at the upstream reaches of the reservoir, sedimentation does not exceed natural seasonal fluctuations, which were observed as high as 5 m during pre-dam monitoring. Closer to the Jirau dam, higher sedimentation is observed above pre-dam bank-full elevations on what was previously floodplain, consistent with the monitoring programs reported cross-sections. Some cross-sections also exhibit high in-channel deposition closer to the dam.

Initial surface suspended sediment concentration (SSSC) results of the grab samples taken up and downstream of the MHC, show an overall decline in sediment concentration along the two in-series reservoirs. From these preliminary observations, it is hard to make any concrete estimations of trapping efficiency. However, if well-mixed, turbulent hydraulic conditions are initially assumed we can infer that sediment is falling out of suspension progressively downstream relative to upstream values. As stated by Annandale et al. (2015), suspended sediment concentration estimates from surface grab samples is not adequate for robust sediment transport estimations, because of the variability of vertical concentration profiles. Additionally, suspended sediment sampling should be done using isokinetic samplers to avoid oversampling sands (Ewards and Glysson 1999). During the May, 2018 field campaign, isokinetic depth and point-integrated samples were collected for surface sample bias-correction and correlation to total cross-section-averaged concentrations. Grain size distribution (GSD) of our samples compared to pre- and post-dam monitoring samples will also provide better sedimentation interpretations. These data will be further compared and validated against the Santo Antonio and Jirau dam company's monitoring program data to assure data is complementary for the proposed modeling.

Conclusion and Future Work

From the initial SSSC results, it appears that average sediment concentrations are declining from upstream to downstream through the reservoirs. Comparison to the MHC's monitoring programs support this finding, although our independent results from the point and depth-integrated samples and GSD will be used for further evaluation. Additionally, bed material was collected to assess bed material GSD for better constraining channel hydraulic modeling. Further synthesis and comparison of our data with the monitoring data is required to predict future sedimentation in the reservoirs under non-stationary climate and upstream development conditions.

Preliminary inspection of the May 2018 field data shows no significant sedimentation along the first 90 km of the 120 km long reservoir. Further downstream, closer to the dam, many sections do not exhibit in-channel deposition outside of natural season fluctuations, while others do. Deposition, however, is noticeably higher, >10m, on what was previously the channel floodplain. Due to the one-dimensional nature of the sediment transport modeling conducted for the EIA and design studies, this horizontal sedimentation variability was not captured, meriting the 3D and physical modeling that was done by the dam companies. Both the physical and computer models suggest sedimentation is close to stabilization under stationary conditions, only a few years after flooding.

From initial reservoir monitoring, it is apparent that direct comparison of cross-sections of pre and post-dam measurements is difficult because of the control section locations, natural dynamism of the channel bed, and the run-of-river dam design. With this in mind, for the proposed future work, related to quantifying sedimentation behind MHC under non-stationary hydrology and sediment loads, at least a two-dimensional sediment transport model will be needed to better model non-uniform floodplain deposition. We propose the use of the SRH-2D model, because of the 2-dimensional mobile bed sediment transport module. Exploration of measurement and model parameter uncertainty will be used together with non-stationary boundary conditions to independently quantify the useful life-span of the reservoirs.

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