Extended Abstract

Uncertainty of Sediment Transport Modeling through Two Run-of-River Mega-dams on the Madeira River

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Introduction

Around the world there has been a global resurgence of dams to meet the increasing need for water storage and hydroelectricity. A major concern for new and existing dams is the loss of storage through reservoir sedimentation that changes sediment regimes and geomorphological equilibrium. As a part of this resurgence in dams, more than 400 dams already exist, are under construction, or are being planned in the Amazon watershed. When it comes to sediment, the Amazon River provides some of the highest loads to the world's oceans that supports regional ecosystem function and global climate (Lefèvre et al. 2017; Neumann-leitão et al. 2018; Newinger and Toumi 2015). Seasonal hydrologic and sediment flux dynamics have extensive social, economic, and ecological importance along the river network. Contributions of sediment from the Amazon's largest tributary, the Madeira River, make up half of the basin's total sediment load. The Madeira watershed continues to develop as the population grows, production of agricultural goods increases, improvements to highways and river waterways are made, and as dams are constructed. In fact, the Madeira River basin has been cited as being the most vulnerable of the 19 major sub-basins to future deforestation and dam construction (Latrubesse et al. 2017). Until recently, however, basin-wide sediment dynamics and river geomorphology had not been well quantified due to data scarcity. The French Research Institute for Development has refined basin-wide sediment balances (Vauchel et al. 2017), and recently built and planned infrastructure has sparked localized sediment monitoring along the Madeira River mainstem.

In the last decade, two "run-of-the-river" (ROR) hydroelectric dams were installed along the Madeira River mainstem, hereafter referred to as the *Madeira Hydroelectric Complex (MHC)*. By definition, ROR dams do not have significant water storage capacity. During the rainy months of the year the MHC reservoirs have no effective storage capacity, while a few days of flow can be stored during average dry season flows. It was also predictable that the ROR concept would hold for sediments, meaning that sedimentation in the reservoirs would quickly stabilize to a dynamic equilibrium, because of the preserved hydraulic energy to move sediment through the system. However, this depositional expectation may not be totally accurate along this large, tropical river with high and historically sparse sediment load estimations.

Since the early planning phases of the dams in 2004, close sediment and geomorphological monitoring has been required to protect future operations and for project environmental licensing. The monitoring reports are rich in data that has not been well synthesized for quantifying Madeira River sediment budget and transport. In these reports and the primary literature, there is a lack of agreement and knowledge about how the dams are affecting sediment transport (Latrubesse et al. 2017; Rivera et al. 2019; PCE 2006, PCE 2009, NHC 2013, PCE 2015). Thus, here we synthesize reported data and model current and future sediment transport conditions using a one-dimensional model, HEC-RAS. *This study's over-arching objectives are* *to present a clear picture of to-date sedimentation behind MHC and predicting future reservoir sedimentation and river readjustments.*

The specific objectives of this work are to synthesize the present hydrologic and geomorphological conditions that govern sediment transport on the mainstem of the Madeira River and to examine how existing uncertainties and data gaps influence the predictive capabilities of sedimentation behind the MHC. The expectation is that this work will highlight knowledge gaps and identify needs for complimentary field studies, subsequently reducing the uncertainty of future projections (and likely, continued development). More explicitly, this work seeks to achieve the following aims:

1. Make available synthesized literature and project monitoring data needed to characterize sediment transport through the MHC system (e.g. hydrology, channel geometry, geomorphology, sediment monitoring data, etc.).
2. Summarize and model reservoir sedimentation to-date using monitoring data from 2013-2020.
3. Quantify observed sediment data, terrain, and to-date model uncertainty
4. Synthesize future climate change literature and project changes to sediment transport through the MHC (focus here on sedimentation of reservoirs) with quantified model uncertainty and non-stationary hydrology.

Study Area

The Madeira River has its headwaters in the Andean mountains of Bolivia and Peru (see figure 1). Smaller tributary rivers originate in the lowlands of eastern Bolivia and the Brazilian shield.

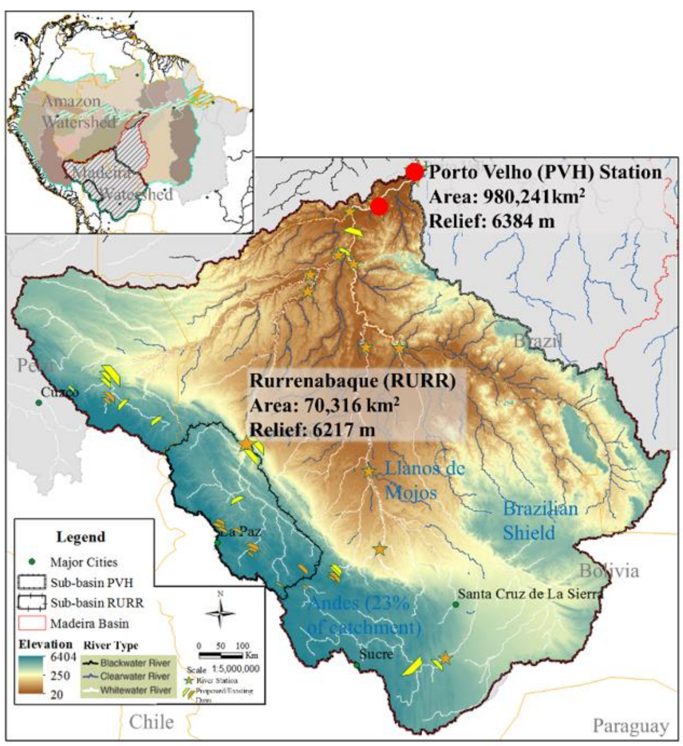

Figure 1. Map of the Madeira River basin. The focus area of this study is the >300 km reach upstream of Porto Velho, Rondonia, Brazil, where two ROR dams (>7000MW) make up the Madeira Hydroelectric Complex (MHC). The map

shows important geomorphic features of the watershed and existing (orange markers) and proposed dams (yellow markers) upstream of the MHC. The study reach (>300 km, between the two red points) passes through numerous waterfalls, where the MHC was installed (2012-2013).

From the Andes, where an estimated 90% of the watershed's total sediment load originates (Vauchel et al. 2017), the Madre de Dios, Beni, and Mamore rivers drop drastically (from an average 4500 to 300 masl in less than 200 km) into the expansive savanna wetland of Llanos de Moxos. The Madeira River is formed after the Mamore has combined with the Guapore River and finds it confluence with the Beni (Figure 1). Mean annual temperature and precipitation in the Andean mountains range from 15-23°C and 200-6000mm, and in the lowlands temperatures average around 25°C (21–31°C) with a north-south latitudinal rainfall gradient from 2500-1000mm (Espinoza Villar et al. 2009; Marengo and Espinoza 2016; Vauchel et al. 2017). The basin is defined by its marked dry and wet season, with more than 75% of the rain falling between December and March.

The Madeira Hydroelectric Complex (MHC) takes advantage of abrupt elevation changes along a series of 19 rapids as the river transitions from the Brazilian Central highlands to the Amazon lowlands (Torrente-Vilara et al. 2011, see Figure 2). Combined, the reservoirs have a maximum surface area >800km2, and a total storage volume > 50km3 (Moreira 2007). At the Jirau and Santo Antonio dams, the maximum intake levels are 90 and 71masl, while spillway invert levels are at 69 and 47.5 masl, respectively. Maximum gross head for both dams is approximately 15m, resulting in a combined maximum energy capacity is approximately 7000 MW. Figure 2 shows the location of each dam and the different waterfalls.

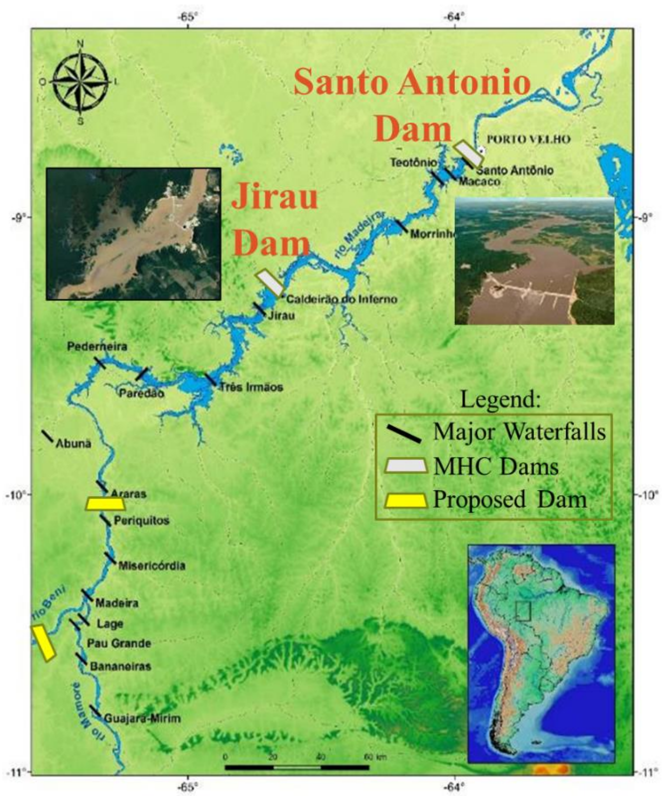

Figure 2. Location of Jirau and Santo Antonio dams along the Madiera River. Water flows from the south to northeast. Red dots indicate the modeled reach.

Preliminary Results and Discussion

In this work, the uncertainty of present and future MHC sedimentation was reassessed using the post-dam monitoring data (2013-2020), data collected on an independent field campaign in 2018, and a one-dimensional sediment transport model. First, the recent field data were synthesized with relevant sediment and geomorphological data from the literature. Modeling of reservoir sedimentation was then conducted for both present and projected future climatic conditions using the HEC-RAS sediment transport model. Reducing uncertainty of modeled future dam effects on Madeira River sediment transport can be achieved through continued sediment monitoring, model uncertainty analyses, and leveraging improved non-stationary predictions of future hydrology in this globally important basin.

Uncertainties attributed to both input data and model parameters were tracked by randomly sampling observed sediment characteristics and all realistic model parameter values. Total likelihood of parameter sets, and marginal parameter probability distributions were established from present-day model runs (2013-2020) and subsequently used to track uncertainty of sediment input data on future projections of sediment transport under different synthetic hydrologic regimes. Since dam construction, monitoring of control cross-sections show major sedimentation near the foot of the dams and on the now flooded, pre-dam floodplains (in some places as high as 10-15m), much more rapidly than previously modeled. In particular, the 2013-2014 flood (estimated as a 300-year return interval flood) caused significant sedimentation above turbine intake elevation at both dams, illustrating the value in considering a range of synthetic, non-stationary hydro-sedimentological future scenarios. Preliminary future results suggest reservoir sedimentation occurs much quicker than modeled in the feasibility and environmental licensing phases of both projects. Additional system sediment transport studies are needed to find the best operating procedures for managing reservoir sedimentation into the future to reach a new dynamic equilibrium. Much higher sedimentation management cost are expected compared to the initial cost benefits analysis.

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