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Mega Dams and Their Impacts On Downstream Sand Bar and Island Dynamics Along The Madeira River, Brazil

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Abstract

This paper investigates the impact of both Santo Antônio and Jirau mega dams on the downstream geomorphology of, more specifically, island and bar dynamics along the Madeira River in the Amazon. Water level data from gauge stations and remote sensing images from 1990 to 2019 were deployed to make sense of the changes in the number, area and volume of islands/bars downstream of the dams. The data indicated that both Santo Antônio and Jirau, which are run-of-river dams have not had significant impacts on the area and volume of islands/bars found in Madeira River's five reaches. A reduction in the volume of islands/bars was marginally more substantial than a negligible reduction in their areal extent. Trapped sediments behind both dams could have accounted for the slight decrease in island/bar volume. Overall, this paper opens up a discussion on the sustainability of fluvial/geomorphological features and water regimes, alongside the installation of run-of-river dams as an allegedly more sustainable alternative to other kinds of hydraulic structures and non-renewable sources of energy. Student-teachers who are taking tertiary courses in physical Geography, as well as A Level Geography educators are likely to take interest in this in-depth and well contextualised case study of mega dams in Brazil.

Introduction

The Amazon River is the world's largest network of river channels and contributes to almost 20% of the total freshwater discharged into oceans globally (Molinier et al., 1995). It is also one of the most biodiverse basins worldwide (Lewinsohn and Prado, 2005), consisting of approximately 15% of all freshwater fish species (Jézéquel et al., 2020). The Amazon river system comprises many large tributaries, with the Madeira River being the largest tributary (in terms of discharge), that accounts for 23% of Amazon's land area (Filizola & Guyot, 2009; Goulding, 1981). The Madeira River provides up to 50% of the Amazon River's sediment load (200-300 million tons of sediment discharge per year; Rivera et al., 2019; Dunne et al., 1998; Filizola & Guyot, 2009; Guyot et al., 1996; Park & Latrubesse, 2019).

Hydropower is the main source of renewable energy in South America (Barros & Field, 2014). Brazil, is heavily dependent on hydroelectricity which accounts for approximately 85% of its electricity consumption (Rosalen, 2017). It is also the second largest producer of hydroelectric power in the world (424 billion kWh; U.S. Energy Information Administration, 2014). To meet the demand for electricity that is expected to rise by 2.2% annually, more than 30 large dams and 170 small dams are also being planned for construction in the Brazilian Amazon over the next 30 years (Timpe & Kaplan, 2017; Rosalen, 2017). Presently, there are at least 1,000 hydroelectric generation centrals (including dams) in the country (de Souza Dias et al., 2018) to

Between 2008 and 2016, two cascading mega-dams were installed along the upper reaches of the Madeira River. Santo Antônio dam was built just above the Porto Velho, (the capital of Rondônia), while Jirau dam was built 117 km further upstream, between Porto Velho and Abunã (a town near Brazil's border; Fearnside, 2014). Santo Antônio and Jirau dams are two of the ten largest mega dams in the Amazon basin in terms of power generation (a capacity of 3,150 MW and 3,750 MW, respectively; Fearnside, 2014; Latrubesse et al., 2017). Both Santo Antônio and Jirau dams are run-of-river dams with little or no active storage of water (i.e. small reservoirs) and are theoretically less likely to alter downstream hydrology (Doyle et al., 2002; Csiki & Rhoads, 2014; Egré & Milewski, 2002). In contrast to impoundment dams, the inflow of water in a run-of-river dam is expected to be equal to the outflow in run-of-river dams.

Studies on the impact of Santo Antônio and Jirau dams on the river's sediment load have not been conclusive or consistent. Some research has shown that the installation of Santo Antônio and Jirau dams could have led to a 20% to 30% decrease in the concentration of fine suspended sediments along the Madeira River (Latrubesse et al., 2017; Rivera et al., 2019; Vauchel et al., 2017). However, data for such reductions in sediment load has been gathered only along the Beni River, which is just one of the three sources of sediments. In comparison, Almeida et al. (2019) have reported no significant reductions in turbidity and fine suspended sediment load downstream post-dam. However, Almeida et al. (2019) have speculated that the back-flooding of tributary valleys similar to a typical storage dam might occur at Santo Antônio dam due to reduced upstream velocity. Similarly, Cochrane et al. (2017) have revealed that the area inundated by Santo Antônio and Jirau dams were 60% larger than what was stipulated in prior environmental impact assessments. More generally, Csiki and Rhoads (2010) aver that while run-of-river dams can cause sediment storage upstream, the geomorphological responses to these dams vary with geographical context.

This study aims to investigate the impact of two cascading Santo Antônio and Jirau dams on Madeira river's downstream morphodynamics, with a specific focus on island/bar sediment mass balance. Variations in the number, areal extent and volume of fluvial bars and islands were assessed vis-a-vis daily water level data from 8 gauge stations between the two mega dams and remote sensing images from 1990 to 2019. The volume of each uniquely identified bar were also calculated using rating curves between island area and river water level. As compared to bars, islands are defined as being at later geomorphic evolutionary stage. Bars become islands when they are colonized and stabilised by vegetation growth.

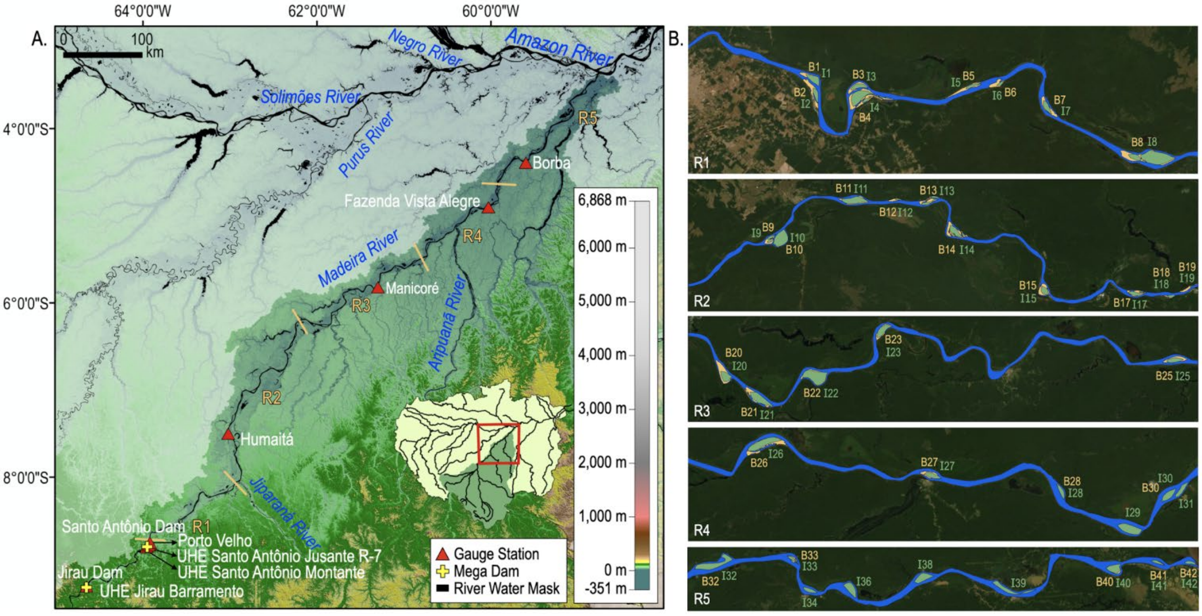
Dams are frequently one of the many other anthropogenic factors (e.g. deforestation) impinging on a drainage basin (Jordan et al., 2019; Loc et al). Although it is usually difficult to attribute causation to a sole factor within the physical environment, the influence that dams can exert on the river's discharge and sediment load is more obvious, especially along the downstream stretches immediately after the dam. Taken together, dam-induced changes in island/bar area and volume dynamics along the Madeira River can have profound implications on the sustainability and preservation of the Amazonian flood and coastal plain ecosystems. A discussion of these implications in this paper seeks to inform more low impact forms of river management strategies.

Data and Methods

Study area

The Madeira River stretches through a total length of 3,240 km, originating from the Bolivian Andes and flowing through Mamoré and Beni rivers (Goulding et al., 2003) before converging with the Amazon main channel downstream (Figure 1). Santo Antônio dam is located 175 km upstream from the city of Humaitá, and the Jirau dam even further at 263 km upstream. The study area is divided into five separate reaches, from R1 to R5 (Figure 1). The major tributaries and gauge stations are evenly distributed as far as possible across these five reaches. Typically, the dry season occurs from August to January while the wet season takes place between April to June (Figure 2B).

Figure 1. A: Map of study area showing the locations of the mega dams and gauge stations, divided into 5 separate reaches; Inset map showing the Amazon River basin and the water river mask of the Amazon RIver system; red box indicating the location of the study area. **B:** Map of the 5 separate reaches of the study area in 2019 with distinctly labeled islands and bars.



Hydrological Analysis of Daily Water Level

Daily water level series between 1990 to 2019 from 8 gauge stations were analysed to create hydrographs that took into account the seasonality of discharge based on wet and dry seasons (Table 1). Dry season Landsat images were also used to better illustrate island/bar morphology.

Table 1: Information on gauge stations and Landsat data availability

Water Level Data					Landsat Data	
Gauge Station (*Code*)	Latitude (°N)	Longitude (°E)	Data	Reach	Satellite	Data
Borba (*15900000*)	-4.39	-59.60	01/01/1990 to 31/01/2020	R5	Landsat 5	28/08/1990 to 05/01/1991
Fazenda Vista Alegre (*15860000*)	-4.90	-60.03	01/01/1990 to 31/01/2020	R4	Landsat 5 and 7	15/08/2000 to 13/11/2000
Manicoré (*15700000*)	-5.82	-61.30	01/01/1990 to 31/01/2020	R3	Landsat 5 and 7	28/08/2010 to 24/12/2010
Humaitá (*15630000*)	-7.50	-63.02	01/01/1990 to 31/01/2020	R2	Landsat 7 and 8	22/08/2019 to 28/10/2019
Porto Velho (*15400000*)	-8.75	-63.92	01/01/1990 to 29/02/2020			
UHE Santo Antônio Jusante R-7 (*15380000*)	-8.78	-63.93	01/09/2008 to 31/12/2017			
UHE Santo Antônio Montante (*15360000*)	-8.80	-63.96	12/11/2011 to 31/08/2012, 01/01/2015 to 31/12/2017			
UHE Jirau Barramento (*15340500*)	-9.25	-64.65	05/07/2013 to 31/12/2016			

*Digitizing the channel and assessment of number/a*rea

Landsat images from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/) for 4 separate dry season periods with 10-year intervals were downloaded (with reference to the hydrographs). The respective years and date range for the Landsat images used for each time period were presented in Table 1. A combination of Landsat 5, 7 and 8 images were mobilised from the Landsat Collection 1 Level-2 series. Band 4 was extracted for the images obtained from Landsat 5 and 7 while Band 5 was extracted for for the images obtained from Landsat 8. These bands represented the near infrared (NIR) bands, which were selected due to the strong wavelength absorption of water in this spectrum (Gao et al., 2016). This allowed for a clear differentiation of land and water surfaces for the digitisation. The path and row range of the Landsat images used were 221 to 224 and 24 to 80 respectively. The Landsat images were mosaiced to cover the entire study area, while the river channel was digitised for the 4 periods. Islands that were 3km^2 or larger were digitised separately. A minimum area of 3km^2 was selected to ensure that the observed changes in the amount of sediments present in islands/bars would be substantial enough to be attributed to the dams.

The digitised islands that were 3km^2 or larger in area were numbered with a unique identification label (Figure 1B) and numbered sequentially, beginning with the one furthest upstream. These islands were then quantified and graphed across the 4 study years. Statistical analysis was also conducted to calculate variations in the sum, mean and standard deviation of the islands/bars' area over the same period in order to investigate how mega dams affect sediment mass balance.

Analyzing Volumetric changes of the Bars

The volume of bars were calculated and comparisons were made across different reaches of the river and time periods. Rating curves were generated for each uniquely identified bar that existed through the pre-dam period (1999 - 2000) to the post-dam period (2018 - 2019, Figure 1B). In each rating curve, the exposed surface area of the bar (x-axis) was plotted against the channel's water level on the day that the Landsat image was taken (y-axis, see Wang and Xu 2018). The water level data for each bar was extracted from the gauge station within its corresponding reach. The rating curves of two separate periods (1999 to 2000, and 2018 to 2019) were plotted for each bar within the same graph to represent bar dynamics before and after the dams were built. The area under the rating curve at respective water levels were used to decipher (changes in) the bar's volume.

Results and Discussion

Hydrological Analysis of Daily Water Level

Daily water level series of 8 selected gauge stations between the mega dams and at the confluence of Madeira River and Amazon main channel from 1990 to 2020 were plotted (Figure 2). The water level remained relatively constant at the 8 gauge stations before and after the two dam's operation. Both dams began construction in 2008, with the Santo Antônio and Jirau dams in operation at around 2012 and 2016 respectively. There had not been any significant changes in the water level series from the downstream gauge stations before and after the mentioned years. Mean annual water levels recorded in Humaitá, Manicoré and Borba only decreased by 3.95%, 1.70% and 1.02% respectively from 2007 to 2017 (Table 2), indicating that the degree of change decreased downstream. Porto Velho, the downstream gauge station closest to the dams reflected the greatest variation in mean annual water level (a reduction of 8.72%).

The gauge station at the Jirau dam (UHE Jirau Barramento; the station furthest upstream) recorded the highest water levels with their peaks and troughs coinciding with the wet and dry seasons. Meanwhile, the Santo Antônio dam (UHE Santo Antônio Montante) experienced little seasonal variability in water levels as the reservoir was kept at bankfull throughout the year after being flooded (Almeida et al., 2019). Additionally, Porto Velho’s water levels (upstream) appeared to be lower than that of other gauge stations (further downstream).

Figure 2: Water level series of gauge stations along the Madeira River from 1990 to 2020 and timeline of dam construction and opening.

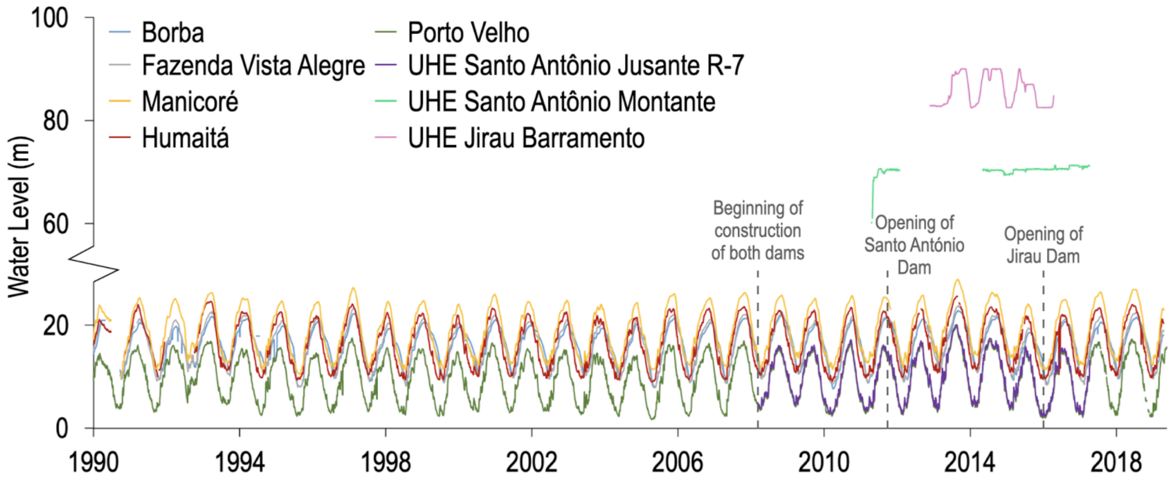


Table 2: Mean annual water level in 2007 and 2017 at 5 downstream gauge stations (Borba, Fazenda Vista Alegre, Manicoré, Humaitá, Porto Velho).

Gauge Station	Mean Water Level (m) (2007)	Mean Water Level (m) (2017)	Change in Volume (%)
Borba	15.9069041	15.7442466	-1.02%
Fazenda Vista Alegre	15.846137	15.8841758	+0.24%
Manicoré	19.1860548	18.8598904	-1.70%
Humaitá	16.7316712	16.0709315	-3.95%
Porto Velho	9.78989041	8.93649315	-8.72%

Research has shown that while run-of-river dams can result in short-term (e.g. daily) fluctuations in discharge downstream, they do not lead to long-term disruptions in the river's regime, as water is allowed to flow through without much impediment (Ashraf et al., 2018; Greimel et al., 2015). Almeida et al. (2020) have also come to a similar conclusion in relation to the effects of the two run-of-river dams on Madeira River's discharge patterns.

Number and Area of Islands and Bars

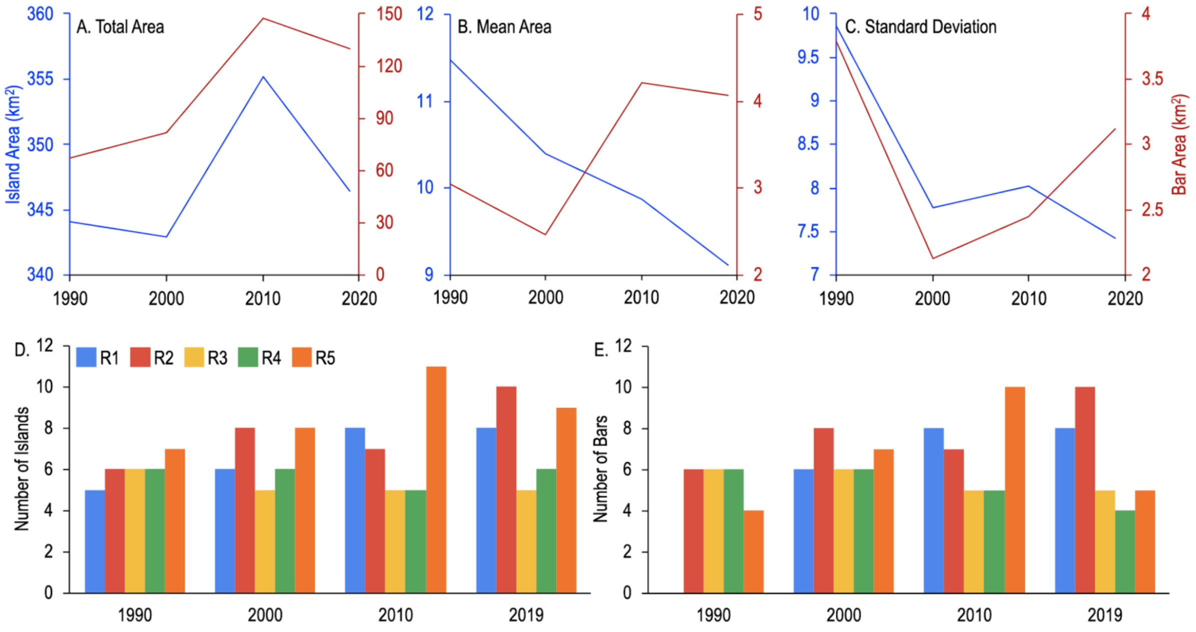
The number of islands/bars larger than $3km^2$ found within the river's 5 reaches were analysed separately (Figure 3). The number of bars showed a general increasing trend across the 40 years, from 22 bars in 1990 to 35 bars in 2010 while the dams were being constructed, which later decreased to 32 bars in 2019 after the dams were in operation (Figure 3E). The total area of bars also increased from 1990 to 2010, then decreased in 2019. This decrease in the number and total area of the bars from 2010 to 2019 could be attributed to the trapping of sand behind the dam reservoirs to some degree when the dams began operating, though the extent of the sediment trapping is not extensive. This resulted in the sediment discharge received in the downstream region of the river being reduced as seen by the extent of the bar formation, compared to the period before the dam was opened.

The total number of islands increased consistently from 1990 (30 islands) to 2019 (38 island; Figure 3D). There was also an increase in the total sum of the islands' areal extent from 2000 to 2010, before it decreased from 2010 to 2019. Interestingly, the mean area of each island decreased from 11.47 km^2 in 1990 to 9.12 km^2 in 2019 although the total area of the islands increased from 1990 to 2010 – this implies that smaller islands were being formed. As mean surface suspended sediment concentration was observed to have decreased by around 20% in the Madeira River (Latrubesse et al., 2017), the amount of fine sediments deposited on the surface of the bars present would decrease, slowing down the colonisation of vegetation that would expand the island and therefore accounting for its size.

Based on the Landsat images captured during dry seasons, minimal change to the areal extent of the islands (a decrease of 2.45%) from 2010 to 2019 was observed. The percentage change in the total areal extent of bars was much larger (81.09% increase) from 2000 to 2010 followed by a significant reduction (11.72% decrease) from 2010 to 2019. Dam construction could have contributed to the river's sediment load thereby resulting in an initial increase in the area of bars from 2000 to 2010.

Within the Madeira Basin, exceptionally high rainfall and hence discharge values (74% higher than normal) were recorded in 2014 while severe flooding occurred in 1992, 1993, 1997, 2007 and 2008 (Bourrel et al., 2009; Espinoza et al., 2014; Ovando et al., 2016; Ronchail et al., 2005). The superimposition of floodwaves from Madeira River's major tributaries also intensified flooding along the Madeira River itself (Ovando et al., 2016). Intense precipitation could have augmented the rate of weathering and erosion which contributed to the river's sediment load. Consequently, the predicted reduction in sediment budget post-dam was less significant. Variations in the area of islands/bars are slight, and are more evident in newly formed and less stable bars.

Figure 3: A: Total area of islands and bars from 1990 to 2019. B: Mean area of islands and bars from 1990 to 2019. C: Standard deviation of area of islands and bars from 1990 to 2019. D: Total number of islands per year at 10-year intervals, divided by reach. E: Total number of bars per year at 10 year intervals, divided by reach.



Volumetric Analysis

Rating curves for each uniquely identified bar from pre to post dam periods (1999 - 2000 to 2018 - 2019) were plotted (Figure 4). The selected bars' volume were calculated vis-a-vis the regression equation shown on the respective curves (Table 3). The results show a volumetric reduction in 23 out of the 25 bars. B13 and B27 were the only two that experienced a slight volumetric increase (0.74% and 11.75% respectively). Such volumetric reductions are typically greater upstream than downstream with the largest being a percentage change decrease of 49.97% at B1 and the smallest being a decrease of 0.30% in B42. The volumetric change in B23 was stated as undetermined because of the water level differences with which the area of the pre and post-dam bars were calculated. The data indicated that some sediments could have been trapped behind the dams, thereby causing a marginal decline in the river's sediment load and in turn a reduction in island/bar volume.

Figure 4: Rating curves of bar surface area and water level for the bars present from the pre-dam period through to the post-dam period in 1999-2000 (blue) and 2018-2019 (red). Regression equations were given for the 2019 curve (top, in red) and 1999-2000 curve (bottom, in blue) along with their coefficient of determination (R^2).

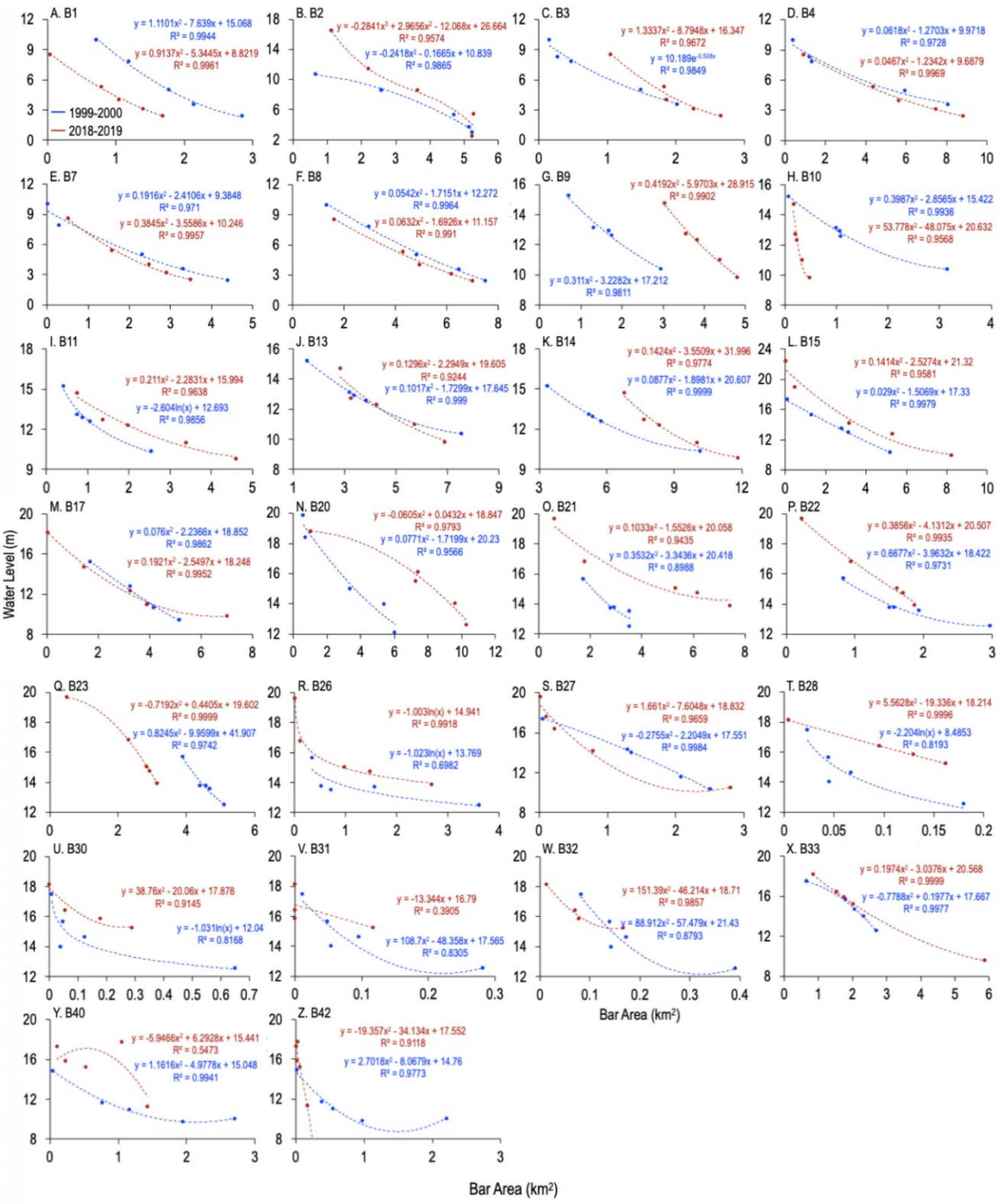


Table 3: Calculated volumes of Bar 2, Bar 15 and Bar 20.

Bar	Volume (km^3) (1999-2000)	Volume (km^3) (2018-2019)	Change in Volume (km^3)	Change in Volume (%)
B1	7.41707	3.71071	3.70636	-49.97%
B2	38.5793	30.5439	8.0354	-20.83%
B3	5.93933	4.73039	1.20894	-20.35%
B4	41.2483	37.7434	3.5049	-8.50%
B7	16.2977	14.732	1.5657	-9.61%
B8	32.4937	28.0191	4.4746	-13.77%
B9	1.59655	1.11467	0.48188	-30.18%
B10	4.48674	3.46606	1.02068	-22.75%
B11	23.0223	20.6456	2.3767	-10.32%
B13	47.3855	47.7385	-0.353	0.74%
B14	41.5165	36.8881	4.6284	-11.15%
B15	81.1868	69.3717	11.8151	-14.55%
B17	42.2971	41.6176	0.6795	-1.61%
B20	90.9464	76.7061	14.2403	-15.66%
B21	30.0863	25.4733	4.613	-15.33%
B22	16.3676	14.9922	1.3754	-8.40%
B23	-	-	-	-
B26	34.2201	31.4706	2.7495	-8.03%
B27	31.0662	34.7159	-3.6496	11.75%
B28	2.55762	2.16421	0.39341	-15.38%
B30	9.52219	8.66242	0.85977	-9.03%
B31	4.0394	3.65201	0.38739	-9.59%
B32	4.457	4.1846	0.2724	-6.11%
B33	29.4258	28.4765	0.9493	-3.23%
B40	5.32097	4.0498	1.27117	-23.89%
B42	1.99828	1.99225	0.00603	-0.30%

Conclusion

The Santo Antonio and Jirau run-of-river dams were built as a response to an ever-increasing demand for sustainable and/or renewable sources of energy. These dams were also purportedly more environmentally sustainable versions of their impoundment counterparts. Although Madeira River's water regime had remained relatively consistent pre and post dam, it is notable that the dams have had a small impact on island/bar dynamics, especially in terms of a volumetric reduction. Nonetheless, the dams seemed to exert a slightly more apparent impact on the volumetric variability of bars, as compared to islands (which were more stable).

This paper is likely to be useful to physical Geography student-teachers in institutions of higher learning as well as as Geography teachers in Singapore's junior colleges. The discussion on Santo Antônio and Jirau dams speaks to all three themes in the current 'A' Level syllabus, that of (a) 'Tropical Environments' (hydrology), (2) "Development, Economy and Environment" (water resource use and management) and (3) "Sustainable Development" (the politics of sustainability). Part of the contents in this paper can inform the preparation of lecture notes while the contextualised geographical data represented can be deployed in the design of formative assessments, particularly for Data Response Questions. Further, the pedagogical purchase of this case study also lies in (a) its potential for teachers to tease out synoptic links (since it cuts across all three topical themes) and (b) its presentation of a more nuanced understanding of dams (especially with respect to run-of-river dams).

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