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Analysis of Suspended Sediment in the Anavilhanas Archipelago, Rio Negro, Amazon Basin

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Abstract: This article analyzes the flows of water and total suspended sediment in different reaches in the lower course of the Negro River, the largest fluvial blackwater system in the world. The area under study is the Anavilhanas Archipelago, which is a complex multichannel reach on the Negro River. Between the years 2016 and 2019, data about water discharge, velocity, and concentration of total suspended solids (TSS) were acquired in sample sections of the Negro River channels located upstream, inside, and downstream of the Anavilhanas Archipelago. In the study area, the Negro River drains an area greater than 700,000 km^2, and the mean water discharge observed before the Anavilhanas was about 28.655 m^3·s^{-1}, of which 97% flows through two channels of the Archipelago close to the right and left banks. The mean TSS concentration of the Negro River upstream and downstream the Archipelago was 3.28 mg·L^{-1} and 1.63 mg·L^{-1}, respectively. Within the Archipelago, we observed more TSS in the channel on the left bank of the Negro River (mean of 4.50 mg·L^{-1}). The total suspended sediment discharge of the Negro River before (3.14 Mt·year^{-1}) and after (1.43 Mt·year^{-1}) the Anavilhanas Archipelago indicates a 55% retention of the suspended load due to the low water slope and reduced flow velocity caused by the backwater effect of Solimões River on the Negro River. The hydro-sedimentary scenario of the low course of the Negro River characterized in this study indicates a slow and continuous sedimentation process in the Anavilhanas Archipelago. The results presented will serve as a baseline to assess the impacts of the dams on the Branco River, the main tributary for both water and sediment in the Negro River basin.

Keywords: large rivers; sediment transport; anabranching; floodplain; amazon basin; fluvial archipelago

1. Introduction

Large tropical rivers play a key role in shaping the landscape, as well as maintaining ecosystems and the climate at different scales [1–4]. The Negro River is the largest tributary of the left bank of the Amazon River. It is considered the sixth largest river in the world in water volume [2], with a mean annual water discharge of 28,400 m^3·s^{-1} [5]. This huge fluvial system also possess an anabranching pattern with the presence of archipelagos [2]. Despite that large amount of water discharge, this river provides little suspended sediment input to the Amazon River [5,6], but its black waters have a high particulate and dissolved organic carbon concentration [7,8]. These hydrological characteristics together with a contrasting physiography (geology, geomorphology, climate, and vegetation) make the Negro River a unique river system flowing across a variety of rocks ranging in age from Precambrian to Quaternary, capable of maintaining large ecosystems of forests flooded by blackwaters, poor in nutrients (Igapó forest), savannas, and the largest fluvial archipelagos on the World, the Mariuá and Anavilhanas [9].

Located near the confluence of the Negro and Solimões rivers, the Anavilhanas Archipelago is the most prominent geomorphological feature on the lower Negro River. It contains an enormous diversity of islands and lakes [9–11], sustains one of the largest flooded blackwater systems in the world [12–14], and maintains a rich biodiversity of fish [15,16] and birds [17,18]. However, previous studies conducted in the region [2,11,19–21] did not deepen our understanding of the current dynamics of water flows and total suspended sediment discharge of this complex anabranching river system.

Suspended sediment transport on the Amazon River has been studied since the 1960s [22]. Currently, there are more than 260 sedimentometric stations on Amazonian rivers managed by Brazilian agencies, but only 6% of them are located in the Negro River basin [23]. The quantification and monitoring of suspended sediment transport is an important tool to understand the sensitivity of river systems to extreme weather events [22,24,25], impacts on soil management [26], and the construction of hydroelectric plants [27–31]. The lack of this type of data makes it difficult to understand the formation and functioning of the landscape, maintenance of habitats, and transport of nutrients [22,27].

The first estimations of the total suspended solids (TSS) concentration in the Negro River were obtained in the 1970s from surveys of the Alpha Helix project [32], indicating values around 5 $mg \cdot L^{-1}$. Data collected by the Hybam Project in the 1990s [33] found that the TSS is composed mainly of inorganic material that varies with water discharge, with lower concentration in the period of low water and higher concentrations during the high water [6,8]. The suspended solids transported by the Negro River come mainly from the of Guiana Shield and from areas covered by savannas, with a mean suspended solid discharge of 8 Mt per year [5,34]. The main tributary of the basin is the Branco River, coming from the northern hemisphere. This river has a mean annual water discharge of 3000 $m^3 \cdot s^{-1}$ and contributes approximately with 40% of the total suspended sediment discharge in the Negro River basin [5,35]. These estimations come from the Serrinha and Caracaraí sedimentometric stations, located inside the basin, hundreds of kilometers from the mouth of the Negro and Branco rivers, respectively. These data are not enough to certify the amount of sediments contributed to the Anavilhanas Archipelago and to understand how this island system works.

The base level of the Negro River in approximately 300 km of its low course is controlled by the Solimões River [36]. This huge river has a mean water discharge of 103,000 $m^3 \cdot s^{-1}$ and generates a backwater effect, whose influence on the hydrological system and transport of suspended solids on the Negro River is not yet well understood. The level of knowledge about the hydrological dynamics and their relationship with the formation of the Archipelago is also limited, resulting in gaps about the evolution of this complex Amazonian river system. The aim of this article is to report data collected at the Anavilhanas Archipelago and lower Negro River, concerning temporal and spatial variability of water and suspended solids flows. In addition, this study put in evidence an important dataset that can be useful to analyze consequences of the hydroelectric dam planned to be done at the Branco River [28,29,37,38], considering the importance of the sediments that can be retained by the dam and that currently feed the rich biodiversity of the Anavilhanas [39].

2. Materials and Methods

2.1. Study Area

With an area of 712,000 km^2, the Negro River basin (Figure 1) is located between 5° N and 3° S and between 58° and 72° W with an altitude ranging from 10 m.a.s.l. to 2900 m.a.s.l. Plains predominate in the basin, with the presence of plateaus, pediplains, and hills [40]. The upper reach of the Negro River flows over crystalline rocks of the Guiana Shield and sedimentary deposits of the Amazon basin. The medium and low course crosses terrains with Paleozoic rocks, restricted to narrower areas of the river. Cretaceous sedimentary rocks belonging to the Alter do Chão Formation, with small areas containing sedimentary rocks from the Solimões Formation, outcrop near the Anavilhanas Archipelago [41], whose substrate consists mainly of Holocene alluvium [11]. The soils in the region are poor in nutrients and covered by a dense equatorial forest [42,43], with an erosion rate ranging from 0 to 10 ton·km^2·year^{-1} [5].

This study was carried out on the 300 km reach of the lower Negro River located upstream, inside, and downstream of the Anavilhanas Archipelago. This Archipelago is located in the municipalities of Novo Airão and Manaus (state of Amazonas, Brazil) and has hundreds of islands, lakes, and small channels on the 120 km reach of the Negro River. As a refuge area for a great diversity of fauna and flora, the Anavilhanas is a National Park, a Ramsar Site [44], a UNESCO World Heritage Site, and a Biosphere Reserve.

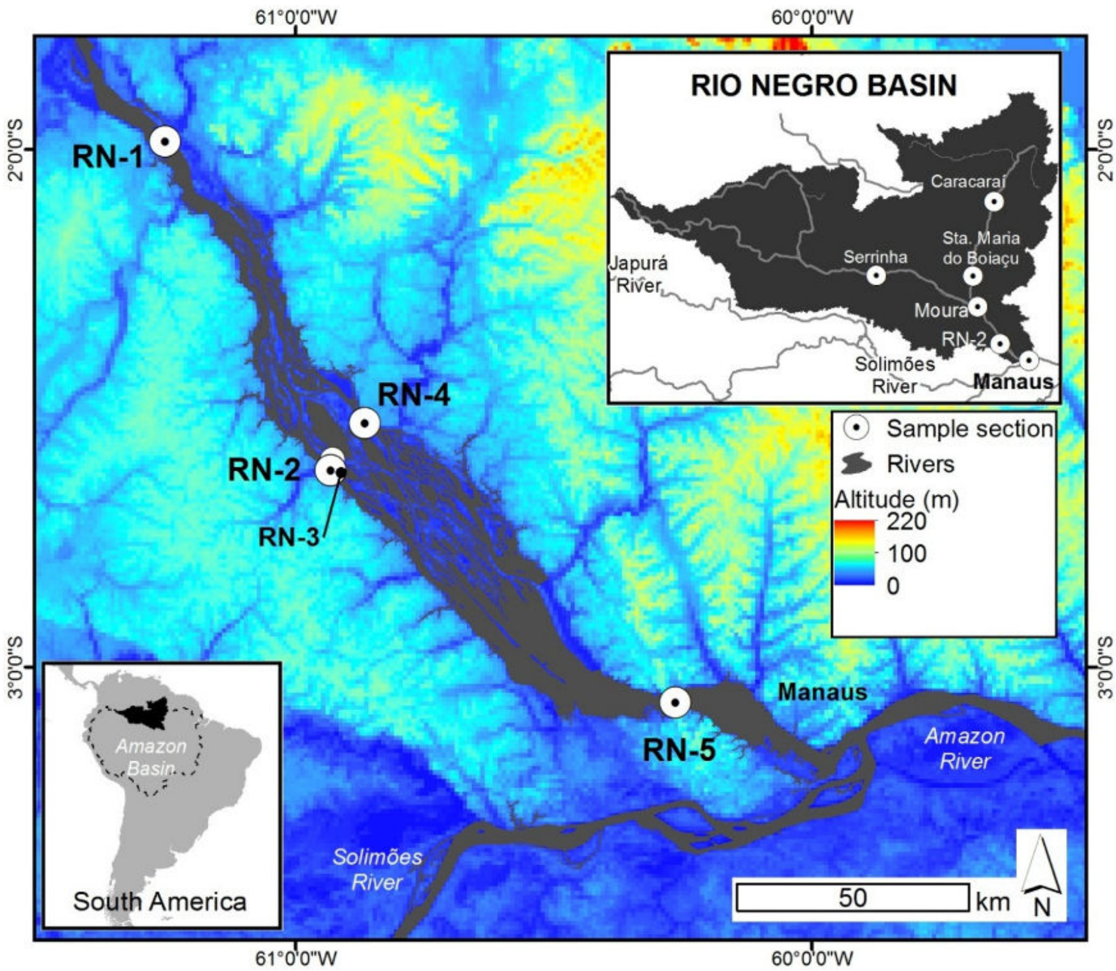


Figure 1. Location of the Negro River basin and sample sections in the Anavilhanas Archipelago (RN-1, RN-2, RN-3, RN-4 and RN-5).

Precipitation in the region has an annual mean of more than 2000 mm and exceeds 3500 mm in the northwestern portion of the basin, mainly from the North Tropical Atlantic and with intense recycling through forest evapotranspiration [45]. The water level of the Negro River in the Anavilhanas has annual variability of about 10 m, with over seven months of flooding, and the maximum and minimum levels occur in the period of June–July and October–November, respectively [46]. Black river water (i.e., based on Sioli classification [47], the main types of water in the Amazon rivers can be grouped into rivers with white, clear, or black water) is typical in the Negro River basin, with predominantly high acidity (pH near 4), low electrical conductivity (<20 µs), high concentration of dissolved organic carbon (>8 $mg \cdot L^{-1}$), and TSS less than 10 $mg \cdot L^{-1}$ [8]. Although it experiences high precipitation, the Negro River basin has a slow denudation rate, in the order of 0.04 $mm \cdot year^{-1}$ [34], due to the presence of the old lands of the Guiana Shield and weak tectonic activity.

2.2. Data Collection and Analysis

Data acquisition took place in five sample sections in the lower Negro River between 2016 and 2019 (Figure 1). The sections are located in the channels of the Negro River upstream (RN-1), inside (RN-2, RN-3, and RN-4), and downstream (RN-5) of the Anavilhanas Archipelago. In the interior of the Anavilhanas, the sections RN-2, RN-3, and RN-4 are located in the central region of the Archipelago. To establish a balance of the total suspended sediment discharge transported by the Negro River before and after the Anavilhanas, measurements of water discharge (Q), mean flow velocity (V), and water surface collections were performed to determine the concentration of total suspended solids (TSS), estimate particle size, and calculate total suspended sediment discharge.

The water discharge and mean flow velocity were obtained using an Acoustic Doppler Current Profiler (ADCP) operating at 600 kHz (Workhorse River Grande, Teledyne RDI), installed on a vessel and coupled with a GPS receiver (R4, Timble). For the water samples, a section area was used, composed of nine georeferenced points for water surface collection according to Filizola et al. [48]. Data on the level of the Negro River observed between 2016 and 2019, from the national hydrometeorological network [23] and altimetric data from the Sentinel-3A satellite available in the Hybroweb Project—THEIA/CNES [49], were used to analyze the variability in water height of the area studied.

The sampling and laboratory procedures for determining TSS followed the protocol of the SO-Hybam Observatory [33], which is based on the recommendations of the UNEP GEMS/Water Program [50] and Filizola and Guyot [6]. Water samples were filtered on cellulose acetate membranes (0.45 µm porosity), weighed beforehand on a precision scale. Then, the filters were dried in an oven at 105 °C for two hours and weighed again after cooling. The TSS was determined from the difference in the initial and final weights of the filters, divided by the volume of water in the sample. The size of the suspended particles was determined using the Malvern Mastersizer 2000 laser granulometer at the Mineral Analysis Laboratory (LAMIN) of the Brazilian Geological Service (CPRM—Manaus).

To assess the variation of TSS in the Negro River as a function of depth, a point sampler (5 L of capacity tied to a 50 kg ballast) was used in sections RN-1 and RN-5 (upstream and downstream of the Anavilhanas). In these sections, nine samples were collected at three points along the Negro River cross section and at three depths (Figure 2). Before filtration, all samples passed through a 63 µm diameter sieve.

Equation (1) was used to obtain the total suspended sediment discharge (Qs) in each sample section:

$$Qs = c \times Q \times TSS \tag{1}$$

where Q is the water discharge ($m^3 \cdot s^{-1}$), TSS is the mean concentration of total suspended solids ($mg \cdot L^{-1}$), and c is the conversion factor 0.0864 used to obtain values in metric tons per day ($ton \cdot day^{-1}$) [5].

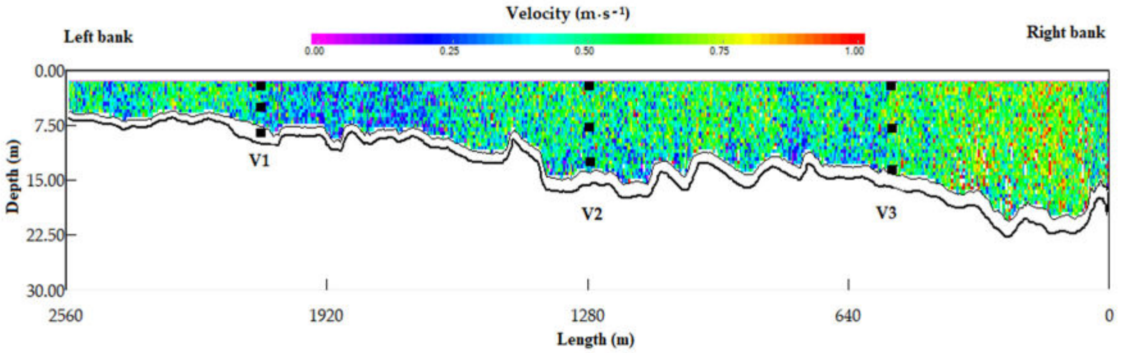
The Negro River sediment transport capacity was assessed using the specific stream power (ω), defined as:

$$\omega = \Omega / w \tag{2}$$

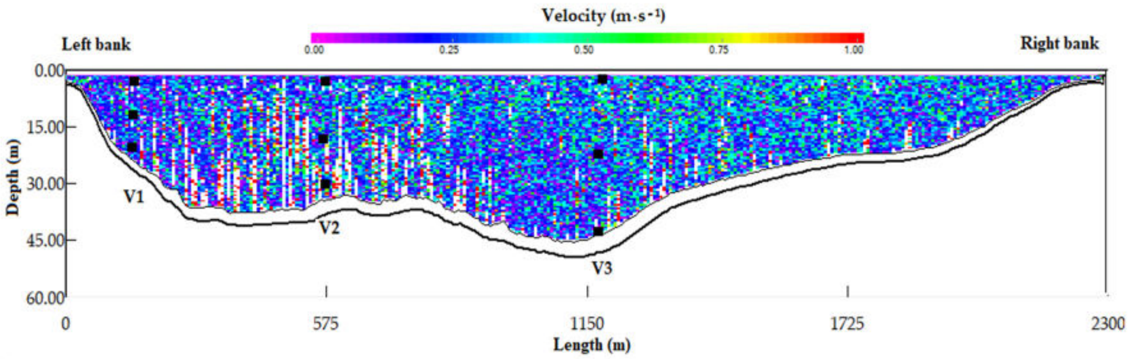
where w is the channel width and Ω is the stream power obtained through Equation (3):

$$\Omega = \gamma \times Q \times s \tag{3}$$

where γ is the specific weight of water, Q is the water discharge, and s is the slope of water surface.



(a)



(b)

Figure 2. Distribution of flow velocity in sections RN-1 (**a**) and RN-5 (**b**) Black dots indicate the location of samples collected at different depths.

Rainfall monthly data (P) was estimated from the satellite-based precipitation product CHIRPS.v2 with 0.05 spatial resolution. Pearson correlation coefficients (r) were calculated with the statistical software PAST (v. 3.20) in order to evaluate the possible relationships between the variables covered in this study (TSS, Q, V, H, and P). An image from the Landsat 8 satellite (OLI Sensor), acquired in 2017 during the high-water period, was analyzed to help interpret the spatial variability of suspended solids in the Anavilhanas.

3. Results

3.1. Water Level Variability in the Negro and Branco Rivers

Records of water levels data indicate that the flood peak of the Negro River occur near the middle of the year (Figure 3a), extending from May to July at Moura and Novo Airão stations (section RN-2), and are a little more in Manaus (May to early August). The influence of the backwater effect from the Solimões River extends for more than 300 km, reaching the Moura station, close to the confluence of the Negro and Branco rivers, indicated by the almost linear relations in Figure 3b. The lower Branco River exhibits a different behavior from the Negro River, with a high period from June to August, but with a well-marked maximum in July. The water levels of the Negro River indicate a low water period in November, while in the lower Branco River the minimum levels occur in February–March.

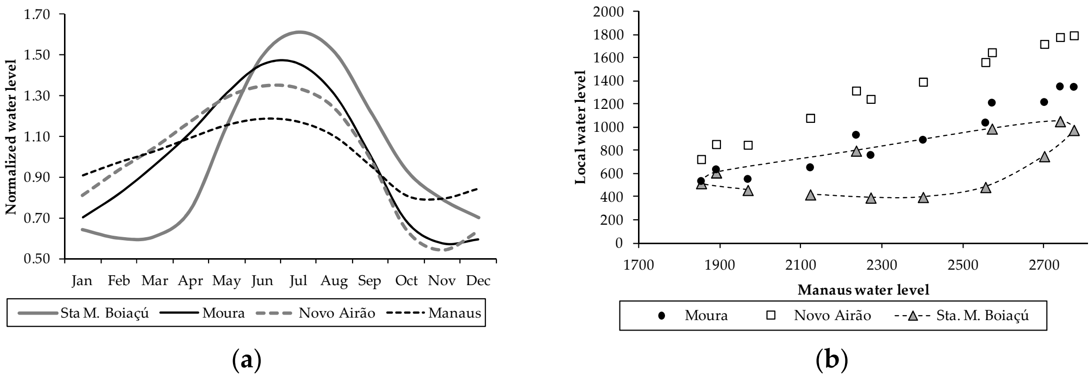


Figure 3. (**a**) Mean monthly water level normalized in relation to the annual mean. (**b**) Mean monthly water level at Manaus station (RN-5) versus mean monthly water level at Novo Airão (RN-2) and Moura stations both on the Negro River and Santa Maria do Boiaçu station on the Branco River. The location of the stations can be seen in Figure 1.

The water level data from conventional fluviometric stations do not allow a detailed analysis of the influence of the backwater from the Solimões River in the Anavilhanas, because Novo Airão is the only fluviometric station on the right bank of the channel in the Anavilhanas (section RN-2 in Figure 1). On the other hand, water level data derived from altimetry satellites can provide insight into this complex fluvial system. Figure 4 shows the longitudinal profile of the Negro River from altimetric measurements of the Sentinel-3A satellite between 2016 and 2019 in the regions upstream, inside, and downstream of the Anavilhanas.

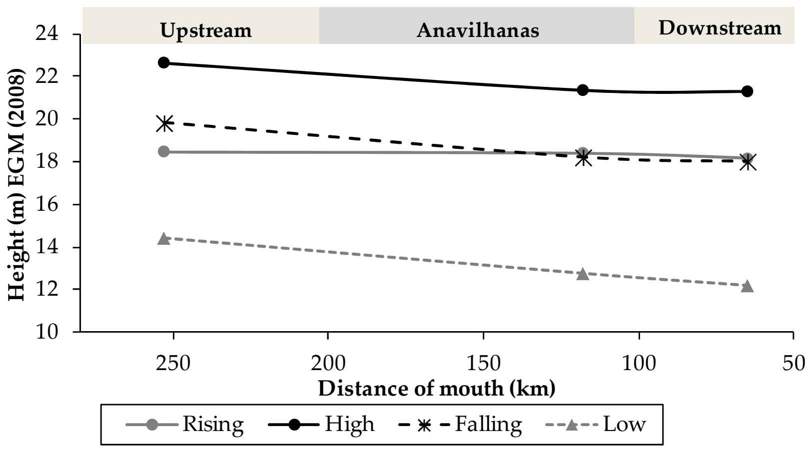


Figure 4. Mean seasonal variation in the elevation of the Negro River water surface upstream, inside, and downstream of the Anavilhanas.

Water level data from radar altimetry indicate that between 2016 and 2019 the mean annual amplitude was around 11 m in the region upstream of the Anavilhanas and 12 m inside of the Archipelago and downstream. These values are similar to those observed by the conventional fluviometric stations. Upstream of the Anavilhanas, the Negro River is above the mean annual level for about six months (between March and August). Inside and downstream Anavilhanas, the river remains above the annual mean level for seven months (February to August). The mean annual height difference of the water surface in the reach before, after and inside Anavilhanas was around 1.54 m, varying from 0.33 m to 2.23 m between rising and low seasons, respectively. The annual mean slope of the water surface was about 0.82 cm·km^{-1}. Values ranging from 0.18 cm·km^{-1} (rising water) until 1.19 cm·km^{-1} (low water).

3.2. The Water Discharge and the Flow Velocity from the Negro River

Table 1 presents the values of water discharge and mean flow velocity in the different sections of the Negro River upstream, inside, and downstream of the Anavilhanas. The water discharge ranged from 14,484 $m^3 \cdot s^{-1}$ to 48,248 $m^3 \cdot s^{-1}$ upstream, and from 13,155 $m^3 \cdot s^{-1}$ to 63,356 $m^3 \cdot s^{-1}$ downstream the Archipelago. The mean water discharge upstream (RN-1), inside (RN-2 + RN-3 + RN-4), and downstream the Archipelago (RN-5) was 28,655 $m^3 \cdot s^{-1}$, 29,589 $m^3 \cdot s^{-1}$, and 34,450 $m^3 \cdot s^{-1}$, respectively. In the region inside of the Anavilhanas, the mean water flow was 3% higher than that observed upstream, since the difference between the interior and downstream regions was +14%.

Table 1. Water discharge and mean flow velocity in the Negro River and Anavilhanas Archipelago.

Field Cruise	Date	Station				
		RN-1	**RN-2**	**RN-3**	**RN-4**	**RN-5**
		Water discharge ($m^3 \cdot s^{-1}$)				
I	16 November	17,676	8177	641	9234	*
II	17 January	30,960	14,692	2110	16,091	*
III	17 March	26,125	13,106	2070	12,924	29,328
IV	17 May	40,626	19,104	2936	19,019	49,529
V	17 July	48,248	22,797	3807	21,976	60,524
VI	17 October	20,425	9767	772	10,685	22,405
VII	17 November	18,253	8847	816	9488	18,863
VIII	18 November	14,484	6644	647	7432	13,155
IX	19 May	24,345	12,181	1985	11,622	31,380
X	19 July	47,376	23,639	3443	24,946	63,356
XI	19 September	35,472	15,733	2089	16,158	41,256
XII	19 November	23,801	10,344	999	12,458	24,238
XIII	19 December	24,717	11,313	1357	12,617	24,918
		Mean flow velocity ($m \cdot s^{-1}$)				
I	16 November	0.55	0.52	0.28	0.48	*
II	17 January	0.70	0.59	0.45	0.62	*
III	17 March	0.51	0.48	0.36	0.48	0.33
IV	17 May	0.70	*	*	*	*
V	17 July	0.87	0.76	0.58	0.78	0.63
VI	17 October	0.66	0.61	0.35	0.57	0.31
VII	17 November	0.57	0.46	0.30	0.49	0.27
VIII	18 November	0.47	0.38	0.24	0.40	0.20
IX	19 May	0.35	0.42	0.32	0.40	0.34
X	19 July	0.84	0.78	0.54	0.74	0.69
XI	19 September	0.77	0.69	0.49	0.70	0.69
XII	19 November	*	0.55	0.34	0.57	0.51
XIII	19 December	0.57	0.55	0.38	0.54	0.33

* Data not available.

Within the Archipelago, the water flows mainly through two channels located on the right bank (section RN-2) and the left bank (section RN-4), with a mean of 47% and 50%, respectively, of the water flow observed upstream (section RN-1). During falling, low, and rising water level periods, the left bank channel had a water discharge of 3% to 12% higher than that on the right bank. During the flooding peak, the water discharge in the RN-2 and RN-4 sections were almost the same, because during this period, the water flow from the Negro River exceeds the limit of its banks and inundates all channels and lakes in the Anavilhanas.

The mean velocity of the water flow observed in the channels within the central region of the Anavilhanas was around 0.50 $m \cdot s^{-1}$, with differences of less than 10% in the hydrological periods analyzed. There was a direct relationship between the water discharge and velocity in sections RN-1, RN-2, and RN-4. Upstream of the Anavilhanas, the mean velocity ranged from 0.35 $m \cdot s^{-1}$ to 0.87 $m \cdot s^{-1}$, while downstream of the Archipelago, it was between 0.20 m·s^{-1} and 0.69 m·s^{-1}, with the maximum and minimum observed in July, 2017 (RN-1) and November, 2018 (RN-5), respectively (Table 1).

The reduction in the mean velocity between the sections located upstream (RN-1) and within the Anavilhanas (RN-2 and RN-4) was 10%, while the mean velocity before (RN-1) and after (RN-5) the Anavilhanas reduced by 32%. Despite the high volume of water and low flow velocity, the Negro River in the Anavilhanas Archipelago does not have much stream power for the fluvial work of erosion and suspended solids transport (Table 2).

Table 2. Steam power, mean width, and specific stream power of the analyzed sections.

Station	Stream Power (W·m^{-1})	Width (m)	Specific Stream Power (W·m^2)
RN-1	3600	2662	1.35
RN-2	1704	1267	1.34
RN-3	229	431	0.53
RN-4	1784	1138	1.57
RN-5	4328	2452	1.76

3.3. *Temporal and Spatial Variability of Suspended Sediment Concentration in the Lower Negro River*

The mean TSS concentration was 3.02 mg·L^{-1} (±5%), ranging from 0.36 mg·L^{-1} to 10.47 mg·L^{-1}. During the period of high and low water, the mean values were 2.29 mg·L^{-1} (±9%) and 3.22 mg·L^{-1} (±5%), respectively. Table 3 shows the mean TSS concentration obtained in each sample section.

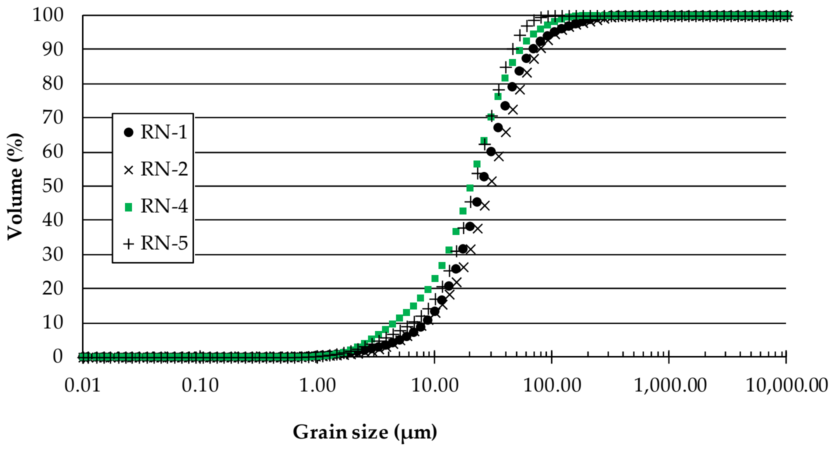
Table 3. Concentration of total suspended solids (mg·L^{-1}) analyzed in 2016–2019.

Field Cruise	Date	Station			
		RN-1	RN-2	RN-4	RN-5
I	16 November	4.19	3.77	4.61	*
II	17 January	3.31	1.60	3.67	*
III	17 March	0.92	0.36	0.54	0.48
IV	17 May	3.82	3.13	3.15	1.15
V	17 July	6.35	0.56	6.60	0.79
VI	17 October	0.44	1.28	4.46	1.93
VII	17 November	2.37	4.78	2.18	1.86
VIII	18 November	4.82	6.15	10.47	2.88
IX	19 May	1.42	1.23	1.67	1.19
X	19 July	2.71	1.05	3.13	1.43
XI	19 September	4.32	2.40	6.05	1.36
XII	19 November	3.72	2.59	6.18	3.24
XIII	19 December	4.25	1.49	5.80	*

* Data not available.

The mean TSS concentration upstream (section RN-1), inside (RN-2 and RN-4), and downstream (RN-5) was 3.29 mg·L^{-1}, 3.09 mg·L^{-1}, and 1.47 mg·L^{-1}, respectively. The left (RN-2) and right (RN-4) channels presented mean concentrations of 3.97 mg·L^{-1} and 2.21 mg·L^{-1}, respectively. Upstream of the Anavilhanas (RN-1), the mean TSS concentration ranged from 0.44 mg·L^{-1} to 6.35 mg·L^{-1}, while downstream of the Archipelago (RN-5), the amplitude was lower (0.48 mg·L^{-1} to 3.24 mg·L^{-1}). The greatest amplitude (0.54 mg·L^{-1} to 10.47 mg·L^{-1}) was observed in the RN-4 section with minimum and maximum TSS obtained in field cruise III and VIII, respectively, during the rising and low water periods of the Negro River. Except in the data collected during cruise VI, the TSS concentration reduced in the Negro River between the RN-1 and RN-5 sections in the different hydrological periods (Table 3).

The particle size of suspended solids in the Negro River indicates a predominance of fine particles (90% less than 80 μm) and D50 ranging from 19 to 29 μm, whereas in the Branco River, 90% of suspended particles observed were less than 60 μm (Figure 5).



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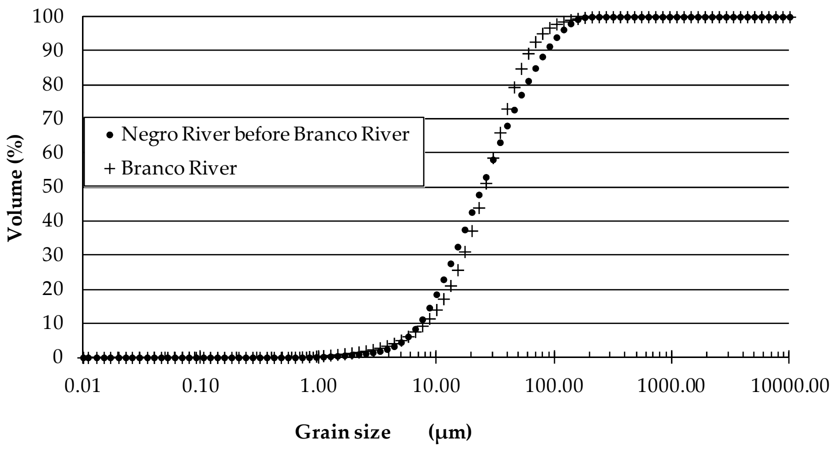
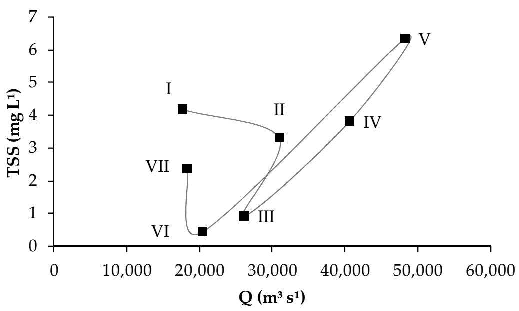


(**b**)

Figure 5. Particles suspended size in the Negro River in the Anavilhanas (**a**) and region of confluence with the Branco River (**b**).

In the Negro River, it was not possible to detect a specific behavior in the TSS and water discharge relationship (TSS = aQ^b), probably due to the large volume of water drained, the type of particles, and the extremely low concentration of TSS. Thus, a clear trend could not be obtained to analyze the TSS = f(Q) in this region (Figure 6).



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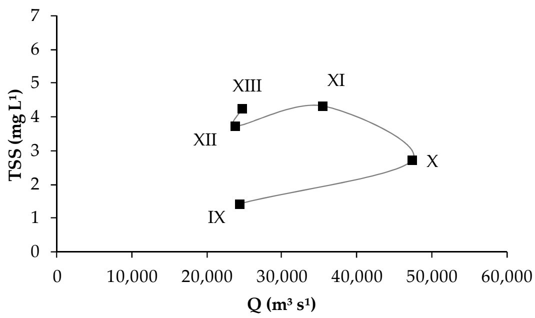


(**b**)

Figure 6. Data of suspended solids concentration versus water discharge in the Negro River in the RN-1 section in 2017 (**a**) and 2019 (**b**). Indexes I to XIII indicate the field cruise number.

In order to evaluate the relationships between TSS, hydrological and climatic variables correlations were determined. As expected, water discharge was found to correlate positively with flow velocity and altimetric water level in all sections. We observed that TSS was significantly correlated with altimetric water level in the sections RN-2 (r = −0.58, $p < 0.05$) and RN-5 (r = −0.62, $p < 0.05$; Supplementary Figure S1). During the high water levels period (Supplementary Figure S2) the TSS was significantly correlated with altimetric water level in the section RN-5 (r = 0.99, $p < 0.05$), while during the low water levels period (Supplementary Figure S3), the TSS was significantly correlated with flow velocity in the section RN-2 (r = −0.83, $p < 0.05$).

3.4. Variation of Suspended Sediment with Depth and in the Water Surface

TSS concentration varies in the Negro River at different depths (V1, V2, V3) mainly in the section RN-5 (Figure 7). On the surface, the TSS concentrations were 4.82 mg·L^{-1} in the RN-1 section and 2.88 mg·L^{-1} in the RN-5 section. When considering all depths, the mean TSS concentrations were 4.11 mg·L^{-1} and 2.07 mg·L^{-1}, in sections RN-1 and RN-5, respectively, indicating a slight reduction in the suspended load as a function of depth. The variability of TSS concentration at RN-1 varied less in vertical 1 due to the influence of the Branco River, which flows into the left bank of the Negro River. Near the mouth (section RN-5), greater concentrations occurred on the surface. In both sections, no particles larger than 63 µm (grains of sand) were observed in both the depth and surface samples.

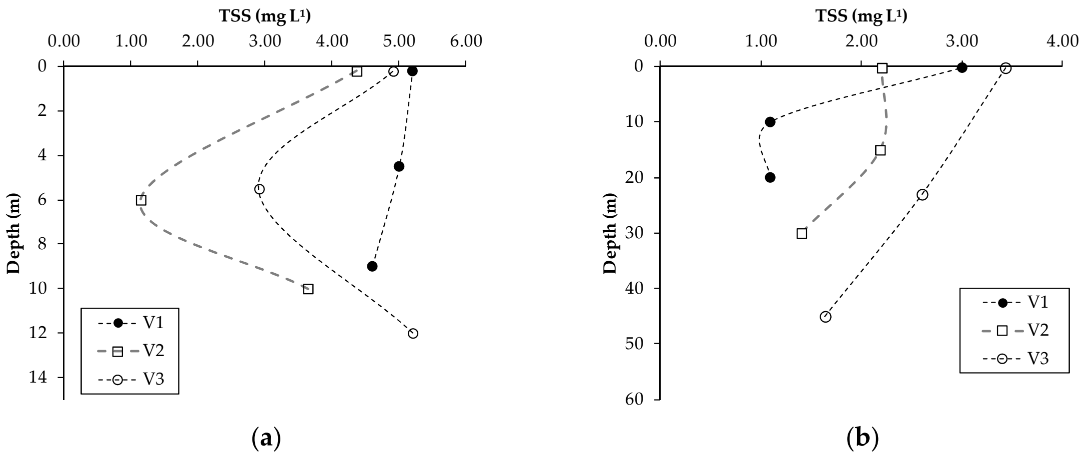
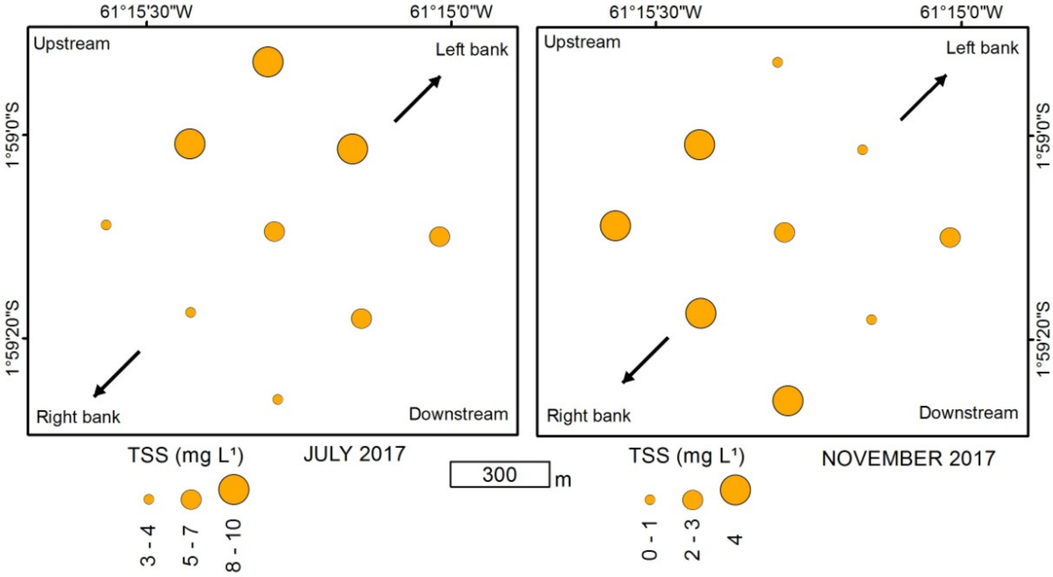


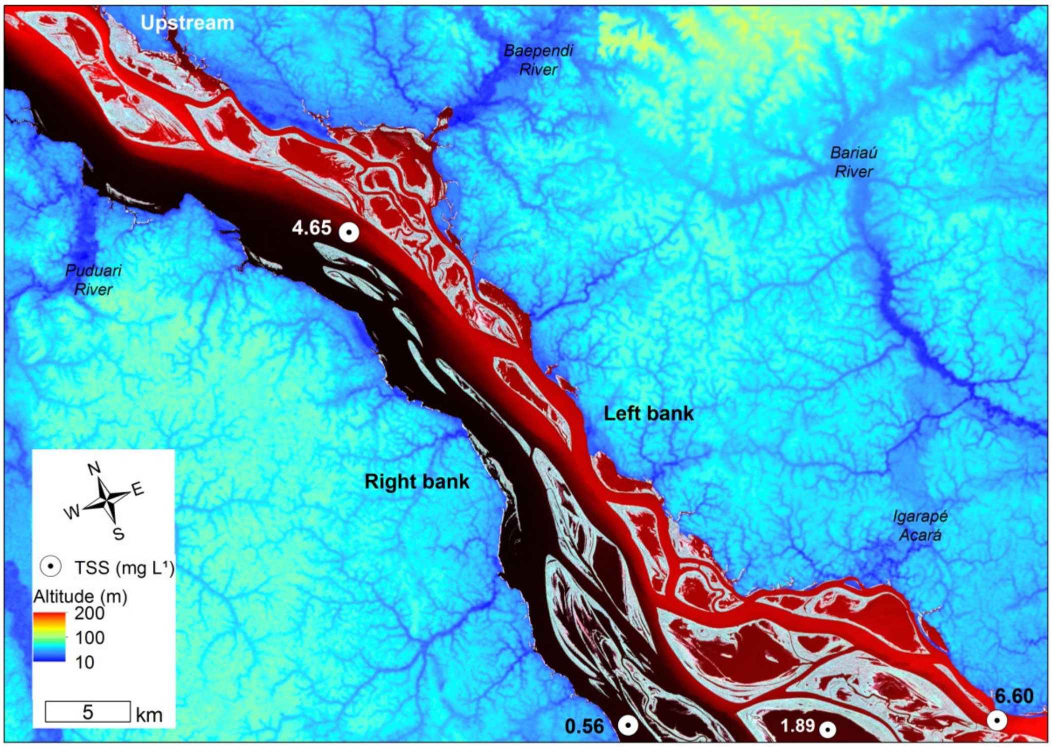
Figure 7. Variability of total suspended solids (TSS) concentration as a function of the depth in the Negro River upstream (**a**) and downstream (**b**) from the Anavilhanas.

The Negro River upstream of the Anavilhanas (Section RN-1) has an average width of 2600 m, and during the period of high water levels, the spatial variability of the TSS on the surface (Figure 8a) became more evident, causing a heterogeneous distribution of the sediment, with higher values close to the left bank in this section. During the low water period, the suspended load from the Branco River was reduced, which caused greater TSS concentration near the right bank of the Negro River channel.

The spatial variation of the suspended sediment in the surface water can also be detected in multispectral images from satellites. Figure 8b corresponds to a 70 km reach of the Anavilhanas Archipelago and illustrates the distribution of the suspended sediment plume close to the left bank of the Negro River at Anavilhanas. The black color in Figure 8b corresponds to the channel on the right bank and the red area indicates the region that receives the greatest amount of suspended sediment from the Branco River.



(a)



(b)

Figure 8. (**a**) Variation of TSS concentration during July 2017 and November 2017 in the sampled section area located upstream of the Anavilhanas. (**b**) Landsat-8 image (composition R-4; G-5; B-6) of the Negro River on 30 July 2017 superimposed on a DEM-SRTM. Red-colored water bodies illustrate greater TSS concentration than black.

The data presented in Table 3 and in Figure 8b indicate spatial variation in the transport of suspended solids by the Negro River from upstream to downstream, and between the channels on the left bank, the central region, and the right bank. The spatial and temporal variability of the load suspended in the channels of the Archipelago indicates more TSS in the RN-4 section.

3.5. Balance of the Suspended Discharge in the Lower Negro River

Table 4 presents estimates of the total suspended sediment discharge (Qs) based on the samplings performed. The Negro River upstream of the Anavilhanas exhibits Qs in the order of 3.14 Mt·year^{-1} (section RN-1). The RN-4 section is located on a channel near the left bank 73 km downstream of RN-1 and had a 38% reduction in the total suspended sediment discharge. In the section of the right bank channel (RN-2) 74 km downstream from RN-1, the difference is −73%. The balance the water flow indicated an increase of 20% (Table 1) and the total suspended sediment discharge reduced by 55% before and after the Archipelago, indicating a mean stored volume of around 1.71 Mt·year^{-1}.

Table 4. Mean of total suspended sediment discharge (Qs), mean error (ε), and observed variation from upstream to downstream (Δ).

Section	Mean Qs (Ton·Day^{-1})	Qs Year (Ton·Year^{-1})	ε (%)	Δ (%)
RN-1	8600	3.14×10^6	±22	
RN-2	2316	0.85×10^6	±16	−38
RN-4	5351	1.95×10^6	±16	−73
RN-5	3908	1.43×10^6	±17	−55

In the central region, the Negro River channel flowing over the left bank of the Anavilhanas Archipelago (section RN-4) exhibited a mean Qs 230% higher than that observed on the right channel (section RN-2). During the 2017 high period (cruise V), the difference in Qs in the RN2 and RN-4 sections was over 1000%.

4. Discussion

The results here described indicate that the Negro River upstream and downstream of the Anavilhanas Archipelago has a behavior that causes the storage of water and suspended solids in the transition periods between high and low water levels. This mainly occurs in the period of rapid water level reduction in the Negro River between the months of August and September, a period of greater contribution of Q and Qs from the Branco River. In addition, the different behavior of the lower Branco River in relation to the Negro River, with high peak of the first between June to August and of the second in June and July, suggests a greater Qs to Anavilhanas at the beginning of the second semester, especially as it is also the season of increased water discharge [6,51].

Relationships analysis between TSS, hydrological, and climate conditions indicated few significantly correlations ($p < 0.05$; Supplementary Figure S4), reflecting a complex dynamic of the suspended sediments in the lower course of the Negro River. However, it is emphasized that an important controlling factor in the transport of suspended solids is the 32% of reduction in the mean velocity of the Negro River from upstream to downstream, which greater deposition of the finer particles due to the extremely slow water flow.

Despite the high volume of water, the Negro River in the Anavilhanas has low power available for fluvial work such as erosion and transport of suspended solids ($\omega < 1.80$ W·m^2). The Negro River at the mouth (section RN-5) has a very low specific stream power compared to other large rivers, such as the Madeira River (23 W·m^2) and the Orinoco River (19 W·m^2) [2]. The low specific stream power of the Anavilhanas channels occurs due to the very low velocity values (Table 1) and the slope of the water surface (Figure 4), as well as the backwater effect from the Solimões River [36]. The low-energy available, together with the fine and cohesive material of the islands and their dense vegetation, contributes to the high stability of the channel banks and a minimal erosion process in the Anavilhanas [2,11,20,41,46].

Concerning TSS, the data in this study indicate a subtle difference between periods of low and high water levels, with less concentration during the high water levels and more during the low water levels period in the Anavilhanas. This seasonal variability can be viewed as a consequence of the suspended load dilution by the larger volume of water available during high waters period, a process similar to that observed on the Amazon River floodplain [52,53] and at the confluence between the Negro and Solimões rivers [54]. The mean TSS concentration of the Negro River obtained in this study was in mean 50% lower than the values of Meade et al. [32], Filizola [55], Moreira-Turcq et al. [8], and Fassoni-Andrade et al. [56]; however, this difference may reflect the sampling methodologies and the period analyzed of those studies.

The reduction of TSS by around 50% of the amount downstream of the Anavilhanas indicates material retention in the Archipelago as observed by Franzinelli and Igreja [41] and quantified in this study. Within the Anavilhanas, the Qs value was greater in the channel on the left bank (section RN-4), this local dynamic influences the types of soils and vegetation of this section of the Archipelago [39,57].

The suspended sediments of the Negro River are composed of minerals such as kaolinite, quartz, gypsum, and traces of mica/illite, with a concentration 30 times less than the Solimões River [58]. As highlighted by Filizola [55] and confirmed in this work, the Negro River has little variation in the transport of suspended material depending on the depth and throughout the hydrological year. Analysis of the flow of velocities, water discharge, and suspended sediment as a function of the depth was performed by Filizola [55] in the Rio Negro downstream of the Anavilhanas. That author indicated that the suspended sediment discharge on the surface corresponds to 81% of the total suspended sediment discharge. The results here presented also indicated that the low variation of TSS as a function of depth can be related to the predominance of fine suspended particles (Figure 5) and the low variation in the vertical distribution of the velocity flow in the analyzed sections (Figure 2), differently in relation to rivers of Andean origin, such as the Madeira and Solimões rivers [22].

The mean annual total solid discharge of 1.43 Mt·year^{-1} obtained in the RN-5 section corresponds to 21% of the value estimated by Filizola and Guyot [5] for the Negro River basin and less than 1% when compared to the Amazon River at Óbidos station, which evidence the almost zero contribution of the sediments from the Guiana Shield to the Amazon River.

4.1. Modern Hydrological Dynamics Versus the Formation of the Anavilhanas

The sediment budget estimated in this study quantified the input, transport, and output processes of the total suspended sediment discharge in the Anavilhanas Archipelago. Data collected in different hydrological periods indicate that only part of the total suspended sediment discharge observed before the Anavilhanas reaches the mouth of the Negro River. This hydro-sedimentary process predominantly retains suspended sediment in this anabranching reach of the Negro River, an area under strong influence of the backwater effect from the Solimões River.

The formation of fluvial archipelagos in the Negro River is intended to be the result of a set of factors such as the low energy of this river, the large amount of fine sediments available, the tectonically controlled valley, and the change in the base level during the transition from the upper Pleistocene to the Holocene, with climate changes that profoundly affected the sediment transport in this period [11,41].

As described by Latrubesse and Stevaux [9], the debate about the origin of the Anavilhanas islands started in the 1970s with Tricart [59], who modeled the formation of the Archipelago from a delta model in the Negro River, as a result of the ascent sea level in the middle Holocene, after the Last Glacial Maximum (LGM). Subsequently, Leenher and Santos [60] indicated the occurrence of flocculation of suspended sediments in the Branco River by the waters of the Negro River, and that this process created deposits on the islands of the Archipelago. In a complementary way, Sioli [61] pointed out that the islands were formed as a consequence of the sediments transported by the Branco River. However, some of these ideas are not confirmed, especially the one about the Branco River contributions, since the Mariuá Archipelago, located above the mouth of the Branco River, has features and geomorphological forms similar to the Anavilhanas, but does not have a current source of sediments, such as the Branco River [9,11].

Some problems in the interpretations of Tricart [59] and Sioli [61] were highlighted by Latrubesse and Franzinelli [11], who claimed that the Anavilhanas islands would have formed between 3700 and

1000 years BP (before present), much more recent than the LGM (~20,000 years BP). These authors pointed out that the Branco is a sandy river, with insufficient suspended load to produce large scale deposition, as observed in the Anavilhanas. As for the formation of the Branco River valley, Cremon et al. [62] estimated the sedimentary filling in this region with a minimum age starting at 18,700 years BP, since this river would have drained towards the Caribbean Sea in the geological past, and with sandy and muddy alluvial deposits.

For the formation of the Anavilhanas Archipelago, a low-energy environment was essential, a significant amount of sediments, mainly clay and silt, as well as a space of linear accommodation in the valley [41], because the substrate for the islands in the Anavilhanas has predominately fine and cohesive sediments (clay and silt) with the presence of very fine and fine sand [63]. Latrubesse and Franzinelli [11] pointed out that in addition to these three components, an increasing base level of the Negro River may have contributed to the development of the islands in the Archipelago. These authors state that during the transition from the Late Pleistocene to the Holocene these conditions were reached, but did not achieve equilibrium, and the floodplains on the lower Negro River today remain unfilled with sediments. Therefore, a tectonically controlled valley together with an increase in the base level are the processes considered to have created the Mariuá and Anavilhanas archipelagos on the Negro River [11,41].

The backwater effect on the Negro River caused by the Solimões River is considered to be one of the key factors for the formation of the Anavilhanas Archipelago [11,20]. This effect is now corroborated by the data presented in this work, namely by the 32% reduction in the mean flow velocity from upstream to downstream (Table 1) and the reduction in the water slope near the mouth of the Negro River (Figure 4). Thus, the decrease in the velocity of the water flow due to the backwater effect from the Solimões River favors in the Archipelago of 55% retention of the sediment discharge transported by the Negro River (Table 3). The migration from the Intertropical Convergence Zone (ITCZ) during the Late Quaternary could have had a major impact on the backwater effect on the Negro River, as it may have affected the liquid discharge of the Solimões River [64]. This backwater effect occurs on a seasonal basis, which causes sedimentation during periods of greater influence of the Solimões River on the Negro River.

Sediment dating from Lake Acarabixi, located on the Negro River floodplain upstream from the Mariuá Archipelago based on radiocarbon dating, indicate that Negro River had more energy and strong seasonality around 10,840 years cal BP [65]. Additionally, that after 8240 years cal BP, a change lowered the energy and reduced the river dynamics. The sedimentation rate of that lake indicates values ranging from 0.09 to 0.47 mm·year^{-1} [66]. Cunha [64], based on OSL dating of quartz grains and sedimentological analysis, interpreted that a greater formation of the islands in the Anavilhanas Archipelago began 7000 years ago. Additionally, according to the same study, the deposition of the islands did not occur continuously, with the greatest deposition periods during the Late Holocene. Finally, Barbosa [63] estimated a sedimentation rate in the order of 3.1 mm·year^{-1} for the substrate of the islands and identified sedimentary gaps in the Late Holocene, with the presence of paleosols in the Anavilhanas islands.

The sediment discharge presented in this work indicates that the volume stored in the Archipelago is around 1.71 Mt·year^{-1} (Table 4). Considering a density of the suspended particles of 2.7 g·cm^{-3} [34], an area of 2050 km^2 of the sedimentary basin in the Anavilhanas [11] and uniformly deposition processes, a current sediment accumulation rate of 0.31 mm·year^{-1} can be estimated, a rate close to the values found by Costa [67] and Silva [68] in lakes in the Negro River floodplain and inside the Anavilhanas, respectively, but lower than the rates estimated by Barbosa [63] and Cunha [64] for the Anavilhanas islands (Table 5).

Table 5. Sedimentation rates in different floodplain units of the Negro River.

Author	Rate (mm·Year^{-1})	Age	Location
Costa [67]	0.09–0.47	<8 ky	Acarabixi Lake
Cordeiro et al. [66]	2.3–19.5	<11 ky	Acarabixi Lake
Barbosa [63]	1.3–5.5	<2.5 ky	Anavilhanas Islands
Cunha [64]	0.10–7.85	<7 ky	Anavilhanas Islands
Silva [68]	0.3–0.7	<2 ky	Anavilhanas Lake
This work	0.31	Present	Anavilhanas

Based on OSL dating, Soares et al. [69] suggested that the onset of sedimentation on the riverbank terraces on the right bank of the Negro River (downstream from the Anavilhanas) occurred around 44,000 years BP. Additionally, based on OSL dates, Sant'Anna et al. [70] affirmed that the bars deposited near the right bank of the Anavilhanas is less than 1000 years, an age that does not agree with the actual hydro-sedimentary dynamics of the Negro River presented in this work. On the other hand, biogeographic studies of the local avifauna indicate that island specialized species in the Negro River basin have been present since the transition from the Middle Pleistocene to the Holocene [18], which would make the presence of the island fluvial environments in the region older than the proposed age of origin of the Anavilhanas Archipelago.

Considering that the formation of islands in anabranching rivers occurs slowly [71], taking into account the actual functioning of the system and the value of 0.31 mm·year^{-1} as a minimum sedimentation rate of the Negro River in a condition of hydro-sedimentary stability in the Late Quaternary, it would have taken approximately 60,000 years to form islands with a substrate of approximately 20 m elevation in the Anavilhanas, older than those suggested by Latrubesse and Franzinelli [11], Barbosa [63], Cunha [64], and Sant'Anna et al. [70].

However, the Negro and Branco rivers were not in a stable condition for sedimentary processes in the Late Quaternary [11,62,65]. Considering that the current conditions of the Negro River were established in the last 1000 years [11,65], the sedimentation rate estimated in this study indicates a deposition of approximately 30 cm of pelitic deposits in the Anavilhanas region. These results reinforce the idea that the Anavilhanas, which have little erosion process, still has areas with active deposition and an environment that continues to slowly form. However, these dynamics are different from the idea of geomorphological heritage proposed by Latrubesse and Stevaux [9].

4.2. Impacts of the Branco River Hydropower Dams on the Fluvial Environment of the Anavilhanas

Mean flow velocity data in the lower Negro River indicate a very slow flow of water due to the backwater effect from the Solimões River on the Negro River, as well as the low water slope and the large number of the Anavilhanas islands. These factors favor the retention and deposition of sediment transported in suspension, especially sediments from the Branco River.

The input of suspended sediments from the Branco River is responsible for the greater fertility of the soil observed along the left bank of the Negro River until the Anavilhanas Archipelago [39,57]. This contribution of suspended sediments could be modified if the Bem Querer hydropower dam is built on the Branco River [37], since a large part of the suspended sediments observed at the Caracaraí hydrosedimentometric station (located downstream from the proposed reservoir area) come from areas drained by the Tacutu and Uraricoera rivers [35], belonging to the Boa Vista and Tacutu sedimentary formation [62,72].

The rivers in the Negro River basin are characterized by a low suspended sediment load [5,6,51], little erosion process [20], channels with a very low migration rate, and moderate annual water level variability [27]. Although this basin has the lowest hydropower dams density in operation in the Amazon, construction projects for at least seven plant are planned [29], with four in the Branco River basin alone [37].

The Bem Querer dam is considered the largest hydroelectric plant that will be built in the Branco River basin. The estimated power is about 650 MW and it has a flooded area of more than 500 km^2 [37]. This hydropower dam seems to have the same potential magnitude for environmental impact on this flooded area as the Belo Monte dam on the Xingu River [73]. As observed in recent research in the Amazon basin [27–29,74], the reduction of sediment input and the regulation of the hydrological system by construction of hydropower dams significantly impacts human populations and the flooded ecosystems located hundreds of kilometers downstream from the reservoir.

The flooded forest and fauna of the Negro River basin are vulnerable to changes in the hydrological system, whether of climatic origin (El Niño/La Niña) or due to the construction of a hydropower dams [38,39]. The regulation of water flows and sediment discharge on the Branco River by the Bem Querer dam and other tributaries in the basin will reduce the amount of sediments that arrive in the Anavilhanas as it was previewed for other areas in the Amazon basin [27,28]. Thus, the floodplains on the lower Negro River will not be maintained and its rich biodiversity may be profoundly altered.

Currently, the four hydroelectric plants planned for the Branco River, together with the easing of environmental licensing and weakening of regulatory agencies are the main threats in the Negro River basin [38,75,76], especially on the Anavilhanas Archipelago. Currently, studies to evaluate the impacts of dams in the Brazilian Amazon mainly consider the area directly affected. However, it is important that discussions include the direct and indirect impacts of the Branco River reservoir on the hydrological and sedimentary system of the lower Negro River.

5. Conclusions

This article investigated the distribution of water and total suspended sediment discharge in different sections of the Negro River in the fluvial complex of the Anavilhanas. The mean concentration of total suspended solids was 3.02 $mg \cdot L^{-1}$, higher in the low-water period (3.22 $mg \cdot L^{-1}$) and lower in the high-water period (2.29 $mg \cdot L^{-1}$). Within the Archipelago, the two main channels of the Negro River did not exhibit differences in water discharge and mean flow velocity; however, the difference in the sediment discharge was in the order of 60%. Despite the large volume of water (≈28,000 $m^3 \cdot s^{-1}$), the Negro River is a low-energy environment ($\omega < 1.80$ $W \cdot m^2$) due to the influence of the backwater effect from the Solimões River, slow velocity (≈0.50 $m \cdot s^{-1}$), and low slope of the water surface (≈0.80 $cm \cdot km^{-1}$).

The Guiana Shield in the area drained by the Negro River was estimated to contribute less than 1% of the total suspended sediment discharge to the Amazon River (≈1.43 $Mt \cdot year^{-1}$). The characterized hydro-sedimentary balance indicated that the main function of the Anavilhanas Archipelago, from the fluvial standpoint, is to act as a sink for suspended sediments, mainly from the Branco River. The current sedimentation rate is about 10 times less than the estimates proposed for the period when the Archipelago formed.

The results of this work can be used as a baseline to assess the possible impacts of extreme climate events and those from the construction of the Bem Querer hydropower dam on the Branco River, especially the reduction of the suspended sediments discharge to the lower Negro River. However, further research must be carried out to better assess the bed-forms of the Negro and Branco rivers, as well as integrate remote sensing, biogeographic, and geochronological data in studies on the evolution of the Negro River and the origin of the Anavilhanas and Mariuá archipelagos.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/4/1073/s1. Figure S1: Correlogram maps of sedimentological, hydrological, and climatological dataset (TSS, Q, V, H, and P) in the study sections, Figure S2: Correlogram of sedimentological, hydrological, and climatological dataset (TSS, Q, V, H, and P) in the study sections for the period of high water levels, Figure S3: Correlogram of sedimentological, hydrological, and climatological dataset (TSS, Q, V, H, and P) in the study sections for the period of low water levels, Figure S4: Correlogram of sedimentological, hydrological, and climatological dataset (TSS, Q, V, H, and P) in the lower course of the Negro River.

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References

1. Latrubesse, E.M.; Stevaux, J.C.; Sinha, R. Tropical rivers. *Geomorphology* **2005**, *70*, 187–206. [CrossRef]
2. Latrubesse, E.M. Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers. *Geomorphology* **2008**, *101*, 130–145. [CrossRef]
3. Gupta, A. *Large Rivers*, 1st ed.; John Wiley & Sons, Ltd.: Chichester, UK, 2007. [CrossRef]
4. Hinderer, M. From gullies to mountain belts: A review of sediment budgets at various scales. *Sediment. Geol.* **2012**, *280*, 21–59. [CrossRef]
5. Filizola, N.; Guyot, J.L. Suspended sediment yields in the Amazon basin: An assessment using the Brazilian national data set. *Hydrol. Process.* **2009**, *23*, 3207–3215. [CrossRef]
6. Filizola, N.; Guyot, J.-L. O Fluxo de Sedimentos em Suspensão nos rios da Amazônia Brasileira. *Rev. Bras. Geociencias* **2011**, *41*, 566–576. [CrossRef]
7. Richey, J.E.; Hedges, J.I.; Devol, A.H.; Quay, P.D.; Victoria, R.; Martinelli, L.; Forsberg, B.R. Biogeochemistry of carbon in the Amazon River. *Limnol. Oceanogr.* **1990**, *35*, 352–371. [CrossRef]
8. Moreira-Turcq, P.; Seyler, P.; Guyot, J.L.; Etcheber, H. Exportation of organic carbon from the Amazon River and its main tributaries. *Hydrol. Process.* **2003**, *17*, 1329–1344. [CrossRef]
9. Latrubesse, E.M.; Stevaux, J.C. The Anavilhanas and Mariuá Archipelagos: Fluvial Wonders from the Negro River, Amazon Basin. In *Landscapes and Landforms of Brazil*; Vieira, B.C., Salgado, A.A.R., Santos, L.J.C., Eds.; Springer: Dordrecht, The Netherlands, 2015; pp. 157–169. [CrossRef]
10. Latrubesse, E.M. Amazon lakes. In *Lakes and Reservoirs*; Hellström, T., Fairbridge, R.W., Bengtsson, L., Wohlfarth, B., Herschy, R.W., Hargeby, A., Blindow, I., Latrubesse, E.M., Hodgson, D.A., et al., Eds.; Springer: Berlin, Germany, 2012; pp. 13–26. [CrossRef]
11. Latrubesse, E.M.; Franzinelli, E. The late Quaternary evolution of the Negro River, Amazon, Brazil: Implications for island and floodplain formation in large anabranching tropical systems. *Geomorphology* **2005**, *70*, 372–397. [CrossRef]
12. Hess, L.; Melack, J.; Novo, E.M.L.M.; Barbosa, C.C.F.; Gastil, M. Dual-season mapping of wetland inundation and vegetation for the central Amazon basin. *Remote Sens. Environ.* **2003**, *87*, 404–428. [CrossRef]
13. Frappart, F.; Seyler, F.; Martinez, J.-M.; León, J.G.; Cazenave, A. Floodplain water storage in the Negro River basin estimated from microwave remote sensing of inundation area and water levels. *Remote Sens. Environ.* **2005**, *99*, 387–399. [CrossRef]
14. Junk, W.J.; Piedade, M.T.F.; Schöngart, J.; Cohn-Haft, M.; Adeney, J.M.; Wittmann, F. A Classification of Major Naturally-Occurring Amazonian Lowland Wetlands. *Wetlands* **2011**, *31*, 623–640. [CrossRef]
15. Saint-Paul, U.; Zuanon, J.; Correa, M.A.V.; García, M.; Fabré, N.N.; Berger, U.; Junk, W.J. Fish Communities in Central Amazonian White- and Blackwater Floodplains. *Environ. Biol. Fishes* **2000**, *57*, 235–250. [CrossRef]

16. Chao, N. Fisheries, diversity and conservation of ornamental fish of the Rio Negro River, Brazil—A review of Project Piaba (1989–1999). In *Conservation and Management of Ornamental Fish Resources of the Rio Negro Basin, Amazonia, Brazil-Project Piaba*; Chao, N., Ed.; Universidade Federal do Amazonas: Manaus, Brazil, 2001; pp. 161–204.
17. Ribas, C.C.; Aleixo, A.; Nogueira, A.C.R.; Miyaki, C.Y.; Cracraft, J. A palaeobiogeographic model for biotic diversification within Amazonia over the past three million years. *Proc. R. Soc. B Biol. Sci.* **2012**, *279*, 681–689. [CrossRef]
18. Choueri, E.L.; Gubili, C.; Borges, S.H.; Thom, G.; Sawakuchi, A.O.; Soares, E.A.A.; Ribas, C.C. Phylogeography and population dynamics of Antbirds (Thamnophilidae) from Amazonian fluvial islands. *J. Biogeogr.* **2017**, *44*, 2284–2294. [CrossRef]
19. Silva, C.L. Análise Da Tectônica Cenozóica Na Região De Manaus E Adjacências. Ph.D. Thesis, Universidade Estadual Paulista, Rio Claro, Brazil, 2005.
20. Alves, N.S. Mapeamento Hidromorfodinâmico Do Complexo Fluvial De Anavilhanas: Contribuição Aos Estudos De Geomorfologia Fluvial De Rios Amazônicos. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 2013.
21. Almeida-Filho, R.; Miranda, F.P. Mega capture of the Rio Negro and formation of the Anavilhanas Archipelago, Central Amazônia, Brazil: Evidences in an SRTM digital elevation model. *Remote Sens. Environ.* **2007**, *110*, 387–392. [CrossRef]
22. Filizola, N.; Guyot, J.-L.; Wittmann, H.; Martinez, J.-M.; Oliveira, E. The Significance of Suspended Sediment Transport Determination on the Amazonian Hydrological Scenario. In *Sediment Transport in Aquatic Environments*; Andrew, J., Manning, Eds.; InTech: Rijeka, Croatia, 2011; pp. 45–64. [CrossRef]
23. Agência Nacional de Águas. Portal HidroWeb. Available online: http://www.snirh.gov.br/hidroweb/apresentacao (accessed on 21 January 2020).
24. Jugaru Tiron, L.; Le Coz, J.; Provansal, M.; Panin, N.; Raccasi, G.; Dramais, G.; Dussouillez, P. Flow and sediment processes in a cutoff meander of the Danube Delta during episodic flooding. *Geomorphology* **2009**, *106*, 186–197. [CrossRef]
25. Filizola, N.; Latrubesse, E.M.; Fraizy, P.; Souza, R.; Guimarães, V.; Guyot, J.-L. Was the 2009 flood the most hazardous or the largest ever recorded in the Amazon? *Geomorphology* **2014**, *215*, 99–105. [CrossRef]
26. Panagos, P.; Borrelli, P.; Meusburger, K.; Alewell, C.; Lugato, E.; Montanarella, L. Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy* **2015**, *48*, 38–50. [CrossRef]
27. Latrubesse, E.M.; Arima, E.Y.; Dunne, T.; Park, E.; Baker, V.R.; D'Horta, F.M.; Wight, C.; Wittmann, F.; Zuanon, J.; Baker, P.A.; et al. Damming the rivers of the Amazon basin. *Nature* **2017**, *546*, 363–369. [CrossRef]
28. Forsberg, B.R.; Melack, J.M.; Dunne, T.; Barthem, R.B.; Goulding, M.; Paiva, R.C.D.; Sorribas, M.V.; Silva, U.L.; Weisser, S. The potential impact of new Andean dams on Amazon fluvial ecosystems. *PLoS ONE* **2017**, *12*, e0182254. [CrossRef]
29. Finer, M.; Jenkins, C.N. Proliferation of Hydroelectric Dams in the Andean Amazon and Implications for Andes-Amazon Connectivity. *PLoS ONE* **2012**, *7*, e35126. [CrossRef] [PubMed]
30. Winemiller, K.O.; McIntyre, P.B.; Castello, L.; Fluet-Chouinard, E.; Giarrizzo, T.; Nam, S.; Baird, I.G.; Darwall, W.; Lujan, N.K.; Harrison, I.; et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **2016**, *351*, 128–129. [CrossRef] [PubMed]
31. Stevaux, J.C.; Martins, D.P.; Meurer, M. Changes in a large regulated tropical river: The Paraná River downstream from the Porto Primavera Dam, Brazil. *Geomorphology* **2009**, *113*, 230–238. [CrossRef]
32. Meade, R.; Nordin, C.F.; Curtis, W.; Rodrigues, F.C.; Vale, C.M.V.; Edmond, J.M. Transporte de sedimentos no rio Amazonas. *Acta Amaz.* **1979**, *9*, 543–547. [CrossRef]
33. Observation Service SO HYBAM. Available online: http://www.ore-hybam.org (accessed on 29 December 2018).
34. Wittmann, H.; von Blanckenburg, F.; Maurice, L.; Guyot, J.-L.; Filizola, N.; Kubik, P.W. Sediment production and delivery in the Amazon River basin quantified by in situ-produced cosmogenic nuclides and recent river loads. *Geol. Soc. Am. Bull.* **2011**, *123*, 934–950. [CrossRef]
35. Sander, C.; Gasparetto, N.V.L.; Santos, M.L.; Carvalho, T.M. Características do transporte de sedimentos em suspensão na bacia do Rio Branco, Estado de Roraima. *Acta Geográfica* **2014**, *8*, 71–85.
36. Meade, R.H.; Rayol, J.M.; Da Conceicão, S.C.; Natividade, J.R.G. Backwater effects in the Amazon River basin of Brazil. *Environ. Geol. Water Sci.* **1991**, *18*, 105–114. [CrossRef]

37. Empresa de Pesquisas Energética–Usina Hidrelétrica (UHE) Bem Querer. Available online: http://www.uhebemquerer.com.br (accessed on 11 December 2018).
38. Naka, L.N.; Laranjeiras, T.O.; Rodrigues Lima, G.; Plaskievicz, A.C.; Mariz, D.; Costa, B.M.; Menezes, H.S.G.; Torres, M.D.F.; Cohn-Haft, M. The Avifauna of the Rio Branco, an Amazonian evolutionary and ecological hotspot in peril. *Bird Conserv. Int.* **2019**, 1–19. [CrossRef]
39. Junk, W.J.; Wittmann, F.; Schöngart, J.; Piedade, M.T.F. A classification of the major habitats of Amazonian black-water river floodplains and a comparison with their white-water counterparts. *Wetl. Ecol. Manag.* **2015**, *23*, 677–693. [CrossRef]
40. Instituto Brasileiro de Geografia e Estatística (IBGE). *Mapa Geomorfologia da Amazônia Legal-Scale 1:250.000*; Diretoria de Geociências: Rio de Janeiro, Brazil, 2009.
41. Franzinelli, E.; Igreja, H. Modern sedimentation in the Lower Negro River, Amazonas State, Brazil. *Geomorphology* **2002**, *44*, 259–271. [CrossRef]
42. Goulding, M.; Leal Carvalho, M.; Ferreira, E. *Río Negro, Rich Life in Poor Water: Amazonian Diversity and Foodchain* Ecology as Seen through Fish Communities; SPB Academic Publishing: The Hague, The Netherlands, 1989.
43. Quesada, C.A.; Lloyd, J.; Anderson, L.O.; Fyllas, N.M.; Schwarz, M.; Czimczik, C.I. Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* **2011**, *8*, 1415–1440. [CrossRef]
44. RSIS Ramsar Information Sheet. Anavilhanas National Park, Brazil. Available online: https://rsis.ramsar.org/ris/2296 (accessed on 2 March 2018).
45. Salati, E.; Marques, J. Climatology of the Amazon region. In *The Amazon Limnology and Landscape Ecology of Mighty Tropical River and Its Basins*; Sioli, H., Ed.; Monographiae Biologicae; Springer: Dordrecht, The Netherlands, 1984; Volume 56, pp. 85–126, ISBN 978-94-009-6544-7. [CrossRef]
46. Montero, J.C.; Latrubesse, E.M. The igapó of the Negro River in central Amazonia: Linking late-successional inundation forest with fluvial geomorphology. *J. S. Am. Earth Sci.* **2013**, *46*, 137–149. [CrossRef]
47. Sioli, H. The Amazon and its main affluents: Hydrography, morphology of the river courses, and river types. In *Amazon Limnology and Landscape Ecology of Mighty Tropical River and Its Basins*; Sioli, H., Ed.; Springer: Dordrecht, The Netherlands, 1984; pp. 127–165. [CrossRef]
48. Filizola, N.P.; Seyler, F.; Helena Mourão, M.; Arruda, W.; Spínola, N.; Guyot, J.-L. Study of the Variability in Suspended Sediment Discharge at Manacapuru, Amazon River, Brazil. *Lat. Am. J. Sedimentol. Basin Anal.* **2009**, *16*, 93–99.
49. THEIA Hydroweb. Available online: http://hydroweb.theia-land.fr/ (accessed on 21 January 2020).
50. Chapman, D. *Water Quality Assessments-A Guide to Use of Biota, Sediments and Water in Environmental Monitoring-Second Edition*; E & FN Spon: London, UK, 1992.
51. Molinier, M.; Guyot, J.-L.; Oliveira, E.; Guimaraes, V. Les régimes hydrologiques de l'Amazone et de ses affluents. In *L'hydrologie Tropicale: Géosciences et Outil Pour le Développement: Mélanges à la Mémoire de Jean Rodier*; Chevallier, P., Pouyaud, B., Eds.; IAHS: Paris, France, 1996; Volume 238, pp. 209–222.
52. Park, E.; Latrubesse, E.M. Modeling suspended sediment distribution patterns of the Amazon River using MODIS data. *Remote Sens. Environ.* **2014**, *147*, 232–242. [CrossRef]
53. Barbosa, C.C.F.; de Moraes Novo, E.M.L.; Melack, J.M.; Gastil-Buhl, M.; Filho, W.P. Geospatial analysis of spatiotemporal patterns of pH, total suspended sediment and chlorophyll-a on the Amazon floodplain. *Limnology* **2010**, *11*, 155–166. [CrossRef]
54. Marinho, T.; Filizola, N.; Martinez, J.-M.; Armijos, E.; Nascimento, A. Suspended Sediment Variability at the Solimões and Negro Confluence between May 2013 and February 2014. *Geosciences* **2018**, *8*, 265. [CrossRef]
55. Filizola, N.P. Transfert Sédimentaire Actuel Par les Fleuves Amazoniens. PhD Thesis, Universite Toulouse III-Paul Sabatier, Toulouse, France, 2003.
56. Fassoni-Andrade, A.C.; Paiva, R.C.D. Mapping spatial-temporal sediment dynamics of river-floodplains in the Amazon. *Remote Sens. Environ.* **2019**, *221*, 94–107. [CrossRef]
57. Scabin, A.B.; Costa, F.R.C.; Schöngart, J. The spatial distribution of illegal logging in the Anavilhanas archipelago (Central Amazonia) and logging impacts on species. *Environ. Conserv.* **2012**, *39*, 111–121. [CrossRef]
58. Allard, T.; Ponthieu, M.; Weber, T.; Filizola Jr, N.; Guyot, J.-L.; Benedetti, M. Nature and properties of suspended solids in the Amazon Basin. *Bull. La Soc. Geol. Fr.* **2002**, *173*, 67–75. [CrossRef]
59. Tricart, J. Types de lits fluviaux em Amazonie Bresilienne. *Ann. Georgr.* **1977**, *437*, 1–54. [CrossRef]

60. Leenheer, J.A.; Santos, H.M. Considerações sobre os processos de sedimentação na água preta ácida do rio Negro (Amazônia Central). *Acta Amaz.* **1980**, *10*, 343–357. [CrossRef]
61. Sioli, H. *Amazônia: Fundamentos De Ecologia Da Maior Região Das Florestas Tropicais*; Vozes: Petrópolis, Brazil, 1991.
62. Cremon, É.H.; Rossetti, D.D.F.; Sawakuchi, A.O.; Cohen, M.C.L. The role of tectonics and climate in the late Quaternary evolution of a northern Amazonian River. *Geomorphology* **2016**, *271*, 22–39. [CrossRef]
63. Barbosa, R.O. Estudos Sedimentológicos E Estratigráficos Dos Depósitos Sedimentares Quartenários Do Arquipélago De Anavilhanas, Município De Novo Airão (Amazônia Central). Master's Thesis, Universidade Federal do Amazonas, Manaus, Brazil, 2015.
64. Cunha, D.F. Da Evolução Sedimentar Do Arquipélago De Anavilhanas No Baixo Rio Negro, Amazônia Central. Master's Thesis, Universidade de São Paulo, São Paulo, Brazil, 2017.
65. Rodríguez-Zorro, P.A.; Turcq, B.; Cordeiro, R.C.; Moreira, L.S.; Costa, R.L.; McMichael, C.H.; Behling, H. Forest stability during the early and late Holocene in the igapó floodplains of the Rio Negro, northwestern Brazil. *Quat. Res.* **2018**, *89*, 75–89. [CrossRef]
66. Cordeiro, R.C.; Turcq, P.F.M.; Turcq, B.J.; Moreira, L.S.; Rodrigues, R.C.; da Costa, R.L.; Sifeddine, A.; Simões Filho, F.F.L. Acumulação de carbono em lagos amazônicos como indicador de eventos paleoclimáticos e antrópicos. *Oecologia Aust.* **2008**, *12*, 130–154. [CrossRef]
67. Costa, R.L. Paleohidrologia Do Lago Acarabixi, Médio Rio Negro, Am, Durante O Holoceno. Master's Thesis, Universidade Federal Fluminense: Niterói, Rio de Janeiro, Brazil, 2006.
68. Silva, V.C. Acumulação De Carbono E Interpretações Paleohidrológicas Do Lago Do Boto–Arquipélago De Anavilhanas Durante O Holoceno Superior. Master's Thesis, Universidade Federal do Amazonas, Manaus, Brazil, 2019.
69. Soares, E.A.A.; Tatumi, S.H.; Riccomini, C. OSL age determinations of Pleistocene fluvial deposits in Central Amazonia. *An. Acad. Bras. Cienc.* **2010**, *82*, 691–699. [CrossRef]
70. Sant'Anna, L.G.; Soares, E.A.D.A.; Riccomini, C.; Tatumi, S.H.; Yee, M. Age of depositional and weathering events in Central Amazonia. *Quat. Sci. Rev.* **2017**, *170*, 82–97. [CrossRef]
71. Nanson, G.C. Anabranching and Anastomosing Rivers. In *Treatise on Geomorphology*; Shroder, J.F., Ed.; Academic Press: San Diego, CA, USA, 2013; pp. 330–345. [CrossRef]
72. Holanda, J.L.R.; Marmos, J.L.; Maia, M.A.M. *Geodiversidade do Estado de Roraima*, 1st ed.; Holanda, J.L.R., Marmos, J.L., Maia, M.A.M., Eds.; CPRM: Manaus, Brazil, 2014; ISBN 978-85-7499-162-7.
73. Fearnside, P.M. Dams in the Amazon: Belo Monte and Brazil's Hydroelectric Development of the Xingu River Basin. *Environ. Manag.* **2006**, *38*, 16–27. [CrossRef] [PubMed]
74. Assahira, C.; Piedade, M.T.F.; Trumbore, S.E.; Wittmann, F.; Cintra, B.B.L.; Batista, E.S.; de Resende, A.F.; Schöngart, J. Tree mortality of a flood-adapted species in response of hydrographic changes caused by an Amazonian river dam. *For. Ecol. Manag.* **2017**, *396*, 113–123. [CrossRef]
75. Ferrante, L.; Fearnside, P.M. Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. *Environ. Conserv.* **2019**, *46*, 261–263. [CrossRef]
76. Laranjeiras, T.O.; Naka, L.N.; Cohn-Haft, M. Using river color to predict Amazonian floodplain forest avifaunas in the world's largest blackwater river basin. *Biotropica* **2019**, *51*, 330–341. [CrossRef]