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Sedimentary Basin Water and Energy Storage: A Low Environmental Impact Option for the Bananal Basin

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Abstract: Groundwater storage is an important water management solution that is overlooked by several countries worldwide. This paper evaluates the potential for storing water in the Bananal sedimentary basin and proposes the construction of canals to reduce sediment obstructions in the river flow and harmful flood events. This would allow for better control of the water level. The water stored in the sedimentary basin can be used as a climate change adaptation measure to ensure that the level of the flood plain is maintained high during a drought or low during an intense flood event. Additionally, the flood plain will function as a water reservoir, regulate the river flow downstream from the flood plain, and enhance hydropower generation. A significantly smaller reservoir area is expected to store water, as the water will be stored as groundwater in the sedimentary basin. Results show that the Bananal basin has the potential to store up to 49 km^3 of water, which can add up to 11.7 TWh of energy storage to the Brazilian energy matrix for a CAPEX energy storage cost of 0.095 USD/kWh. This is an interesting solution for the Araguaia basin and several other basins worldwide.

Keywords: water management; hydropower; energy storage; renewable energies; sedimentary basin; water

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1. Introduction

Sedimentary basins are locations where sediments are trapped and accumulated [1]. Flood plains are usually locations with rich fauna and flora biodiversity. However, they are highly vulnerable to changes in the use of water and climate change [2]. Sedimentary basins store a significant amount of water and are also called wetlands or polders. Globally, wetlands are estimated to be 6% of the Earth's total land surface area [3]. Wetlands are among the most productive ecosystems on earth [4] and provide various services. These services include biological diversity, recreation, surface and floodwater storage, nutrient reduction, carbon sequestration, seasonal water, and energy storage [5–12].

Sedimentary basins naturally regulate the flow of the river. This is because some of the river flow or rain is absorbed by the sedimentary basin and stored. With the reduction in the rivers water level, the water stored is slowly released from the sedimentary basin into the river. Existing projects with the intent of flood control, irrigation, and some water storage are present in the lower Indus basin in Pakistan [13]. The Indus river has 15 barrages and headworks used to diverge the river flow into irrigation channels [14–16], as shown in Figure 1. Due to their low viability, these barrages have small heads and are not used to generate electricity. The lower Indus basin consists of a sedimentary basin made of unconsolidated sediments, with a high potential for storing water [17]. However, the Indus river only has an average yearly water level variation of 3 m [18]. The Araguaia river varies on average 5 m annually in the Bananal sedimentary basin [19].

Figure 1. Layout of Indus River system network of barrages and reservoirs [20].

The mid-Araguaia sedimentary basin also called the Bananal basin, is a large plain that is covered by quaternary deposits, which reach a maximum thickness of 170–320 m and are composed of unconsolidated, yellowish to brownish, ferruginous silts and sands [21]. It spreads over approximately 106,000 km^2 (Figure 2a). Every 10 to 15 years, during years with particularly high rainfall in the basin, an area of 88,119 km^2 is flooded (Figure 2b), which corresponds to 83% of the entire Bananal basin and 23% of the total Araguaia basin. This floodplain's fine-grained sediments consist of clay minerals (kaolinite, gibbsite, goethite, and Al-chlorite), all of which are poor in Mg, Ca, and K. This indicates the low soil fertility of the floodplain [22,23]. In other words, it can be called a dead zone.

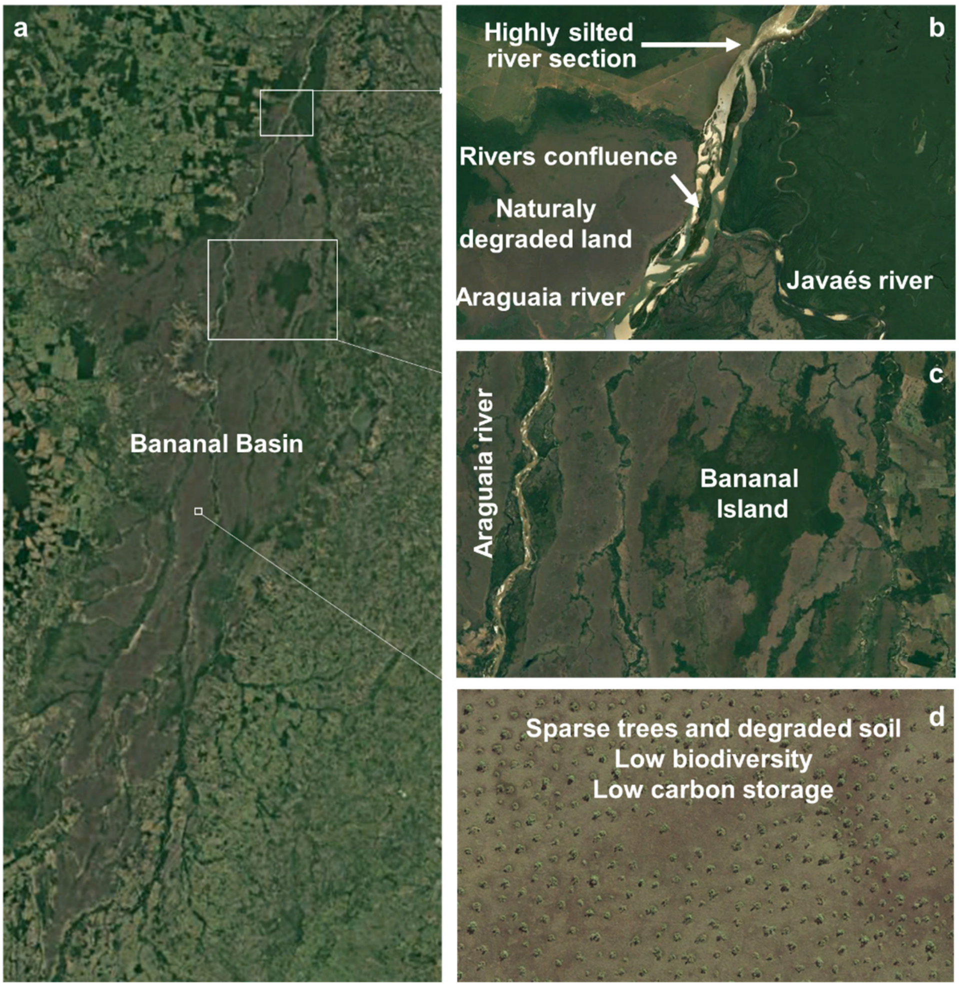

Figure 2. (**a**) Bananal basin, (**b**) silted bottleneck that causes flow restriction and floods, (**c**) Bananal Island, with higher altitude than the surrounding area, not regularly flooded and manages to sustain a dense forest, (**d**) Bananal plain, degraded land with sparse trees and low biodiversity and carbon storage [24].

On the other hand, during the dry period, only 3.3% of the area is covered by water [23]. The Bananal Island (Figure 2c) consists of an area that is not flooded every 10 to 15 years, which allows the region to sustain a tropical forest and makes it the largest fluvial island in the world spanning around 1.600 km^2 [25]. These interannual flooding events are caused by sediments that build up in the outlet of the Bananal basin and the confluence between the Araguaia and Javaés Rivers (on the border between the States of Pará, Mato Grosso, and Tocantins), which restricts the river flow from the Bananal basin, causing the basin to flood. The flood results in the lack of biodiversity in the flooded region (Figure 2d). Every year, the level of the Araguaia river in the Bananal basin varies by 5 m in altitude [19]. The region suffers from climatic variability. The hydrological regime of the basin is well defined, with floods from October to May and which peak in February. The rivers dry up between June and September. Every 10 to 15 years, the river level increases to 12 m, which causes extensive floods in the basin. The most recent large-scale floods happened in 2013, 2002, 1990, and 1980. According to the Gravity Recovery and Climate Experiment (GRACE), the groundwater seasonal storage capacity of the whole Tocantins basin (Figure 3), including the Araguaia and Tocantins basins, has been estimated to be around 300 km^3 [26].

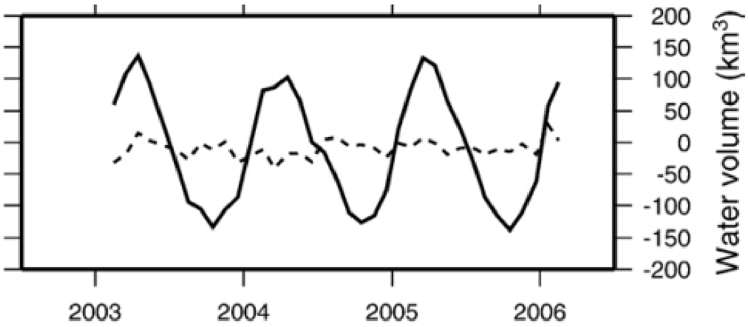

Figure 3. Water storage variation in the Tocantins basin (865,000 km^2 area). The solid line is the change in water volume stored in the basin compared to the average. The dotted line is the 12-month average change in water volume stored [26].

Another issue in the Araguaia basin is the lack of river flow regulation, which results in a significant loss in hydropower potential in the Tucuruí hydroelectric power plant in the Tocantins River. The spilled and turbine water flow of the Tucuruí dam is presented in Figure 4.

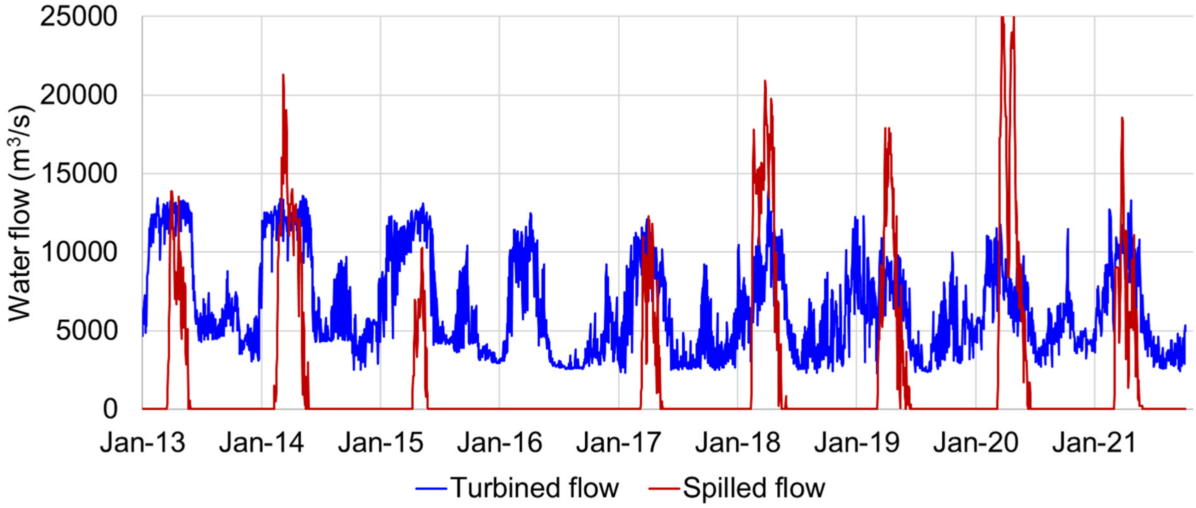

Figure 4. Tucuruí dam turbined water flow (blue) and spilled water (red).

This paper proposes two water management solutions for the Bananal River basin. The first one is the construction of a dredged canal that can increase the cross-section flow in the current bottleneck of the Bananal basin, which will end the current 10 to 15-year flood episodes and allow the use of the basin for agricultural development. The second one is the construction of a low-head dam that will generate hydropower in the basin and can also control the water outflow from the Bananal basin and thus store water without requiring the creation of a superficial reservoir; this is similar to how it is done in the lower section of the Indus basin. The reduced reservoir in this proposal significantly reduces the environmental impacts on water storage in the Araguaia basin [27,28]. The regulation of the Araguaia River flow will significantly increase the hydropower generation at the Tucuruí Dam and increase the viability of the existing dam potential [29]. This is particularly interesting because Brazil has been suffering from an energy crisis since 2014 [30–32].

2. Methodology

The methodological framework implemented in this paper is described in Figure 5. The methodology is divided into three major steps. Step 1 intends to estimate the water basin sedimentary basin storage capacity. This consists of analysing the available plain for storage with basin topography, analysing the basin's sedimentary composition, and estimating the impact of river level on basin water storage. Step 2 proposes two water management solutions to allow the use of the basin for agricultural production and water storage. This consists of detailing the costs and the project of a flood canal to control the water flow outlet from the basin to avoid it flooding in the future and a hydropower plant to control the water level of the basin during the dry period to increase the residence time of the water and regulate the flow of the river. Step 3 consists of estimating the gains in hydropower generation, assuming that there are existing and planned power plants in the future. This consists of an analysis of the basin river flow, sedimentary basin impact on the river flow, and dams in the cascade to estimate the hydropower generation gains in the cascade. The data sources used in this methodology are shown in Table 1.

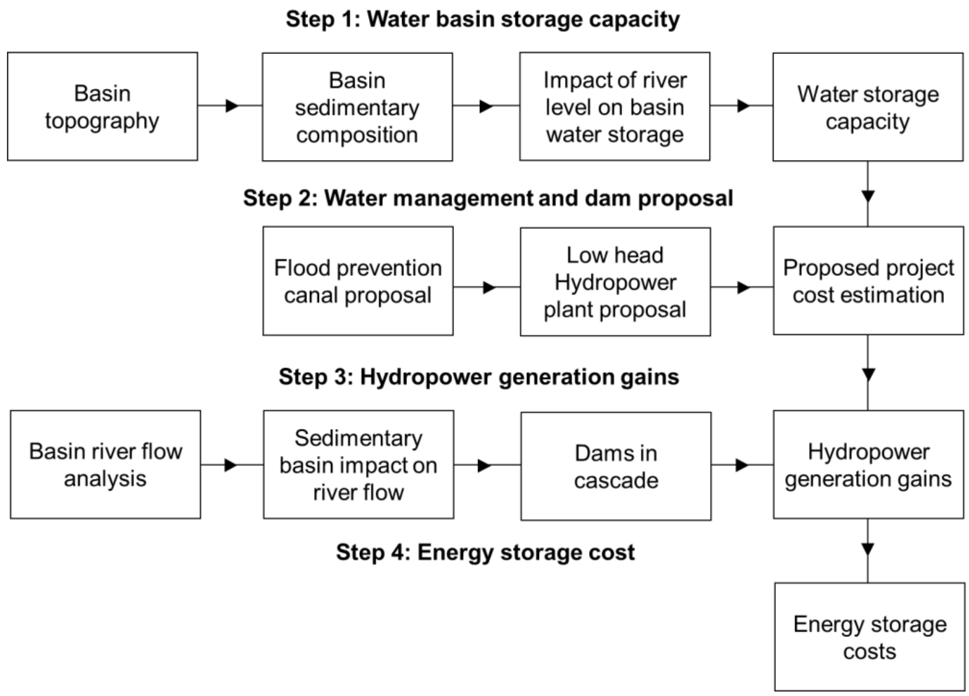

Figure 5. Methodological framework to estimate the potential for storing water and energy in the Bananal sedimentary basin.

Table 1. Data sources applied in the methodological framework.

Step	Data	Description	Reference
1	Topographic data (STRM)	Data resolution of 3 s (equivalent to 90 × 90 m in the equator).	[33]
	Geological composition	Geological composition of the Bananal sedimentary basin consists of clay-silt-sandy sediment, unconsolidated fluviolacustrine with colour varying from yellowish, grey to reddish. Sand granulometry predominates.	[34]
		Soil particle-size classes with different concentrations of sand, clay, and silt are presented in Figure 6.	[35]
		The available water storage capacity for different soil particle-size classes is presented in Table 2. This paper assumes that the available water capacity (AWC) is 0.18 cm^3/cm^3. That is, 18% of the soil volume can store water.	[36]
2	Proposed project cost estimation	Data on the cost estimates for the flood prevention canals and the low head hydropower plants to estimate the energy storage costs of the project.	[37]

Table 1. *Cont.*

Step	Data	Description	Reference
3	Hydrological data	Hydrological data (river level and river flow) at different points in the Araguaia basin. These points are shown in [38].	[38]
	Basin river flow analysis	Data on Araguaia River flow at different points [38] were used to estimate the impact of the sedimentary basin on the river flow downstream from the Bananal basin.	[39]
	Dams in cascade	Data on existing dams downstream from the Bananal basin is used to estimate the overall gain in hydropower that results from the proposed use of the Bananal basin for water and energy storage.	[40]

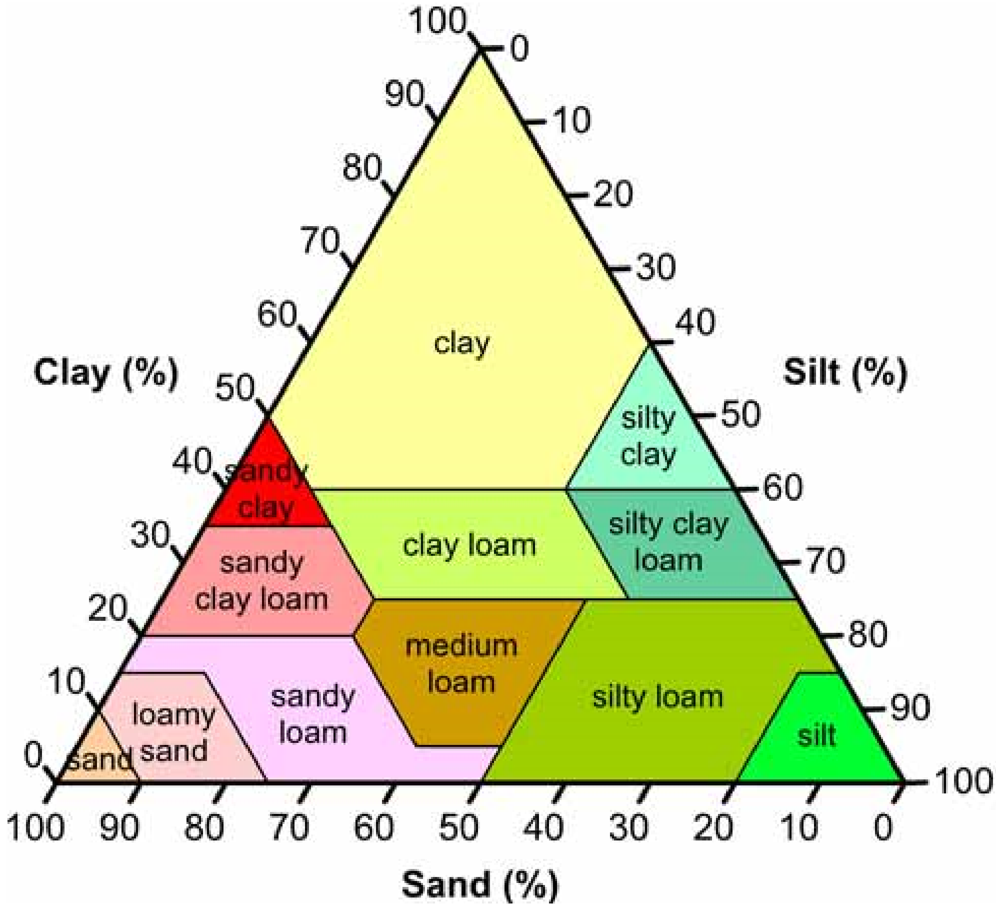

Figure 6. Soil particle-size classes with different concentrations of sand, clay, and silt [35].

Unconsolidated sedimentary basins with sandy loam composition [34] have high porosity and can store 13–29% of the ground volume in water, as shown in Table 2. This paper, being conservative, estimated that 18% of the ground volume could store water. The region in blue in Figure 7 is composed of a mixture of sand, silt, and clay, mainly a sandy loam composition [34]. Field Capacity is the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation in previous soils of uniform structure and texture. The physical definition of field capacity is the bulk water content retained in the soil at −33 kPa (or −0.33 bar) of hydraulic head or suction pressure [41,42].

Table 2. Available water capacity (cm^3/cm^3), field capacity, and different soil particle-size classes [36].

Soil Particle Size Classes	AWC at 3 kPa, in cm^3/cm^3	AWC at 1500 kPa, in cm^3/cm^3	Field Capacity (v%)
Sand	0.02–0.16	0.01–0.06	10
Loamy sand	0.06–0.19	0.02–0.09	12
Sandy loam	**0.13–0.29**	**0.03–0.16**	**18**
Silt loam	0.26–0.40	0.08–0.19	31
Silty clay loam	0.30–0.43	0.14–0.28	38
Silty clay loam	0.19–0.32	0.09–0.21	27
Clay loam	0.25–0.39	0.12–0.28	36
Silty clay	0.33–0.44	0.19–0.31	41
Clay	0.33–0.47	0.21–0.34	42

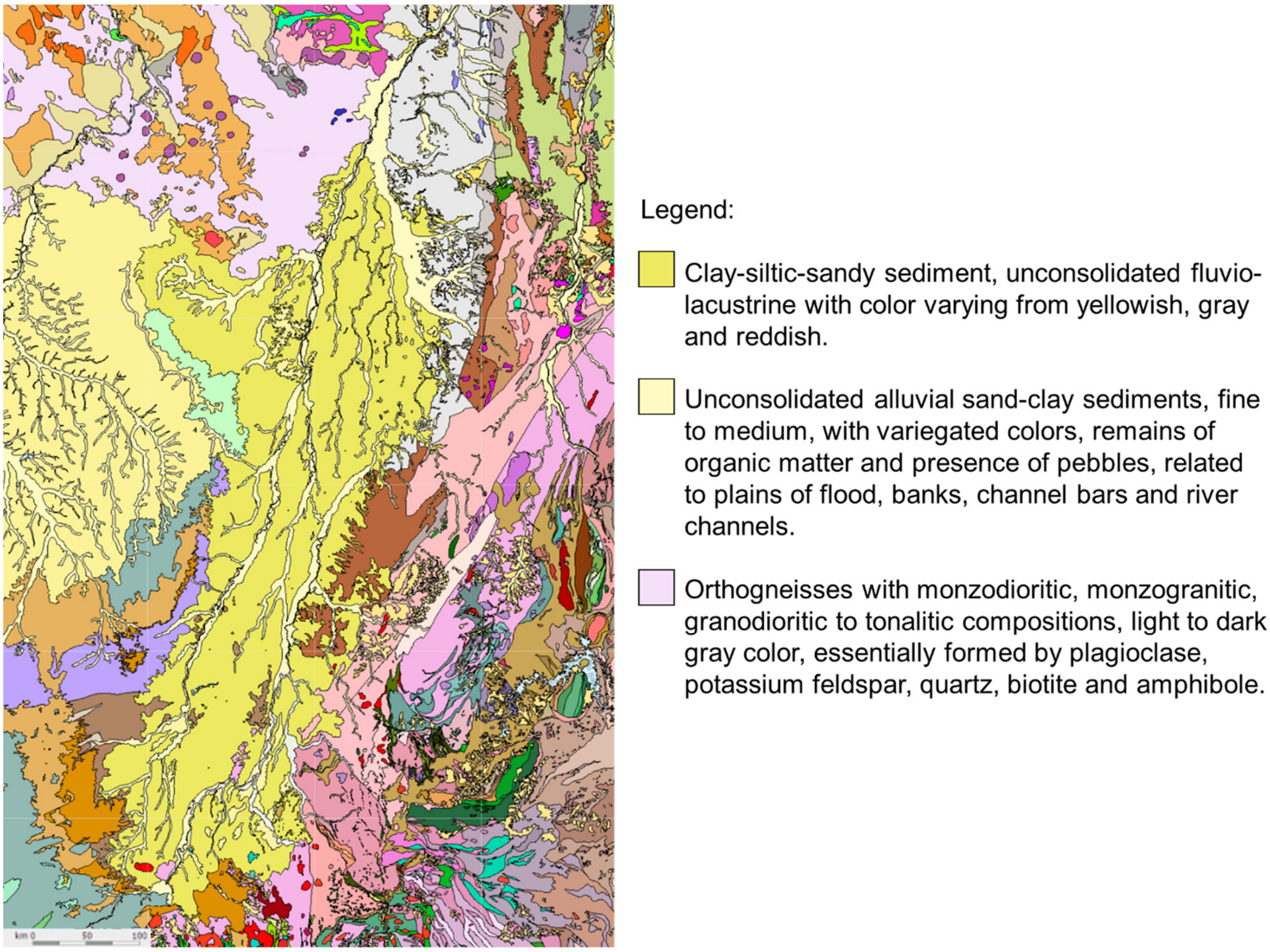

Figure 7. Data on soil geology characteristics [34]. The legend describes the soil relevant to the proposed solution presented in the paper.

Impact of River Level on Basin Water Storage

The basic principle behind the proposed solution for sedimentary basin energy and water storage is the impact of the river level variation on the amount of water stored in the sedimentary basin. This concept is presented in Figure 8. During the wet period (Figure 8a), the precipitation on the basin fills the sedimentary basin with water, and due to the increase in the Araguaia River level by up to 5 m, water from the river percolates on the soil of the sedimentary basin. Water is stored in the pores of the sedimentary basin, similar to a sponge. During the dry period (Figure 8b), water from the river exits the Bananal basin with the natural flow of water, and the water stored in the sedimentary basin contributes to maintaining the river flow high for a longer period. With the control of the water flow out of the Bananal basin (dam), the river level during the dry season remains high, and the sedimentary basin stores significant amounts of water (Figure 8c). The control over the water storage in sedimentary basins intends to use them as water and energy storage reservoirs and reduce the vulnerability of floodplains to global warming and changes in climate.

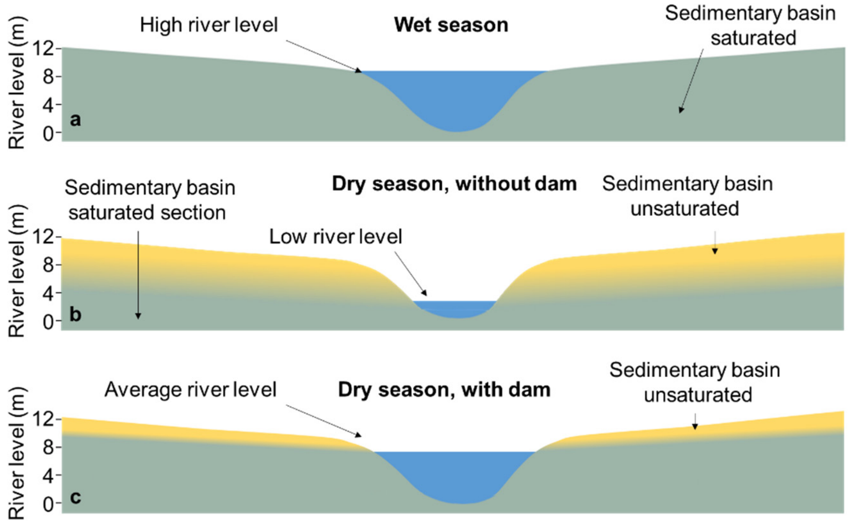

Figure 8. Diagram representing the saturation of sedimentary basins and their impact on river level during (**a**) wet season and (**b**) dry season without dam, and (**c**) dry season with the dam.

The calculation of groundwater storage capacity depends on the sedimentary basin's characteristics [43]. Groundwater storage capacity has been estimated by combining effective porosity values with the saturated thickness of aquifer systems and their areal extent. The approach presented in Equation (1) was proposed by [43]:

$$V_{sc} = A\ H_{sat}\varphi_e \tag{1}$$

where V_{sc} is the groundwater storage capacity (km^3), A is the surface area extent available for storage (km^2), H_{sat} is the saturated thickness (m), and φ_e is the effective porosity (dimensionless). The surface area (A) is the non-compacted soil, with a topography 10 m higher than the river level during the wet period. The saturated thickness (H_{sat}) is assumed to be the water level variation from the wet to dry seasons. Effective porosity (φ_e) assumes estimates to their assigned lithological units as developed and mapped in [34–36].

3. Results

3.1. Bananal Basin Water Storage Capacity

To estimate the water storage capacity of the basin, the groundwater storage capacity (km^3) needs to be calculated, as shown in Equation (1). The surface area (km^2) estimated to store water groundwater in the basin is assumed to be the non-compacted soil, with a topography 10 m higher than the river level during the wet period. This area was estimated with topographical data from [33] and is shown in Figure 9. Applying the proposed methodology, the estimated area available for water storage in the Bananal basin was found to be 41,398 km^2.

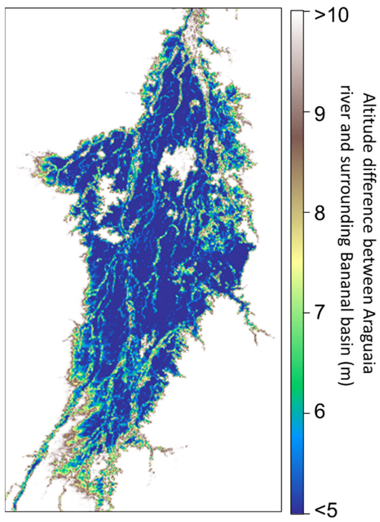

Figure 9. Bananal basin area available for sedimentary storage. The area in blue represents the topography 10 m higher than the river level during the dry period.

The saturated thickness (m) variation (seasonal) can be estimated from the Araguaia River level variation in the Bananal basin, and φ_e is the effective porosity (dimensionless). The seasonally saturated thickness (H_{sat}) is assumed to be the water level variation from the wet to dry seasons. This value was estimated with data from São Felix, located in the middle of the basin, from 1973 to 2020 [38]. The assumed value for the saturated thickness is 4.5 m, equal to the difference between the maximum and minimum river level average in Figure 10 from 1973 to 2020. Figure 10b shows the histogram of monthly river levels. The river level at São Felix is occasionally below 2 m during drought years and reaches above 10 m during the massive flood events mentioned in the introduction. The effective porosity (φ_e) assumed is 18% of the ground volume, as the prevailing composition of the basin is sandy loam [34]. Applying Equation (1), the estimated water storage volume with the sedimentary basin water storage solution is 33.5 km^3. Assuming that the operation of the new reservoir and the improved sediments management results in the river level reducing its minimum altitude by one or two meters, the estimated water storage volume with the sedimentary basin water storage solution increases to 41 and 48 km^3, respectively.

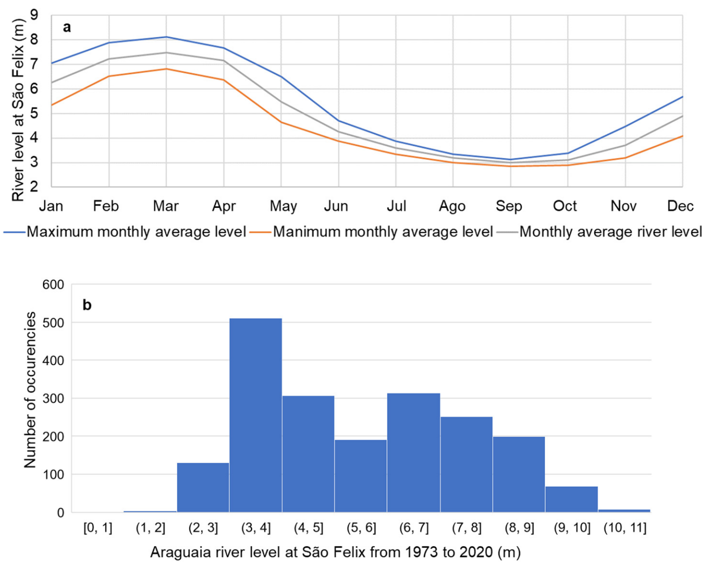

Figure 10. Araguaia's monthly river level at São Felix do Araguaia presented by (**a**) maximum, minimum and average monthly river level (**b**) histogram of monthly river level from 1973 to 2020 [38].

3.2. Hydropower Generation Gains

Currently, the only hydropower plant affected by the sedimentary basin storage project operation is the Turucuí dam, as presented in blue in Figure 11b. The Marabá and the Santa Isabel dams have already been proposed. the São José dam is proposed by the authors (red in Figure 11b). These dams have not been built due to environmental concerns and the lack of hydropower generation during the dry season. The proposed Bananal sedimentary basin storage dam is described in this paper. It will significantly increase the hydropower generation capacity of the dams downstream with the regulation of the Araguaia River flow (green in Figure 11b). During the wet period, the rain is stored in the soil.

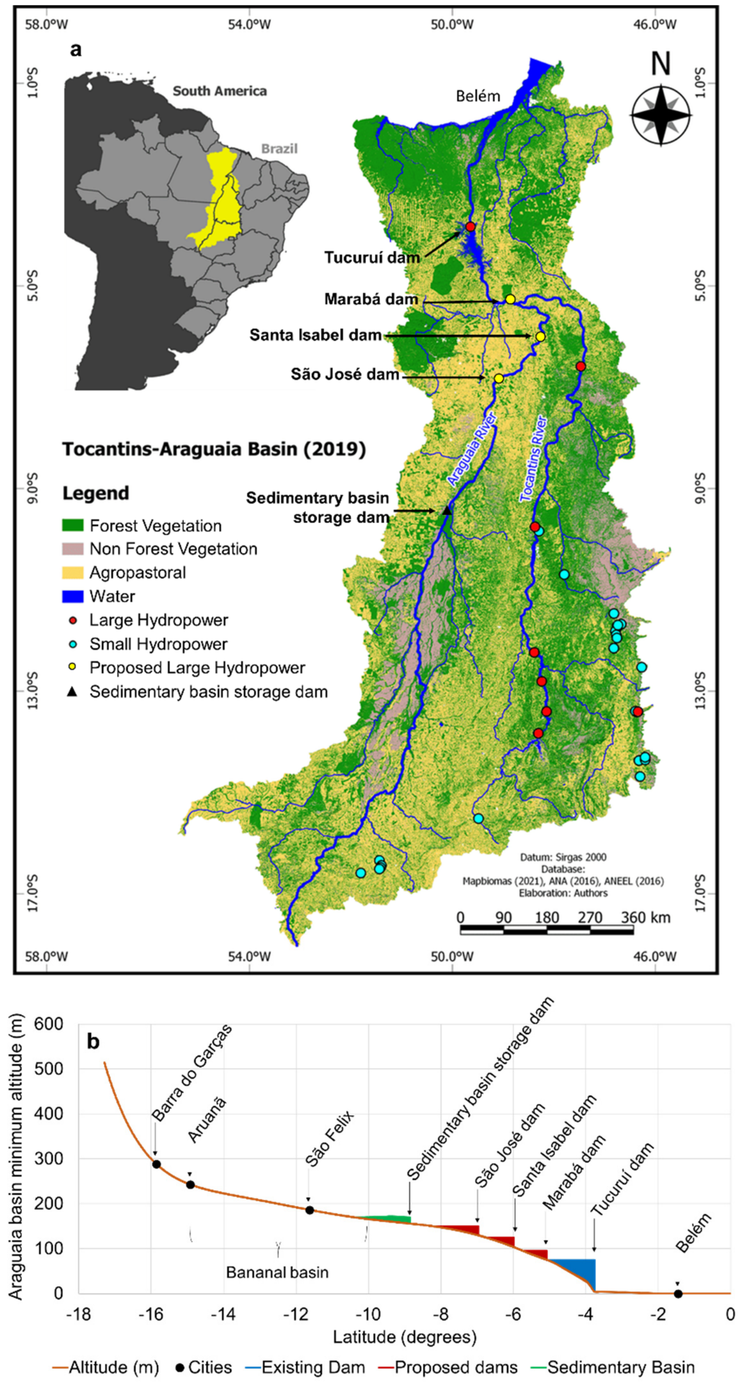

Figure 11. Hydropower dams in cascade in the Araguaia and Tocantins rivers (**a**) in a map (adaptation from [44]) and (**b**) along their latitude.

Figure 12 presents the observed (Obs) sedimentary basin river level and water storage (in blue). These values assume the observed average river level presented in Figure 10a. This is the sedimentary basin storage capacity operation, which already provides some level of storage to the river flow. However, due to the lack of control of the river level, the water exits the basin rapidly after the end of the wet period. Figure 12 presents three proposed operations for the Bananal sedimentary basin storage. The three proposed operations include the São José, Santa Isabel, and Marabá dams described in Figure 11b. The first proposal (P1) adds the Sedimentary basin storage dam, which controls the water exiting the basin and allows the water to remain for a longer time in the sedimentary basin. The second proposal (P2) adds the Sedimentary basin storage dam and involves the construction of a shallow canal, which allows more water to be extracted from the basin during the dry period and, thus, more water can be stored in the basin. The third proposal (P3) adds the Sedimentary basin storage dam and involves the construction of a deep canal, which allows even more water to be stored in the basin. Note that P2 and P3 have to be analysed with great care, as deliberately lowering the river level of the river during the dry period could have detrimental impacts on the environment and society (mainly tourism, fishing, and waterways [45]). These impacts should be considered when developing the project. Figure 13 shows the impact of the sedimentary basin water storage operation in the inlet flow to the dams downstream. The methodology implemented to create these scenarios was a simple mass balance equation assuming no changes in evaporation in the basin and with the intent of maximining hydropower generation. Figure 14 shows the impact of the operation of the sedimentary basin storage in the turbined flow of the dams downstream.

More details on the dams described above are presented in Table 3. The addition of the Bananal reservoir increases the hydropower generation in the existing and proposed hydropower dams (Figure 11) is 2.3 TWh for the P1 scenario, 6.0 TWh for the P2 scenario and 11.7 TWh for the P3 scenario, compared with the observed scenario. The capacity factor of the proposed dams without the Bananal sedimentary basin reservoir is small (50–60%). However, with the P3 scenario, the capacity factor increases to (70–80%), which significantly increases the viability of the proposed dams.

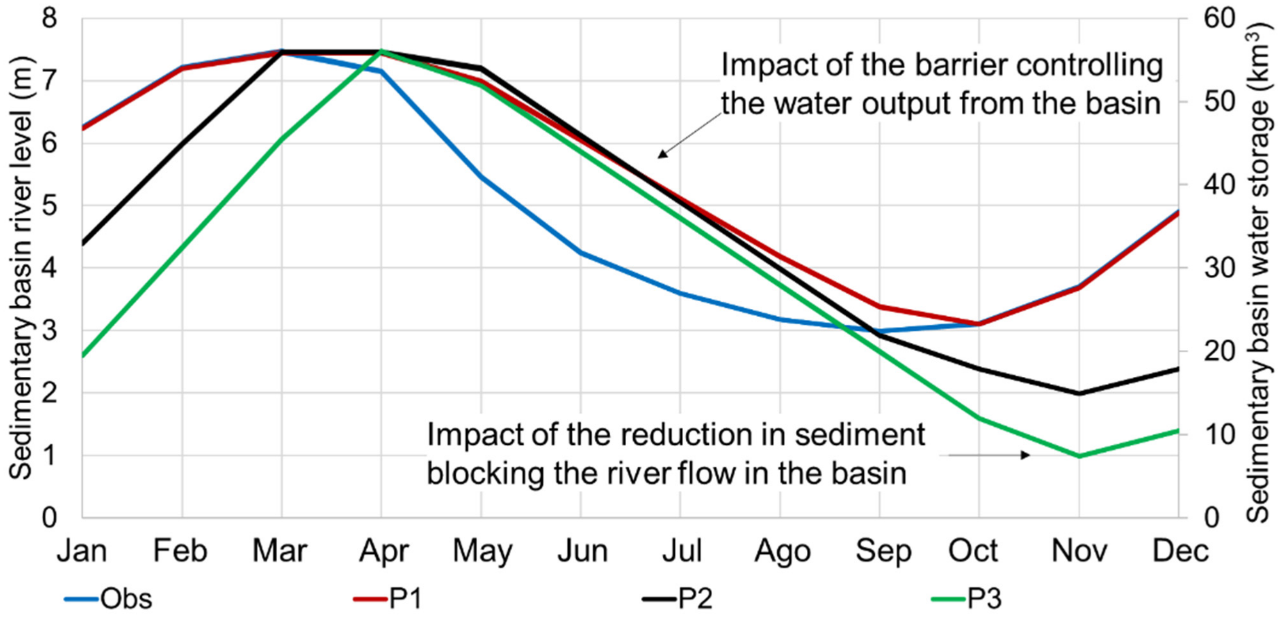

Figure 12. Observed and proposed sedimentary basin river level and water storage.

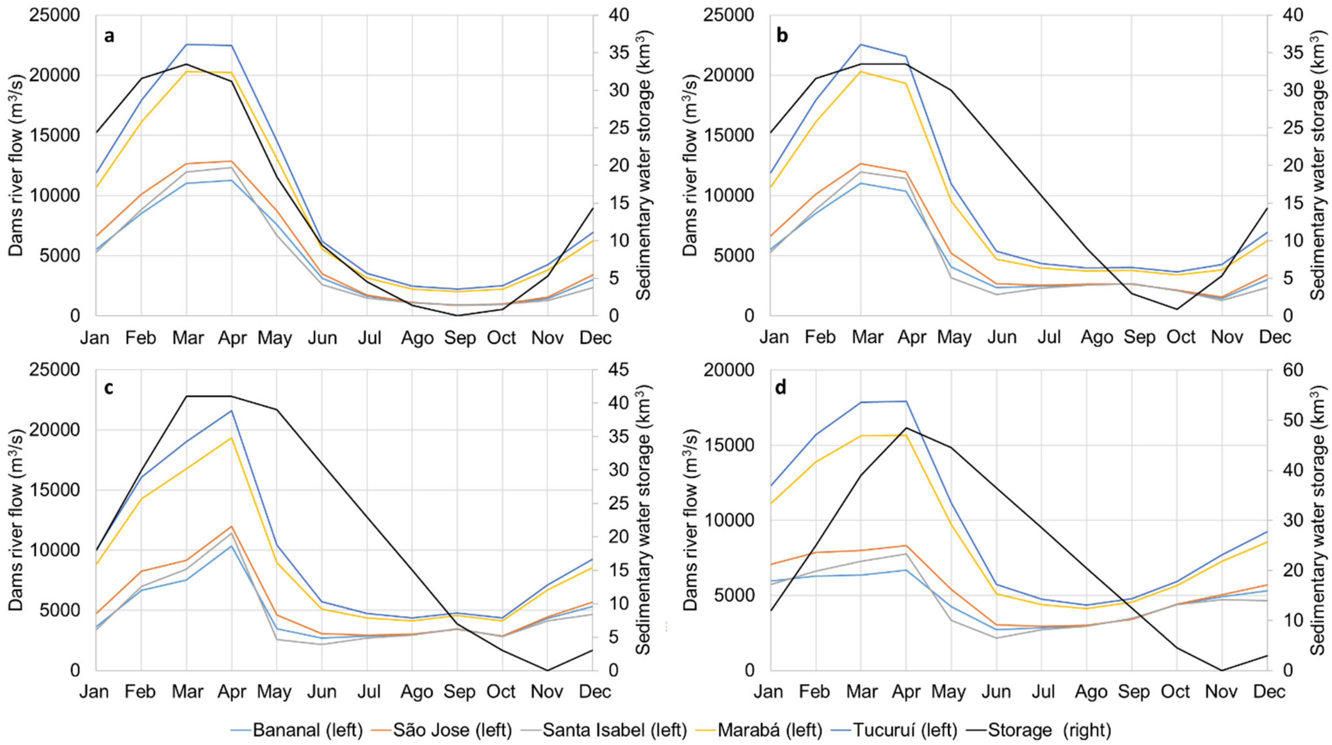

Figure 13. Estimated inlet river flow in existing and proposed dams and sedimentary basin water storage (**a**) Observed, (**b**) P1, (**c**) P2, and (**d**) P3.

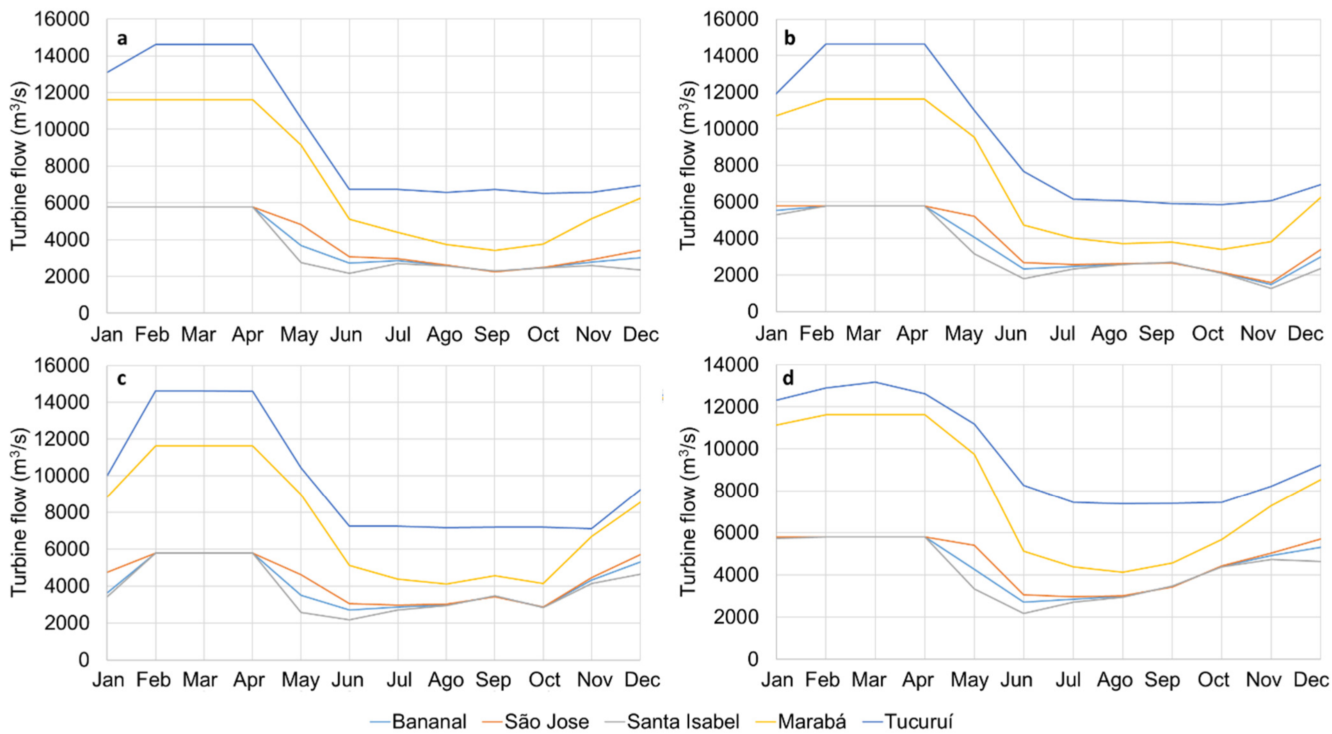

Figure 14. Estimated turbine flow in existing and proposed dams (**a**) Observed, (**b**) P1, (**c**) P2, and (**d**) P3.

Table 3. Gains in hydropower generation with the Bananal sedimentary basin storage reservoir construction.

Dam	Tucuruí	Marabá	Santa Isabel	São José	Bananal
Reservoir type	Storage	Run-of-the-river	Run-of-the-river	Run-of-the-river	Storage
Turbine type	Francis	Kaplan	Kaplan	Kaplan	Moveable HEPP
Installed capacity (MW)	8535	2160	1087	1087	815
Turbined flow (m^3/s)	14,626	11,616	5784	5784	5784
Maximum flooded area (km^2)	3024	1115	240	220	0.0
Minimum flooded area (km^2)	761	-	-	-	0.0
Maximum volume (km^3)	50.3	5.58	1.85	1.60	33.5
Minimum volume (km^3)	11.3	-	-	-	-
Useful volume (km^3)	39.0	-	-	-	Obs: 33.5/P1: 33.5/P2: 41/P3: 49
Volume used yearly (km^3)	31.2	-	-	-	Obs: 33.5/P1: 33.5/P2: 41/P3: 49
Maximum level (m)	74	96	125	150	170
Minimum level (m)	51.6	-	-	-	Obs: 165.5/P1: 165.5/P2: 164.5/P3: 163.5
Downstream level (m)	8.5	75	104	130	154
Generation head (m)	65.5	21	21	20	16
Yearly river flow (km^3)	310	279	147	169	140
Spillage in scenario Obs (km^3)	32	61	44	58	40
Spillage in scenario P1 (km^3)	27	55	39	46	33
Spillage in scenario P2 (km^3)	20	41	25	32	19
Spillage in scenario P3 (km^3)	0	27	11	21	6
Additional generation in scenario P1 (TWh) *	0.8	0.3	0.2	0.6	0.3
Additional generation in scenario P2 (TWh) *	1.9	1.0	1.0	1.3	0.8
Additional generation in scenario P3 (TWh) *	5.1	1.8	1.7	1.8	1.4
Total yearly generation in scenario Obs (TWh)	44.7	11.2	5.3	5.4	3.9
Total yearly generation in scenario P1 (TWh)	45.5	11.5	5.6	6.0	4.2
Total yearly generation in scenario P2 (TWh)	46.5	12.3	6.3	6.7	4.8
Total yearly generation in scenario P3 (TWh)	49.8	13.0	7.0	7.2	5.3
Capacity factor in scenario Obs (%)	60	59	56	57	55
Capacity factor in scenario P1 (%)	61	61	58	63	59
Capacity factor in scenario P2 (%)	62	65	66	71	67
Capacity factor in scenario P3 (%)	67	69	73	76	74

* Additional hydropower generation assumes the generation head in the table.

3.3. Energy Storage Costs

To implement the proposed Bananal sedimentary basin energy storage dam with the reservoir presented in Figure 15a, the sediments that restrict the flow of the river should be removed, and the river should be dredged, as shown in Figure 15b. The reservoir of the riverbed downstream from the river (orange section) should be dredged. The increase in kinetic energy resulting from the dam will help push the sediments down the basin.

Also, creating a reservoir will contribute to eroding some of the sediments surrounding the reservoir and facilitating the flow of sediments down the chokepoint. More details on the estimated costs of the project are described in Table 4. This canal would allow the water to flow out of the sedimentary basin, controlled by a dam and spillways.

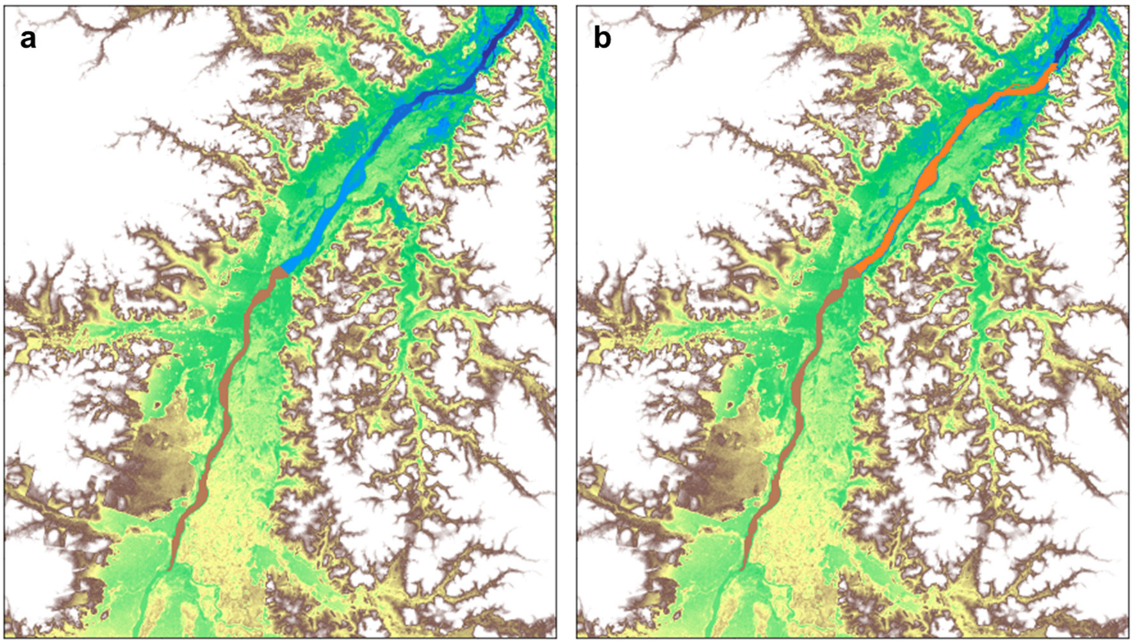

Figure 15. (**a**) Hydropower reservoir from the Bananal sedimentary basin storage hydropower plant (in brown), (**b**) riverbed area to be dredged to prevent flood and regulate the river flow (in orange).

Table 4. Energy storage cost estimation for the Bananal sedimentary basin water storage project.

Description	P1	P2	P3
Dam investment cost (billion USD) [37]	2.0	2.0	2.0
Canal investment cost (billion USD) [37]	-	1.0	2.0
Canal length (km)	-	160	160
Canal depth (m)	-	5	5
Total energy storage cost (billion USD)	2.0	3.0	4.0
Energy storage capacity (TWh)	2.3	6.0	11.7
Energy storage cost in CAPEX (USD/kWh)	0.874	0.498	0.341
Lithium storage cost in CAPEX (USD/kWh) [46]		150	
Energy storage cost comparison (sedimentary hydro storage vs. lithium storage)	172	301	440

The proposed dam to manage the Bananal sedimentary basin water storage level is the Moveable Hydropower Power Plants (HEPP), as shown in Figure 16. This is a low-head dam in which the upstream level of the reservoir is equal to the level of the river during the wet period. There is no spillway because the water flows above and below the plant during the wet period. This also increases the theoretical head of the plant due to the Venturi effect caused by the spilled water [19]. Another benefit of this technology is that the sediments from the Bananal basin can easily pass through the bottom of the dam with no restriction during the wet period.

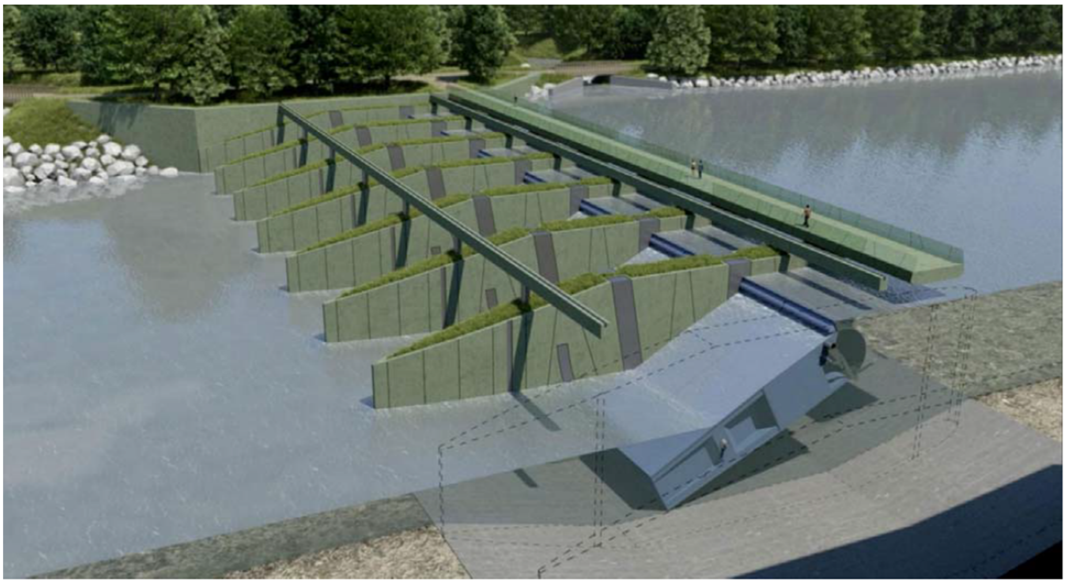

Figure 16. Moveable HEPP, proposed dam for the river basin [19].

Assuming a total construction cost of four billion USD for the Bananal sedimentary basin water storage project, as described in Table 4, the energy cost estimate for the project is 0.341 USD/kWh, which is 440 times smaller than the cost for energy storage in lithium-ion batteries, assuming a battery cost of 150 USD/kWh [46]. Note that the excavation requirements to tap into the water stored in the sedimentary basin in P2 and P3 scenarios should be better assessed in future work.

4. Discussion

Seasonal floods are good for tourism, and fishing occurs during times of flood. On the other hand, large floods cause great damage to the region's environment and economy. These can flood entire cities and make them practically disappear, like in the great flood of Araguaia in 1980, the most severe flood of the 20th century, where cities like Cocalinho and Marabá were submerged, and people with boats carries out several rescues to save residents from the roofs of their houses. The dry months bring undeniable benefits to the region. With the reduction of the river level, river beaches are formed and attract tourists worldwide. Fishing is also an attraction at this time of year, and inns offer complete services for sport fishing lovers. The so-called 'ethnic tourism' also takes place near the municipality of São Felix do Araguaia, where guides take tourists to get to know the indigenous villages of the region, all with the authorization of Justice's National Foundation for Indigenous Affairs (FUNAI) and the indigenous associations themselves. The local economy is greatly benefited at this time of year. Nowadays, the main challenge for the basin is the increase in the severity of the drought in the region during the dry season.

Currently, the world is undergoing a shortage of sand [47]. The sand removed from the dredging of the Araguaia River can be transported by barges during the wet period to the Tucuruí Dam and lowered with the Tucuruí lock and then transported to locations around the world that have a high demand for sand, such as Singapore. To use the Araguaia River as a waterway, rocks at the beginning of the Tucuruí reservoir must be removed. The price for this removal is not significant. Alternatively, a sediment dam could be built close to the river section for dredging, and the sediments can be pumped by water to the sediment dam.

Since the fall of the USSR, there has been strong global lobbying pushed by NGOs, to stop the construction of hydropower around the globe and promote natural gas for electricity generation. Even though developed countries push this lobbying, the developed countries themselves use 60–80% of their hydropower potential, while developing countries in Latin America and Africa use only 10–40% of their hydropower potential. Currently, with the increase in influence from Russia on the global energy supply and the possibility of using hydropower to complement the electricity generation from intermittent sources (solar and wind power) [48–52], the interest in hydropower from Western countries is resuming [53].

Similar water and energy services could be implemented in other sedimentary basins in South America., such as in the Beni, Mamoré, and Yata rivers in Bolivia, the Amazonas River in Brazil and Peru, and the Paraguay River in Brazil, Paraguay, and Argentina. Most rivers in the Amazon basin have water levels varying between 10 to 20 m. Due to this fact, sedimentary basin water storage has a huge potential in the Amazon. For example, the Santo Antônio dam in the Madeira River could be used to manage the water stored in the sedimentary basin surrounding the reservoir. An estimate for other rivers is presented in Table 5.

Table 5. Sedimentary basin energy storage capacity in different rivers in South America.

Sedimentary Basins	Beni, Mamoré, Guaporé & Madeira	Paraguay
Basin area (km^2)	87,500	63,000
Level variation (m)	5 to 20	2 to 3
Water storage (km^3) *	66	19
Average generation head (m) **	72	52.8
Energy storage (TWh)	11.6	2.5

* Assuming a 15% soil porosity. ** Assuming that 60% of the available hydropower generation head is developed.

5. Conclusions

The paper has shown the vast potential for increasing the electricity generation in the Araguaia and Tocantins basin in Brasil with the improved use of the Bananal sedimentary basin capacity for storing water and energy. The paper proposed three different approaches to enhance the sedimentary basin's potential use. The first proposal (P1) adds the dam, which controls the water exiting the basin and allows the water to remain for a longer time in the sedimentary basin. It is estimated an investment cost of two billion USD for this project and an increase in generation of 2.3 TWh yearly. The second proposal (P2) adds the dam and involves the construction of a shallow canal, which allows more water to be extracted from the basin during the dry period and, thus, more water to be stored in the basin. It is estimated an investment cost of three billion USD for this project and an increase in generation of 21.7 TWh yearly. The third proposal (P3) adds the dam and involves the construction of a deep canal, which allows even more water to be stored in the basin. It is estimated an investment cost of four billion USD for this project and an increase in generation of 11.7 TWh yearly. Further potential for sedimentary energy storage of 11.6 TWh was estimated for the Beni, Mamoré, Guaporé & Madeira, and 2.5 TWh for the Paraguay river basin. Sedimentary basin storage has shown to be an alternative to increase hydropower, improve water supply and reduce the impacts of massive flood events that impact both the economy and the environment of the basin.

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