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Energy crisis in Brazil: Impact of hydropower reservoir level on the river flow

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ABSTRACT

Water management strategies can have considerable impacts on the regional climate and hydrology. It is usually the case that the construction and operation of hydropower reduce the river flow downstream due to the increase in evaporation. However, this paper shows that in humid regions, such as in Brazil, the hydropower storage reservoirs contribute to increase the flow of the river. This observation has been tested with historical reservoir levels and river flow data from several dams in Brazil. It was found that the operation of reservoirs in Brazil has a considerable impact on its river flows. The higher the storage level at the beginning of the humid period, the higher the river flow during the wet period. The paper proposes strategies to allow the reservoirs to fill up and to maintain the reservoirs filled in the future, with the intention of increasing hydropower generation and reducing the intermittency of other renewable energy sources.

1. Introduction

Land use can have a substantial impact on the climate and precipitation profile of a region. These impacts can be very diverse. For instance, conversion of forest into agricultural land affects precipitation patterns [1–3], deforestation can affect regional average temperatures [4] as have other impacts [5–7]. Apart from the changes in land use, water consumption patterns, which affect the evapotranspiration of a region, also affect the regional climate [8–10]. A particular area of research that has gained much attention is the impact of agriculture irrigation on regional temperature and precipitation [11–14]. Looking in detail into these studies, it can be concluded that agricultural irrigation increases the humidity of the soil and atmosphere, and, for evaporation to occur, water extracts heat from the air, which reduces the regional average temperature. In other words, land and water management have an important impact on regional climate [15,16]. This correlation between land and water management and climate has even been proposed as a regional adaptation measure for global warming [17] and included in weather forecast models [18].

After the end of the Soviet Union in 1991, the hydropower industry rapidly dwindled and was replaced by natural gas. The current need to reduce CO_2 emissions is giving back the focus on hydropower generation. Even the IEA, has mentioned that hydropower will be a key electricity generation source in the future [19]. Future hydropower projects should be designed to mitigate major ecological impacts and to help countries and basins better cope

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Acronyms

SPHS Seasonal Pumped Hydropower Storage

with vulnerabilities caused by climate change, such as droughts and floods [20,21].

Looking at the impact of large reservoirs on the overall basin flow, large hydropower reservoirs result in high levels of evaporation, which reduces the overall yearly river flow downstream [22–25]. For example, the impact of the Keban Dam in Turkey on precipitation patterns was negligible [26] and the river flow downstream of the dam was reduced due to the evaporation in the reservoir. There are several research projects on the impact of climate change on hydropower generation [27–33]. Other studies on the impact of the hydropower reservoir on the river flow can be seen in Refs. [34–36].

In Brazil, the Southeast region presents two well-defined seasons, of which one is a dry season where relative humidity strongly decreases. Usually, relative humidity is at its minimum from August to the beginning of October, and evaporation peaks. Although this period is long, it occurs when reservoir levels and river flows are at their lowest levels [37], which reduces evaporation losses. During the wet season in the Southeast region in Brazil, the average relative humidity of the atmosphere at the surface is very high, and this considerably reduces the reservoir evaporation. On the other hand, by increasing the regional humidity through evaporation, the evaporation contributes to the increase in precipitation in the region. This paper argues that in the Brazilian Southeast river basins, the larger the hydropower reservoir level, the higher the precipitation in the region and the larger will be the flow of the river. Many studies discuss this point and can be cited to back up this affirmation [38–40], particularly for the São Francisco river in Brazil [41–43].

A recently published study [44] proposed a possible explanation for the impact of reservoirs in humid climates is that, during the wet period, in the Southeast region of Brazil (between November and April), the average humidity is around 70% with low average wind speeds [45]. Thus, the evaporation is low and the additional evaporation contributes to increasing regional precipitation, which ultimately increases the river flow of the reservoir. When the storage reservoirs are full, the flooded area and the soil humidity surrounding the reservoir increase. This increases evaporation rates, which increases the humidity of the air and reduces the temperature of the regional climate. With a more humid and colder atmosphere, when a warm and humid weather system reaches these reservoirs, the chance of precipitation increases. On the other hand, when storage reservoirs are empty, the flooded area and soil humidity surrounding the reservoir is lower. This reduces evaporation rates, which reduces the humidity of the air and increases the temperature of the regional climate. With a less humid and warmer atmosphere, when a warm and humid front reaches these reservoirs, the chance of precipitation reduces. A visual representation of this phenomenon is shown in Fig. 1.

Historically, the Brazilian energy sector has been affected by multiple energy crises of different durations and geographic ranges such as the crises of the years 1924, 1944, 1955, 1964, 1986, 2001 and 2014 [46,47]. In most cases, the causes of crises were associated with climatic conditions, which directly impact the hydro dominant power system of the country. In 2021 this trend is repeating, and the Brazilian Southeast has been suffering a considerable reduction of river flow and hydropower generation, a trend that has initiated in the 2014–2015 drought, as shown in Fig. 2. Fig. 2 presents a comparison between the hydropower potential and the energy stored in the different regions of Brazil. It's well understood and accepted that the level of the reservoirs increases with the increase in precipitation on a weekly an monthly scale.

The objective of this paper is to demonstrate that, on a yearly scale, the reservoir levels have a higher impact on the river flow than the impact of the river flow in the reservoir levels. In other words, if the reservoir is empty, there will be less precipitation in the basin and the river flow will reduce significantly. This is the first paper that analyses the impact of the operation of reservoir levels in the river flow. This paper is divided into four sections. Section 2 presents the methodology implemented in this paper. Section 3 presents the results of the paper. Section 4 discusses the findings of this research. Section 5 concludes the paper.

2. Methodology

The methodology applied in this paper is described in Fig. 3 and consists of the following steps. Step 1 consists of gathering historical data on the reservoir levels and natural river flow of the dams analyzed (Fig. 3a). Natural river flow is an estimation of the river flow assuming that there is no water extraction from the river, water storage, or evaporation in reservoir dams. This allows the natural river flow estimated in 1970 to be compared with the estimated natural river flow in 2020. Note that there might be errors or changes in methodology for estimating the natural river flow during this period. The data sources and other details for the dams selected are described in Table 1. The source of data on the natural river flow of all dams is [48].

Step 2. consists of comparing the dam reservoir level at the end of the dry season (end of October), with the average flow of the following wet season (November to April). The reservoir level in October was selected because it is usually the lowest in the year, and it is just before the wet period starts. The average river flow from November to April (wet period) was selected because, it is close to October, which increases the influence of the level of the reservoir in October, and because it is the period when the river flows is usually at its highest in the Southeast region. These data are then plotted on a graph and a linear regression is created to estimate the impact of the reservoir level in the river flow.

After the impact of the reservoir level in the river flow is estimated, Step 3 consists of calculating the volume of water required to fill up the reservoirs and the energy stored in the reservoirs. These estimations are then used to propose which hydropower plants should be filled first with the objective of reducing the requirement of thermoelectric power plants and CO_2 emissions. A final analysis intends to show the optimum dam reservoir level at the end of October with the intent of maximizing hydropower generation, considering the possibility that water might be spilled without generating hydropower if the reservoirs are too high, and considering different average generation capacity factors during the wet period. This methodology is limited to hydropower dams that have useful reservoir storage capacity. It cannot be applied to run-of-the-river hydropower plants. Additionally, the selection of the monthly reservoir level and average river flow will vary from basin to basin.

Fig. 4 presents the main storage hydropower dams in Brazil, highlighting the dams selected in this study. These dams were selected with the following criteria: i) large dam at the head of the major river, ii) pluriannual reservoir storage capacity, iii) highly seasonal flow with the minimum storage level is reached in October, iv) historical reservoir levels data availability.

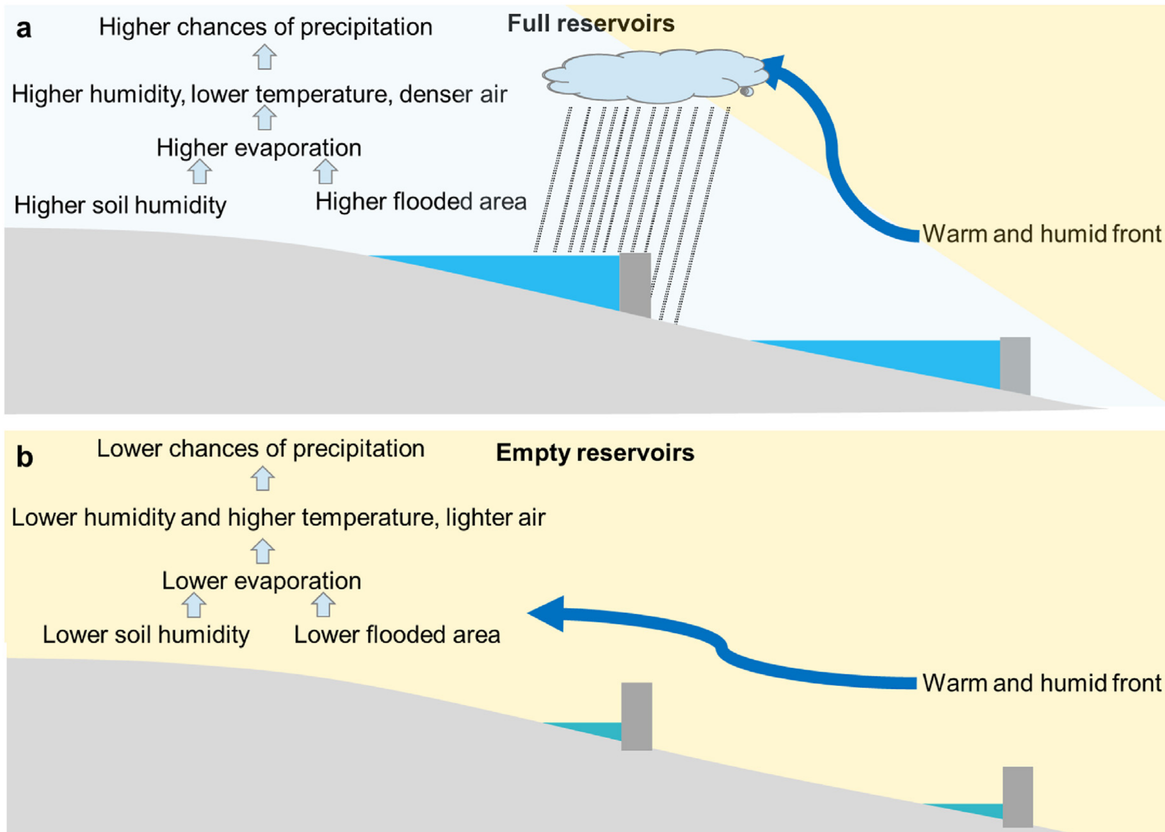

Fig. 1. Diagram explaining the impact of the hydropower reservoir levels on regional precipitation.

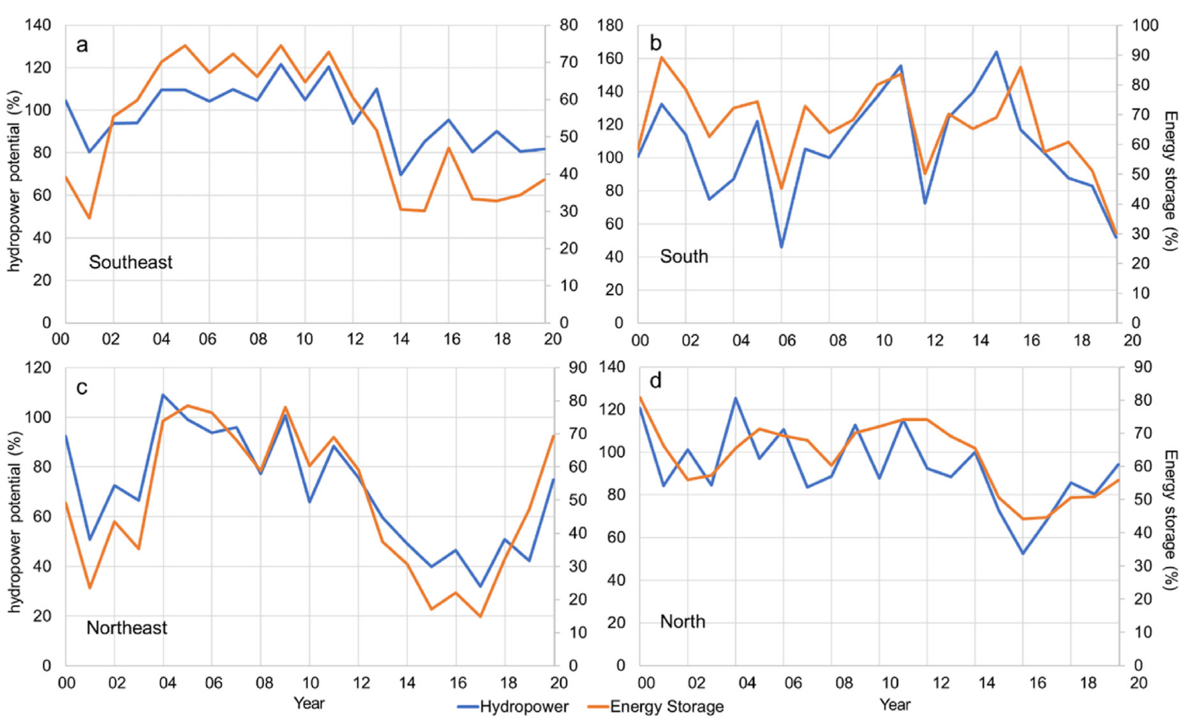

Fig. 2. Comparison between the hydropower potential and the energy stored in the (a) Southeast, (b) South, (c) Northeast and (d) North regions of Brazil (years 2000–2020).

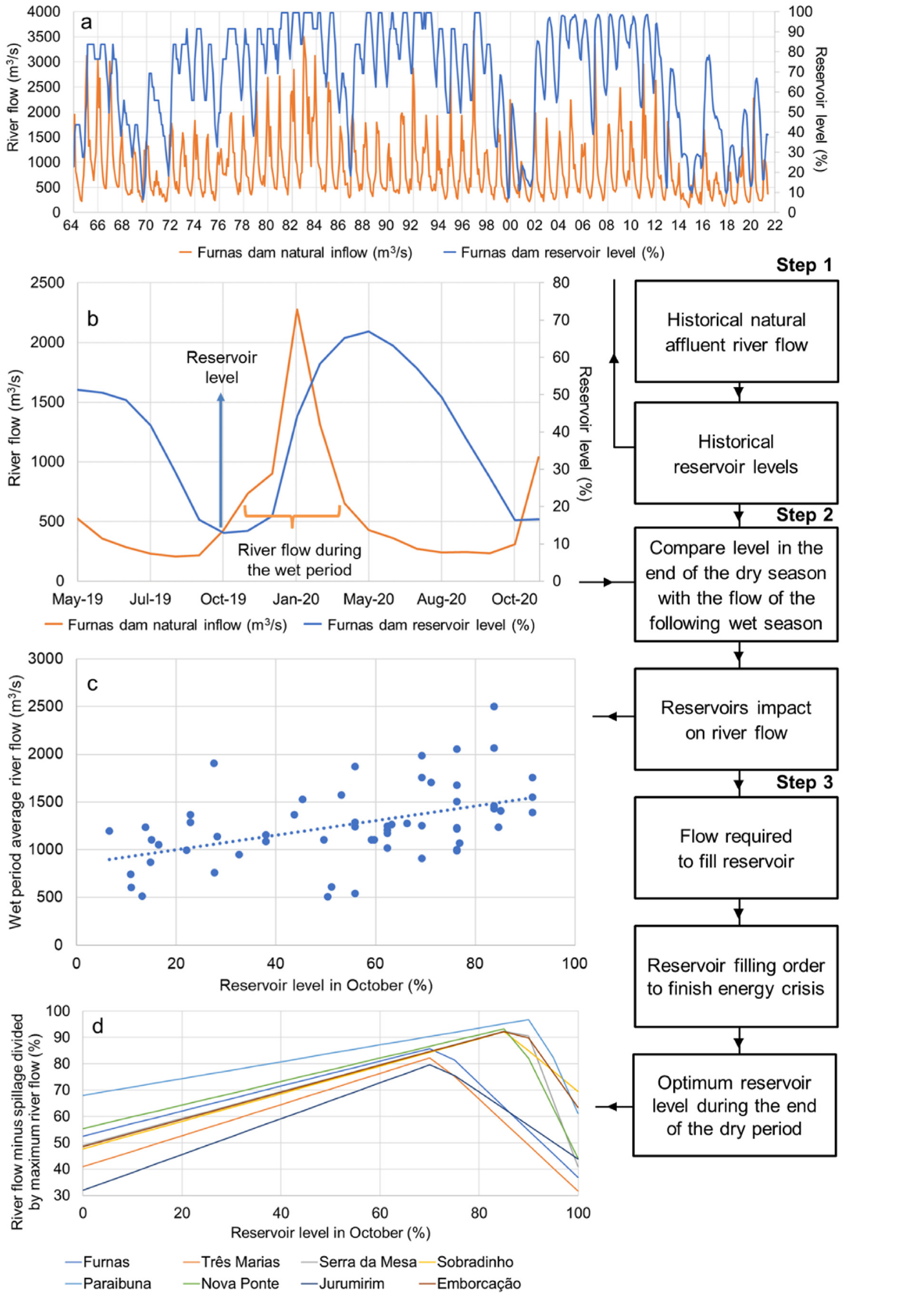

Fig. 3. Flow chart describing the methodology implemented in the paper, highlighting (a) the historical reservoir level and river flow, (b) the data considered in the analysis, (c) comparison of reservoir level and river flow, (d) optimum operational reservoir level.

Table 1
Dam and hydrological data and data sources.

Dams	Reservoir area (km^2)	Reservoir storage (km^3)	River name	Reservoir data from	Reservoir level data source
Jurumirim	450	3.17	Paranapanema	1999	[49]
Três Marias	1064	15.28	São Francisco	1976	[50]
Sobradinho	4196	28.67	São Francisco	1998	[51]
Furnas	1442	17.22	Grande	1972	[52]
Emborcação	478	10.38	Paranaíba	1982	[53]
Nova Ponte	442	10.38	Araguari	1999	[49]
Serra da Mesa	1783	43.25	Tocantins	1999	[49]
Paraibuna	177	2.64	Paraíba do Sul	1993	[54]

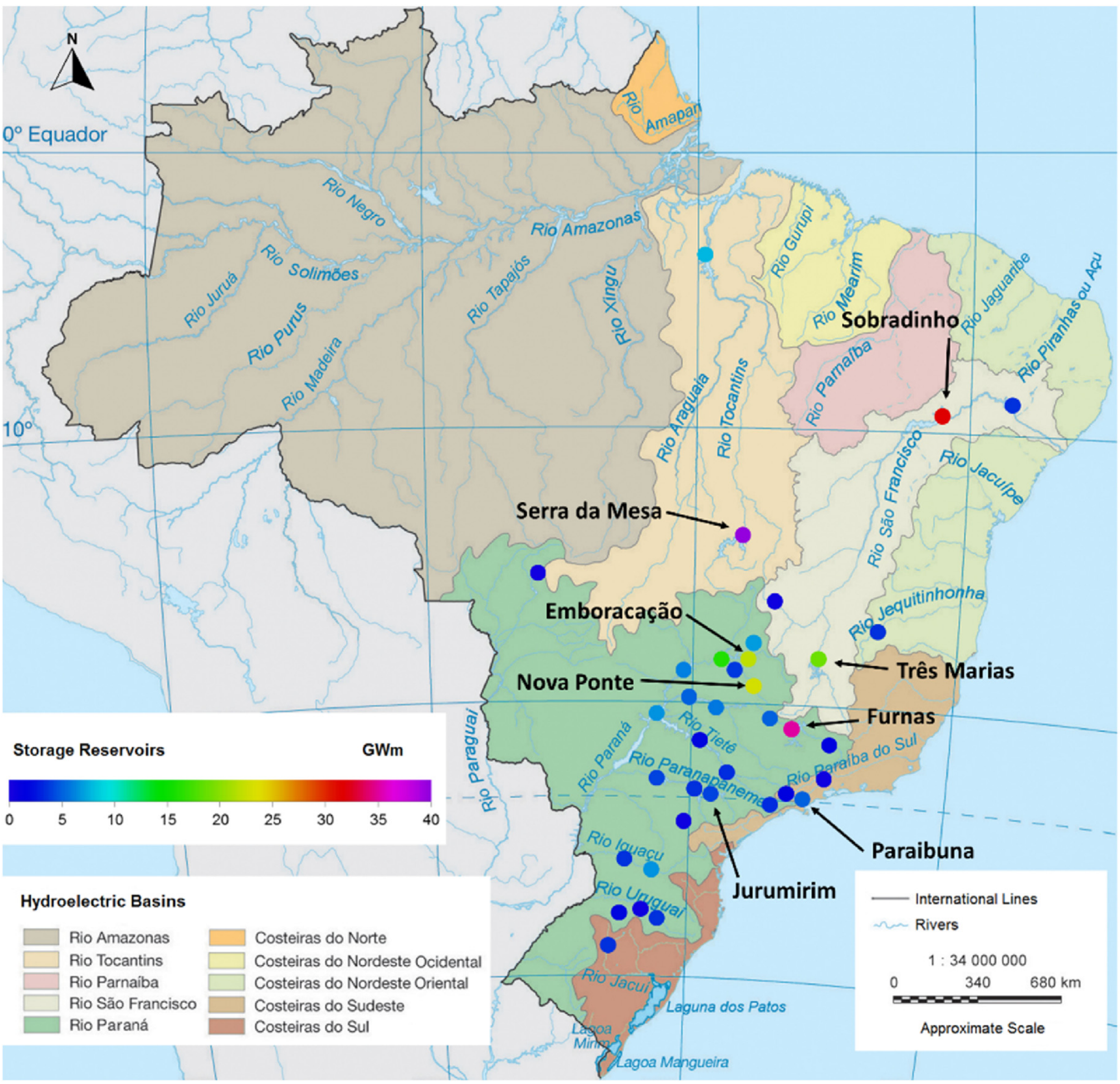

Fig. 4. Main storage hydropower plants in Brazil and dams studied in this paper.

3. Results

Step 2 results are shown in Fig. 5 and Table 2. Fig. 5 presents a comparison between the reservoir level in October and the average wet period river flow in Furnas, Três Marias, Emborcação, Serra da Mesa, Jurumirim, Nova Ponte, Sobradinho and Paraibúna dams. As it can be seen in all dams, the average wet period inflow of the river increases with the reservoir levels in October before the wet period starts. Note that the flow analysis of the figure is the natural river flow, which already removes the influence of water evaporation in the reservoir and other human disturbances to the flow. This results in a good comparison of the river flow, without human disturbances.

Table 2 shows that, on average, the flow of the river in all dams increases 112% if the reservoir is full in October, compared to if the reservoir is empty. The dam that has the highest increase in river

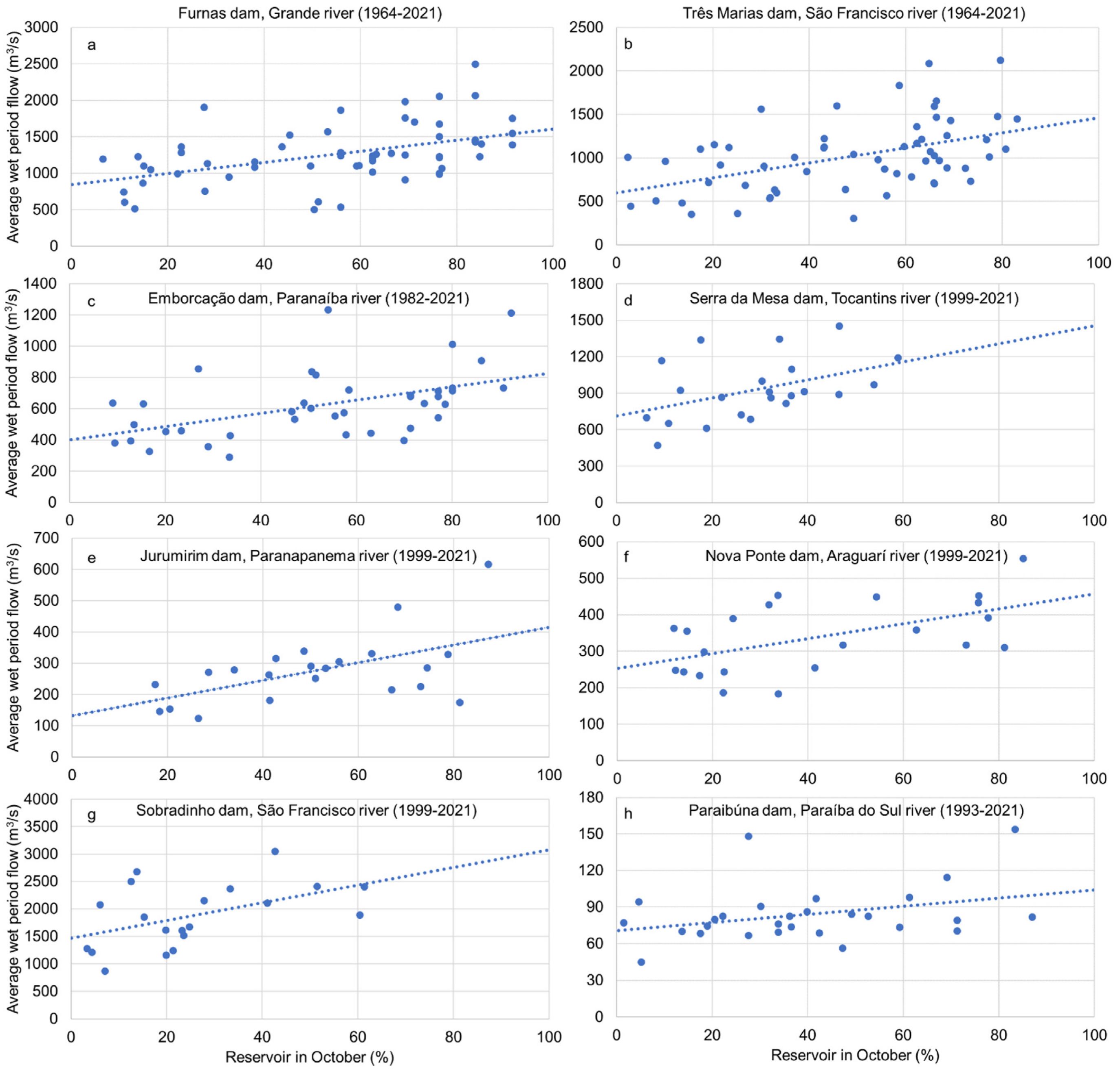

Fig. 5. Comparison between reservoir level in October and the average wet period river flow in (a) Furnas, (b) Três Marias, (c) Emborcação, (d) Serra da Mesa, (e) Jurumirim, (f) Nova Ponte, (g) Sobradinho, (h) Paraibúna dams.

flow with a full reservoir is Jurumirim on the Paranapanema river, which results in an increase of 213% in river flow. The dam that the reservoir level has the least impact on the river flow is the Paraibuna reservoir on the Paraíba river, with an increase in flowrate of 47.1%. The coefficient of determination (R^2) is calculated to estimate the extent to which the reservoir volume in October impacts the average river flow of the wet period. Standard residuals larger than 2 or lower than −2 are removed and the R^2 with no unusual data is also estimated. The dam with the highest and lowest R^2 with and without unusual data is Jurumirim with 0.301 and 0.418 and Paraibuna with 0.113 and 0.143.

Step 3 results are shown in Fig. 6, Fig. 7, Table 3 and Table 4. With the intent of estimating the increasing the hydropower generation, the head of the dam under analysis and the dams in cascade were added. The storage reservoir that has the largest hydropower generation head downstream is Nova Ponte with 641.6 m, as shown in Table 3. The storage reservoir with the smallest generation head out of the selected dams is Sobradinho with 306.9 m. Multiplying this generation head by the increase in river flow in Table 2, the acceleration of gravity and assuming a generation efficiency of 90% the increase in cascade generation is found. The dam with the largest increase in cascade generation with the change in reservoir level in October is Sobradinho dam with an average increase of 4.36 GW during the wet period. The dam with the smallest increase in generation is Paraibuna with 0.09 GW.

An important aspect to plan the order of filling the reservoirs is

Table 2
Increase in river flow with a total change in reservoir level and regression line constants.

Dams	Increase in Flow (%) (full vs empty)	Regression line in Fig. 5 (Y = aX + b)		R^2	R^2 no unusual data >2
		a	b		
Jurumirim	213.1	2.8258	132.6	0.301	0.418
Três Marias	144.7	8.6263	596.3	0.224	0.229
Sobradinho	109.7	16.1032	1468.3	0.240	0.240
Furnas	90.3	7.6322	845.0	0.221	0.302
Emborcação	105.8	4.2475	401.3	0.245	0.281
Nova Ponte	80.5	2.0367	253.0	0.294	0.294
Serra da Mesa	103.9	7.4064	712.9	0.189	0.295
Paraibuna	47.1	0.3327	70.5	0.113	0.143
Average	111.9	–	–	0.228	0.275

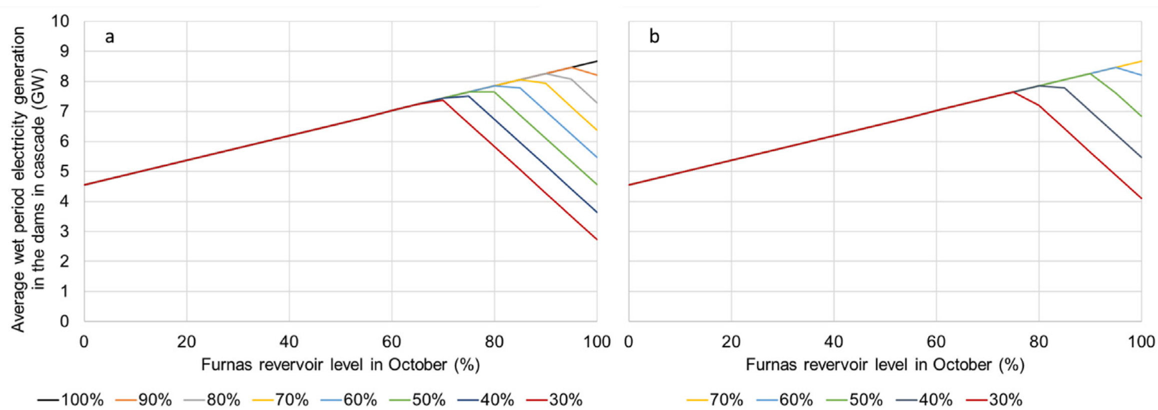

Fig. 6. Average wet period electricity generation in the dams in cascade with different Furnas reservoir levels in October and different generation capacity factors in the dams in cascade (a) with existing installed capacity and (b) with 50% higher installed capacity.

the energy storage capacity of the reservoir dams. If the hydropower generation is reduced to allow the reservoirs to recompose, the supply of electricity for the country will have to come from other sources, or the electricity demand be reduced. Out of the dams analyzed in this study, the one with the highest energy storage capacity is Serra da Mesa with 47.6 GWm (this is energetically equivalent to a power plant generating 47.6 GW of electricity continuously for one month). The dam with the smallest storage capacity in Paraibuna with 3 GWm. The dams that should be filled up first are the ones that will have the highest increase in hydropower generation with the least energy storage requirement. This is found by dividing the "Increase in cascade generation (GW)" columns by the "Reservoir storage capacity (GWm)" column. The higher the values, the higher the priority for filling up the dam.

After all reservoir dams in Brazil are filled up, the focus is to operate the reservoirs with the intention of increasing the river flow as much as possible, but at the same time minimize the losses in flow with spillage. The lower the level of the reservoir in October, the higher the capacity of the dam to store excess river flow and reduce spillage. However, if the reservoir level is too low, then the flow of the river significantly reduces, as shown in this paper. The higher the hydropower generation capacity factor during the wet period, the lower is the spilled flow. Fig. 6 an assumes that Furnas dam operates at 100 to 30% of its generation capacity and shows the average wet period electricity generation in the dams in cascade assuming that the river flow follows the regression lines in Fig. 5 and Table 2. Note that this is an average river flow, thus there will be years with higher flow and years with lower flow, which is not considered in this paper. Methodologies to further minimize spillage are proposed in Refs. [55,56].

Given that the hydropower potential in the future will be used to complement the generation with wind and solar power sources, a good generation capacity of the wet period is around 50% (green line in Fig. 6a and b) [57,58]. In this case, the optimum level of the Furnas dam in October is 80%, assuming the existing generation capacity (Fig. 6a), which results in an average wet period electricity generation of 7.65 GW, and 90% if the generation capacity of Furnas dam and dams in cascade is increased by 50% (average wet period electricity generation of 8.25 GW).

Fig. 7a presents the river flow minus spillage divided by maximum river flow if the dams operate a generation capacity factor of 70%. The maximum value of each dam consists of the optimum reservoir level in October. These values are presented in Table 4. As it can be seen the reservoirs with large storage capacity compared with the river inflow, such as Serra da Mesa Sobradinho and Paraibuna should operate with a reservoir level of 95%. The dam with large inflow and not so large storage potential should operate with 80%, such as Jurumirim. Changing the generation capacity factor to 50%. The dam that should operate with the highest reservoir level is Paraibuna with 95% reservoir storage capacity in October. The dams that should operate with the lowest reservoir level are Jurumirim, Três Marias, Furnas, Nova Ponte 70% reservoir storage capacity.

4. Discussion

4.1. Flood control

One important aspect that should be considered in the operation of the dams and that is not considered in this paper is the use of the storage reservoirs for flood control. This issue is important because a high reservoir level contributes to increasing the river

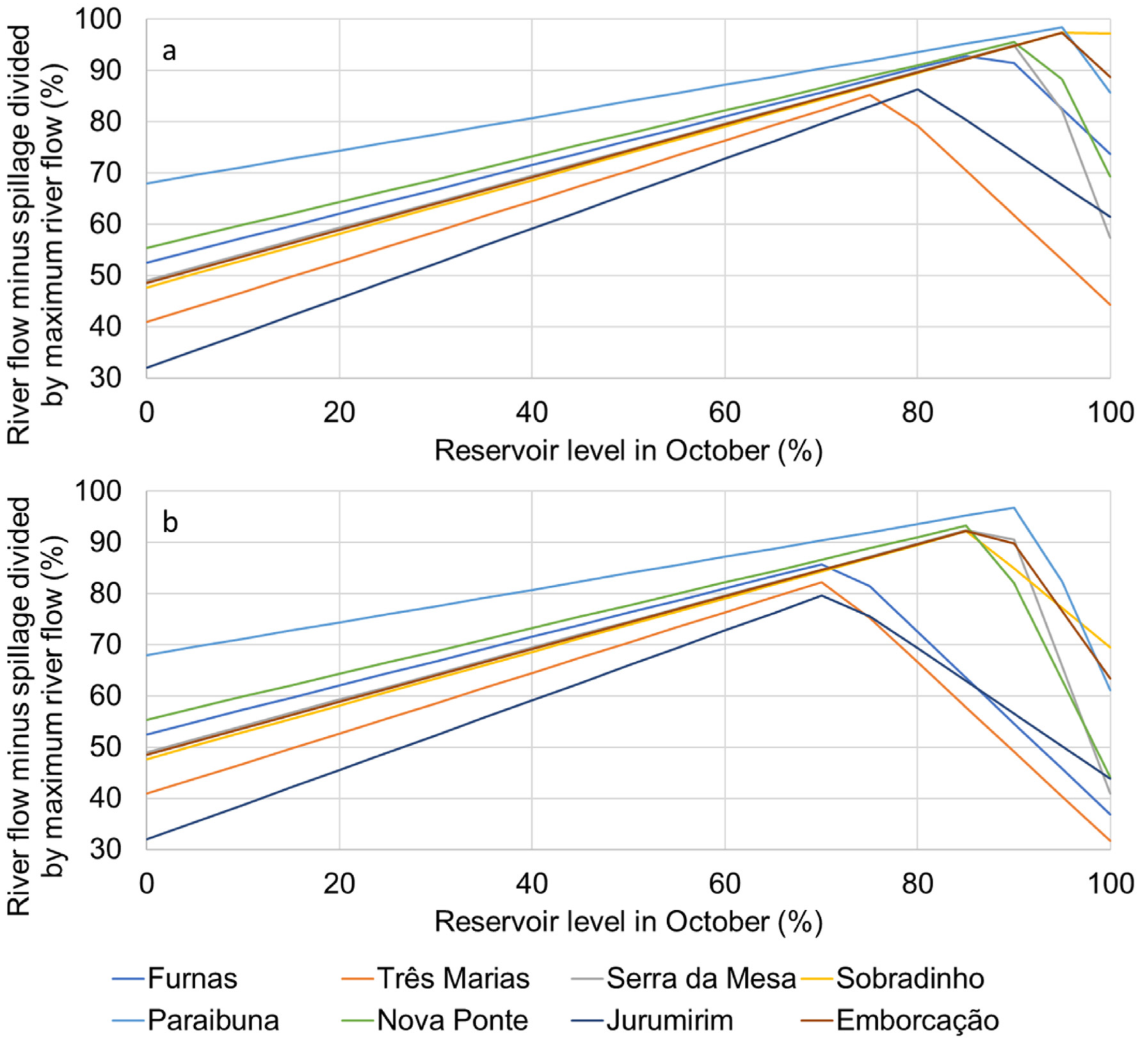

Fig. 7. River flow minus spillage divided by maximum river flow (%), assuming (a) a generation capacity of 70% and (b) generation capacity of 50%.

Table 3
Dam description, analysis and reservoir filling order.

Dams	Generation head, including dams downstream (m)	Increase in cascade generation (GW)	Reservoir storage capacity (GWm)	Increase in generation/storage capacity	Reservoir filling order
Jurumirim	385.30	0.96	4.2	0.229	1
Três Marias	357.1	2.72	18.6	0.146	2
Sobradinho	306.9	4.36	30.0	0.145	3
Furnas	610.25	4.11	35.8	0.115	4
Emborcação	510.15	1.91	22.7	0.084	5
Nova Ponte	641.65	1.15	22.7	0.051	6
Serra da Mesa	323.4	2.11	47.6	0.044	7
Paraibuna	336.7	0.09	3.0	0.030	8
Total	–	17.41	184.6	–	–

flow, as shown in this paper. Further study should be implemented to estimate the minimum storage capacity required to contain large floods in each of the dams analyzed. In Brazil, it is usually assumed that the dam should be kept at a maximum of 90% during normal operation, with the intent of storing large discharges of water during flood events.

4.2. Increase in river flow vs evaporation

The average evaporation over the year for the Sobradinho reservoir operating with the full reservoir throughout the year is estimated to be 269 m^3/s [59]. This is significantly smaller than the increase of 1600 m^3/s in the São Francisco river flow as a result of operating it at a high level at the end of October, as shown in Fig. 8.

4.3. Environmental river flow

It is of utmost importance to always maintain the environmental flow of the river downstream a dam to sustain a balanced aquatic and terrestrial fauna and flora [60,61]. To guarantee that the

Table 4
Dam ideal reservoir level in October with different wet period hydropower generation capacity factors.

Dams	Ideal level in October with 70% capacity factor	Ideal level in October with 50% capacity factor
Jurumirim	80	70
Três Marias	75	70
Sobradinho	95	85
Furnas	85	70
Emborcação	90	85
Nova Ponte	90	70
Serra da Mesa	95	85
Paraibuna	95	90
Average	88	78

required river flow to sustain a healthy environment downstream the dam, the reservoirs should always operate at high levels in case of a drought happens, there will be water to maintain the river flow. Also, as shown in this paper. If the reservoir levels are maintained high, the chance of a drought reduces in the dams analyzed in this paper.

4.4. Power dispatch optimization

Another important reason for maintaining the hydropower reservoirs high is to guarantee that there will be water to operate the existing turbines to supply power to the grid, as shown in Fig. 9a. During the energy crisis of 2014, there was a lack of water in the reservoirs in the Southeast region to guarantee the power demand in the system, which raised alarms for the need for investment in technologies to supply power to the grid such as peaking thermoelectric plants and energy storage solutions. Another example of drought that impacted the capacity of the hydropower dams to supply power requirements in the South region is shown in Fig. 9b. The grid operator should have conserved water in the reservoirs in the South during off-peak hours to guarantee that it could generate hydropower during peak hours.

Brazil has an installed hydropower capacity of over 120 GW to supply a maximum electricity demand of 90 GW. If there is water stored to use the existing hydropower generation capacity, power will not be a problem for a while. This increases, even more, the importance of maintaining the existing hydropower reservoir levels high. Following this rationale, with the supply of water resolved, future power requirements in the country could be supplied with the increase in installed capacity in the existing dams and allow hydropower to complement solar and wind power generation.

4.5. Thermal electricity generation

Brazil has seen a major switch in the regulation in its electricity generation market in 2021. The price of electricity switched from a weekly based cost to an hourly based. This change in regulation also resulted in a change in the operation of thermal electrical power plants. For example, Fig. 10 shows the change in dispatch in the Cuiaba gas-based closed-cycle plant after February 2021, and a comparison with the dispatch of diesel generation. Given that Brazil still has large hydropower reservoirs and generates more than 60% of hydropower, the gas-based closed-cycle power plants in the country should operate as baseload, including during weekends and reduce as much as possible the generation in diesel power plants that have a higher operational cost and CO_2 emissions, and allow the hydropower dams to recompose.

Assuming that the reservoir recomposition will be performed with the operation of an additional 5 GW of thermal electric power plants operating in baseload and the required increase in energy storage in Brazilian reservoirs is 165 GWm, it would take 2 years and 9 months to fill up the storage reservoirs. Note that, during this period when the hydropower plants are generating less than they were intended to generate, regulations should be put in place to guarantee that dam owners' contracts are not breached.

4.6. Seasonal pumped hydropower storage

An option to allow the hydropower reservoirs to operate close to full, with the intention of increasing the river flow, and at the same time reduce the risk of flood and losses with spillage is the construction of seasonal pumped hydropower storage (SPHS) plants in parallel to the main river (Fig. 11a) [62]. SPHS plants extract water from existing hydropower reservoirs dams and pump to a new or

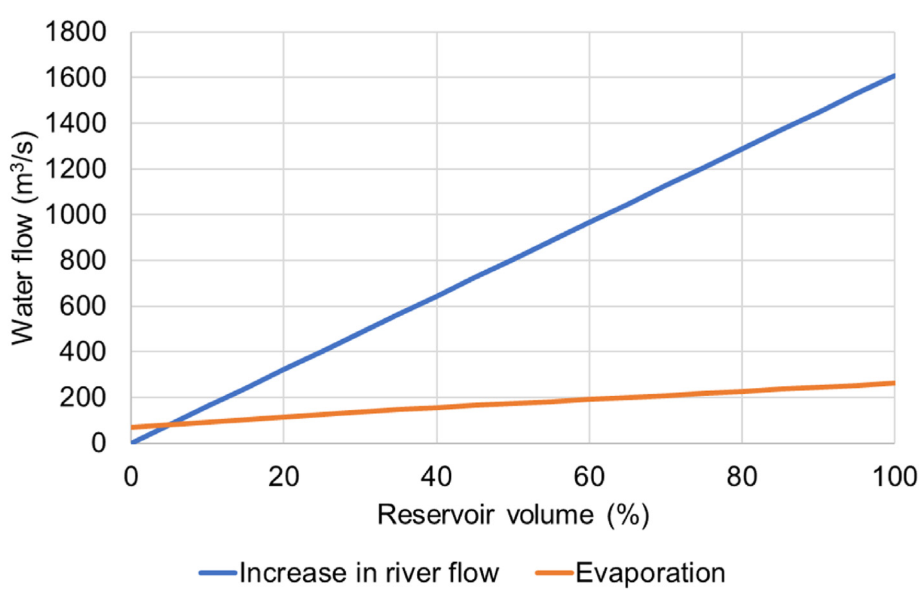

Fig. 8. Comparison between the increase in river flow and evaporation with different reservoir levels.

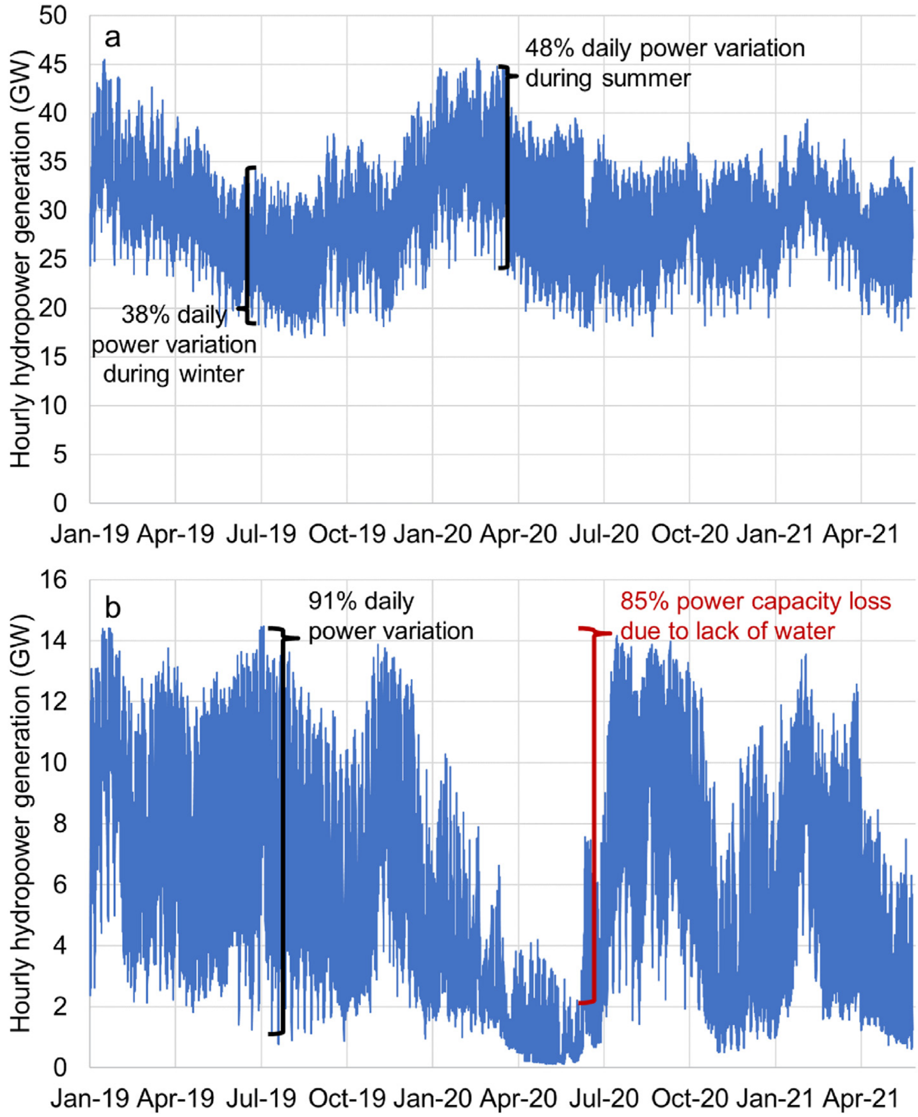

Fig. 9. Power supply with hydropower in the (a) Southeast and (b) South region.

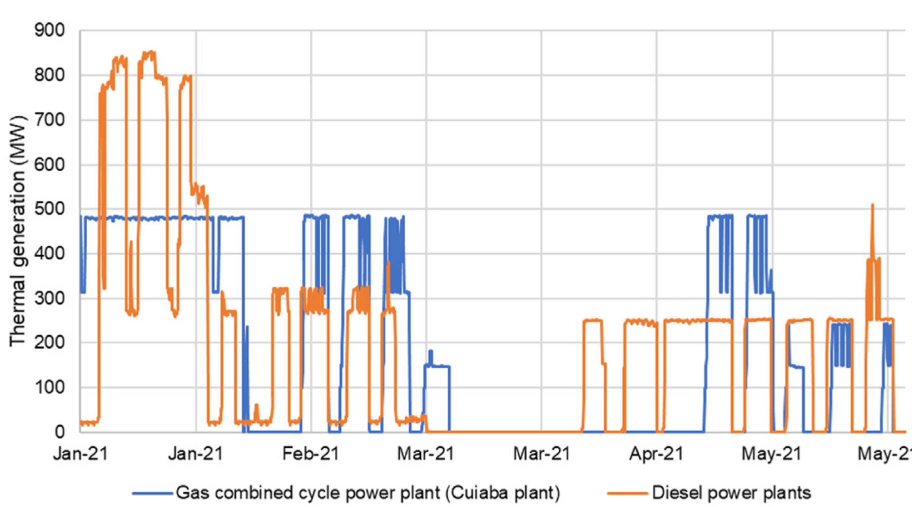

Fig. 10. Thermal electric power generation with gas combined cycle and diesel power plant under the new operational scheme.

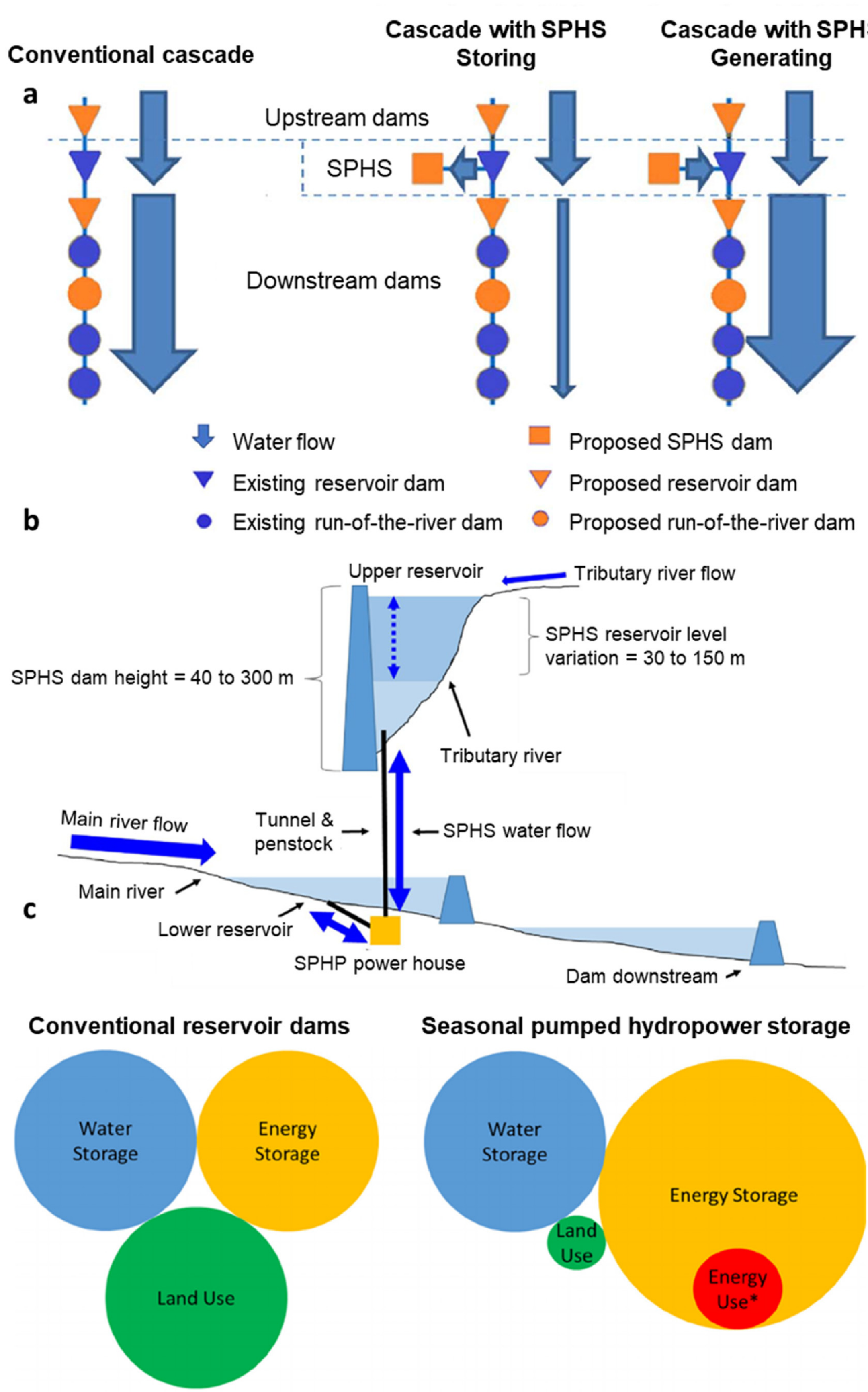

Fig. 11. Seasonal pumped hydropower storage plants (a) represented in a cascade, (b) lateral view and (c) a comparison between water and energy storage, and land use [64] for conventional reservoir dams and SPHS plants.

existing upper reservoir in smaller affluent rivers of the main river (Fig. 11b). Apart from increasing the hydropower generation in the cascade, and water supply for multiple purposes [63], SPHS can be used to store seasonal excess of electricity generation in wind power plants in the Northeast region. SPHS requires a small area to store a large amount of water and energy due to its large reservoir level variation (Fig. 11c [64]). Several SPHS plants have been proposed for Brazilian river basins in Refs. [65–67]. Different newly proposed arrangements for SPHS can be seen on [68]. Another option for storing energy and water seasonally parallel to a major river is with energy crop storage, as shown in Ref. [69].

5. Conclusion

This paper has shown that the reservoir levels of the hydropower plants have a significant impact on the river flow in the Southeast region in Brazil. On average, the impact of the reservoir level in October of the dams analyzed can be as much as an increase in 112% in the river flow. This aspect shows that the river inflow impacts the reservoir level at a weekly and monthly scale, however, looking at a yearly scale, it is the reservoir level that influences the river flow, as shown in Fig. 2.

The dams that should be filled first to reduce the requirement for thermal electricity are Jurumirim, Três Marias, Sobradinho, Furnas, Emborcação, Nova Ponte, Serra da Mesa, then Paraibuna. After the reservoirs are filled up, the average level of the reservoirs at the end of October should be 78% and the hydropower plants in cascade should operate with a capacity factor of 50%. This low capacity factor will allow the hydropower potential to generate electricity when there is no solar or wind power in the grid. Which in turn allows more solar and wind power to be added to the grid without the need for new storage solutions.

Brazil has a large potential for hydropower, which has not been explored to its fullest since the drought in 2014 and 2015. The country should focus on generating thermoelectricity, solar and wind power, and conserving energy to allow the reservoirs to rise so that the country can generate more hydropower with existing dams, reduce its electricity costs and reduce CO_2 emissions from thermal electricity sources.

Credit author statement

Conceptualization, writing original draft preparation J.H.; Data curation, Formal analysis, N.W.; writing review and editing, Methodology, B.Z.; Data curation, Visualization, A.D.; Investigation, P.B.; Project administration, Funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript. Julian Hunt: Conceptualization, writing original draft preparation; Andreas Nascimento: Writing – review & editing; Carla Schwengber ten Caten: Methodology Fernanda Tomé; : Data curation; Paulo Schneider: Software; André Thomazoni: Investigation; Nivalde Castro: Project administration; Roberto Brandão: Supervision; Marcos Freitas: Resources; José Martini: Validation; Dorel Ramos: Formal analysis; Rodrigo Senne: Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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