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Optimizing hydropower generation with reservoir level management in humid regions

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ABSTRACT

It is well known that water management practices can have a significant impact on the climate and hydrology of a region. As a rule, the average flow downstream decreases due to the construction of new hydropower plants and the operation of new dams, as evaporation increases in the upstream dams. However, this is not the case in every situation. This study shows that dams in humid areas such as Brazil can help to increase river flow. This phenomenon occurs due to the high humidity and low wind conditions in the region, which leads to low evaporation in the reservoirs. At the same time, full reservoirs help to maintain high humidity around the reservoirs, which increases precipitation in the catchment. To test this hypothesis, water storage and hydropower generation data from Brazilian catchments in the Southeast region were used. Reservoir data are compared with future hydropower generation to investigate the correlation between the two variables. We find that the operation of reservoirs has a significant impact on Brazilian river flows. On average, the annual hydropower potential of a catchment with a full reservoir is 111 % higher than with empty reservoirs. To increase the flow of the river, the study proposes solutions to fill the reservoirs after an energy crisis and keep the reservoirs at full capacity.

1. Introduction

Land and water management can have a significant impact on the climate and precipitation in a region. These effects can vary greatly. Regional climate is influenced by changes in land use and water consumption, which affect evapotranspiration in a region (Zou et al., 2018; Liu et al., 2018; Hunt and Leal Filho, 2018). The effects of agricultural Irrigation on local temperatures and precipitation have attracted much attention in specific research areas (Kueppers et al., 2007; Chen and Dirmeyer, 2019; Chen and Jeong, 2018; Thiery et al., 2017). Agricultural irrigation increases soil and air moisture. Since evaporation requires the removal of heat from the atmosphere by water, it lowers the average temperature in the region. Therefore, some experts propose a regional climate change adaptation strategy (Hirsch et al., 2017) to address this relationship between land and water management and climate (Li et al., 2018).

Considering the war in Ukraine and the global rise in natural gas prices, renewable energy generation in the form of hydropower is attracting a lot of attention, particularly due to its high operational flexibility and low CO_2 emissions. In this sense, the International Energy Agency (IEA) has recognized that hydropower will play a pivotal role in the future of electricity generation (IEA, 2021). Future hydropower projects should be planned to reduce significant environmental impacts and help to better cope with climate change-related vulnerabilities such as droughts and floods (Kuriqi et al., 2020, 2021).

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Nomenclature

ANE	Affluent Natural Energy
IEA	International Energy Agency
R^2	Coefficient of determination of a linear regression
SPHS	Seasonal Pumped Storage Hydropower Plants

Water evaporation is a natural phenomenon in hydropower plants that can reduce downstream flow (Zhang et al., 2015; López-Moreno et al., 2014; Beilfuss, 2010; Digna et al., 2018). For example, a recent study has shown that the construction of the Keban dam in Turkey had little effect on precipitation patterns and reduced river flow downstream of the dam due to high evaporation in the reservoir, among other reasons (Downing et al., 2006). This makes hydropower optimization a critical matter in such regions (Coban and SAUHATS, 2022). However, this is not the case in very humid regions, such as southeastern Brazil. In this region, there are two distinct seasons. One is a dry season in which the relative humidity drops sharply. This occurs when the water levels of the rivers and reservoirs reach their lowest point between May and October (Althoff et al., 2020).

Conversely, the relative humidity is particularly high during the rainy season. Evaporation in the reservoirs helps to maintain the high humidity and increases regional rainfall (Hunt et al., 2020a, 2022). It has been shown that the construction of reservoirs in southeastern Brazil has helped to increase the river flow of the Itaipú reservoir in the Paraná basin by an average of 30 % (Hunt et al., 2020a). The operation of these reservoirs also has a decisive influence on the average flow of the river upstream of the dam (Hunt et al., 2022). The hypothesis that water levels in reservoirs increase rainfall frequency, consequently, the runoff in the southeastern region of Brazil is less intuitive. Still, it has been confirmed in a few studies (Degu et al., 2011; Duerinck et al., 2016; Lathuilliere et al., 2016), focusing particularly on the Brazilian São Francisco River (Santana et al., 2020; Barreto et al., 2017, 2019).

The effects of reservoirs in humid climates can be explained by the fact that the average humidity between November and April, during the rainy season in southeastern Brazil, is around 70 %. The average wind speed is low, consequently leading to little evaporation (INPE, 2019). Any additional evaporation helps to increase rainfall in the region, which in turn increases the runoff from the reservoir. The flooded area and soil moisture around reservoirs increase as they fill. This increases the rate of evaporation, which increases humidity and lowers the temperature of the local climate. When a warm, humid weather front approaches these reservoirs in an environment with higher humidity and lower temperatures, the likelihood of precipitation increases (Hunt et al., 2022).

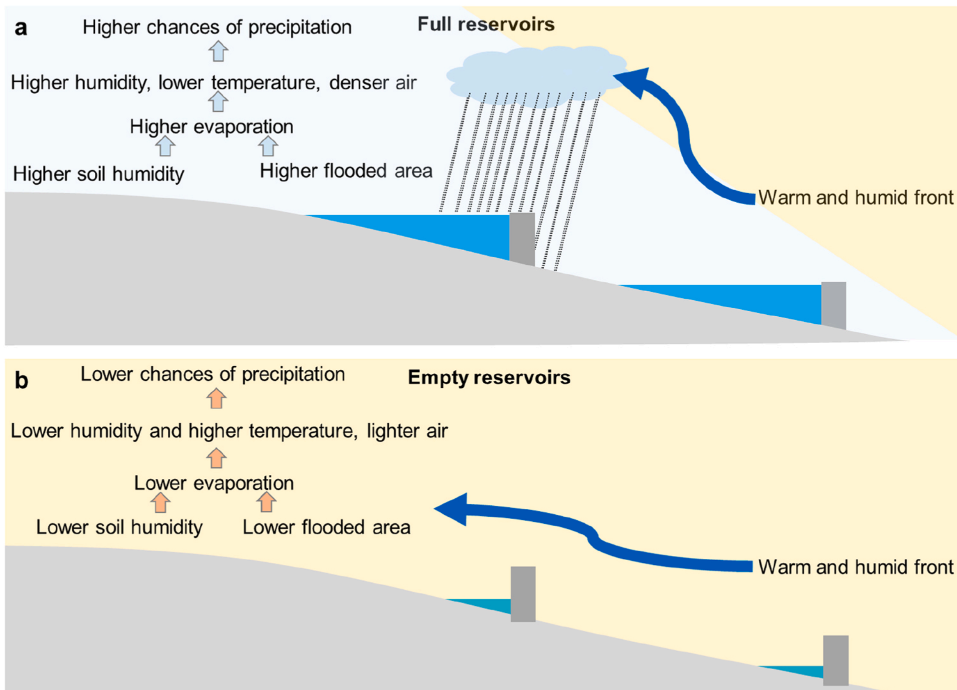

Fig. 1. Diagram illustrating how hydroelectric reservoir levels affect local precipitation.

Conversely, the flooded area and the surrounding soil moisture are lower when the useful volume of the reservoir is empty. This reduces the evaporation rate, which lowers the humidity and warms the local climate. The likelihood of precipitation decreases as the atmosphere becomes warmer and less humid when a warm, humid front approaches these reservoirs; Fig. 1 illustrates this phenomenon in a simplified way.

To the best of our knowledge, this study aims to show, for the first time, the impact of reservoir storage levels on the average total hydropower generation of the respective catchments in the southeastern region of Brazil. This study identifies the possible reasons for these effects. The research gap consists of extending the method presented in (Hunt et al., 2022), that investigates the impact of reservoirs on the river flow, improving it and applying it to entire basins instead of individual hydropower plants, and comparing hydropower generation instead of river flow. This article brings a new look to the existing literature in the following areas: (i) impact of land use and water management in regional climate, (ii) land, water and energy nexus, (iii) climate vulnerability and (iv) climate change adaptation. The study consists of five sections. The methods used in this paper are presented in Chapter 2. Chapter 3 describes the results of experimental research along with their interpretation. Chapter 4 discusses the findings from this study and policy implications, indicating their limitations, practical application and future work. Chapter 5 presents the final conclusions of the research.

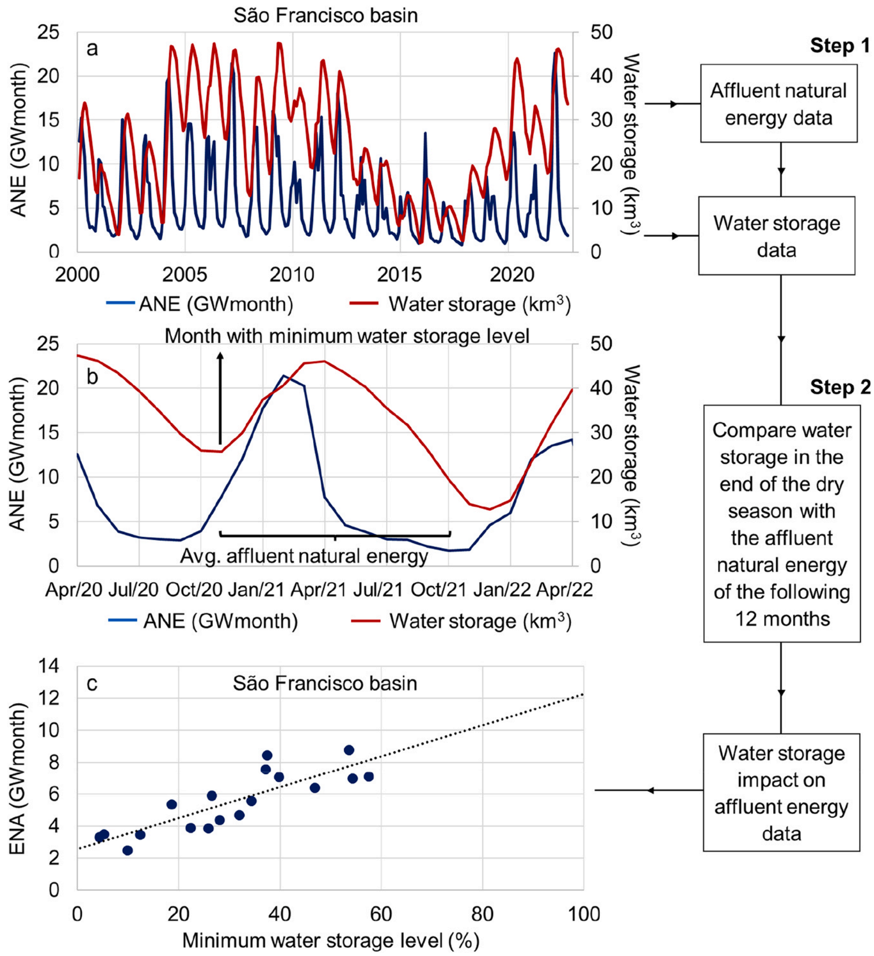

Fig. 2. Flow chart describing the technique used in the study, showing a) the historical levels of the reservoirs and rivers, b) the data used for the analysis, and c) a comparison of the levels of the reservoirs and rivers.

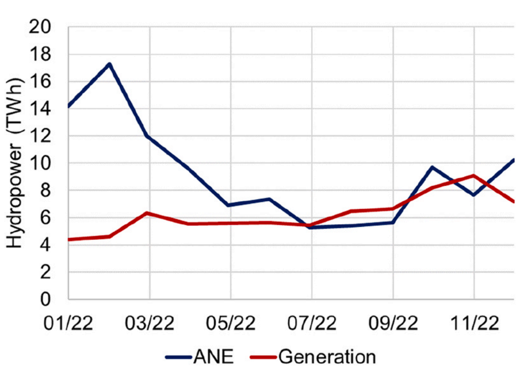

Fig. 3. Comparison between ANE and hydropower generation in the Paraná River in 2022.

2. Methodology

The methodology used in this work is described in Fig. 2 and consists of the following steps. In step 1, historical data on the water storage volume and the inflowing natural energy of the analyzed catchments are collected (Fig. 2a). The reservoir storage volume and the inflow of natural energy (ANE) data were taken directly from (Brazilian National Electric System Operator, 2021) without any further processing. The ANE estimates the hydropower potential that could be extracted from the river course with existing hydropower plants, no water is withdrawn from the river, no water is stored in the reservoir, and no evaporation occurs in the reservoirs. It is assumed that the reservoirs operate as run-of-river power plants, i.e., that the water inflow is always equal to the water outflow. ANE is a variable calculated by the Brazilian government to estimate the hydropower potential of a catchment area so that the national hydrological models can optimize the operation of hydropower plants in the Brazilian power grid. For reasons of convention in Brazilian legislation, the ANE calculation assumes that the existing dams generate electricity when their reservoirs are 65 % full (Silveira et al., 2016). This fixed value is used to intentionally disregard possible effects of the operation of the dams when estimating ANE. It is also assumed that all the water flowing through the dams in the catchment is used to generate electricity, even if there are not enough turbines installed in the dams to generate electricity from the water (da Silva et al., 2021). To illustrate the difference between the ANE and the actual electricity generation from hydropower, look at Fig. 3.

As you can see, hydropower generation at the beginning of 2022 was significantly lower than the ANE. This is because the reservoirs of the Parana Basin were very low, and it rained a lot in the Parana Basin. The difference between the ANE and the actual generation primarily shows the amount of energy that was stored in the Paraná Basin at the beginning of the year. The Paraná River consists of the Itaipú, Porto Primavera, Jupiá, and Ilha Solteira dams.

In step 2 (Fig. 2b), the month with the lowest water level in the basin is determined, which varies from August to December. The minimum reservoir level is compared with the average ANE for the following 12 months (i.e., from November to October of the following year) to determine the impact of the reservoir level on the river flow. This data is then plotted on a graph, and a linear regression is developed. It is as if

Table 1
Basins considered in this study and their respective reservoirs.

Basins	Reservoir dams
São Francisco	Queimados, Retiro Baixo, Três Marias, Sobradinho, Itaparica
Paranaíba	Nova Ponte, Serra do Facão, Batalha, São Simão, Emborcação, Itumbiara, Miranda, Corumbá, Corumbá III, Corumbá IV, Caçu, Barra dos Coqueiros, Espora
Grande	Camargos, Furnas, Mascarenhas de Moraes, Marimbondo, Água Vermelha, Caconde
Tietê	Billings, Guarapiranga, Ponte Nova, Barra Bonita, Promissão, Três Irmãos
Paranapanema	Jurumurim, Chavantes, Capirava, Mauá
Paraíba do Sul	Paraibuna, Santa Branca, Jaguani, Funil

the level of the reservoirs can predict the future hydropower potential of the catchment. The following criteria were used to select these dams: catchments with large reservoirs at the headwaters of the main river and highly seasonal runoff, with the lowest reservoir level reached at the end of the southeastern dry season. Table 1 shows the catchment areas considered in this study and their respective reservoirs. In summary, the methodology consists of a simple regression analysis comparing the minimum level of the reservoir at the end of the dry period with the average hydropower generation for the next 12 months, using data from the last 23 years of the selected basins.

3. Results

Results from Step 2 are displayed in Fig. 4 and Table 2. Fig. 4 compares the average ANE in the São Francisco, Paranaíba, Grande, Tietê, Paranapanema, and Paraíba do Sul basins (i.e., from November to the following October) with the reservoir minimum reservoir level at the end of the dry period (i.e., August to January). As seen in all basins, the higher the reservoir levels just before the wet period begins, the higher the ANE of the following year. The basin power generation potential is closely related to the basin inflow and the regulation capacity of cascade reservoirs. For a certain level year, the overall regulation capacity of the basin's reservoirs is the main reason for increasing the power generation potential.

Table 2 shows that the ANE of the Southeast region would increase by 110 % on average when comparing the reservoirs full or empty at the end of the dry season. The São Francisco catchment causes a 230 % increase in ANE, making it the catchment with the largest increase in ANE when the reservoir is full. The Paraiba do Sul catchment, with a 31.7 increase in flow, is the catchment where the reservoir level has the least impact on hydropower. This could be due to its proximity to the ocean. To determine the extent to which the reservoir affects the typical river flow during the rainy season, the coefficient of determination (R^2) is calculated. The R^2 without anomalous data is also estimated after eliminating standard residuals greater than 1 or less than −1.

The outliers were set to 1 because this removes unusual climate patterns, such as strong El Nino and La Nina years, from the data. São

Table 2
River flow increases with overall reservoir level change and regression line constants.

Basins	Increase in ANE (%) (full vs empty)	Regression line in Fig. 4 (Y = aX+b)		R^2 no unusual data > 1	R^2
		a	b		
São Francisco	230.1	0.0643	3.3722	0.6116	0.2647
Paranaíba	112.5	0.0351	3.099	0.5277	0.2332
Grande	75.5	0.0245	3.2450	0.4952	0.2170
Tietê	40.6	0.0095	0.6757	0.1620	0.0433
Paranapanema	173.4	0.0152	0.8766	0.4906	0.1677
Paraíba do Sul	31.7	0.0023	0.7264	0.2709	0.1125
Average	110.6	-	-	0.4263	0.1731

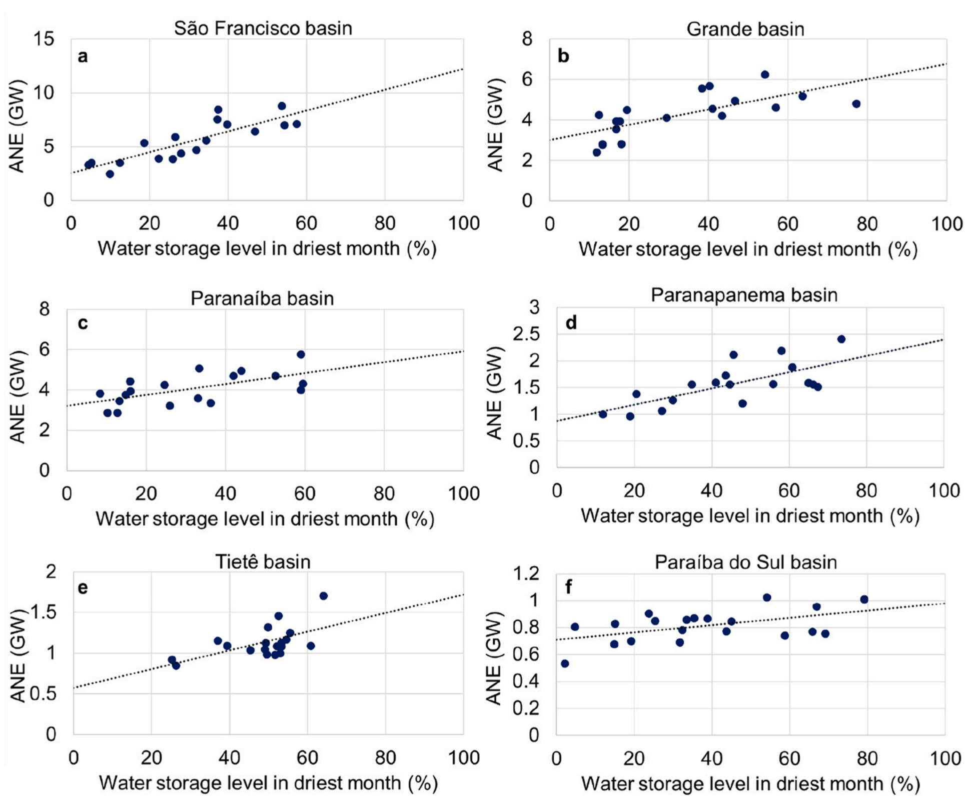

Fig. 4. Comparison of the month with the lowest water level and the average ANE of the following 12 months in the São Francisco, Grande, Paranaíba, Paranapanema, Tietê and Paraíba do Sul catchment areas.

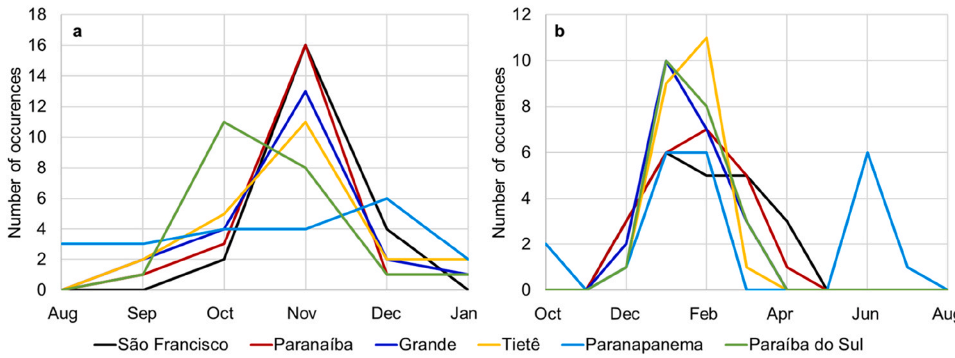

Fig. 5. Number of occurrences of the (a) month with minimum water storage level and (b) maximum ANE per basin.

Table 3
Description, evaluation, and reservoir filling sequence for a dam (ONS, 2013).

Basins	Reservoir maximum surface area (km^2)	Reservoir area variation (km^2)	Basin area (km^2)	Reservoir storage: water (km^3)	Reservoir storage: energy (TWh)	Increase in generation capacity with full reservoir (GW)	Increase in generation/storage capacity (GW/TWh)	Reservoir filling order
São Francisco	6164	4010	641,000	48.0	39.5	7.02	0.177638	1
Paranaíba	5437	3504	223,000	45.1	48.5	3.51	0.0724	4
Grande	2891	1669	143,000	31.3	40.1	2.45	0.061103	6
Tietê	1752	545	72,000	9.5	9.5	0.95	0.099628	3
Paranapanema	1509	506	100,800	12.6	9.4	1.52	0.162334	2
Paraíba do Sul	299	147	56,500	4.3	3.4	0.23	0.06813	5

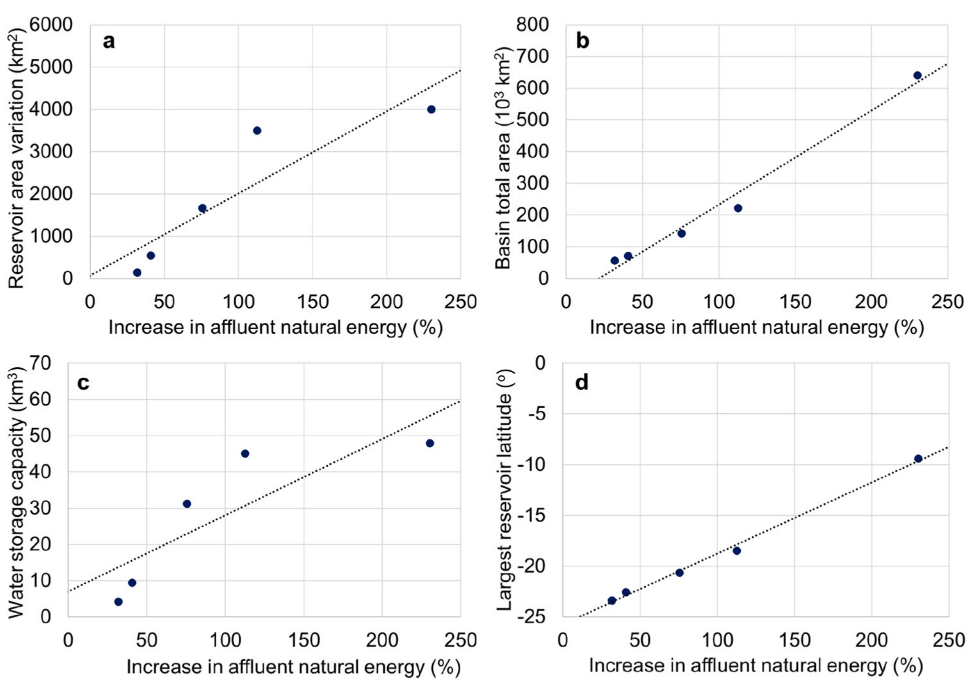

Fig. 6. Correlation between (a) the change in the catchment area (R^2=0.8121), (b) total catchment area (R^2=0.9831), (c) catchment water storage capacity (R^2=0.7147), (d) latitude of the largest catchment (R^2=0.9954) and the increase in ANE.

Francisco and Tietê have the highest and lowest R^2 values with and without atypical data at 0.62 and 0.26 and 0.16 and 0.04, respectively. Fig. 5 shows the number of occurrences per month with minimum water level and maximum ANE per basin. The driest month with the most occurrences for São Francisco, Paranaíba, Grande, and Tietê was November, for Paranapanema was December and for Paraíba do Sul was October. The highest ANE months with the most occurrences for São Francisco, Grande, and Paraíba do Sul was January, for Paranaíba and Tietê was February, and for Paranapanema there are six occurrences in January, February and June.

As shown in Table 3, São Francisco is the catchment with the greatest variation in the reservoir area, i.e., maximum reservoir area minus minimum reservoir area, catchment area, water storage capacity, and increase in power generation when the reservoir is full (from Fig. 4). The Paranaíba catchment is the catchment with the largest energy storage capacity. The basin whose hydropower generation increased the most

Table 4
Comparison between the impact of reservoir levels in the hydropower generation of a basin and the river flow of a reservoir.

Basin level			Reservoir level (Hunt et al., 2022)		
Basin	Increase in ANE (%) (full vs empty)	R^2	Reservoir	Increase in river flow (%) (full vs empty)	R^2
Paranapanema	173.4	0.1677	Jurumirim	213.1	0.301
São Francisco	230.1	0.2647	Três Marias	144.7	0.224
Paranaíba	112.5	0.2332	Emborcação	105.8	0.245
Grande	75.5	0.217	Furnas	90.3	0.221
Paraíba do Sul	31.7	0.1125	Paraibuna	47.1	0.113
Average	110.6	0.1731	Average	120.2	0.2208

with the filling level of the reservoir is São Francisco, with an average increase of 7.02 GW. Paraíba do Sul is the dam with the smallest increase in generation at 0.

The ability of dams to store energy is an important factor in determining the order in which reservoirs should be filled. The country's electricity supply must come from other sources, or electricity demand must be curtailed when hydropower generation is reduced to allow the reservoirs to refill. The Paranaíba basin has a maximum energy storage capacity of 48.5 TWh. The Paraíba do Sul catchment area has the lowest storage capacity at 3.4 TWh. The catchment area that increases hydropower generation the most and, at the same time, requires the least energy storage capacity should be filled first. To determine this, the columns "Generation increase with full reservoir (GW)" and "Reservoir storage: Energy (TWh)" are mixed up. The priority for filling the reservoir increases as the values increase. Thus, the basins that should be filled first are São Francisco, then Paranapanema, then Tietê, then Paranaíba, Paraíba do Sul, then Grande.

Fig. 6 shows the relationship between the increase in ANE of all basins analyzed, except for the Paranapanema basin. The Paranapanema basin was excluded because it is located between the South and Southeast regions and has different climate dynamics than the other five regions. Fig. 6 shows that the greater the variation in catchment area, water storage capacity, and catchment latitude, the greater the impact of water levels in the catchments. This means that (i) the larger the area variation of the reservoirs in the basin, the greater the impact of reservoirs on climate and hydropower generation, (ii) the larger the total reservoir area of the basin, the greater the impact of reservoirs on climate and hydropower generation, (iii) the larger the total volume storage capacity of the basin, the greater the impact of reservoirs on climate and hydropower generation, and (iv) the higher the latitude of the catchment, the greater the impact of reservoirs on climate and hydropower generation, These correlations contribute to further highlight the impact of that reservoirs have in the regional climate. It can also be assumed that the construction of new reservoirs in the region would increase the river flow of these basins.

4. Discussion

This paper examined the impact of several reservoirs in a catchment on future hydropower generation in that catchment. In a recent study, the impact of a reservoir on the discharge of its downstream reaches was investigated (Hunt et al., 2022). Table 4 compares the catchment study in this study with the study on individual reservoirs in (Hunt et al., 2022). Fig. 7(a) shows that the increase in inflowing natural energy for the catchment level is like the increase in river flow in the individual reservoirs in the Paraíba do Sul, Grande, Paranaíba, and Paranapanema catchments. However, it is clearly different in the São Francisco catchment. This could be because the São Francisco basin has two large reservoirs, Três Marias and Sobradinho. Sobradinho is a larger reservoir located in the northeastern region, while the Três Marias reservoir is located in the southeastern region.

Fig. 7b shows that the R^2 is similar in the basins of Paraíba do Sul, Grande, Paranaíba, and São Francisco. However, it is significantly different in the Paranapanema basin. This might be because the Paranapanema basin has three other large reserves (i.e., Chavantes, Capivara, and Mauá). Mauá is also located in the South region, which has different climate dynamics compared to the Southeast region.

The analysis of the basin linear regression indicator shows a weak correlation between the variables, and the data points are rather small. Thus, these results should be carefully analyzed. Filling the reservoirs is a challenge. This is due to the feedback loop: low reservoirs lead to low river flows. In addition, environmental flow is needed to maintain the ecosystem between reservoirs. Therefore, any inflow higher than the environmental flow should be used to fill the reservoirs. Once all Brazilian reservoirs are filled to the maximum at the end of the rainy season, the focus will be on operating the reservoirs to maximize river flow while minimizing river losses due to overflow. The capacity of the catchment to store more flow and reduce overflow losses increases with low reservoir levels. However, this study shows that the natural flow of the river is greatly reduced at a low reservoir level. The optimal minimum reservoir level, which increases hydropower generation and minimizes runoff, varies from basin to basin and from year to year. However, it can be assumed to be between 60 % and 70 % (Hunt et al., 2022). Each reservoir should also always maintain a certain storage capacity for flood control downstream of the dam. Once the reservoir is filled, maintaining the ecological flow is no longer a challenge as water availability in the catchment increases significantly.

One disadvantage of very high reservoir levels is that the increase in precipitation will also increase the risk of flooding in the catchment area. For example, 1981 was the only year in October when the reservoirs in the southeastern region of Brazil were almost 100 % full. This was done to accelerate the filling of the Itaipú reservoir (i. e., Brazil's largest hydroelectric power plant) (Fernandes Franciscato et al., 2022).

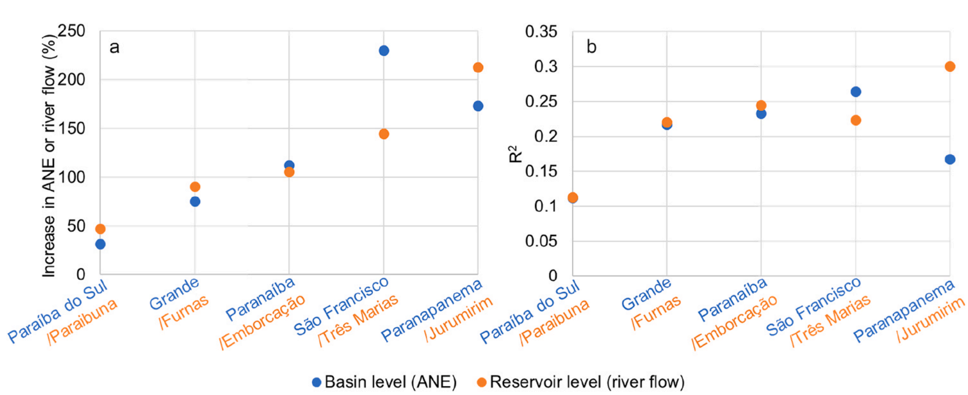

Fig. 7. Comparison between the basin and individual reservoir levels and their (a) increase in affluent natural energy and (b) R^2.

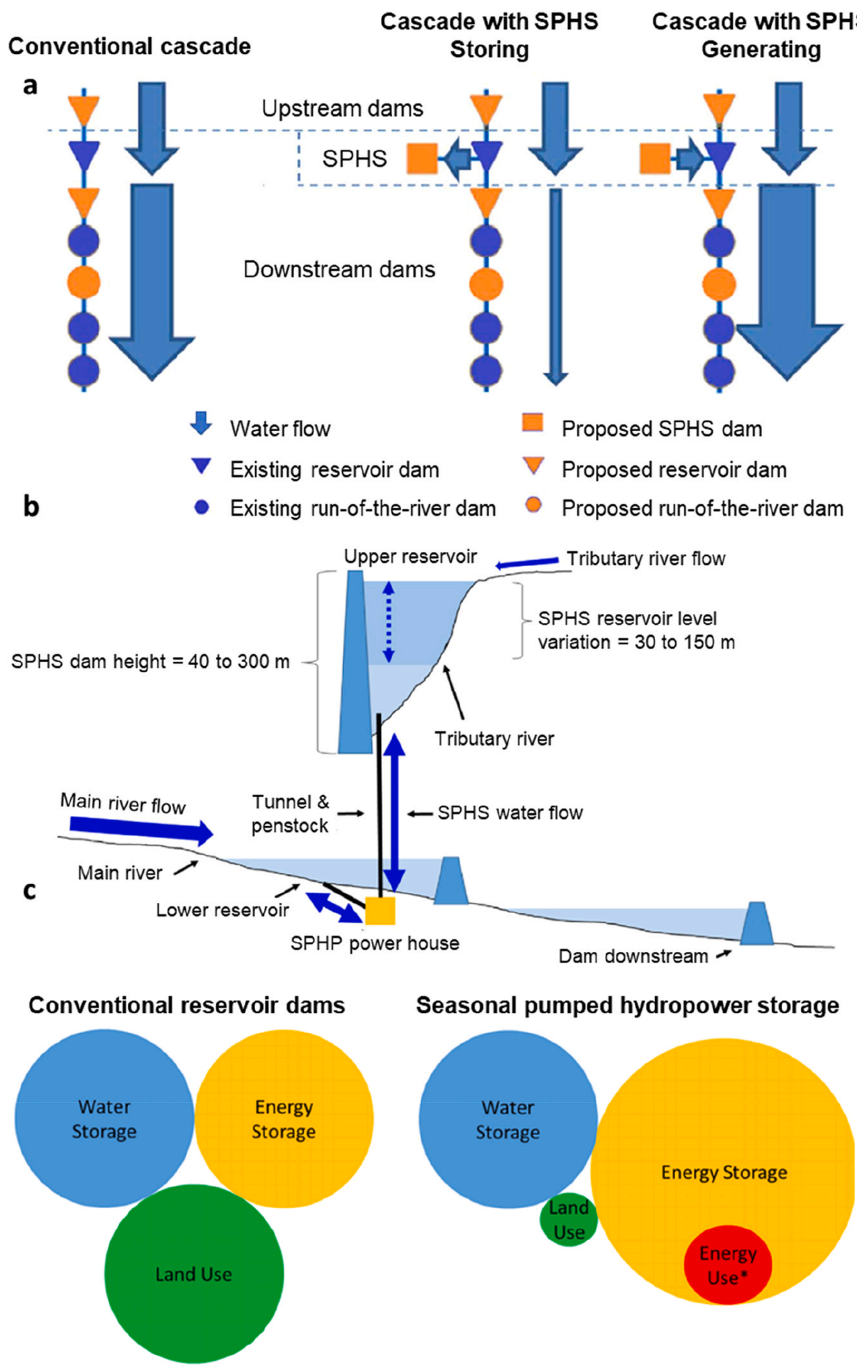

Fig. 8. Seasonal pumped storage power plants (SPHS) a) in cascade, b) lateral perspective, and c) a comparison between conventional reservoir dams, and SPHS water and energy storage, and land use.

In the rainy season of 81–82, it rained so much that the annual average ANE of the southeastern basins, including the Paraná, exceeded 200 %, and the reservoir filled up within six months. This rapid flooding made it impossible for the animals to migrate out of the reservoir area and led to their death. Therefore, measures and investments should be taken to mitigate and adapt to floods to reduce the impact of floods in the catchment area.

The increase in seasonal energy storage capacity of Brazil would allow the existing reservoirs to be kept full and contribute to an increase in precipitation in the main hydropower basins. This could be performed with hydrogen production or with the construction of seasonal pumped storage hydropower (SPHS) plants. The construction of SPHS plants parallel to the main river increases the water and energy storage capacity of the basin and reduces spillage of the dams downstream the SPHS plant (Fig. 8a,b) (Hunt et al., 2021). The Northeast Region SPHSs can store additional seasonal power from wind turbines and augment cascade hydropower generation and water supply for various purposes (Hunt et al., 2017; Gonzalez-Salazar and Roger Poganietz, 2022). Due to the significant water level variation of SPHS plants, little space is needed to store a lot of water and energy (Fig. 8c (Hunt et al., 2018)). Several SPHS facilities have been proposed for Brazilian river basins (Hunt et al., 2017, 2020a; GESEL, 2021). In (Hunt et al., 2020b), many recently proposed plants for SPHS are presented. Energy crop storage is another way to store energy and water seasonally in parallel with a large river, as seen in (Hunt et al., 2016).

The phenomena described in this paper, that hydropower reservoirs

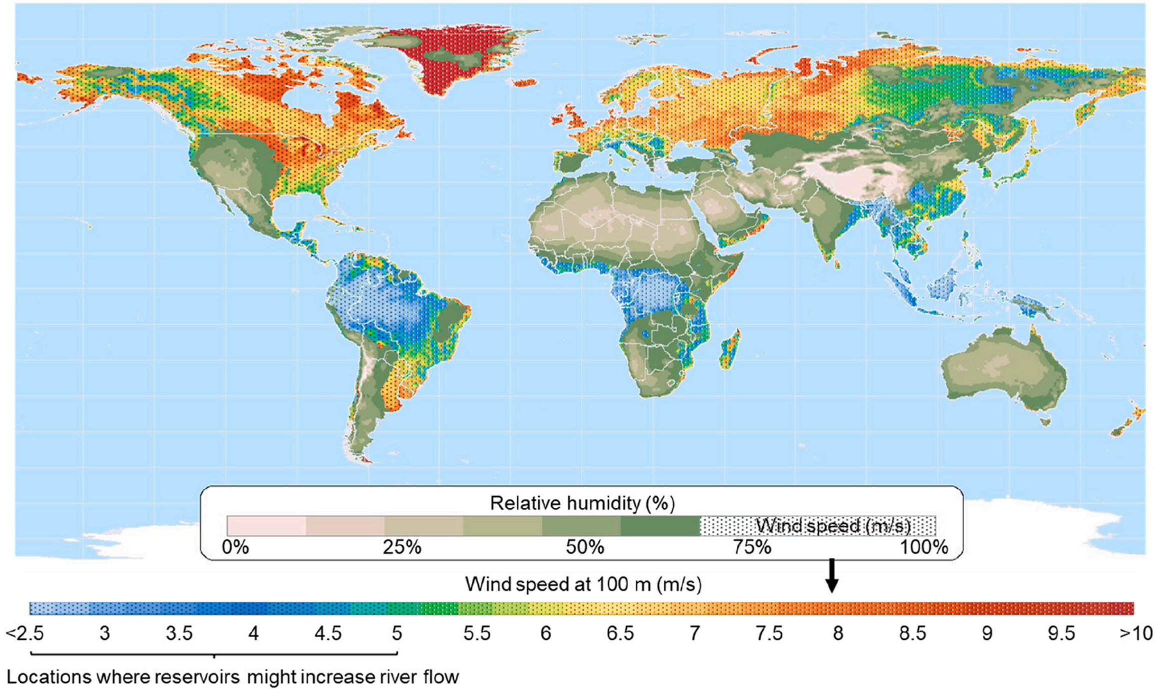

Fig. 9. Global relative humidity map (Center for Sustainability and the Global Environment, 2024), replacing locations with humidity higher than 70 % by wind speeds (DTU, 2023).

can increase the downstream water flow, could potentially happen in other basins with high humidity and low wind speeds. In basins with high humidity and low wind speeds, little evaporation happens, but the reservoir contributes to maintaining humidity in the basin high, which increases the chances for precipitation. Fig. 9 presents the global relative humidity map (Center for Sustainability and the Global Environment, 2024), replacing locations with humidity higher than 70 % by wind speeds (DTU, 2023). In locations with relative humidity higher than 75 % and wind speeds lower than 5 m/s, the construction of reservoirs could potentially contribute to increasing the flow of the river downstream of the dam. Future work will investigate how reservoir levels of large dams in the areas indicated in Fig. 9 to investigate if the same phenomena highlighted in this paper happen in other basins around the world.

5. Conclusions

This study has shown that reservoir levels have a significant impact on hydropower generation and river flow in the southeastern region of Brazil. The average impact of the minimum reservoir levels can increase the river flow in the catchment area by up to 110 % in the following 12 months. This aspect shows that the river inflow influences the reservoir level on a weekly and monthly basis. In contrast, the water level of the reservoirs determines the river flow in the catchment area on an annual basis. To reduce the demand for thermal electricity and overcome an energy crisis in Brazil, the reservoirs should be filled in the following order: São Francisco, Paranapanema, Tietê, Paranaíba, Paraíba do Sul and Grande. Brazil has considerable hydropower potential that has not been fully exploited since the drought in 2014 and 2015. To increase hydropower production with the existing dams, reduce electricity costs, and reduce CO_2 emissions from thermal power sources, the country should focus on generating electricity from other renewable sources such as solar and wind energy and save energy so that the reservoirs in the southeastern region are re-dammed and kept high.

CRediT authorship contribution statement

Yoshihide Wada: Project administration. **Roberto Brandão:** Project administration. **Dorel Soares Ramos:** Formal analysis. **Alban Kuriqi:** Investigation. **Mauricio Tiomno Tolmasquim:** Visualization, Software. **Marcos Aurélio Vasconcelos de Freitas:** Funding acquisition. **Julian David Hunt:** Writing – original draft, Methodology, Conceptualization. **Andreas Nascimento:** Methodology, Investigation. **Behnam Zakeri:** Writing – review & editing, Methodology. **Ansir Ilyas:** Resources, Data curation.

Declaration of Competing Interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

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Data availability

Data will be made available on request.

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