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Review

An Overview of Hydropower Reservoirs in Brazil: Current Situation, Future Perspectives and Impacts of Climate Change

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Abstract: Global climate change, related to the greenhouse gases emission, impacts hydroelectric power generation mainly due to the increase in air temperature and changes in the precipitation patterns. As a consequence, it affects basin evapotranspiration process, runoff, sediment transport as well as evaporation of reservoirs. This study analysed the current and future Brazilian context of hydroelectric reservoirs and investigated the potential impacts of climate change on hydropower generation and possible mitigation adjustments, giving relevant examples from around the world. Moreover, it is key to consider other factors that influence the availability of water resources such as: (a) upstream development of reservoirs, mainly the development of agricultural systems, which can contribute to increased water demand; (b) changes in land use, which can have an impact on soil degradation and sediment transport. Hydroelectric dams are a possible alternative to mitigate the impacts of climate change considering that those impacts could generate the need of adaptive actions. The assessment of climate change impacts' projections anticipates possible future scenarios and can assist in strategic planning together with the definition of adaptive operational policies.

Keywords: hydropower plants; climate changes; reservoirs; Brazil

1. Introduction

Hydroelectric plants are the main sources of electricity in some countries (e.g., Paraguay, Norway, Brazil, Austria and Canada). Hydropower contributes about 85% of global renewable electricity [1,2]. It is the main source of renewable energy in South America, followed by biofuels [3]. In several regions of the world (e.g., Southeast Asia and South America), the hydroelectric plants are one of the pillars for the production of renewable energy, but, at the same time, they are vulnerable to the impacts of climate change [4]. These changes are causing the majority of the variations in hydroelectric potential [5]. Other factors, such as changes in land use and demand for upstream irrigation, can also influence water availability for energy generation [5–7].

Brazil has one of the largest hydroelectric potentials and it is believed that hydroelectricity will continue to play an important role in the next ten years [8]. In the country, 80% of the energy generated

comes from renewable sources [9]. The Brazilian energy matrix is composed mainly of hydroelectric plants (60.9%), followed by fossil fuels (16.11%), biomass (8.74%), eolic (7.52%), import (4.91%), nuclear (1.20%) and solar (0.61%) [10]. The 85 solar power plants account for 1,021,602 kW of the installed capacity, and only 0.61% of the energy matrix [10]. Even though the country has areas with high solar irradiation, there are no available technologies for its deployment, showing a clear need for investments in national technologies [11]. Most of the equipment required for the installation of solar photovoltaic and concentrated solar thermal plants is imported, which implies high costs [12].

Regarding energy sources, hydroelectric plants are likely to be more affected by changes in annual and seasonal precipitation as well as temperature increase [13,14], with smaller impact on other energy system sources [15]. Two opposite sides must be considered in terms of energy generation and climate change: on one hand, there is energy generation producing emissions (including hydroelectric; through the decomposition of organic matter in reservoirs), which requires mitigation strategies; and, on the other hand, the impact of climate change on renewable energy sources, requiring adaptation strategies [13].

Water resource use for generation of energy is dependent on hydrological and climatic conditions [4–6,8,15–19]. Global warming may influence the intensity and duration of rainfall, the discharge volume of rivers, the increased evaporation rate of reservoirs and the amount of evapotranspiration of plants [20]. Thus, these factors interfere in the water availability for energy generation and may trigger indirect effects such as changes in land use and an increased demand for irrigation [18].

Several impacts of climate change on hydroelectric reservoirs can be considered: hydrological changes, variation in sediment load due to flooding, variation in volume and river flow due to changes in precipitation, and the occurrence of extreme events (e.g., droughts and floods) that can generate the need for dam design and safety improvements [1–6,8].

Hydropower reservoirs are less susceptible to climate change than run-of-river schemes due to its storage capacity as well as being less seasonal flow dependent [18]. This resilience depends on dry season duration [13]. The changes in the flow affect the level of reservoir and, consequently, the capacity of energy generation [18,19]. In Brazil, there are expectations that future hydroelectric installations will be of run-of-river due to environmental restrictions for the construction of large reservoirs, resulting in the use of the total installed capacity of water flow schemes only during the rainy season. In the dry season, other plants, such as thermoelectric plants, would need to be used to meet the energy demand [21].

Climate change must be taken into account in the process of water resources planning and management, so that measures are taken to adapt to future climate scenarios [6]. Adaptation strategies for the operation of reservoirs should be implemented [5,16,22], since hydroelectric plants are fundamental for electricity in Brazil [19].

Through a review of the literature, this study aims:

- To provide an overview of the current state of hydroelectric plants in Brazil, focusing on reservoir plant types, providing insights into recent policies for the development of hydropower (Section 2);
- To assess the potential for new hydroelectric plants in the country (Section 3);
- To put the current state of hydroelectric plants in Brazil into context in comparison with other countries (Section 4);
- To present the possible impacts of climate change on hydroelectric power generation. To analyse and compare methodologies and results of studies that evaluate the impact of climate change on energy generation by hydroelectric reservoirs (Section 5);
- To identify measures to adapt to future climate scenarios that have been the focus of studies in Brazil and in other countries. (Section 6);
- To present a framework directed to the study of climatic and environmental impact on the generation of hydroelectricity (Section 7).

2. Current Situation of Brazilian Hydroelectric Plants

Brazil has a great hydroelectric potential, totalling 101,268,561 kW, which corresponds to 60.9% of the energy matrix. There are 1313 operating plants ranging from hydroelectric generation centrals (with up to 1 MW of power installed), small hydropower plants (between 1.1 MW and 30 MW) and hydroelectric power plants (with more than 30 MW). The 218 hydroelectric power plants (HPP) are responsible for 60.5% of the total installed capacity in the country, adding up to 95,619,468 kW. The small hydroelectric plants (SHP), 428 in total, answer for 3.2% of the total installed power. The 667 hydroelectric generation centrals (HGC) in operation account for only 0.4% of the installed power [23].

The largest Brazilian hydroelectric power plant is Itaipu, located in the Paraná River [8]. After its construction, the Belo Monte hydroelectric in the Amazon basin will be the third largest hydroelectric power plant in the world (11,233 MW). The second largest is Itaipu, producing 14,000 MW, and the largest in the world is the Three Gorges hydroelectric plant in China, producing 22,500 MW [2,8]. The main Brazilian plants with regularization reservoirs are presented in Table 1 and sorted by region and importance in useful volume.

Table 1. Main Brazilian hydropower plants with reservoirs—based on data from [24].

Region	Name	River	Power (MW)	Useful Volume (km ³)	Storable Useful Volume (km ³ /GW)
North	Tucuruí	Tocantins	8370	38.98	4.7
North	Balbina	Uatuma	250	10.22	40.9
Northeast	Sobradinho	São Francisco	1050	28.67	27.3
Southeast/Midwest	Serra da Mesa	Tocantins	1275	43.25	33.9
Southeast/Midwest	Furnas	Grande	1312	17.22	13.1
Southeast/Midwest	Tres Marias	São Francisco	396	15.28	38.6
Southeast/Midwest	Emborcação	Paranaíba	1192	13.06	11.0
Southeast/Midwest	Itumbiara	Paranaíba	2280	12.45	5.5
Southeast/Midwest	Nova Ponte	Araguari	510	10.38	20.4
South	Foz do Areia	Iguaçu	1676	5.80	3.8
South	Passo Real	Jacui	158	3.36	21.2

The Serra da Mesa hydroelectric power plant on the Tocantins River has the highest useful volume, at 43.25 km³; followed by the Tucuruí plant, in the same river, at 38.98 km³, which stands out in terms of installed power at 8370 MW [24]. Usually the levels of the reservoirs are higher in the summer, from December to March (more abundant rainy period), and lower between April and November, when there is the dry season [8].

Recent studies addressed the current situation of SHP in Brazil, exposing regulations and policies for the growth of the number of plants and the perspectives for the sector [25]. Brazilian SHPs are expanding due to their characteristics of small area occupancy and minor environmental impact, besides the possibility of installation closer to the places of consumption, which reduces the loss of energy in the transmission and, consequently, results in a reduction of costs for the consumer.

The main Brazilian hydroelectric reservoirs are in the Paraná river basin. The concentration of hydroelectric power plants is higher in the Midwest, South and Southeast regions (Figure 1). The Southwest region accounts for 70% of the energy storage capacity. The largest hydroelectric reservoirs are installed near the regions of greatest demand. When full, these reservoirs can store energy to meet the demands for five months, a much shorter period than that observed in the 1970s, when the energy stored in the reservoirs, at maximum capacity, could meet the demand for three or four years [26]. These changes arise as a result to the increase in energy demand caused by population growth, in addition to climate and environmental changes.



Figure 1. Brazilian hydroelectric plants by hydrographic basin—based on data from [27].

Recent Policies for the Development of Hydropower

In Brazil, renewable energy sources are considered fundamental for sustainable development [28]. Two strategies with regard to the energy sector have been incorporated in Brazil, one focusing on a clean and renewable energy matrix, mainly hydroelectric, and the other promoting efficient use and conservation [11]. However, the country needs to review current energy policies in the context of economic growth and also to consider climate change, with investments in energy efficiency, renewable sources and the necessary technological improvements [29].

Brazil has opted to increase energy security levels, increase energy generation capacity, and, with this expansion, environmental and social problems have arisen. In order to avoid greater environmental impacts, the main strategy goes towards new projects for run-of-river. However, this policy ends up affecting the generation of energy during dry periods, due to lesser river flow [30]. To achieve energy security, the country has invested in hydroelectric and thermal plants, in order to compensate for the lower generation of hydropower during dry periods [29].

In run-of-river schemes, energy costs are higher due to the possibility of inactivity in dry periods caused by the absence of a reservoir. The construction time is shorter, on average two years. With regard to environmental impacts, the cumulative effects of several run-of-river installed in the same basin

must be considered [8]. In addition, the implementation of run-of-river hydropower plants can also contribute to the increase of emissions indirectly, with the need to complement the hydroelectric potential with thermoelectric plants [29].

In contrast, large reservoirs maximise electricity production, ensuring greater energy security of the system during periods of drought [5,31]. However, some factors may affect the decision on the construction of hydroelectric reservoirs such as: building time; greenhouse gas emissions; fragmentation of the rivers; changes in water quality; relocating or displacing humans; interference in migration and spawning fish.

The average building time of large dams is 8.6 years [32]. Since the 1990s, possible emissions from reservoirs have attracted the attention of several researchers [33–36]. Even though it is a renewable source of energy, there are potential greenhouse gas emissions from reservoirs, such as: methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂). Large amounts of organic matter remain in the reservoir when the area is flooded, leading to the production of these gases. One of the major concerns is the emission of methane [37]. According to Zarfl et al. [38], the quantitative emissions depend on how water is released in dams. The release of deep water contributes most significantly for emissions.

Studies carried out in areas in riparian and grassland environments of the Belo Monte hydroelectric complex (Pará) indicate that the most significant concentrations were CO₂ with a daily mean value of $10,448.41 \pm 3036.48 \text{ mg m}^{-2}$ for pasture and $8004.50 \pm 1314.98 \text{ mg m}^{-2}$ for forest [2]. The Belo Monte mill may produce 1 million tons of CO₂ per year during the first ten years [12,39]. Dams such as Jirau and Santo Antônio will have lower emissions, due to the size of the reservoirs [40].

The amount of emissions varies according to the age of the reservoir, the type of land use before impoundment, management practices, climatic conditions [1,2] and/or the location and morphometry of the reservoir [38]. Moreover, it should also be noticed that greenhouse gas emissions in reservoirs are higher in the first 10 years [39,40].

The construction of reservoirs also contribute to the fragmentation of the rivers, relocating or displacing humans (especially of indigenous) [38], changes in water quality [41], interference in migration and spawning fish, flooding and drainage of areas for fish production [42]. Pringle et al. [43] relate some fish-related effects: population fragmentation and isolation, migration interference, increases in exotic lentic-adapted species (non-native fishes) and the threat of extinction of some species. Therefore, dams are fundamental for the maintenance of society; however, one must think about environmental sustainability and socio-economic impacts, i.e., the best way to build, operate and maintain dams [44].

3. The Potential for New Hydropower Plants in Brazil

Considering the focus of the hydroelectric expansion in the Amazon, due to the nearly exhausted hydroelectric potential in other Brazilian regions [30], important environmental concerns are raised regarding the hydroelectric potential in the Amazon region and studies reporting the impacts caused by dams in this region, such as the emission of greenhouse gases due to flooding of forest areas, the loss of conservation areas, changes in water quality, interference with the displacement and reproduction of aquatic animals, a decline in biodiversity as well as social and cultural impacts [29,31].

The socio-environmental constraints and vulnerabilities of the use of hydroelectric potential, for each Brazilian region, include flood risks in large areas (Northern region), few perennial rivers (Northeast and South), border rivers, floods and agro-industrial pollution (Southeast) and border rivers with high levels of sedimentation (Midwestern region) [30]. Most of the hydropower plants under construction are located in the state of Mato Grosso and Parana (Table 2). The hydropower reservoir (Sinop) and run-of-river (São Manoel) located in the Amazon basin are scheduled to start operating in 2018 [45].

Table 2. Hydroelectric plants: Under construction and planned—data from [23].

Under Construction			Planned		
Plant	Power Generated (kW)	River/State	Plant	Power Generated (kW)	River/State
Sinop	400,000	Teles Pires/MT	Pai Querê	292,000	Pelotas/RS e SC
Baixo Iguaçu	350,200	Iguaçu/PR	Itaocara I	150,000	Paraíba do Sul/RJ
Colíder	300,000	Teles Pires/MT	Santa Branca	62,000	Tibagi/PR
São Roque	141,900	Canoas/SC	São João	60,000	Chopim/PR
Tibagi Montante	32,000	Tibagi/PR	Itumirim	50,000	Corrente/GO
Ponte de Pedra	30,000	Ponte de Pedra/MT	Cachoeirinha	45,000	Chopim/PR
			Bom Retiro	35,180	Taquari/RS

4. Comparison to Other Countries

Most of the large dams around the world were built between the years of 1950–1989 and are related to population growth and consequently increased energy consumption. Regarding their main use, 39% were built for power generation, 29% for irrigation, 14% for flood control, 8% for water supply and 10% for other uses [44]. The reduction in growth rate of number dams built since the 1990s is due to social and environmental concerns, high financial costs and reduction of favorable locations [44]. In Brazil, there was an increase in the deployment of large hydroelectric plants in the 1960s and 1970s due to changes in tax criteria, followed by a reduction in construction of new developments in the 1980s and 1990s due to higher inflation and two oil shocks [46].

The five largest producers of hydroelectricity in the world are: China, Canada, Brazil, the United States and Russia [47]. According to estimates, hydroelectric production may double by 2050, contributing to the reduction of CO₂ emissions from fossil fuel plants [1]. When predicting population growth, water, food, energy consumption and dam development from 2010–2050, Chen et al. [44] foresee about 36,813 dams worldwide, with a total reservoir capacity of 9204 km³ in 2050, and, in 2010, there were 32,473 dams with a capacity of 7975 km³. In terms of energy consumption, the estimate is an increase from 134,000 to 183,000 TW h.

Future dams will be concentrated in developing countries and emerging economies (Southeast Asia, South America and Africa). Approximately 75% of the dams will be of medium and small size (1–100 MW) and 93% of the future hydroelectric power capacity will be provided by large dams (more than 100 MW). In Brazil, the dams under construction are concentrated in the North and South regions and those planned are in the South and Southeast regions of the country [38].

5. Possible Impacts of Climate Change on the Generation of Hydroelectricity

The increase in greenhouse gas emissions and consequently climate change demonstrates having an impact on energy production in Brazil, as well as in other countries that rely heavily on hydropower [29]. Climate change affects the performance and safety of dams in various ways [14], such as: increased sediment load of rivers, impacting turbine operation and loss of storage; increasing reservoir surface evaporation, reducing the amount of water available; generating changes in rainfall and river flows, interfering with the turbines full capacity operation; and increasing the magnitude of floods that can lead to failures in dams. The main factors that interfere in the generation of hydroelectric power globally [13] are:

- Reduction in average precipitation that implies a reduction in runoff (three to four times).
- Increase in average precipitation. Depending on storage and turbine capacity, increased precipitation can lead to an increase in power generation potential. However, this does not always occur, considering that plants are designed for a certain river flow, and the increase of this flow would only lead to unproductive spills.
- Increase in average temperature. Rising temperatures will affect soil moisture levels, interfering with the runoff and storage of water in dams. In addition, increase of temperature causes changes in atmospheric pressure and wind patterns. These changes can alter the precipitation patterns [30].

- Extreme droughts. Depending on the duration of the drought period, the reservoirs act as a buffer, maintaining normal power generation capacity.
- Flooding. It entails sediment loads beyond what is expected, and depending on installed capacity, they do not always bring benefits in terms of increasing the potential for generating power.

There are also the indirect impacts of climate change: water scarcity and competition among other sectors (e.g., agriculture, industries, urban consumption); soil degradation and siltation, depending on the vulnerability of the soil to the action of rainwater and river, scarcity of vegetation and soil desiccation during periods of drought, promoting erosion and transport of sediments to reservoirs [13].

The most cited studies in the literature on the impact of climate change on hydroelectric power production are that of Christensen et al. [48] and Lehner et al. [49]. Lehner et al. [49] analysed the effects of global changes on Europe's hydroelectric potential by applying the WaterGAP model (Water-Global Assessment and Prognosis) [50] for runoff calculations and compared current climate and water use conditions with future scenarios. The study pointed out severe future changes in the discharge regimes that will lead to instability in the European hydroelectric potential that could be reduced by 6% by the 2070s. Christensen et al. [48] simulated future climatic conditions and their effects on the Colorado River basin. The results of this study indicated warming, reduced precipitation, decreased runoff and a significant reduction in annual hydroelectric power generation: 56% (2010–2039); 45% (2040–2069); and 53% (2070–2098) in relation to the simulated history.

For South America, the projections indicate an increase in temperature and an increase (or decrease) in precipitation up to 2100; for some regions, there are large uncertainties related to precipitation. Warming varies from 1.7 to 6.7 °C by 2100 and precipitation varies according to the region (−22% in Northeastern Brazil, +25% in South-Eastern South America). In Brazil, the Amazon is highlighted as a hotspot of global warming, a region most vulnerable to climate change [3].

In Brazil, few studies have evaluated the impacts of climate change on hydropower reservoirs [21,51]. Some studies have more generally evaluated the impact on river basins, not directly evaluating hydroelectric reservoirs [52,53]. Other studies analysed the vulnerability of hydroelectric generation to changes in climate [30,54].

Soito and Freitas [30] reported the risks to energy security in Brazil; the generation of electricity depends significantly on the hydrological availability that can be threatened by increasing water demands (driven by demographic growth and economic development), droughts in the Northeast, and degradation of rivers in the Southeast region (pollution, silting, etc.). In a more recent study, Sorribas et al. [53] examined projections of climate change (2070–2099) and their impacts on discharges from the Amazon basin and identified that, for some regions of the basin, there will be an increase in river discharge (Northwest, annual mean +9%) and, for other regions (central Amazon, annual minimum −15.9%), there will be a possible reduction of flow in dry seasons, which may impact the generation of energy from future hydroelectric plants.

Lucena et al. [21] evaluated the impacts of climate change on Brazilian river basins. The results point out a tendency for reduction in average annual flow in the period 2071–2100, mainly in the Parnaíba (−10.3%), São Francisco (−26.4%) and Tocantins-Araguaia (−15.8%) basins (North and Northeast regions of Brazil). In the South and Southeast regions, impacts will not be significant, so, in these regions, reservoir management would mitigate the effects of climate change. According to the results of an investigation by Ribeiro Júnior et al. [51], if climate change scenarios are confirmed, Furnas reservoir levels may decline sharply. The authors proposed a methodology that considers the determination of the length and transgression frequency of level to minimise the conflicts of water use and the impacts on the generation of energy.

Analysis conducted by Nóbrega et al. [55] in the Grand river basin showed an increase in average river flow at the Agua Vermelha reservoir (+10% in the A2 Scenario, from 2508 m³s^{−1} to 2748 m³s^{−1}). Still, according to the study, the increase of 3 °C in global mean temperature can result in an increase in average river flow by 24% (from 2475 m³s^{−1} to 3070 m³s^{−1}) generating flood risks. However, some projections indicate a reduction in average river flow by up to 20%.

In assessment of climate change impacts on river basins, there are uncertainties about greenhouse gas (GHG) emission scenarios and global circulation models (GCMs), as well as uncertainties regarding downscaling and hydrological modelling [6]. GCMs produce climate projections, providing information on climate uncertainties and water availability more roughly, and are used directly in forecasting runoff in more general studies [14]. The simulations of climate change impacts are generally carried out with a control period and future scenarios of 30 years, comprising three phases of simulation, namely: model development, control simulation (base period), and simulation of future scenarios [4], in addition to using different variables (Figure 2).

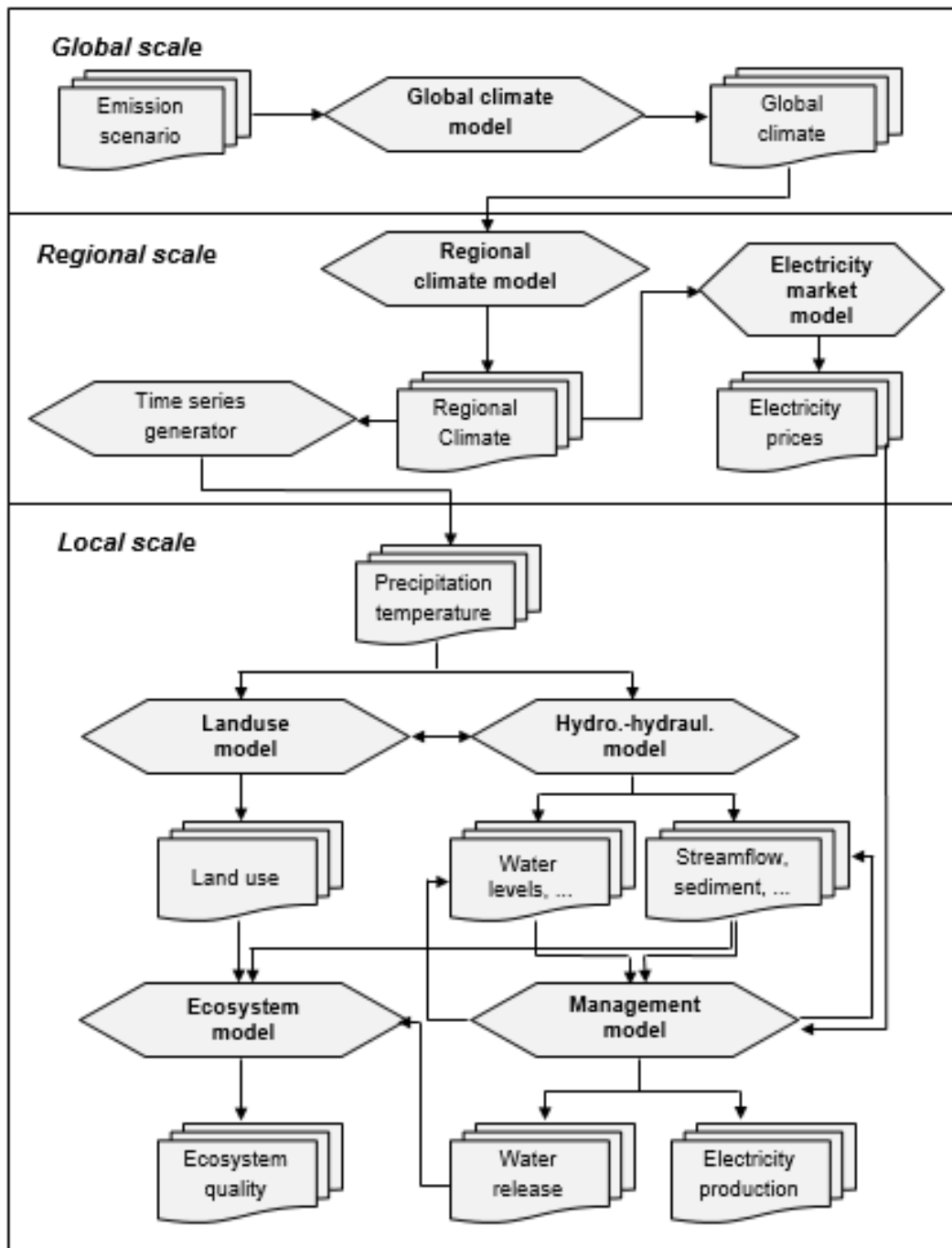


Figure 2. Scheme for simulating the impact of climate change from Schaepli [4].

Assessing the impact of climatic changes in impoundment schemes is rather complex [4,18], requiring information such as inter-basin transfers and design specifications. The existing literature generally evaluates single locations, not establishing how to include multiple sites at national or regional levels, due to the need for detailed information on the operational behavior of each site. As reservoirs can serve different uses (e.g., irrigation), the indirect impacts of climate change on hydroelectric dams should also be evaluated [19].

The meteorological variables temperature and precipitation are important in climate change studies for hydroelectric management [13,16,20,56,57]. Some authors only model precipitation, considering it the higher impact factor on the availability of water for power generation [21]. Other authors propose a combined study between climatic changes and changes in land use [6,7] or between climate changes and demands for irrigation [5]. The inclusion of sediment load assessment in hydroelectric basins tends to be a significant contribution to the study of hydrological models. Another approach complements the gap: the need for an analysis of water demand, mainly for irrigation.

Some studies adopt only one scenario, not considering the different views of the general circulation models on the evolution of the climate and its repercussion in terms of the river basins, different from the one done by Haguma et al. [6], López-Moreno et al. [7], Gaudard et al. [17] and Parkinson et al. [57]. The use of several scenarios assists in the estimation of different uncertainties involved in hydro-climatic modelling [57], such as parameter uncertainty and model structural uncertainty. Climate models that consider a multi-model set, such as ENSEMBLES or CMIP5, provide more reliable assessment since they include different uncertainties [4].

Table 3 presents some insights on the possible climatic changes and their consequences in the runoff, flow of the rivers and generation of energy in hydroelectric reservoirs. The table includes the methodology used in each study to evaluate how different uncertainties (observational uncertainty, parameter uncertainty and model structural uncertainty) were included. A comparison between Brazil and other countries was also carried out.

In order to assess the impacts of climate change on water resources, it is necessary to predict the runoff of the basin. A model commonly used is the IHACRES, introduced by Jakeman and Hornberger [58], which interfaces climate change input data (temperature and precipitation). The IHACRES is a rainfall–runoff model used to calculate the flow of a river, considering climatic changes.

In some regions, such as in Canada, Manic-5 and Toulouste reservoirs, studies indicated positive effects in relation to climate change and power generation. These results are associated with the specific characteristics of the basins; however, as highlighted by the authors, in the long-term, global warming will provide potential negative effects on energy generation [6].

Table 3. Methodologies and main results of studies on impacts of climate change on reservoir management.

Study	Local	Climate Model and Greenhouse Emission Scenarios (IPCC)	Downscaling Method	Components of the Model	Hydrologic Model	Simulation and Optimization Approach	Future Periods	Main Results (Projected Changes)
[16]	Karoon-4 reservoir (Iran)	HADCM3 model ^a (GCM), A2 ^b	Proportional approach	Temperature and precipitation	IHACRES rainfall-runoff model ^c [58]	Non-dominated sorting genetic algorithm II (NSGA-II)	2025–2039 2055–2069 2085–2099	Temperature: −1.35, −1.45 and −2.20 °C; Precipitation: −18%, −0.4% and −30%; Inflow to the Karoon4 reservoir would decline in the future periods.
[17]	Mauvoisin reservoir and Chanrion run-of-river power plant (Switzerland)	10 regional climate models (RCM) Ensembles project (ensembles-eu.metoffice.com), A1B	Delta method	Temperature, scenarios of energy consumption and prices	Glacier Evolution Runoff Model (GERM) [59,60]	Threshold Accepting	2011–2100	Inflows are expected to decrease at average by 18% from 2001–2010 to 2091–2100; Power generation: −20%; Power generation after optimization: −16%.
[20]	Khersan 1, Karoon 3 and Karoon 4 reservoirs (Iran)	HADCM3 model (GCM), A2	Proportional approach	Temperature and precipitation	IHACRES model	Systems dynamics (SD)/Nonlinear programming (NLP)	2025–2039 2055–2069 2085–2099	Temperature increase; Decrease of precipitation and inflow; Power generation (simulation) multi-reservoir after optimization: −23%, −7% and −34%.
[57]	Reservoirs and run-of-river schemes (Canada)	8 GCM with 23 downscaled climate projections, A1B, A2 e B1	Downscaled climate projections of Pacific Climate Impacts Consortium (PCIC)	Temperature and precipitation	Variable Infiltration Capacity (VIC) model [61]	Robust optimization	2050	Temperature increase; Increased precipitation trend in most seasons and annually; More runoff available in the winter and spring seasons, and with drier conditions in the summer; Hydropower potential: +11%.
[6]	Reservoirs (Manic-5 and Toulouste) and run-of-river hydropower plant (Manic-1, Manic-2 and Manic-3) (Canada)	Climate model ensemble (13 GCM) A1B, A2 and B1	Downscaling method proposed by Widmann et al. [62].	Temperature, precipitation, relative humidity, solar radiation, wind speed, topography and soil types and land uses	Soil and Water Assessment Tool (SWAT)	Sampling Stochastic Dynamic Programming (SSDP)	2010–2039 2040–2069 2070–2099	Temperature (2070–2099): +3 to +10 °C; Precipitation in the winter (2070–2099): +5 to +60%; Annual inflow volume: +4.3%, +9.1% and +13.5%; Average annual power generation: +4.2%, +8.7% and +14.1%; Unproductive Spills increase.
[7]	Yesa reservoir (Spain)	Climate model ensemble (12 RCM), A1B	Delta method	Temperature, precipitation, reservoir inflows and outflows, storage level, soil types and land cover	Hydro-Ecologic Simulation System (RHESys)	-	2021–2050	Temperature: +1 to +2 °C; Annual average rainfall: −10%; Annual streamflow: −13.8%; Annual runoff (considering evolution of land cover): −16%; Annual runoff (combined effects of climate and land cover change): −29.8%.
[5]	Major existing and planned new hydropower plants (reservoir and run-of-river) of Zambezi river basin (Southern Africa)	2 GCM (CNRM-CM3 and ECHAM5 MPI-M) ^d , A2	Direct use of regional models	Temperature, precipitation and irrigation development	Water Evaluation and Planning (WEAP) [63–65]	-	2050–2070	Higher average temperatures; Potentially reducing average electricity generation (12% in the Kariba reservoir); Reduction in the average annual generation in usual irrigation growth (6%); Reduction in the average annual generation when irrigation is prioritized (20% in Cahora Bassa)
[66]	Tekeze reservoir (Ethiopia)	CORDEX-Africa (RCM), RCP4.5 and RCP8.5 climate scenarios ^e	-	Temperature, precipitation, topography and soil types and land uses	Soil and Water Assessment Tool (SWAT)	HEC-ResPRM Optimization Model ^f	2011–2040 2041–2070 2071–2100	Mean annual temperature: +1.1 °C and +3.38 °C under RCP4.5 and RCP8.5 scenarios; Mean annual precipitation: +45%; Results showed increase in annual and monthly inflow into the reservoir except in dry months from May to June.

Table 3. Cont.

Study	Local	Climate Model and Greenhouse Emission Scenarios (IPCC)	Downscaling Method	Components of the Model	Hydrologic Model	Simulation and Optimization Approach	Future Periods	Main Results (Projected Changes)
[21]	Reservoirs (Brazil)	HADCM3 model (GCM), A2 e B2	PRECIS (Providing Regional Climates for Impacts Studies) model (Hadley Centre, UK)	Precipitation	Linear rainfall–flow model for elasticities	SUISHI-O ^g	2071–2100	Firm power (A2 and B2 emission scenarios, respectively): –1.58% and –3.15%; General negative trend in flow with varying seasonal impacts; São Francisco basin seemed to be the most affected (decrease in energy production would reach more than 7% in the B2 scenario).
[51]	Furnas reservoir (Brazil)	HADCM3 model (GCM), A1B	Regional ETA model (National Institute for Space Research—INPE, Brazil)	Temperature, precipitation, relative humidity, solar radiation, wind speed, topography and soil types and land uses	MGB-IPH model ^h [67]	Frequency and duration model	2011–2040 2041–2070 2071–2099	Increased trend of rain rates, not reflecting on flow; Period 2041–2070: prolonged drought, the reservoir can be emptied completely so that the energy demand is met; Increase in generation by 32% while maintaining the fullest reservoir.

^a Hadley Centre Coupled Model, version 3 (Met Office Weather Centre—UK); ^b IPCC's Special Report on Emissions Scenarios (SRES) contains data on the scenarios of greenhouse gas emissions (GHG) and presents different trends, such as low emission or optimistic scenario (B2), moderate emissions (A1B) and high emissions or pessimistic scenario (A2) [68]; ^c IHACRES model—Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data; ^d Drawn from the European Union (EU) WATCH3 dataset of statistically downscaled climate models; ^e IPCC's Fifth Assessment Report—CMIP5: established new scenarios of climate change: high emission scenario (RCP 8.5), medium stabilization scenarios (RCP 4.5 and RCP 6.0) and mitigation scenario (RCP 2.6) [69]; ^f HEC-ResPRM—US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model; ^g SUISHI-O—Modelo de Simulação a Usinas Individualizadas de Subsistemas Hidrotérmicos Interligados developed by CEPEL—Centro de Pesquisas de Energia Elétrica (Electric Power Research Centre), Brazil; ^h MGB-IPH—Modelo Hidrológico de Grandes Bacias (Hydrological Model of Large Basins) developed by IPH—Instituto de Pesquisas Hidráulicas (Institute of Hydraulic Research) of the Federal University of Rio Grande do Sul, Brazil.

6. Adaptations to Reduce Vulnerability and Increase Resilience

Soito and Freitas [30] suggested that, in addition to the management of Brazilian reservoirs in terms of optimisation and adaptation to climate change, other measures should be taken into account for planning, execution and control phases of the plants, namely: establishment of an orderly use of the soil in the drainage basin; conservation of vegetation growth; regulation of the rivers flow and their tributaries; and the controlled disposal of industrial waste. It should also be considered the monitoring of sediment transport [70]. An overview of different adaptation strategies to reduce vulnerability of hydroelectric reservoirs to climate change is given in Table 4.

Table 4. Adaptations to reduce vulnerability of hydroelectric reservoirs to climate change.

Study	Adaptations to Reduce Vulnerability of Hydroelectric Reservoirs to Climate Change
[13]	Obtaining information on the climatic impacts (monitoring of the climate and the runoff of the basins) in the hydroelectric generation and incorporating climatic risks in its management; Investments in adequate infrastructure, with equipment designed to operate in different climate conditions (e.g., turbine types); Modernization of plants to enable long-term sustainability; Development of drought management plans to deal with water competition; Modifications to operating rules; Management of land use to reduce soil erosion in the basin and reservoir; Consideration of the diversification of the energy matrix.
[22]	Dynamic management with water allocation adjustments.
[30]	Controlled disposal of industrial waste; The conservation of vegetation growth; Regulation of flows of rivers and their tributaries.
[57]	Adaptations between hydroelectric and alternative scenarios involving other sources of energy.
[6]	Adaptation of the operational policy to the future hydrological regime with adjustments in reservoir levels in seasons.
[7]	Simplified water management schemes based on the operational history of the dam, applying restrictions to the releases of water from the dam.
[17]	Operational rules optimized for balancing power generation (optimization through hydraulic loading).
[4]	Flexibility in the storage of water obtained through pump-storage HPP systems.
[51]	To apply restrictions to the releases of water from the dam.
[26]	Store energy by pumping water to a new reservoir during the wet period and generate energy by releasing the stored water during the dry period (Enhanced-Pumped-Storage).

The adaptability of hydroelectric schemes to climate change is dependent on local characteristics, specifically: project specifications; storage volume; morphological regime and environmental legislation [4,18]. For example:

- Reservoirs with smaller surface area and greater depth tend to be less affected by global warming, which increases evaporation rate of reservoir (according to previous study, 1.1 m depth on average per year) [13].
- Some hydropower systems offer flexibility of water storage, pump-storage HPP. In periods of lower demands, the water is rebounded to a reservoir with higher elevation, and, in periods of higher demand, the water is released by the turbines. In this case, the generation of hydroelectricity is less dependent on changes in the hydrological regime [4]. The limitations for the construction of these hydroelectric schemes in Brazil are related to the establishment of regulatory bases and economic viability.
- Optimised operating rules can balance power generation [7,16,17,20,57]. An example of such operational policies would be raising and lowering reservoir level during some seasons. Haguma et al. [6] proposed as adaptive operational policies for Manicouagan Reservoir (Canada)

the lowering in reservoir water level during winter and raising during spring. For the Furnas HPP reservoir (Brazil), Ribeiro Júnior et al. [51] proposed an operative rule that contemplates the time and the cycle of attendance to a certain level of the reservoir, to attend to the generation of energy and to guarantee the sustainability of multiple uses of water for the future climate.

Analyses indicate that hydroelectric managers usually consider historical hydro-meteorological data in the planning and design of new hydropower stations, but data should be also included on the possible impacts of climate change [14]. In Brazil, this new strategy is also necessary. With the inclusion of climate change impacts in planning, even if there are changes in flows, the plant can act in a balanced way, reducing losses in energy generation.

According to Lumbroso et al. [14], this strategic management leads to a set of possible options for hydroelectric schemes and impacts the amount of energy generated and future economic return. In Brazil, there is a need for climate and hydrological forecasting to anticipate hydrological risks and to assess the impacts and vulnerability of hydroelectric plants considering changes in climate and adaptation measures [30,51]. However, the influence of the actions taken is greater during the hydroelectric planning and design phases [14].

The diversification of the energy mix is considered a form of adaptation [13]. Thus, in Brazil, different sources of renewable energy can be managed in parallel:

- Encouraging the use of solar and wind energy can contribute to the reduction of greenhouse gases and to Brazilian social and economic development [28]. Biomass as an energy source is also interesting due to the amount of waste from agriculture and forest products industries, extracted mainly from the sugar and alcohol industry [11,12].
- Sources such as biomass (from bagasse and sugar cane straw) and wind power can contribute significantly to the generation of energy in periods with lower rainfall intensity, as it coincides with the more intense potential of these sources [8]. It can complement the generation of hydroelectricity in the period of greater fragility, especially the run-of-river hydropower plants.
- The great annual variability in the hydrological conditions and the intense rain seasonality can put at risk the Brazilian hydrothermal energy generation system. However, a complementarity between hydroelectric, wind and solar photovoltaic systems could contribute to the stability of production and a decrease in thermoelectric generation [71].

7. Discussion

The assessment of projections of climate change allows better understanding of the magnitude of water and energy risks as well as the adoption of adaptation measures to meet future energy demands. The vulnerability and resilience of each hydroelectric plant depends on specific characteristics such as the type of plant (reservoir, pumped-storage or run-of-river), operating strategies, turbine resistance to sediments and the vulnerability of the hydrological regime.

Studies of the impact of climate change on the hydrological regime anticipated possible future developments, but interpretation should cover modelling uncertainties, especially related to climate change scenarios. These studies provided an overview of the trends and enable the establishment of hydroelectric reservoir management strategies. The impacts on the availability of water to the reservoirs can be predicted, which facilitates the designation of a plant operation strategy in order to mitigate the effects throughout the year or the adoption of other measures to guarantee demand to be met.

When establishing adaptive strategies, it is also necessary to investigate the impacts of adaptive actions on ecological integrity of rivers downstream of the reservoir, and there should be concerns related to maintenance of environmental flows, as highlighted in Spalding-Fecher et al. [5].

The analyses of the temperature and precipitation variables are fundamental in projections of climatic changes and in the evaluation of impacts on the generation of energy by hydroelectric plants. Precipitation directly influences the refilling of aquifers and river flow, i.e., the availability of

water resources. Temperature influences the evaporation of the reservoir and the evapotranspiration of the vegetation—also impacting the availability of water in the reservoir. Variations in temperature also impact the behavior of other climatic variables (wind speed, humidity, precipitation). Investigations also highlighted the need for joint evaluation of temperature and precipitation, since evapotranspiration and evaporation may counterbalance precipitation [5,6,30]. That is, even if there is an increase in rainfall in some regions, higher temperature would increase the rates of evaporation of the reservoir and evapotranspiration in the basin, generating loss of water to the atmosphere. Other variables that can complement the analysis: demand for irrigation and land use—related to the silting of river banks and changes in evapotranspiration rates.

In Brazil, climate change trends indicate that the regions that will suffer the most changes will be the Amazon and the Northeast. Considering the Amazon, strategies should be implemented, due to the clear tendency, for the region, of construction of run-of-river plants, the kind of power plant in which the impacts of global warming are most significant. Considering the Northeast, in strategic terms, the country can opt for complementarity with the development of other renewable sources of energy, such as wind and solar, given its enormous potential for generation, as evaluated in the study of Jong et al. [12].

Based on the study of several articles dealing with the impact of climate change on the management of hydropower reservoirs and other related articles, a framework was elaborated (Figure 3).

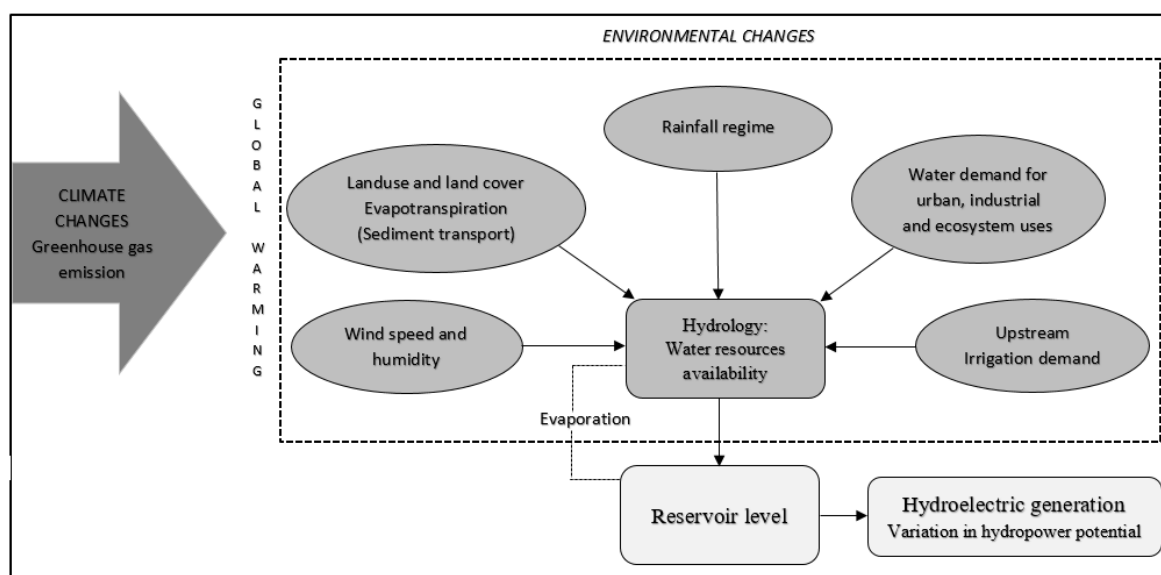


Figure 3. Framework—Climate change and reservoir management.

This research provides several conclusions related to climate and environmental changes in the context of hydropower reservoirs, which are useful for the academic and industry communities. A summary of the relationship between different variables is presented (see also Figure 3):

- Global climate change affects power generation in hydropower reservoirs;
- The increase in temperature causes changes in atmospheric pressure and wind patterns and consequently in precipitation and humidity patterns;
- The combination of changes in precipitation and temperature affect the moisture levels of soil;
- Increase of temperatures results in an increase in potential evaporation;
- Changes in wind speed and humidity may compensate for or amplify the increase in temperature, which may interfere with the evaporation rate of the basin and reservoirs;
- Precipitation is the climatic variable that most affects the flow of rivers;

- Increased precipitation can lead to a rise in river flow; however, the increase in temperature may counterbalance the effect of this rise, as it increases the rate of evaporation of the reservoirs and the evapotranspiration in the basin;
- Global warming increases the demand for water for agricultural exploitation (mainly irrigation) and other socio-environmental demands;
- Changes in land cover alters the rate of evapotranspiration, which may imply changes in runoff characteristics;
- Some changes in land cover can lead to soil degradation (silting), which can affect both the basin and the reservoir level due to sediment transport—aggravating the negative impacts of climate change;
- Hydrological impacts vary according to: precipitation intensity, basin characteristics, type of vegetation and/or changes in land cover;
- As a chain effect, changes in runoff can affect the production of electricity.

8. Conclusions

In summary, climatic and environmental variables impact the volume of water available for the generation of energy in hydropower reservoirs, hence the need for combined studies (considering these different variables) to develop reliable scenarios for the future availability of water resources for hydroelectric power generation and for the establishment of rules for flexible reservoir operation.

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