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The Water–Energy Nexus of Leakages in Water Distribution Systems

Rui Gabriel Souza [1], Alan Barbosa [2] and Gustavo Meirelles [2,*]

[1] Civil Engineering Department, Polytechnical Institute of PUC Minas, Belo Horizonte 30535-901, Brazil; rui.g182@gmail.com
[2] Hydraulic Engineering and Water Resources Department, School of Engineering, Federal University of Minas Gerais, Belo Horizonte 31270-901, Brazil; alan.1995.barbosa@gmail.com
* Correspondence: limameirelles@gmail.com

Abstract: Leakages in water distribution systems (WDSs) profoundly affect their operations, elevating water production demand and treatment and pumping costs. Moreover, they strain the energy system by increasing power requirements at pumping stations. In regions heavily reliant on hydropower, such as Brazil, there is a nuanced implication: diminishing reservoir water levels due to increased WDS flow withdrawal. This not only immediately affects hydropower generation by reducing available head but, over time, may lead to interruptions in hydropower generation. This paper investigates the water–energy nexus, specifically focusing on WDS leakages in Brazil. It begins with an overview of the current situation and future outlook, considering evolving policies to enhance WDS efficiency and also the evaluation of different climate change scenarios. A more in-depth case study explores a reservoir utilized for both energy and water production. In this context, leakage management assumes critical importance, given the various water uses within the reservoir that impact the available energy and water resources. Overall, this study offers a comprehensive perspective on the water–energy nexus within WDSs, underscoring the critical importance of leakage control and its direct and indirect consequences, particularly on energy generation capacity, the environment, and the economy.

Keywords: water–energy nexus; hydropower; water supply; leakages

Citation: Souza, R.G.; Barbosa, A.; Meirelles, G. The Water–Energy Nexus of Leakages in Water Distribution Systems. *Water* **2023**, *15*, 3950. https://doi.org/10.3390/w15223950

Academic Editors: Marco Franchini and Stefano Alvisi

Received: 6 October 2023
Revised: 24 October 2023
Accepted: 3 November 2023
Published: 14 November 2023

1. Introduction

Water and energy are both extremely important resources for social and economic development. From the consumer perspective, if asked which one they would prefer, at first, energy looks more attractive, as it is often related to comfort (use of the internet, watching television, and heating/cooling the environment). However, when confronted with a long-term shortage, water gains great relevance, as it is critical for sanitation and health. In reality, both resources are intrinsically related: electric energy requires a large amount of water to be produced, directly as in hydropower or in auxiliary thermoelectric systems, especially in cooling systems; on the other hand, the production of potable water requires energy for treatment and distribution [1]. Therefore, the scarcity of one of these resources affects the second, increasing the problems to be confronted.

The relationship between water and energy is evident and has been studied in various other sectors. An examination of the interaction between water and energy in agriculture, with a specific focus on the utilization of groundwater pumping for irrigation purposes, was carried out by [2], where the study's findings unveiled a potential annual gain of USD 1.1 billion, indicating a significant contribution to the enhancement of food security in Nepal. Moreover, initiatives in mining often lead to an increase in energy consumption, and [3] highlighted that tools for understanding the synergy between water and energy are essential elements in promoting the development of sustainable practices in this sector.

Furthermore, within the oil and gas industry, the water–energy nexus, as highlighted by [4], requires more attention regarding the practice of water injection for oil and gas recovery, as well as the potential harm caused by the transport of contaminants into the environment due to well integrity issues and/or abandoned wells. Another example of the relationship between water and energy is investigated by [5] through a thermal model aiming to understand the interaction between energy and water in three buildings in London. The results indicate that the energy–water relationship is influenced by both the type of building infrastructure and the environmental conditions of the location. These findings highlight the significance of sustainable construction as an integrated approach to managing energy and water.

A noteworthy point of view is the relationship between water, energy, and food (WEF). However, as highlighted by [6], there are still few successful instances of its operationalization. To delve deeper into this matter, the authors assess the sustainability impact assessment (SIA) protocols in the interdisciplinary operation of the WEF nexus in five case studies in Central Asia. The observed results emphasize that challenges among various stakeholders persist, wherein the role of water governance is critical in managing the WEF nexus, and land management is pivotal in minimizing local-level trade-offs. Furthermore, it is important to underscore the challenges stemming from the COVID-19 pandemic and its impacts on the supply of water, energy, and food, as discussed by [7]. This study highlights the necessity of anticipating impacts and developing strategies to address adverse situations. The findings presented by [7] also underscore the existing gaps in discussions concerning the WEF nexus, as mentioned by [6], particularly those related to risk management. Additionally, they reinforce the advantages of sustainable (green) solutions and stress the importance of adapting production chains to tackle critical situations, including contingency planning, storage, diversification, and self-sufficiency.

Another notable example of the water–energy nexus is observed in water distribution systems (WDSs), considering both energy production and water supply. This connection was observed in Brazil in 2014 and described by [8]. A severe drought affected the southeast region. Water resources became scarce, and the supply in several cities suffered, with many cases of intermittency or complete interruption in the supply. As the majority of electricity production is made by hydropower, energy production also suffered, with more thermometric plants operating, which led to an increase in energy costs and, later, the creation of three tariff levels according to the reservoir levels. In 2021, another severe drought occurred, and a fourth level had to be created, but it was already disabled after the peak of the drought was surpassed [9]. Ref. [10] highlights that the planning and management of multiple-use reservoirs in Brazil requires great advances to avoid conflicts like this. The use of optimization algorithms can be helpful in these cases [11–13].

When confronted with water and energy scarcity, consumers and industries search for more efficient uses of resources, such as rainfall reuse, the substitution of equipment for new ones with lower energy and water consumption, and modifying habits and operations that cause inefficient use of resources [14–16]. As an industry that intensively uses both resources in water supply systems (WSSs), the improvement in the use of one of them is reflected in the second one. Leakages are commonly a major problem for WSSs and also a great example of the water–energy nexus: the increase in leakage obviously increases the water consumed, and indirectly, it requires a higher power in pumping stations to attend to this additional flow [17]. Thus, focusing on leakage control has a great economic and environmental impact, as shown by [18].

The water–energy nexus is also a challenge due to the emission of greenhouse gases into the atmosphere, which has been associated with the acceleration of climate change. In general, conflicts between users tend to increase when water availability decreases [19]. To provide information for prospecting and investigating climate change scenarios, the Intergovernmental Panel on Climate Change (IPCC) provides periodic reports with information associated with different greenhouse gas emission projections in Global Circulation Models (GCMs). The scenarios most covered in the literature are Representative Concentration

Pathway (RCP) 4.5 and 8.5. The RCP 4.5 scenario assumes that emissions begin to decrease in the coming decades and stabilize, while the RCP 8.5 scenario assumes that the release of greenhouse gases continues to increase throughout the century [20,21]. However, the projections developed from GCMs have limitations, mainly in terms of their spatial and temporal resolution. Thus, downscaling techniques may be applied in regional studies [22].

Considering the Brazil case, with the major electric energy produced by hydropower, this paper evaluates the water–energy nexus of leakages in WSSs. First, an overview of the energy consumption and leakage rates in WSSs is presented for the entire country. Then, a specific case study is evaluated, where a reservoir has multiple uses: generating energy and supplying water. For this case study, different leakage rates are evaluated to quantify the net energy provided by the system since the water supply is made through a pumping station. Finally, the reservoir operation is evaluated from the perspective of climate change for the following years. The results showed that 0.64% of the total energy produced in Brazil is wasted through leakages (1.12% of hydropower). However, the case study showed that this value can be higher, as not only do leakages increase the pumping power, but they can also impair the hydropower operation due to the reduction in reservoir level and create a deficit in the net energy of the system with the increased power required by pumping stations.

2. General Overview of Leakage Water-Nexus in Brazil

2.1. Multiple Uses of Water: Hydroelectric x Water Supply

Hydropower plants have reservoirs that can serve multiple purposes that are essential for water security [23]. They can be classified as non-consumptive, where there is no water withdrawn from the reservoir, such as navigation and recreation, or consumptive, where a certain flow is withdrawn to attend to a certain demand, as in irrigation and water supply systems. The volume of water withdrawn directly affects the reservoir level, which can reduce the energy production of the hydropower plant due to the reduced head available for the turbines. In addition, if the reservoir level reaches the minimum operational value, the turbines must stop, and the energy production is completely interrupted.

Obviously, as the water supply is mandatory for public health, maintaining the conditions to allow its flow to be withdrawn from the reservoir is the priority. However, this flow encompasses not only the water used by the consumers but also the water lost in leakages present in the entire distribution system. Thus, part of the reservoir level could be preserved if leakages are well controlled. In addition to this direct impact, leakages also impact the energy required in pumping stations, as higher flows increase the power necessary. If more energy is required, part of the flow passing through the hydropower plant could be avoided, also assisting the maintenance of the reservoir level.

Figure 1 shows a basic example of a reservoir used both for energy production and water supply. Considering a theoretical inflow of 100 units and the maintenance of the reservoir level, cases (a) and (b) exemplify how the leakage reduction could improve the hydropower operation, both by reducing the water volume lost and the energy consumed in the pumping station.

For a single case, the leakage impact hardly has significant relevance and could be easily surpassed using different energy resources, even if it is not an efficient solution. However, looking at the Brazilian scenario, almost 57% of the electricity is produced by hydropower plants [24]. Thus, the combination of several small losses can lead to a significant amount of resources, both environmentally and economically, saved. The following Sections 2.2 and 2.3 provide a general overview of the potential savings that could be achieved in the Brazilian case.

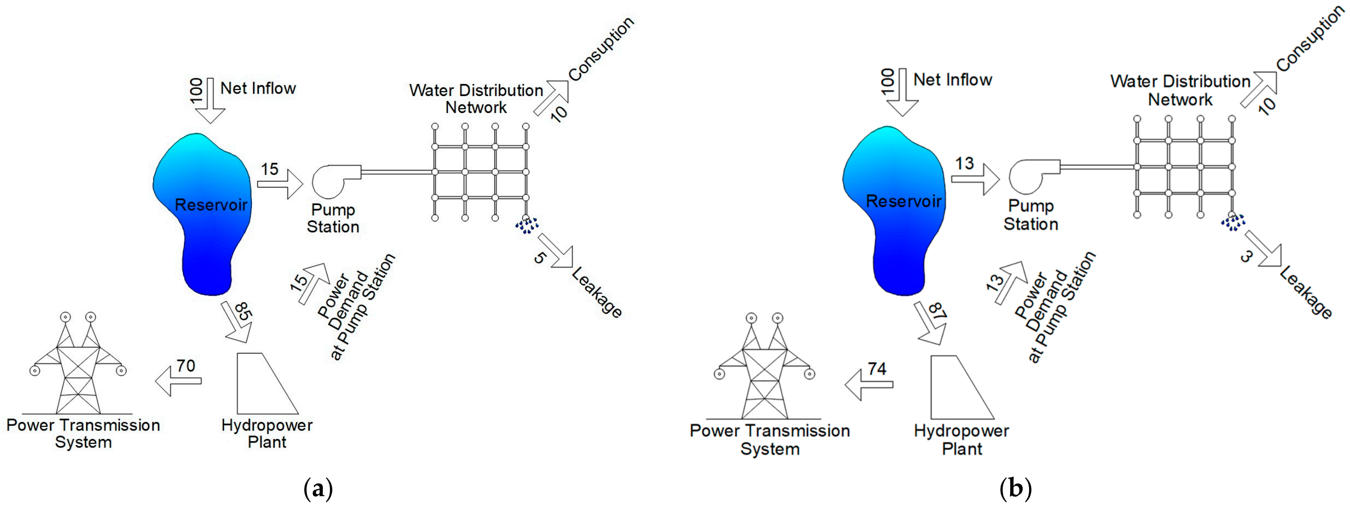


Figure 1. Theoretical example of the water–energy nexus in a reservoir: (**a**) high leakage; (**b**) low leakage.

2.2. Estimation of Energy Wasted by Leakages

To estimate the direct energy lost due to leakages in water distribution systems, the database provided by the Sanitation Information System (SNIS) was used [25]. Two indicators were collected for the years 2007–2021: (i) leakage rate by connection (Equation (1)) and (ii) specific energy consumption (Equation (2)). Figure 2 shows an overview of these two indicators for 2021. In general, the worst results for the leakage rate are observed in states with higher demographic concentration, especially in the south and southeast regions. The same is observed for the specific energy consumption, which can be explained by the increased demand and topography of these regions, requiring more pumping stations to attend to the consumers. However, it is also important to highlight that the data obtained from SNIS are provided by the water companies and, therefore, are subject to high uncertainty. In addition to these indicators, the value of the total connections was also collected. Thus, the total volume of water lost through leakages is calculated by Equation (3), and the corresponding energy wasted is calculated by Equation (4).

$$I_L = \frac{V_P + V_I - V_C - V_S}{N_{conn}} \frac{10^6}{365} \quad (1)$$

$$I_E = \frac{E_{total}}{V_P + V_I} \quad (2)$$

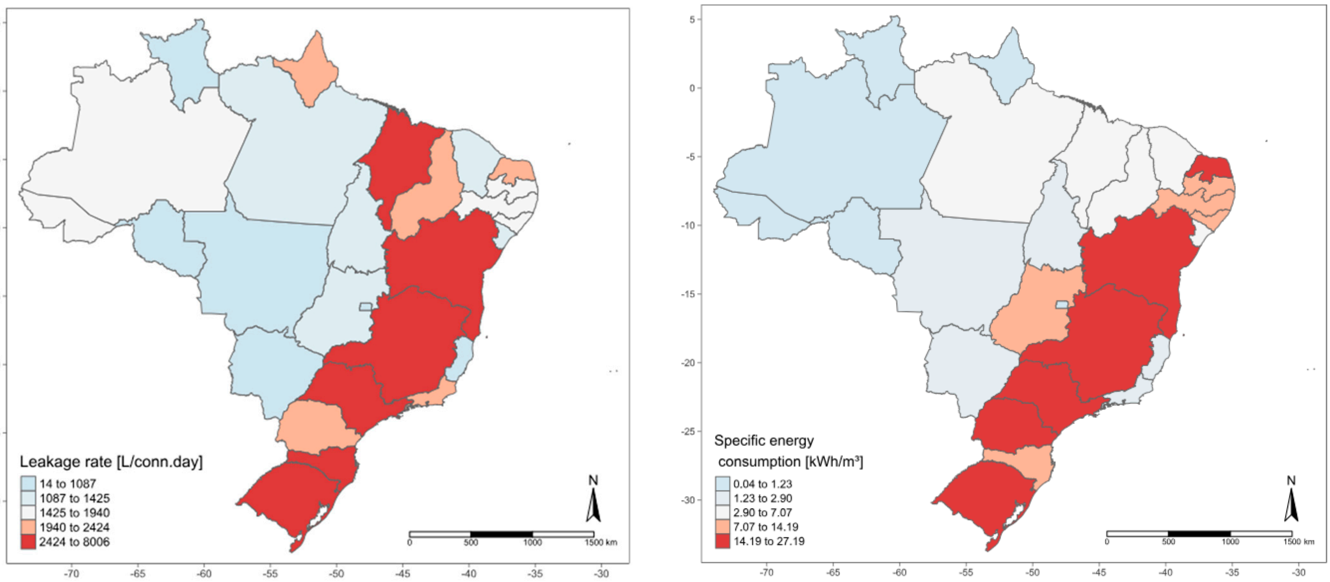
$$V_{leak} = I_L N_{conn} \quad (3)$$

$$E_{leak} = V_{Leak} I_E \quad (4)$$

in which

I_L [L/conn.day]—leakage rate by connection indicator;
V_P [Mm^3]—the total volume of water produced in a year;
V_I [Mm^3]—the total volume of water imported in a year;
V_C [Mm^3]—the total volume of water consumed in a year;
V_S [Mm^3]—the total volume of water used for internal services in a year;
N_{conn} [conn]—the total number of connections;
I_E [kWh/m^3]—the specific energy consumption indicator;
E_{total} [GWh]—the total energy consumed in the water supply in a year;
V_{leak} [m^3]—the total volume of water lost through leakages in a year;

E_{leak} [kWh]—the total energy wasted due to leakages in a year.

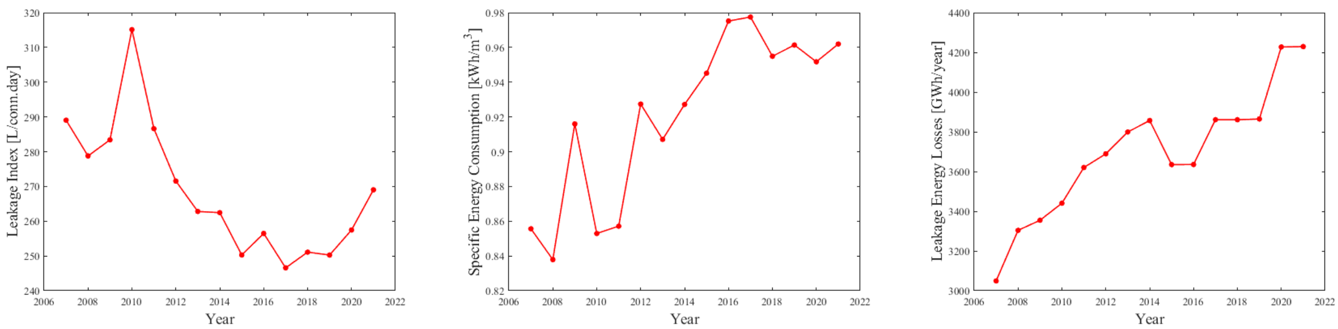


(**a**) (**b**)

Figure 2. Overview of the performance indicators in water supply in Brazil: (**a**) leakage rate; (**b**) specific energy consumption.

2.3. Results and Discussion

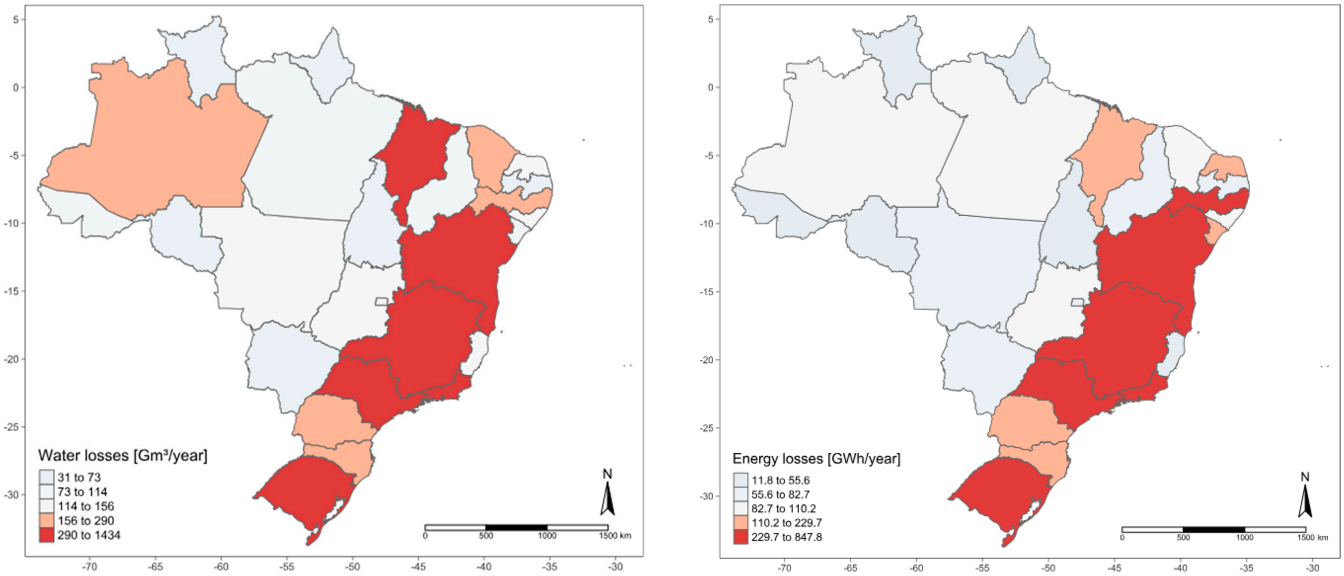
Figure 3 shows the historical data for Brazil for both indicators collected (leakage rate and specific energy consumption) and the energy wasted due to the presence of leakages in water distribution. It can be inferred that the leakage rate has a decreasing trend, with an increase in the last three years. On the other hand, the specific energy consumption increased during this period. This shows that, despite the efforts to reduce leakages, the distribution system is more energy-intensive, which can be the result of population growth and verticalization, with no reinforcement of the distribution network, requiring additional power from pumping stations to surpass the elevated head losses. Finally, it is important to highlight that the leakage rate is still far from benchmarking values [26] and also far from the goals established by the Brazilian government [27]. For 2021, the energy wasted due to leakages represents 0.64% of the total electricity produced in Brazil or 1.12% of the electricity produced by hydropower plants.



(**a**) (**b**) (**c**)

Figure 3. Historical evolution of indicators in Brazil: (**a**) leakage rate; (**b**) specific energy consumption; and (**c**) energy wasted due to leakages.

Figure 4 shows the water and energy loss distribution in Brazil. It can be seen that the south and southeast regions have high losses, which is very harmful to its environmental and economic sustainability since it is a region with high energy demand suffering from water stress. The northeast region also presents high losses and is a region constantly suffering from prolonged droughts. Thus, the regions with the greatest need for operational efficiency are the ones with the highest waste of resources, showing an important value in leakage control in these regions.



(**a**) (**b**)

Figure 4. Overview of the losses due to leakages in water supply in Brazil: (**a**) water; (**b**) energy.

3. Case Study

The case study has the same layout as presented in the theoretical example of Figure 1. Originally, this case was studied by [28] to evaluate the impact of water withdrawal on the hydropower operation. The authors showed a reduction of 20% in the average power of the plant due to the multiple use of the reservoir. However, the leakage impact was not quantified. This case study is a micro example of the water–energy relation of leakages, where the water withdrawal from the reservoir directly affects energy production. Thus, it is easy to evaluate the real impact that leakages can have on energy production. However, on a large scale, other energy sources, such as thermal or gas, could provide the additional energy to attend leakages. In this scenario, the impact on energy production would be smaller, as the reduction in energy offer is diminished. Thus, the real impact of leakages should be carefully evaluated according to the energy matrix, with locales with a predominance of hydropower plants potentially having bigger losses. In addition, the perspective for the reservoir operation in the following years was also not evaluated by [28], where climate changes can have a significant impact. Thus, in this paper, both leakages and climate change were evaluated to quantify the impacts they have on the water and energy production of the reservoir.

3.1. Hydraulic Modelling

The hydropower plant has two Francis turbines, with a total capacity of 28 MW. The efficiency of the generating group (turbine and generator) is 79%, and the minimum flow of them is 7.5 m^3/s. Figure 5a shows the characteristic curve of the turbines. The water level of the reservoir can vary from a minimum of 610 m to a maximum of 642 m. These values can be translated to the volume stored using the curve presented in Figure 5b.

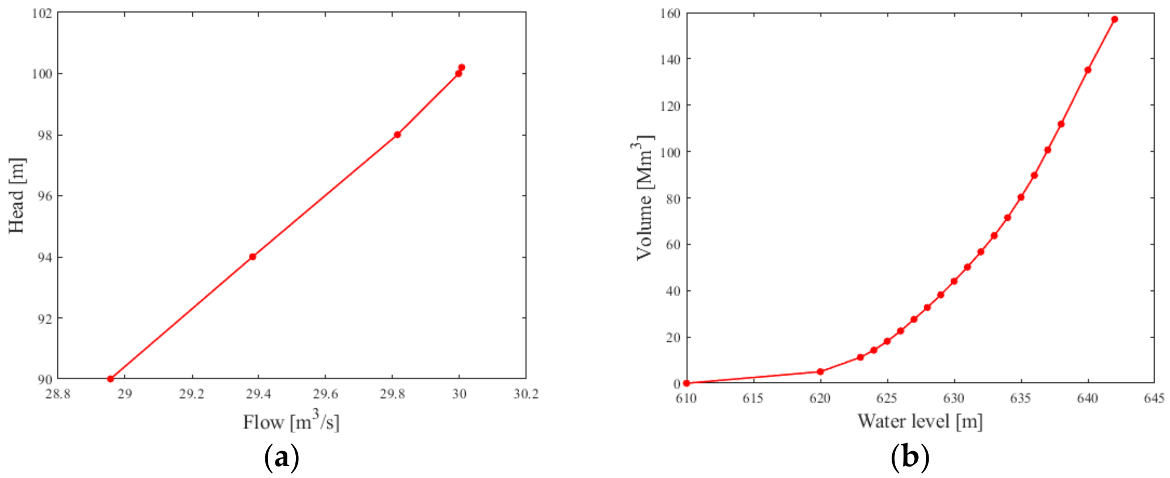


Figure 5. Hydropower plant characteristics: (**a**) turbine curve; (**b**) reservoir curve.

The pumping station withdrawing water from the reservoir for the WDS is composed of five pumps, operating with only four in normal conditions. The total flow capacity of the pumping station is 6 m^3/s, operating 20 h per day, with a head of 360 m, resulting in an average required power of 24.6 MW in a day. The average flow comprises both the water demand and the water lost by leakages. Considering the region being supplied, the leakage rate is 32%. Thus, from the 6 m^3/s, only 4.1 m^3/s is effectively consumed.

Considering that the water supply is the priority for the reservoir operation and that the pumping station requires a minimum level of 630 m, the net energy production and the net volume of the reservoir can be calculated daily during a year of operation. The flowchart presented in Figure 6 summarizes the system modeling with the operational restrictions described.

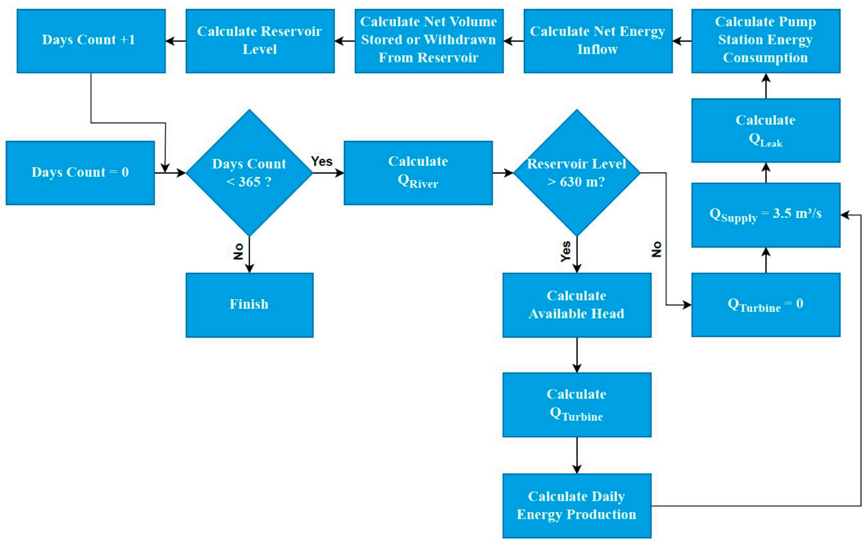


Figure 6. Flowchart to calculate the energy and water balance of the system.

3.2. Hydrologic Modelling

The long-term natural inflow of the reservoir from 1959 to 2011 [28] is shown in Figure 7. The term "natural flow" refers to the hypothetical flow observed in a section if there were no human interventions upstream [29]. In order to represent the seasonality better, the data were separated by month. For each monthly dataset, the fit of probability distributions Weibull, log-normal, and Gamma were compared, as suggested by [30], for modeling flows. To analyze the quality of the probabilistic models, the Bayesian

Information Criterion was estimated, as shown in Table 1. It may be inferred that the log-normal distribution is best fitted to the data.

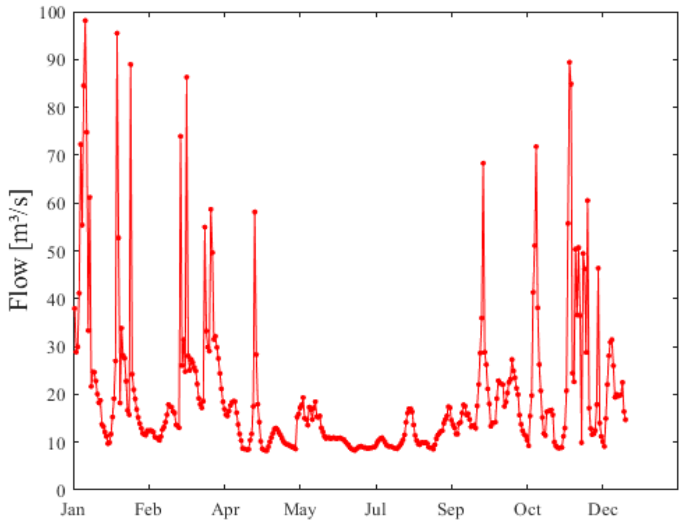


Figure 7. Natural flow of the river.

Table 1. Bayesian Information Criterion for each monthly dataset.

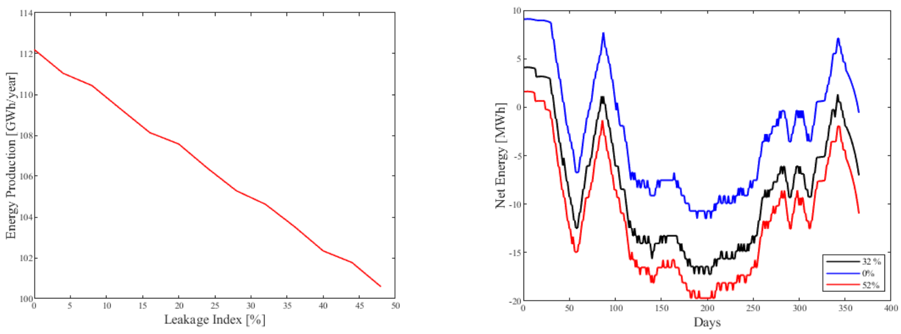
Distribution	Jan.	Feb.	Mar.	Apr.	Mya	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Weibull	282.2	217.1	255.8	236.2	182.9	155.9	80.3	156.0	223.5	208.6	262.5	245.2
Gamma	280.1	208.8	248.4	231.9	172.1	150.5	68.5	147.1	212.3	203.0	260.4	241.2
Log-Normal	276.5	198.5	241.4	227.7	168.0	149.3	67.6	144.9	203.6	202.3	255.6	238.2

For the estimation of scenarios associated with climate change, the parameters of probability distributions were modified. In this context, based on discharge projections presented by [22], the mean variations were applied to the position parameter of the log-normal distribution, creating three different scenarios: (i) a conservative scenario associated with the actual emission scenario; (ii) an optimistic scenario associated with the RCP 4.5 emission scenario; and (iii) a pessimistic scenario related to the RCP 8.5 scenario. Based on the adjusted distributions for the three scenarios, a set of 100 time series, with daily projections for the following five years, was created. These series were used as input data for the operating model.

3.3. Results and Discussion

3.3.1. Leakage Impact

As a first analysis, only the leakage impact was evaluated in the reservoir operation. Thus, the leakage index varied between 0 and 52%, simulating both an improvement or deterioration of the water distribution efficiency. Figure 8a shows the reduction in the energy produced by the hydropower plant, simply by the impact on the reservoir water level. As the leakage rate increases, the water level reduces more rapidly, and consequently, the hydropower has to stop its operation more frequently to maintain the minimum water level required for the pumping station of the water supply. The availability of hydropower drops from 53.6% when no leakage is observed and drops to 48.1% when the leakage is maximum, which represents a reduction of 11.6% in the energy produced. However, in addition to the reduction in energy produced, there is an increase in the energy consumed in the pumping station as the leakage rate increases, and a higher flow is required for the supply. Figure 8b compares the net energy of the system for three different leakage rates during a year. In all cases, especially during the dry season, there is a requirement for additional energy sources, as the hydropower plant is not capable of supplying the demand. Comparing the ideal scenario of no leakages with the worst scenario with a leakage rate of 52%, the net energy deficit increases by 330%. Comparing the current situation, where the leakage rate is 32%, with the worst scenario, the increase in the net energy deficit is 110%. On the other hand, with the improvement in water supply achieving a leakage rate of 20%, the net energy deficit drops 35%. This shows how important leakage management is, not only from an environmental perspective but also from an economic view, impacting the electrical grid directly (reservoir water level) and indirectly (pumping energy consumption).



(**a**) (**b**)

Figure 8. Leakage impact in hydropower operation: (**a**) energy reduction for different leakage rates; (**b**) net energy in a year for original, minimum, and maximum leakage rates.

3.3.2. Climate Change Impact

Using the forecasted natural flow of the river for five years of operation, Figure 9 shows the monthly net energy of the system for three different climate change scenarios. It can be observed that during the dry season, the net energy has a lower variation, as the natural flow is more constant due to the lack of rain. Consequently, the net energy is severely affected, requiring an additional 500 MWh per month from external power plants to attend to the energy consumption of the pumping station, as the energy produced by the existing hydropower plant of the system is not sufficient. During the rainy season, the river flow variability is higher, and therefore, the net energy is also more variable. Despite the increase in available power, energy production can be limited by the turbine's capacity and the reservoir storage capacity. For the case study, these problems were not significant for the net energy of the system, i.e., the spilled flow is low. However, comparing the three scenarios during the rainy season, it is clear that in a pessimistic scenario of climate change, in addition to the water resources scarcity, the energy available is also severely affected. Finally, comparing the climate change impact with the leakage impact, it is clear that the lack of water resources is potentially more harmful to the system, as it drastically reduces the hydropower plant availability.

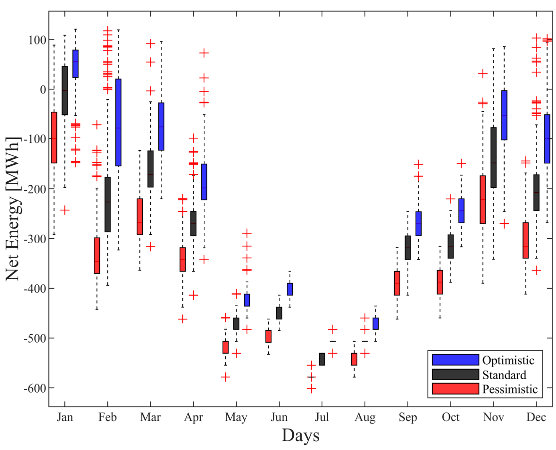


Figure 9. Net energy of the system for different climate change scenarios.

4. Conclusions

This paper presented the water–energy nexus in the context of water supply systems, highlighting the impacts that leakage can have on energy production. Firstly, an overview of the Brazilian case was presented, showing that the energy losses due to leakages are 0.64% of the total energy produced. Considering only the hydropower energy, these losses represent 1.12%, which in the Brazilian case is significant, as the major electrical energy source is hydropower. Secondly, a more detailed study was made in a system where a reservoir is used both for energy production and water supply. The results showed that leakages not only affect the energy consumption in pumping stations but also reduce the water stored in the reservoir. Consequently, the energy produced by the hydropower drops, which, during dry periods, can lead to a negative net energy in the system, i.e., there is a necessity to import energy from other power plants to maintain the water supply. Finally, the climate change impact was evaluated for three different scenarios. The results showed that in a pessimistic scenario, the lack of water resources can be more harmful to the net energy of the system than leakages. The variations during the dry season were not high, as the river flow was more constant. However, during the rainy season, comparing the optimistic and pessimistic scenarios, the net energy goes from positive or close to zero to a negative value. For the case study, the spilled flow is relatively low and does not significantly affect energy production. However, in a climate change scenario where extreme conditions are more severe and common, the reservoir storage capacity or the turbine power could be redesigned to avoid significant energy losses during rainy periods.

Author Contributions: Conceptualization, A.B., R.G.S. and G.M.; methodology, A.B., R.G.S. and G.M.; software, A.B., R.G.S. and G.M.; validation, A.B., R.G.S. and G.M.; formal analysis, A.B., R.G.S. and G.M.; writing—original draft preparation, A.B., R.G.S. and G.M.; writing—review and editing, A.B., R.G.S. and G.M.; supervision, G.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support from the National Council for Scientific and Technological Development (CNPq) through the Productivity Scholarship PQ-2 (CNPQ No 305256/2021-1) and Universal Demand Project (CNPQ No 404605/2021-4), and the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) through the project APQ 01320 21.

Data Availability Statement: All data of the model used in this research can be requested from the corresponding author through the indicated e-mail.

Conflicts of Interest: The authors declare no conflict of interest.

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