Mechanic and Energy
Mecânica e Energia

The impact of residual flow on energy generation in hydroelectric power plants

http://dx.doi.org/10.1590/0370-44672023770013

Walker Matheus Ferreira da Silva[1,3]
https://orcid.org/0000-0003-3471-3060
Adriano Silva Bastos[2,4]
https://orcid.org/0000-0003-4879-4295
Edna Maria de Faria Viana[1,5]
https://orcid.org/0000-0002-3853-1355
Carlos Barreira Martinez[1,2,6]
https://orcid.org/0000-0002-0653-5298

[1]Universidade Federal de Minas Gerais – UFMG, Programa de Pós-Graduação em Engenharia Mecânica, Belo Horizonte - Minas Gerais - Brasil.

[2]Universidade Federal de Itajubá - UNIFEI, Programa de Pós-Graduação em Engenharia Mecânica, Itajubá - Minas Gerais – Brasil.

E-mails: [3]walkermatheus@ufmg.br, [4]adriano.bastos@unifei.edu.br, [5]ednamfv@ufmg.br, [6]cmartinez@unifei.edu.br

Abstract

In Brazil, 65% of the electric power production comes from hydroelectric power plants (HPPs). In some cases, these power plants divert the course of rivers, resulting in regions impacted by the absence of water, which are known as reduced flow sections (RFS). These sections are regulated by legislation and aim to maintain the minimum flow necessary to preserve the fauna, flora, fish, and human consumption in the region. Depending on the time of year, this minimum flow, also known as ecological flow (residual flow), can reach significant values, resulting in the interruption of power generation in these HPPs. This article presents a study case of two hydroelectric power plants located in different Brazilian states. The objective of this study is to explore the feasibility of implementing auxiliary generator groups that can operate uninterruptedly at different drop heights while ensuring the preservation of residual flow during low flow periods or taking advantage of the overflow flow by spillways during high flow periods. This auxiliary system would use the same set of structures and transmission systems as the main power plant, minimizing environmental impacts and implementation costs, allowing this solution to be implemented in HPPs that face this type of problem in Brazil. The results obtained indicate that HPPs with larger reservoirs have a greater ability to maintain residual flows with minimal generation loss and that run-of-the-river power plants are the most impacted by the maintenance of residual flow.

Keywords: generation losses, ecological flow, hydroelectric power plants.

1. Introduction

The Brazilian energy matrix is mainly composed of renewable resources, with 65% of its production coming from hydroelectric power plants (HPPs). These facilities use equipment and structures to convert potential hydraulic energy into mechanical energy through the interaction between the water and turbines. The potential energy can come from the accumulation reservoir, or the water flow itself. The generated energy is then transmitted to substations or transmission and distribution systems, with the final goal being the end consumer. Despite the abundance of water resources in Brazil, there are still challenges in meeting energy demand, such as the high cost of implementing an HPP and its increasing distance from consumer centers. Another factor that has become increasingly relevant in recent decades is that many HPPs built since the beginning of the 21st century do not have accumulation reservoirs or regulation, making them vulnerable to seasonal hydrological variation, directly impacting energy production.

Despite the majority of the HPPs not having a large reservoir, interference in the environment still exists and can cause serious harm to the local ecosystem. One strategy for preserving this downstream ecosystem from hydropower plants is to maintain a minimum flow in the watercourse. This minimum flow is known as the ecological flow, residual flow Q_{res}, or reduced flow. In the last two decades, some alternatives have been adopted to mitigate the problems caused by reduced downstream flow. Perhaps the most emblematic case is the Belo Monte hydropower plant on the Xingu River, where an auxiliary powerhouse was built to generate energy by taking advantage of the minimum water flow that is designated as residual flow.

The issue of maintaining the residual flow in rivers where a Hydroelectric Power Plant (HPP) is installed is a common topic of discussion. One concern is how residual flow affects energy generation, particularly during periods of water scarcity (Silva *et al.*, 2021). Interest in the subject has increased with the creation of new projects that operate in the "run-of-river" system, which results in a reduction of the available flow for energy generation purposes. Furthermore, during periods of low affluence, it is possible that the available flows may not be sufficient to maintain the reservoir level, even when the power plants utilize the "run-of-river" system. In more severe cases, this can even prevent the activation of the generators. As a result, the HPP is obligated to release the flow through spillways and, in some cases, through dispersion valves. In these cases, the spilled flows do not generate energy, indicating the need to quantify the actual impact of residual flow on energy generation in these power plants.

2. Literature review

2.1 Brazilian legislation and flow grants

In Brazil, each state establishes a methodology for the quantitative and qualitative determination of ecological or residual flows (Buenaga, 2019). The former National Department of Water and Electric Energy (DNAEE), now the National Agency of Electric Energy (ANEEL), developed regulations to determine minimum flows for water resource exploitation projects. These regulations established values based on a historical data series with a minimum duration of 10 years. For smaller generation enterprises, the established flow rate could not be lower than the minimum monthly average flow rate. This determination was based on calculations derived from annual observations at the enterprise locations (Buenaga, 2019; DAEE, 2005).

The National Water Resources Policy and the National Water Resources Management System were established in 1997 through Law no. 9433. This law establishes parameters for granting rights to use water resources and ensures access rights to water in the country (ANEEL, 2000). According to Santilli (2007), granting water rights is crucial for guaranteeing the quality and quantity of water in Brazil. These rights minimize the conflicting effects of uncontrolled use of the water resource and play an important role in water resource management. The National Water and Basic Sanitation Agency (ANA) outlines criteria based on the characteristics of the water resources to be exploited. According to ANA (2020a), the goal of granting water rights is to ensure the quantitative and qualitative control of water use and effective exercise of access rights to water resources.

In Brazil, the capture or extraction of surface water or groundwater for various purposes, such as the discharge of sewage and liquid waste, macro-drainage, and hydroelectric generation, requires a grant. According to several studies (Benetti *et al.*, 2003; Facuri, 2004; Gasques *et al.*, 2018), water concessions must maintain the integrity of the granted flow rate for sustainably to meet the demands for water resources usage.

Each state in Brazil establishes its own criteria for granting rights in water usage, which indirectly defines their approach to residual water flow management (Collischonn *et al.*, 2006). Vestena *et al.* (2012) highlight that the criteria for granting permits for water usage in Brazil are based on historical data and often favor hydrological methodologies. However, the use of multiple methods for determining ecological flow criteria can provide a more rational and correct utilization of water resources (Vestena *et al.*, 2012). Table 1 presents a brief overview of the various laws in Brazilian states regarding the maximum grants allowable in water usage.

Table 1 - Legislation for water allocation in the states.

State of the Federation	Requirement of granting
Acre (IMAC, 2010)	Water balance. Reference flow rate calculations are obtained by using historical series. Maximum allowable flow rate in the course of interest.
Alagoas (SEMARH, 2001)	Guaranteed regulated annual discharge of 90%. The sum of the volumes of water granted in a basin cannot exceed nine-tenths of the annual regulated flow.
Amapá (IMAP, 2017)	Local water balance. Calculation of reference flows. Maximum flow needed in the river area of interest.
Amazonas (IPAAM, 2016)	Guaranteed flow rate of 95% by volume, either equal to or higher. When there is a lack of information, the lowest local measured flow in the dry season is adopted. Outside the dry season a reduction coefficient is used. The sum of the maximum flows cannot exceed 75% of the 95% guaranteed reference flow rate.
Bahia (INEMA, 2014)	Sum of maximum flows may not exceed 80% of the 90% of the guaranteed reference flow rate. Individual usage may not exceed 20% of the 90% of the guaranteed reference flow rate.
Distrito Federal (ADASA, 2001)	Depending on the region, $Q_{7,10}$ or Q_{90} is adopted, and the sum of the flows cannot exceed 80% of the guaranteed flows.
Espírito Santo (AGERH, 2005)	Reference flow rate should be less than, or equal to $Q_{7,10}$, and cannot exceed the watercourse's dry period flow rate.
Goiás (SECIMA, 2005)	The sum of the flows cannot exceed 70% of the guaranteed reference flow rate of 90%. Conservative methodologies of 50% of the reference flow rate are admitted.
Maranhão (SEMA, 2011)	Downstream flow from bypasses may not exceed 80% of the 90% of the guaranteed reference flow rate.
Mato Grosso (SEMA, 2007)	The sum of the maximum flows cannot exceed the 95% of the guaranteed reference flow rate.
Mato grosso do Sul (IMASUL, 2014)	Maximum allowed flow rate at 70% of the reference flow, with 95% guaranteed. Individual usage cannot exceed 20% of the 95% of the guaranteed reference flow rate.
Minas Gerais (IGAM, 2001)	Maximum flow rate of 30% of the reference flow rate $Q_{7,10}$ of the watercourse. Maximum limit of 70% of the reference $Q_{7,10}$, when reservoirs are used.
Pará (CERH, 2010)	The sum of flows is limited to 70% of the reference flow rate, with 95% guaranteed. The sum of unavailable flows is limited to 30% of the reference flow rate, with 95% guaranteed. The maximum limit for capturing by reservoirs is 100% of the regularized flow, with 95% guaranteed, as long as 70% is guaranteed downstream. The maximum limit for individual withdrawal is 20% of the reference flow rate with 95% guaranteed. The maximum limit for unavailable flow is 10% of the 95% guaranteed flow.
Paraíba (AESA, 1997)	The sum of the volumes may not exceed 9/10 of the annual regulated flow, with 90% guaranteed. In lakes or ponds, the limit is reduced by 1/3.
Paraná (AGUASPARANÁ, 2001)	Flows should correspond to the assured energy. Maximum swallowing flow rate. Guaranteed downstream flows. Design flows.
Pernambuco (APAC, 1998)	The allowed flow cannot exceed 90% of the reference flow, with 90% guaranteed.
Piauí (SEMAR, 2004)	Flow for rivers with average monthly flow with 95% guaranteed, and reservoirs with 90% guaranteed. For derivations and surface water withdrawal, an ecological flow rate of 20% of the reference flow rate was determined. Maximum allocation of 80% of the 95% guaranteed flow rate for rivers, and 80% of the 90% of the guaranteed flow rate for reservoirs.
Rio de Janeiro (INEA, 2007)	Minimum environmental flow of 50% of $Q_{7,10}$, of the selected watercourse.
Rio Grande do Sul (FEPAM, 1996)	Maximum allowed flow of 70%, of the reference flow with 90% guaranteed.
Rio Grande do Norte (IGARN, 1997)	Grantable flow rate between 80% and 95% of the reference flow rate, with 90% guaranteed.
Rondônia (SEDAM, 2004)	Allocable flow rate of 70% of $Q_{7,10}$, of the chosen watercourse.
Roraima (FEMARH, 2007)	Flows measured in months of the dry period of the state. Studies, that include accepted users downstream of the capture point, or where there was no conflict of use. $Q_{7,10}$, Q_{90}, or Q_L, can be used as the reference flow rate.
Santa Catarina (SDS, 2006)	Grantable flow rate of 50% of the reference flow rate, with 98% guaranteed, considering a technical reserve of 10% of the reference flow rate, with 98% guaranteed.
São Paulo (DAEE, 2005)	Maximum allowed flow of 50% of $Q_{7,10}$ of the chosen watercourse, limited to 20% of $Q_{7,10}$, for individual uses.
Sergipe (SEMARH, 1999)	Maximum authorized flow rate between 85% and 95% guaranteed. Individual usage is limited to 30% of the adopted reference flow rate.
Tocantins (NATURATINS, 2005)	A maximum grantable flow rate on-stream of 75% of the reference flow rate, with 90% guaranteed. Maximum flow rate authorized with a reservoir of up to 90% of the reference flow rate, with 90% guaranteed. Individual usage limits at 25% of the reference flow rate, with 90% guaranteed.

2.2 Methodologies to calculate reference flow rates in Brazil

In Brazil, several methodologies are commonly employed for the calculation of reference water levels, as noted in Mendes (2007). These methodologies include:

- Seven-day minimum flow with a recurrence period of 10 years ($Q_{7,10}$).
- The Tennant/Montana method, based on long-term average flow (Q_{MLT}).
- Permanence Curve Analysis.

2.2.1 Seven-day minimum flow with ten-year recurrence period ($Q_{7,10}$)

The methodology of "Seven-day Minimum Flow with a Ten-Year Recurrence Period" ($Q_{7,10}$) is a hydrological approach that relies solely on historical data to determine the minimum flow levels in rivers. Unlike other methodologies, $Q_{7,10}$ does not consider aquatic habitats. This methodology has the advantage of not requiring in-field data collection, except for flow parameters.

According to the study conducted by Benetti *et al.*, (2003), the flow rate is obtained by calculating the daily moving average over 7-day intervals for a full year. The minimum value of the average is recorded. This process is repeated for a minimum recurrence period of ten years, resulting in a series of minimum flow values for 7 consecutive days. The data is sorted in ascending order, and its distributional function and return period are estimated. Within this distributional function, the duration of the minimum 7-day flow with a 10-year return period is calculated.

Equation 1 mathematically defines the indices necessary to calculate the $Q_{7,10}$ flow rate (Benetti *et al.*, 2003):

$$Q_{7,10} = \overline{v} + \sigma\,[0.4500 + 0.7797\,[\,\ln\left(\frac{TR}{TR - 1}\right)] \qquad (1)$$

In this equation, the following variables are considered: $Q_{7,10}$: Minimum Seven-Day Flow with a Ten-Year Recurrence Period; v: Minimum Seven-Day Moving Average with a Recurrence Period of One Year; σ: Ten-Year Standard Deviation; TR: Recurrence or Return Rate.

2.2.2 Tennant/Montana Method based on long-term average flow

The 'Tennant/Montana Method' is based on the calculation of the long-term average flow rate (Q_{MLT}) for each hydrological site. This methodology considers varying percentages for dry and wet periods (dry / rainy seasons) (Benetti *et al.*, 2003). It involves the calculation of average annual flow rates. Table 2 presents the recommended percentages based on the period of time.

Table 2 - Q_{MLT} flow recommended. Adapted from (Benetti *et al.*, 2003).

Condition of the river	Recommended flow rate (% of Q_{MLT})	
	Dry period	Wet period
Exceptional	40	60
Excellent	30	50
Good	20	40
Regular or deteriorating	10	30
Poor or minimal	10	10

The Tennant Method is widely used for determining the ecological and permissible reference flow. It has undergone modifications to suit the characteristics of different regions, rather than being limited to the region of its inception and development (ANA, 2020b; Benetti *et al.*, 2003). The models generated using this method, based on historical data, are efficient and uncomplicated and do not require fieldwork. However, it is advisable to use them in a safe and limited way, by considering both primary characteristics and those that are similar to the region in which the method was developed, to minimize potential negative impacts.

2.2.3 Permanence curve analysis

The "Permanence Curve Analysis" methodology is a commonly used approach in Brazil for analyzing discharge statistics. It compares the flow rate to the probability of its occurrence over time. This comparison is made by using historical data to calculate daily, monthly, or annual variability. The methodology also accounts for the specific characteristics of the river being analyzed by ordering the data in ascending order and performing several steps, including determining the minimum and maximum flows of the analyzed events, defining class intervals between selected values, determining the flows contained in the intervals, obtaining the frequency distribution, accumulating of values in descending order, and plotting the data in permanence curve graphs. As shown in Figure 1, the flow rate corresponds to 75% of the permanence curve, indicating that 75% of the time, the flows are greater than or equal to the Q_{75} value. Drought periods with probabilities greater than 95% occur when flows are below the 5% level of the permanence curve (Mendes, 2007).

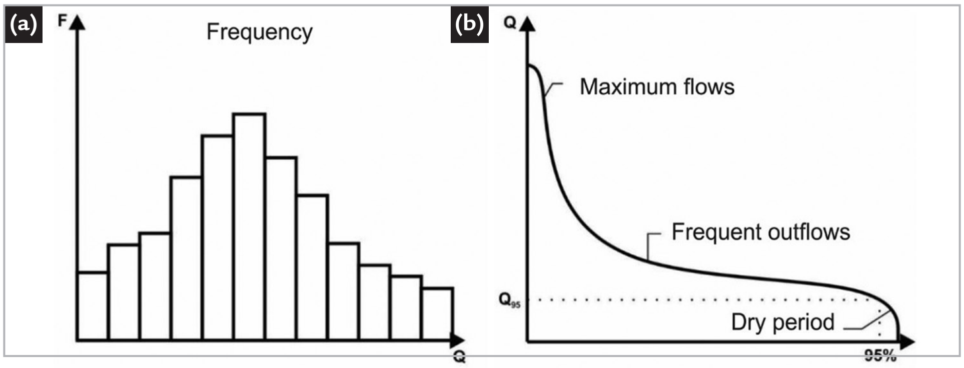

Figure 1 - Permanence curve. Adapted from (Mendes, 2007).

3. Materials and methods

3.1 Case study

The present study aims to analyze the operational dispatch flows and determine the residual/ecological flows in two hydropower plants (HPPs), Retiro Baixo and Serra do Facão, located in the states of Minas Gerais and Goiás, Brazil, respectively (FURNAS, 2014). The historical series data for these two areas were obtained from the Reservoir Monitoring System (SAR) of the National Water and Basic Sanitation Agency (ANA).

3.1.1 HPP Retiro baixo description

The Retiro Baixo Hydroelectric Power Plant is located in the state of Minas Gerais, Brazil, and is the subject of study for residual flows in this research. The historical series related to the Retiro Baixo Hydroelectric Power Plant was obtained through the Reservoir Monitoring System (SAR) maintained by ANA. According to the power plant administrators, FURNAS (2020a) and RBE (2020), the Retiro Baixo HPP is a "run-of-river" plant located on the Paraopeba River, approximately 5 km from the Três Marias HPP. Its characteristics are presented in Table 3.

Table 3 - Characteristics of HPP Retiro Baixo. Source: (FURNAS, 2020a).

River	Paraopeba
Basin	São Francisco
Axis location	Latitude: 18° 53" 40' S
	Longitude: 44° 46" 54' W
Reservoir area and volume	22.58 km², 241690 m³
Maximum turbine flow rate	256.36 m³/s
NA minimum, maximum and maximorum	614 m, 616 m and 617m
Installed power	82 MW (2 Kaplan turbines with 41 MW)
Local firm power	38.5 MW average
Nominal unit flow rate	128.18 m³/s

3.1.2 HPP Serra do Facão description

The Serra do Facão Hydroelectric Power Plant, located in the state of Goiás, Brazil, was selected as part of the study area in this research for the analysis of operational dispatch flows and identification of residual/ecological flows. The historical series pertaining to the Serra do Facão Hydroelectric Power Plant was obtained

Table 4 - Characteristics of the HPP Serra do Facão. (SEFAC, 2020).

River	São Marcos
Basin	Paraná
Axis location	Latitude: 18° 04" 00' S
	Longitude: 47° 40" 00' W
Reservoir area and volume	218.84 km², 5199000000 m³
Maximum turbine flow rate	310.99 m³/s
NA minimum, maximum and maximorum	732.5 m, 756 m, 756.98 m
Installed power	212 MW (2 Francis turbines with 106 MW)
Local firm power	178.8 MW average
Nominal unit flow rate	155.49 m³/s

via the Reservoir Monitoring System (SAR) maintained by ANA. According to information provided by the plant administrators FURNAS (2020b) and SEFAC (2020), the Serra do Facão Hydroelectric Power Plant is a run-of-river type located on the São Marcos River. The characteristics of the plant are presented in Table 4.

3.2 Methodology

The maintenance of residual flow is currently governed by a range of environmental, economic, and social factors, among others (ANA, 2011, 2020a). The granted flow rate criteria for the two HPPs studied in this research, Retiro Baixo and Serra do Facão, are analyzed based on the data presented in Table 1. The criteria used by IGAM-MG are more stringent compared to those outlined by SECIMA-GO, as a result of differences in the granting methodology adopted by each state. Most hydroelectric enterprises are typically exempt from granting criteria due to previous evaluation, unavailability of historical flow series, or current water usage legislation, or due to minimum operating parameters that surpass the requirements set by the competent agency. Although scientifically validated methodologies are employed for granting flow permits, there is ongoing debate regarding the criteria and methods used to consider the water resource ecosystem and watercourse characteristics. Hence, each enterprise should undertake comprehensive and necessary procedures for optimal local alignment.

3.2.1 Determination of power and energy

The installed power capacity of an HPP (‘Pinst’) is directly dependent on both the specific mass of the water (‘ρ’), the design flow ’Q’, the existing unevenness of the site ‘’, the acceleration of gravity ‘g’, and the overall efficiency of the plant (‘η’). The product of these quantities, results in the total power of the plant, as seen in Equation 2 (Doland, 1954).

$$P_{inst} = \frac{\rho . g . Q . H . \eta}{1000} \; (kW) \qquad (2)$$

The Firm Energy corresponds to the maximum production that a plant can supply. It considers the driest period registered in the flow history without the occurrence of deficits, as well as the entire historical record of its affluence, as presented in Equation 3. In the same equation, $T_{av. time}$. is the average operation time of the installation, in months or years (Hicks *et al*., 1974).

$$E_{firm} = P_{inst.} \cdot T_{av.time.} \quad (kW) \qquad (3)$$

In order to calculate the revenue loss (Parrec) related to the dispatch of the residual flow in a certain period of time, the commercialization value of energy (Venerg) in the Brazilian currency of ‘reais’ (R$) / kWh is multiplied by the sum of the flow dispatched by the spillway systems or dispersing elements with environmental purposes (‘$\sum Q_{res}$’), as well as by the specific mass of the water (‘ρ’), the existing slope at the site (‘H’), the acceleration of gravity (‘g’), and the global efficiency of the installation (‘η’); as presented in Equation 4.

$$P_{arrec.} = V_{energ} * \sum Q_{res} * \rho * g * H * \eta * 24h \, [R\$] \qquad (4)$$

3.2.2 General procedure

Initially, the total water levels of the HPP studied were obtained from data collected in the SAR source. Subsequently, an analysis of the allocated flows and their usage considerations was conducted based on current legislation. This allowed for the determination of the characteristics of the current system and the proposed energy cogeneration system, utilizing residual flows as a secondary energy source. To accurately depict the energy generation process, the following were considered: i) comparison of the dispatched residual flows with the calculated flows; ii) analysis of load losses in the generation system coupled with the residual flow maintenance system; and iii) design of the generation system based on the site characteristics.

3.2.3 Study of the flow of the hydroelectric power plants Retiro Baixo and Serra do Facão

For the analysis of flow rates of each Hydroelectric Power Plant (HPP) under study, historical data obtained from the Reservoir Monitoring System (SAR) provided by ANA (2020b) were utilized. SAR is responsible for monitoring the flow series of all reservoirs and waterways in Brazil and regulating and supervising agencies in each state of the country. The data re-

Table 5 - Characteristics of HPPs Retiro Baixo and Serra do Facão.(ANA, 2020b).

Period: 24/09/2010 to 24/09/2020	Retiro Baixo	Serra do Facão
Post	19118 – Central	19016 - Central
Minimum pouring	7.00 m³/s	0.50 m³/s
Maximum pouring	28.00 m³/s	288.50 m³/s *
Average pouring	17.80 m³/s	3.28 m³/s
Average Turbine	58.68 m³/s	115.48 m³/s

* Dispatched flow in a short flood period.

corded by SAR includes quantitative and qualitative parameters of the reservoirs and watercourses, including turbine flow, which refers to the flow that passes through the turbines for power generation, and spilled flow, which is discharged through spillways and/or bottom valves. The flow data of both HPPs Retiro Baixo and Serra do Facão are presented in Table 5.

3.2.4 Retiro Baixo HPP

According to the reports obtained via SAR (ANA, 2020b), a few particularities can be observed in the operation of the HPP Retiro Baixo. First, since this HPP is characterized as a run-of-river plant, all the flow is dispatched by turbine, by spill, or by both. Secondly, once the HPP is geographically located close to the Três Marias reservoir, the HPP also regulates the flow of one of the affluent rivers of this reservoir. By analyzing the environmental flow dispatch, according to SAR, and respecting the need of feeding the basin of the reservoir, it is noticeable that the dispatched flows that did not pass by the turbine depend on a few factors. These are the following: i) the affluent flow of the HPP Retiro Baixo; and ii) the need of continuous flow of the river. By considering that, we find the environmental flows (spilled) between 7 and 28 m³/s (ANA, 2020b).

3.2.5 Serra do Facão HPP

The characteristics of the Serra do Facão HPP, according to the reports obtained by means of SAR (ANA, 2020b), are presented in Table 5 and Figure 2.

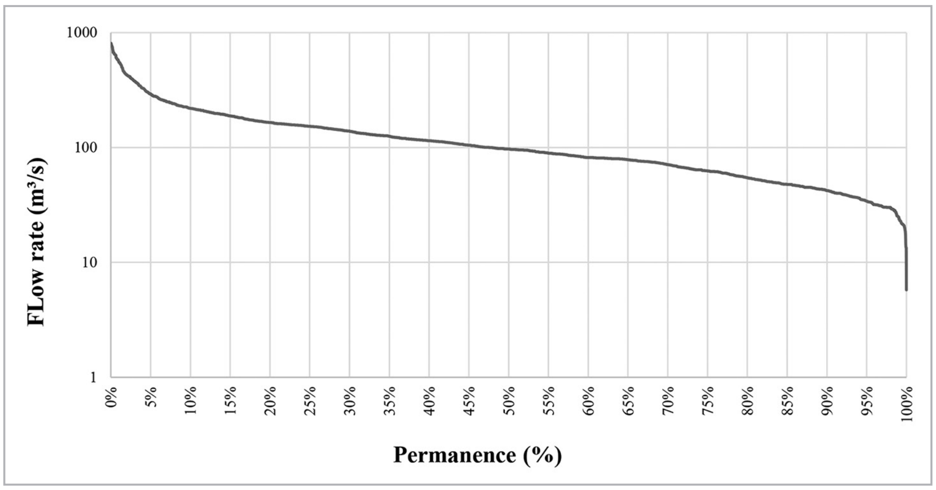

Figure 2 - HPP Serra do Facão permanence curve.

By analyzing the particularities of data collected, it is considered that this plant is characterized as an accumulation plant. Its function is to regulate the flow of the main watercourse of the 'São Marcos' River, according to SAR. As such, it can be said that there is practically no environmental flow dispatch, with exceptions in periods of drought or when the use of turbines is unavailable. Additionally, notice that the minimum spill flow observed was 0.5 m³/s.

4. Results and discussion

4.1 Determination of flow rate for the HPP of 'Retiro Baixo' and 'Serra do Facão'

In order to determine the flow rate of the Retiro Baixo Hydroelectric Power Plant (HPP), located in Minas Gerais, the $Q_{7,10}$ flow criterion was employed. This criterion takes into account statistical correlations of experimental parameters and is calculated using Equation 1. On the other hand, the Serra do Facão HPP, located in Goiás, utilized the Q_{95} flow criterion. This criterion is based on an analysis of the flow permanence curve from historical series, with a minimum observational period of 10 years. Essentially, the Q_{95} flow criterion assumes that 95% of the time, the watercourse flow rate will be equal to, or higher than, the value determined by the permanence curve analysis.

4.2 Retiro Baixo hydroelectric power plant

The Retiro Baixo HPP has been operating for commercial purposes since March of 2010. Data on minimum average mobile flows presented in Table 6 were obtained according to the historical series provided by ANA via SAR.

Table 6 - Annual 7-day mobile minimum average flows with a recurrence time of 10 years.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Flow rates(m³/s)	26.7	24.5	26.3	23.5	5.7	11.0	6.7	4.1	21.0	18.5	26.6

By applying Equation 1 to this data, we found the value of 5.89 m³/s of ecological flow ($Q_{7,10}$). Considering the current legislation applicable to the state of Minas Gerais, 70% of this flow should be maintained in the reduced flow section which corresponds to 4.12 m³/s. When analyzing data provided by SAR, it is noticeable that for flows lower than 7 m³/s, there is no use of turbines. This flow is dispensed by the overflow system of the HPP. The HPP Retiro Baixo has a minimum turbinable flow of 15% of the nominal swallow value, it means, 19.20 m³/s. The history of generation or dispatching by spillways made available by SAR indicates that the minimum dispatched flow (ecological flow) was 7 m³/s higher than the required ecological flow, which is 4.12 m³/s.

Despite the ecological flow rate being 4.12 m³/s, Retiro Baixo maintained, in some periods, flows up to seven times this value. This happened even during periods of low affluence of flows to the reservoir. As a result, during 441 days over the 10 years considered, there were spills in the facility. Respecting the minimum turbine flow limit of 15% of the nominal flow (19.20 m³/s), the hypothesis that flows lower than this one, and higher than the ecological flow will be stored in the reservoir was adopted. The balance between the turbined and spilled flows for the purpose of maintaining the residual flow is presented in Table 7. It indicates that the loss of energy generation in the available history is 2.75% of the energy generated. When applying an average hydraulic energy price of R$ 183.82/MWh for the period between 06-2020 and 06-202 (CCEE, 2021), one finds a loss in value of commercialized energy of more than R$ 8 million; as shown in Table 7.

Table 7 - Monitoring of flows and generation loss at HPP Retiro Baixo.

Sum of turbine water flows in 10 years	205,806.81
Sum of the outflows discharged for maintenance of Q_{res} in 10 years – m³/day (24 h)	5,665.00
Percentual generation loss	2.75%
Income loss due to residual flow dispatching (R$)	8,414,342.86

4.3 Serra do Facão hydroelectric power plant

The Serra do Facão HPP has been in operating for a commercial purpose since October of 2010. The legislation of the state of Goiás requires the residual flow in the TVR to be 70% of the Q_{95} obtained from the flow permanence curve. From Figure 2, we obtain that Q_{95} has an approximate value of 34.33 m³/s, which indicates a residual flow of 24.03 m³/s. This HPP has a minimum turbinable flow of 15% of the nominal swallow, that is, 23.33 m³/s. The history of generation/dispatching by spillways made available by SAR indicates that the minimum dispatched flow (ecological or residual flow) was 0.5 m³/s lower than the required ecological flow, which is 24.03 m³/s. Thus, over the 10 years analyzed, this HPP has dispatched residual/ecological flows through the spill system for 94 days. For this study, we adopted the hypothesis that the operation of the hydroelectric plant will only dispatch from the generating group flows higher than 24.03 m³/s. Flows lower than this and higher than the residual flow will be stored in the reservoir. The balance between turbine flows and spilled flows for the purpose of maintaining the residual flow is presented in Table 8. It indicates that the generation loss in the available history is only 0.25% of the energy generated.

Table 8 - Monitoring of flow and generation loss at HPP Serra do Facão.

Sum of turbine water flows in 10 years	289,532.08
Sum of the outflows discharged for maintenance of Q_{res} in 10 years – m³/day (24 h)	714.54
Percentage generation loss	0.25%
Income loss due to residual flow dispatching (R$)	1,953,813.84

5. Conclusion

In Brazil, the legal requirement for residual/ecological/reduced flow maintenance values varies across states. Some state legislation mandates low residual flows along rivers, which is 70% of $Q_{7,10}$ in the state of Minas Gerais, while in states such as Goiás, the flow should be 70% of Q_{95}. The studies carried out and analyzed show that the percentage reduction of the turbine flow is minimal, ranging from 0.25% to 2.75% for the HPPs Serra do Facão and Retiro Baixo, respectively. It is worth noting that the residual flow requirement for the Serra do Facão HPP is proportionally greater than that of Retiro Baixo HPP. However, the flow characteristics and existence of the accumulation reservoir provide greater flexibility in maintaining residual flow and minimizing generation losses.

The data and results indicate that the impact of maintaining residual flow is small and amounts to less than R$16,300.00 and R$70,200.00 per month for Serra do Facão and Retiro Baixo, respectively. It is important to note that HPPs with larger reservoirs generally have a better ability to maintain residual flows while reducing energy generation losses. It is preliminarily concluded that the reduction of energy generation can be considered minimal and that adjustments in load dispatch can further minimize this loss. Further studies involving a larger number of HPPs and incorporating environmental requirements into load dispatch rules should be conducted to minimize this loss even more. Additionally, the impact of energy generation reduction in HPPs could be incorporated into the cost of installation and energy generation.

Acknowledgments

This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001; CNPq - license number PQ: 304370/2018-5 305059/2022-0; Fapemig - license number PPM-00252-18; and SEFAC/ANEEL - license number PD-06899-2912/2016 & PD-06899-2812/2016.

References

AGÊNCIA ESTADUAL DE RECURSOS HÍDRICOS - AGERH. ***Resolução normativa do CERH nº 5***, 2005.

AGÊNCIA EXECUTIVA DE GESTÃO DAS ÁGUAS DO ESTADO DA PARAÍBA - AESA . ***Decreto nº 19260,*** 1997.

AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO - ANA. ***Outorga de direito de uso de recursos hídricos.*** Brasília: [s.n.].

AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO - ANA. ***Outorga e fiscalização.*** [s.l: s.n.].

AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO - ANA. ***Sistema de Acompanhamento de Reservatórios - SAR.***

AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA - ANEEL. ***Introdução ao gerenciamento de recursos hídricos.*** Brasília: [s.n.].

AGÊNCIA PERNAMBUCANA DE ÁGUAS E CLIMA - APAC. ***Decreto nº 20423,*** 1998.

AGÊNCIA REGULADORA DE ÁGUA, ENERGIA E SANEAMENTO BÁSICO DO DISTRITO FEDERAL - ADASA. ***Decreto nº 22358, 22359 de 2001, resolução ADASA nº 350,*** 2001.

BENETTI, A. D.; LANNA, A. E. L.; COBALCHINI, M. S. Metodologias para determinação de vazões ecológicas em rios. ***Revista Brasileira de Recursos Hídricos,*** v. 8, n. 2, p. 149–160, 2003.

BUENAGA, F. V. A. de S. C. ***Alternativa metodológica para definição da vazão ecológica em trechos de vazão reduzida em hidrelétricas.*** Rio de Janeiro: Universidade Federal do Rio de Janeiro, 2019.

CÂMARA DE COMERCIALIZAÇÃO DE ENERGIA ELÉTRICA - CCEE. ***Preço de Liquidação das Diferenças - PLD.*** Availabe in: <https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/como_ccee_atua/precos/preco_horario>. Accessed in: 8 fev. 2023.

CONSELHO ESTADUAL DE RECURSOS HÍDRICOS - CERH . ***Resolução nº 10,*** 2010.

CONSELHO ESTADUAL DO MEIO AMBIENTE, CIÊNCIA E TECNOLOGIA - CEMACT. ***Resolução nº 004,*** 2010.

COLLISCHONN, W.; SOUZA, G. R.; PRIANTE, G. K.; FREITAS, R. T.; AGRA, S. G. A. ***Da vazão ecológica ao hidrograma ecológico.*** CONGRESSO DA ÁGUA. ***Anais*** [...], 2006.

DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA - DAEE. ***Guia prático para pequenas obras hidráulicas.*** São Paulo, [s.n.].

DOLAND, J. J. ***Hydro power engineering***: a textbook for civil engineers. [s.l.] Ronald Press Company, 1954.

FACURI, M. F. ***A implantação de usinas hidrelétricas e o processo de licenciamento ambiental***: a importância da articulação entre os setores elétrico e de meio ambiente no Brasil. Itajubá: Universidade Federal de Itajubá, 2004.

FUNDAÇÃO ESTADUAL DE PROTEÇÃO AMBIENTAL DA SECRETARIA DO AMBIENTE E DESENVOLVIMENTO SUSTENTÁVEL - FEPAM. ***Decreto nº 37033,*** 1996.

FUNDAÇÃO ESTADUAL DO MEIO AMBIENTE E RECURSOS HÍDRICOS - FEMARH. ***Decreto nº 8123-E,*** 2007.

FURNAS. ***Usinas Hidrelétricas.***

FURNAS. ***Usina de Retiro Baixo.*** Availabe in: <https://www.furnas.com.br/subsecao/131/usina-retiro-baixo>. Access at: 8 fev. 2023a.

FURNAS. ***Usina de Serra do Facão.*** Availabe in: <https://www.furnas.com.br/serradofacao/?culture =pt>. Access at: 8 fev. 2023b.

GASQUES, A. C. F.; NEVES, G. L.; SANTOS, J. D. dos; MAUAD, F. F.; OKAWA, C. M. P. Regionalização de vazões mínimas: breve revisão teórica [Regionalization of minimum flows: brief theoretical review]. ***REEC - Revista Eletrônica de Engenharia Civil,*** v. 14, n. 2, 6 mar. 2018.

HICKS, R.; GAGNON, C.; JACOBY, S.; KOWALIK, J. Large scale, nonlinear optimization of energy capability for the pacific northwest hydroelectric system. ***IEEE Transactions on Power Apparatus and Systems,*** v. PAS-93, n. 5, p. 1604-1612, Set. 1974.

INSTITUTO DAS ÁGUAS DO PARANÁ - AGUASPARANÁ. ***Decreto nº 4646,*** 2001.

INSTITUTO DE GESTÃO DAS ÁGUAS DO RIO GRANDE DO NORTE - IGARN. ***Decreto nº 13283***, 1997.

INSTITUTO DE MEIO AMBIENTE DE MATO GROSSO DO SUL - IMASUL. ***Decreto nº 13990***, 2014.

INSTITUTO DE MEIO AMBIENTE E ORDENAMENTO TERRITORIAL DO AMAPÁ - IMAP. ***Resoluções IMAP nº 008 e 009,*** 2017.

INSTITUTO DE NATUREZA DO TOCANTINS - NATURATINS. ***Decreto nº 2432,*** 2005.

INSTITUTO DE PROTEÇÃO AMBIENTAL DO AMAZONAS IPAAM. ***Resoluções CERH-AM nº 01 e 02 e Portaria normativa/SEMA/IPAAM nº 01***, 2016.

INSTITUTO DO MEIO AMBIENTE E RECURSOS HÍDRICOS - INEMA. ***Resolução CONERH nº 96,*** 2014.

INSTITUTO ESTADUAL DO AMBIENTE - INEA. ***Portaria SERLA nº 567,*** 2007.

INSTITUTO MINEIRO DE GESTÃO DAS ÁGUAS - IGAM. ***Decreto nº 41578,*** 2001.

MENDES, L. A. ***Análise dos critérios de outorga de direito de usos consuntivos dos recursos hídricos baseados em vazões mínimas e em vazões de permanência.*** [s.l.] Universidade de São Paulo, 2007.

RETIRO BAIXO ENERGÉTICA - RBE. ***Usina Hidrelétrica de Retiro Baixo.*** Availabe in: <http://www.rbe.com.br>. Accessed in: 8 fev. 2023.

SANTILLI, J. Aspectos jurídicos da política nacional de recursos hídricos. ***Série Grandes Eventos - Meio Ambiente,*** 2007.

SECRETARIA DE ESTADO DO DESENVOLVIMENTO AMBIENTAL - SEDAM. ***Decreto nº 10114, Portaria SEDAM nº 38,*** 2004.

SECRETARIA DE ESTADO DO DESENVOLVIMENTO ECONÔMICO SUSTENTÁVEL - SDS. ***Decreto nº 4778,*** 2006.

SECRETARIA DE ESTADO DO MEIO AMBIENTE - SEMA. ***Decreto nº 336,*** 2007.

SECRETARIA DE ESTADO DO MEIO AMBIENTE - SEMA. ***Decreto nº 27845,*** 2011.

SECRETARIA DE ESTADO DO MEIO AMBIENTE E RECURSOS HÍDRICOS - SEMARH. ***Decreto nº 6,*** 23 de janeiro de 2001.

SECRETARIA DE ESTADO DO MEIO AMBIENTE E RECURSOS HÍDRICOS - SEMARH. ***Decreto nº*** 18456, 1999.

SECRETARIA DO MEIO AMBIENTE, RECURSOS HÍDRICOS, INFRAESTRUTURA, CIDADES E ASSUNTOS METROPOLITANOS DO ESTADO DE GOIÁS - SECIMA. ***Resolução CERH nº 09 e Instrução Normativa no 12,*** 2005.

SECRETARIA ESTADUAL DE MEIO AMBIENTE E RECURSOS HÍDRICOS - SEMAR. ***Decreto no 11341, Resolução CERH nº 4,*** 2004.

SERRA DO FACÃO ENERGIA - SEFAC. ***Ficha técnica - Usina Hidrelétrica de Serra do Facão.*** Availabe in: <http://sefac.com.br/energia/ficha-tecnica>. Access at: 8 fev. 2023.

SILVA, W. M. F. da; BASTOS, A. S.; SANTOS, I. G. M.; VIANA, E. M. F.; MARTINEZ, C. B. A influência da vazão residual na redução da capacidade das usinas hidrelétricas - Um estudo de caso de duas UHEs XXIV SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 24., 2021,Belo Horizonte. ***Anais*** [**...**] Belo Horizonte: ABRH, 2021.

VESTENA, L. R.; OLIVEIRA, É. D. de; CUNHA, M. C. da; THOMAZ, E. L. Vazão ecológica e disponibilidade hídrica na bacia das Pedras, Guarapuava - PR. ***Ambiente e Água - An Interdisciplinary Journal of Applied Science,*** v. 7, n. 3, p. 212–227, 31 dez. 2012.

Received: 24 February 2023 - Accepted: 13 August 2023.