Integrated hydrological–energy analysis of a hypothetical forebay storage system for enhancing run-of-river hydro-power generation

Eliza-Isabela Tică[1], *Angela* Neagoe[1], *Florica* Popa[2], *Ángel* Gómez Hurtado[3], and *Bogdan* Popa[1*]

[1]National University of Science and Technology Politehnica Bucharest, Department of Hydraulics, Hydraulic Machinery and Environmental Engineering, 060042 Bucharest, Romania
[2]University Valahia of Târgoviște, Department of Electronics, Telecommunication and Energy Engineering, 130004 Târgoviște, Romania
[3]Cuerva Energía, S.L.U., Calle Santa Lucía, 1K, 18194, Churriana de la Vega, Granada

Abstract. This study presents an integrated hydrological-energy assessment of a hypothetical fore-bay storage system for the La Vega run-of-river small hydropower plant in southern Spain. Daily discharge records from 2017–2025 were analyzed using flow duration curves, storage simulations, and hydropower energy calculations to evaluate the effects of temporary water retention on electricity generation. Several storage scenarios were inves-tigated to assess their influence on turbine utilization and annual energy production. Re-sults indicate that temporary storage can significantly improve plant performance. The optimal storage volume of approximately 600 th.m³ increased annual generation by 18.05%, from 2935.8 to 3465.9 MWh/year.

1 Introduction

Run-of-river (RoR) hydropower plants represent one of the most sustainable and environmentally compatible forms of renewable electricity generation due to their reduced storage requirements and limited alteration of the natural river regime. Unlike conventional storage hydropower systems, RoR schemes rely directly on river discharge variability, making their energy production strongly dependent on seasonal and short-term hydrological fluctuations. Consequently, these systems are particularly vulnerable to flood events, prolonged droughts, and the increasing hydrological uncertainty associated with climate variability and climate change [1,2].

In recent decades, the growing demand for flexible and resilient renewable energy systems has increased interest in improving the performance and reliability of small hydropower plants (SHPPs). Although RoR facilities generally present lower environmental impacts than large storage reservoirs, their limited storage capacity makes energy production highly dependent on river discharge variability. As a result, RoR plants may experience suboptimal turbine operation, reduced electricity generation during low-flow periods, and

* Corresponding author: bogdan.popa@upb.ro

operational challenges associated with fluctuating hydrological conditions [3,4]. These limitations are particularly significant in Mediterranean basins, where hydrological regimes are characterized by high interannual variability, rapid runoff response, and seasonal water scarcity [2].

Several studies have demonstrated that hydrological regulation measures can substantially improve hydropower reliability and operational efficiency. In RoR hydropower systems, small storage facilities such as pondage reservoirs, regulating basins, and forebay storage systems can reduce short-term flow variability and improve turbine operation. Recent research has shown that the use of forebay storage volumes can increase operational flexibility and expand the range of operating conditions available for RoR SHPPs [5].

In Mediterranean mountain catchments, where climate change is expected to intensify hydrological variability, alter runoff seasonality, and increase the frequency of drought conditions, water availability for RoR hydropower generation is becoming increasingly uncertain [2]. Under such conditions, the implementation of a forebay storage system may provide significant operational benefits for this type of hydropower plants. Previous studies have shown that forebay storage volumes can increase operational flexibility and expand the range of operating conditions available for small hydropower facilities [5]. By temporarily storing excess water during high-flow periods and releasing it during lower-flow conditions, forebay systems may increase the duration of flows within the turbine's optimal operating range and improve discharge management. The potential effects on spill reduction, water-resource utilization, annual energy generation, and operational reliability are investigated in the present study.

Although forebay structures are commonly employed for operational control in hydropower schemes, their contribution to long-term energy optimization remains insufficiently understood. Existing research have primarily focused on hydraulic performance and operational flexibility [5], while the influence of storage capacity on hydropower generation has received comparatively less attention. In particular, the extent to which different forebay volumes affect turbine utilization, spill reduction, and annual energy production has not been comprehensively quantified for RoR SHPPs.

Complementary to studies on storage regulation, some papers have increasingly focused on improving hydropower planning and operation through advanced hydrological analysis and forecasting techniques. Gjika in [6] investigated the influence of climatic seasonality on hydropower production, highlighting the strong relationship between river discharge variability and energy generation. In paper [7], it was proposed a methodology for extending discharge records in ungauged catchments, providing reliable long-term datasets for hydropower resource assessment where monitoring data are limited. Ahmad in [8] compared several forecasting models for long-term hydropower generation, demonstrating the value of accurate prediction tools for energy planning. More recently, in [9] was developed an artificial intelligence-based reservoir inflow forecasting system based on interval type-2 fuzzy logic and neural networks, illustrating the increasing role of AI in supporting hydropower operation. Although these studies significantly improve hydrological characterization and forecasting capabilities, they do not investigate how temporary forebay storage affects long-term energy production, turbine utilization, spill reduction, and overall operational efficiency in RoR hydropower plants.

This study investigates the influence of upstream forebay storage on the operational performance of the La Vega SHPP located in southern Spain. Different storage scenarios are evaluated to assess their impact on river discharge availability, turbine utilization, spill reduction, and energy production. The analysis is based on observed flow records and discharge-based energy calculations, allowing the quantification of potential gains in hydropower generation resulting from temporary upstream storage.

Attention is given to the relationship between forebay storage capacity and the frequency of turbine-operating discharges, with the aim of identifying storage volumes that maximize energy benefits while maintaining a low environmental footprint.

The main objectives of the study are:

- To evaluate the effect of upstream forebay storage on the availability of flows suitable for hydropower generation.
- To quantify the impact of temporary storage on annual energy production.
- To assess the potential reduction of spill losses and improvement of turbine utilization.
- To compare the effectiveness of different forebay storage capacities in increasing annual energy production.

The proposed approach contributes to the development of sustainable water–energy management strategies by highlighting the potential role of temporary storage polders in improving the efficiency and operational flexibility of RoR SHPPs under variable hydrological conditions.

The selected case study is particularly relevant because the La Vega SHPP is located within the Sierra Nevada region in southern Spain, an area characterized by high ecological value and multiple environmental protection designations, including Natura 2000 sites and the Sierra Nevada National and Natural Parks. Previous studies have highlighted the strong relationship between water resources, hydropower infrastructure, landscape identity, and ecosystem services in the Monachil River valley, where the La Vega hydropower scheme operates [10]. Existing hydropower facilities are generally perceived as integrated elements of the local landscape, while stakeholders have emphasized the importance of minimizing additional pressures on river ecosystems, biodiversity, and landscape values [10]. Within this context, the hypothetical implementation of a small forebay storage system adjacent to the existing intake structure represents a potentially low-impact alternative for improving hydropower performance without requiring the construction of large reservoirs or substantial modifications to the protected river corridor.

The proposed approach therefore provides an opportunity to explore the potential benefits of limited storage enhancement while maintaining compatibility with the environmental constraints of a protected mountain catchment.

2 Study area and existing hydropower system

The study focuses on the La Vega SHPP, located in southern Spain within a mountainous Mediterranean catchment characterized by pronounced seasonal and interannual flow variability. The hydropower facility operates as a RoR system, meaning that electricity generation depends directly on the river discharge available at the intake and is only minimally influenced by storage regulation.

River flows in the basin exhibit substantial fluctuations throughout the year, alternating between periods of high discharge and periods of limited water availability. During high-flow events, river discharge may exceed the installed turbine capacity, resulting in water spillage and reduced utilization of the available hydraulic resource. During low-flow periods, during low-flow periods, insufficient discharge may limit turbine operation, decrease energy production, or lead to temporary interruptions in power generation.

The existing hydropower scheme consists of a water intake structure, a conveyance channel, a penstock, and a powerhouse equipped with hydraulic turbines. Due to the absence of significant storage capacity, plant performance is strongly dependent on the natural variability of river flows.

To improve operational stability and increase the effective use of available water resources, this study investigates the integration of an upstream temporary storage forebay.

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The proposed storage structure is intended to retain part of the excess inflow during high-discharge periods and release stored water during lower-flow conditions. Such regulation may increase the duration of flows within the turbine operating range, reduce spill losses, and enhance overall energy production.

The analysis is based on measured inflow discharge data and recorded energy production time series from the La Vega SHPP. Multiple storage scenarios are evaluated to quantify the influence of upstream forebay integration. The study focuses specifically on the relationship between forebay storage capacity and hydropower performance to identify storage volume that maximizes energy benefits while maintaining a limited environmental footprint within a protected mountain catchment.

This section describes the study area, the existing La Vega hydropower scheme, and the proposed forebay storage system considered in the present analysis. Figure 1 illustrates the catchment upstream of the La Vega intake together with the location of the La Vega SHPP. The figure also shows the spatial distribution of elevation within the watershed, which ranges from approximately 1269 to 3327 m a.s.l.

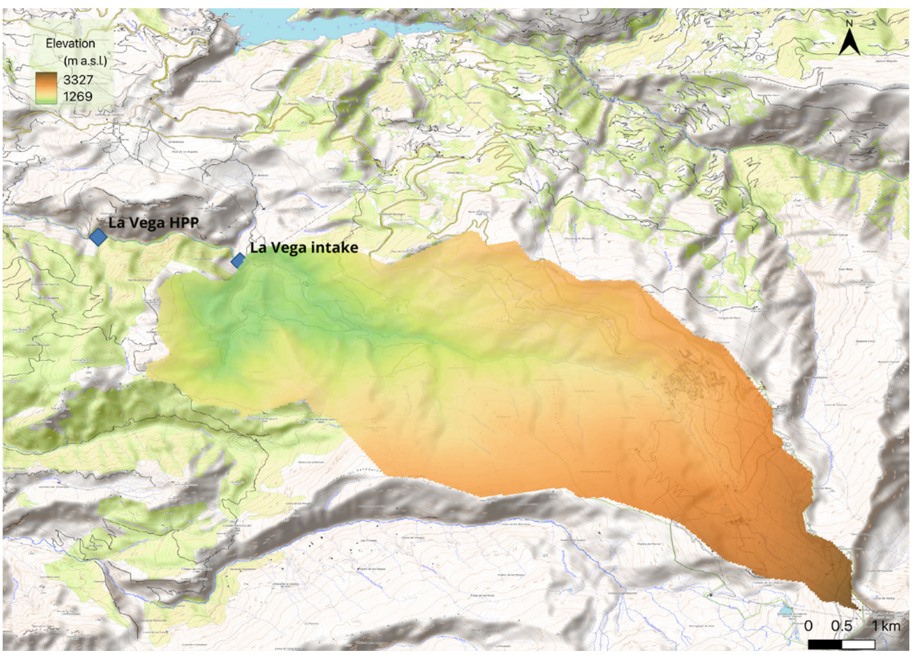

Fig. 1. Digital elevation model (DEM) of the catchment upstream of the La Vega SHPP intake.

Figure 2 presents a schematic representation of the flow regulation concept based on temporary upstream storage and controlled water release, illustrating the conceptual integration of a forebay storage system within the La Vega hydropower scheme.

The proposed forebay storage system is intended to temporarily retain part of the excess inflow during high-discharge periods and release stored water when river flows decrease. By moderating short-term discharge variability, the system may increase the availability of water for hydropower generation, reduce spill losses, and improve turbine utilization.

Table 1 summarizes the key hydrological and operational characteristics of the La Vega SHPP considered in the present study.

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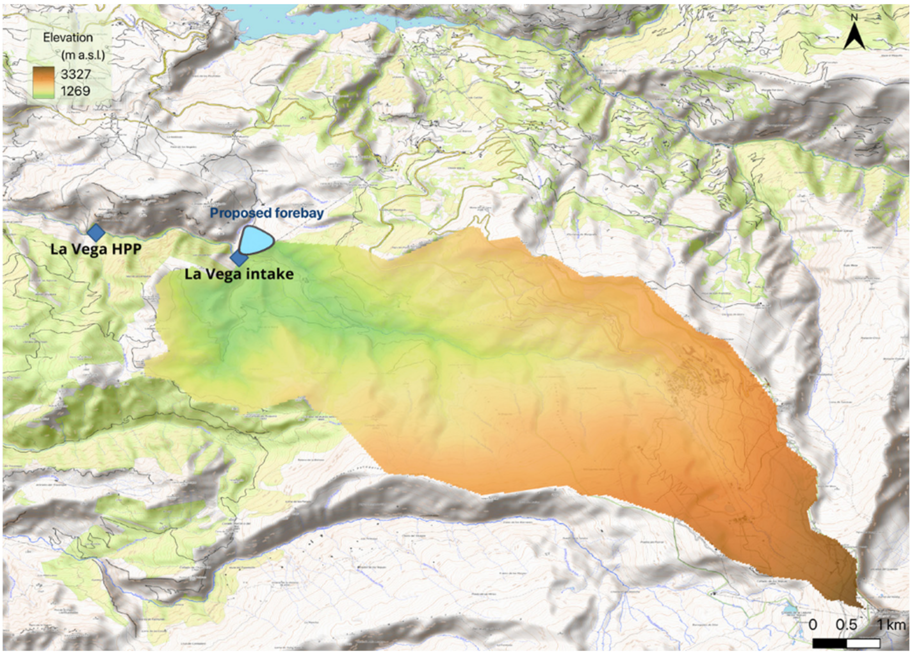

Fig. 2. Conceptual position of the proposed forebay storage structure at the La Vega RoR SHPP.

Table 1. Main hydrological and operational characteristics of the La Vega SHPP.

River mean flow (m3/s)	Ecological flow (m3/s)	Turbine flow range (m3/s)	Gross head (m)	Installed capacity (kW)	Turbine type
0.453	0.15	0.2 – 1.5	183.5	2407	Pelton

The existing operational configuration of the La Vega SHPP provides an opportunity to investigate the potential benefits of integrating a small forebay storage structure adjacent to the existing intake. As illustrated in Figure 2, the proposed forebay is conceptually located between the intake and the penstock and is intended to provide hourly-to-daily regulation of the river inflows diverted for hydropower generation.

During high-flow conditions, part of the excess water that would otherwise bypass the hydropower system may be stored within the forebay and subsequently released in a controlled manner when river discharge decreases. This operational approach can increase the duration of flows within the turbine operating range, thereby improving turbine utilization and reducing interruptions associated with insufficient water availability.

Unlike conventional reservoirs, the proposed forebay is not intended for long-term storage or seasonal regulation. Its primary function is short-term flow balancing, providing temporary attenuation of discharge fluctuations while preserving the run-of-river character of the hydropower scheme.

The conceptual storage system therefore represents a potentially low-impact solution for improving flow availability and operational flexibility without substantial modifications to the existing infrastructure.

To further characterize flow availability within the catchment and its implications for hydropower generation, a flow duration curve (FDC) was developed using the complete observed inflow record covering the period 2017–2025, extracted from [11].

The FDC provides a statistical representation of the long-term flow regime, indicating the percentage of time during which a given discharge is equaled or exceeded, as shown in Figure 3.

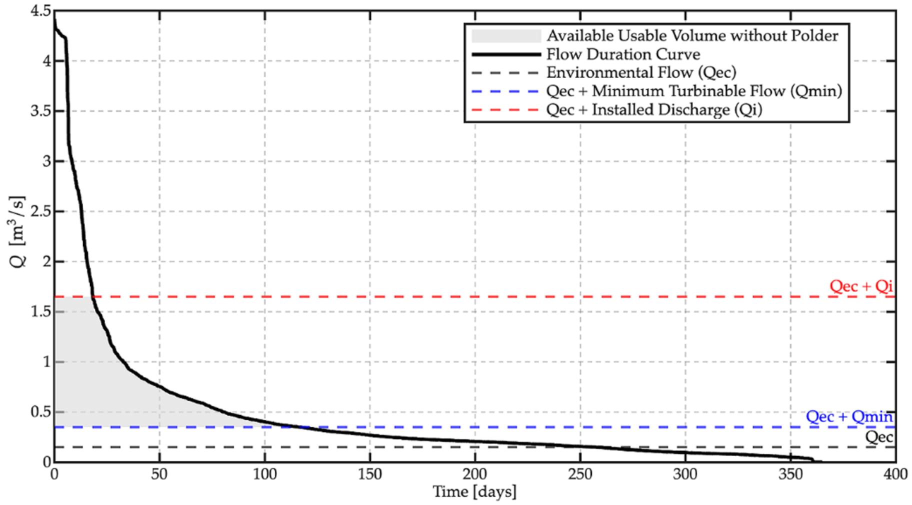

Fig. 3. Flow duration curve (FDC) of the observed inflow series at the La Vega SHPP intake for the period 2017–2025.

Figure 3 highlights the characteristic discharge values used in the analysis: Q_{ec} – the ecological flow, Q_{min} – the minimum discharge required for turbine operation, and Qi – the installed discharge. The annual water volume available for hydropower generation at the La Vega SHPP is represented by the grey shaded area bounded by the FDC and the discharge limits $Q_{ec} + Q_i$ and $Q_{ec} + Q_{min}$.

For the La Vega SHPP, the FDC provides a useful framework for evaluating the relationship between river discharge and turbine operation. Flows exceeding the installed turbine discharge of 1.5 m³/s represent spill conditions under the current configuration, whereas lower discharges may limit turbine utilization and reduce energy production. Consequently, the flow duration analysis highlights both the availability of the hydraulic resource and the operational constraints associated with the absence of storage regulation.

As shown in Figure 3, the FDC reflects the strong seasonal variability of the Mediterranean mountain catchment. High-flow conditions occur mainly during periods of intense winter precipitation and spring snowmelt, whereas prolonged low-flow conditions are typical of the dry summer season. Consequently, the curve is dominated by discharges below the turbine design flow of 1.5 m³/s, while higher flows occur only during relatively short periods associated with intense precipitation and snowmelt events. Consequently, turbine operation is frequently constrained by insufficient water availability, whereas a portion of the excess water occurring during peak-flow events cannot be effectively utilized under the current run-of-river configuration. These findings highlight the potential value of temporary forebay storage as a means of capturing part of the excess discharge and releasing it during lower-flow periods, thereby improving turbine utilization and overall water-resource use efficiency.

The flow duration analysis therefore confirms the coexistence of excess-flow and low-flow conditions that may adversely affect the operational performance of the existing hydropower scheme. This characteristic hydrological behavior provides the basis for evaluating the potential contribution of forebay storage to enhanced hydropower generation and operational continuity.

3 Average annual energy production of the La Vega SHPP

The hydrological analysis presented in the previous section provides the basis for evaluating the hydropower potential of the La Vega RoR SHPP. Since electricity generation is directly governed by river discharge availability, the observed inflow regime can be used to estimate average annual energy production under both existing and regulated flow conditions.

This study proposes an integrated hydrological–energy assessment framework for evaluating the influence of a hypothetical upstream forebay storage system on the operational performance of the La Vega SHPP. The methodology combines flow duration curve analysis, temporary storage simulation, hydropower production assessment, and storage-volume optimization to quantify the potential benefits of forebay integration. The adopted methodological workflow is illustrated in Figure 4.

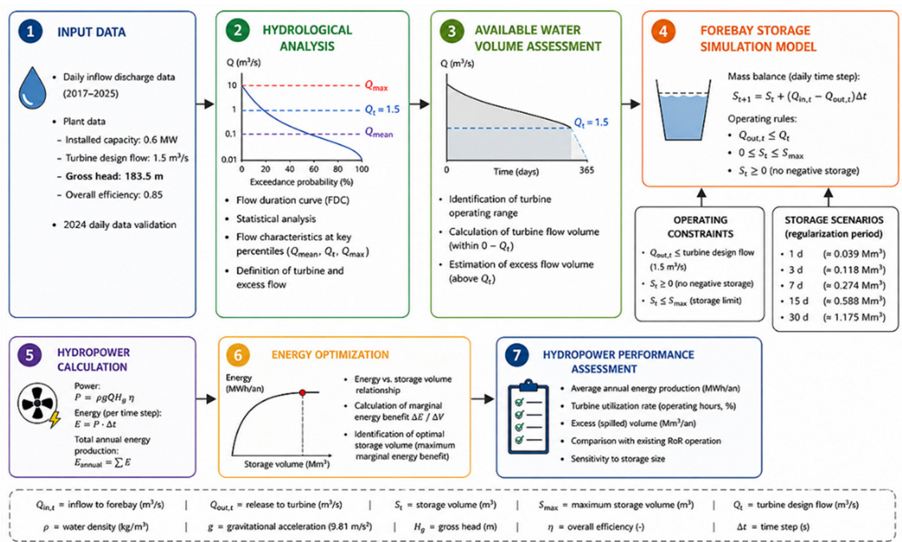

Fig. 4. General methodological workflow adopted for the hydrological–energy analysis.

The analysis was performed using historical inflow discharge records and operational hydropower data corresponding to the study period. Several storage scenarios were investigated to evaluate the effects of temporary flow regulation on turbine operation, energy generation, storage utilization, and overall hydropower performance.

The methodological procedure consists of five principal stages:

1. Inflow discharge data analysis inflow discharge data analysis.
2. Flow duration curve construction.
3. Temporary storage simulation.
4. Hydropower generation assessment.
5. Storage optimization and performance evaluation.

3.1 Material and methods

The analysis was based on measured daily inflow discharge data recorded at the intake of the La Vega SHPP during the period January 2017–December 2025. The dataset was used to characterize river flow variability through basic hydrological statistics and the flow duration curve presented in the previous section. These analyses provided the basis for quantifying water availability for hydropower generation and evaluating the potential benefits of forebay storage.

Three operational discharge thresholds were considered in the analysis. The environmental flow (Q_{ec}) was set to **0.15 m³/s**, the minimum turbine operating discharge (Q_{min}) is **0.20 m³/s**, and the installed flow (Q_i) of the La Vega SHPP is **1.50 m³/s**. These discharge thresholds define the operational limits of the hydropower system and were used to quantify the fraction of the annual water volume available for energy production. The lower operational limit was defined as the sum of the environmental flow and the minimum turbine discharge, while the upper operational limit corresponded to the sum of the environmental flow and the installed turbine discharge:

$$Q_{\text{lower}} = Q_{ec} + Q_{min} \tag{1}$$

$$Q_{\text{upper}} = Q_{ec} + Q_i \, . \tag{2}$$

The area enclosed by the flow duration curve and these operational thresholds represents the annual water volume available for hydropower generation.

The proposed upstream storage system was represented as a temporary retention polder designed to regulate river discharge before entering the hydropower plant.

The temporal variation of stored water volume was calculated using the storage continuity equation:

$$S_{\text{t+1}} = S_t + (Q_{in} - Q_{tb})\Delta t, \tag{3}$$

where S_t is the storage volume at time step *t*; Q_{in} represents the natural river inflow at the intake river section; Q_{tb} is the turbine discharge and Δt is the simulation time step.

The storage volume was constrained according to the maximum polder capacity:

$$0 \leq S_t \leq S_{max}, \tag{4}$$

where S_{max} represents the maximum storage capacity of the polder. Whenever the storage exceeded the maximum allowable capacity, the excess volume was considered spilled water and was not available for electricity generation.

The operating strategy aimed to maximize energy production while maintaining compliance with the technical operating limits of the SHPP.

At each simulation step, the turbine discharge was determined as:

$$Q_{\text{tb}} = min\,(Q_i, S_{available}/\Delta t), \tag{5}$$

where $S_{available}$ is the water volume available for turbine operation.

The turbine was allowed to operate only when the available discharge exceeded the minimum turbine operating discharge. Otherwise, the turbine remained out of operation. This operating strategy allows excess inflows to be temporarily stored during wet periods and released during low-flow periods, thereby increasing water utilization efficiency.

Hydropower production was determined using the standard equation:

$$P = \rho g Q_{tb} H \eta, \tag{6}$$

where P is the generated power (W); ρ is the water density (kg/m³); g is the gravitational acceleration (m/s²); Q_{tb} is the turbine discharge (m³/s); H is gross hydraulic head (m); η is the overall efficiency of the SHPP and is set to an average value of 0.85.

The generated energy during each simulation interval was calculated as:

$$E = P\,\Delta t. \tag{7}$$

The total energy production was obtained by summing the energy generated during all simulation intervals over the entire simulation period.

3.2 Storage scenarios for forebay

To evaluate the impact of short-term flow regulation on hydropower generation, a series of temporary forebay storage scenarios was investigated. For each scenario, the required storage volume was determined based on the installed discharge according to:

$$V = Q_i \cdot t, \tag{8}$$

where V is the storage volume (m^3); t is the storage duration (s). Five storage durations were considered, corresponding to 1, 3, 7, 15 and 30 days. The investigated scenarios are summarized in Table 2.

Table 2. Temporary storage capacities, corresponding to different flow regulation durations.

Scenario	Storage duration (days)	Storage volume (th.m3)
S0	No storage	0
S1	1	39
S2	3	117
S3	7	274
S4	15	587
S5	30	1174

In addition to the predefined storage scenarios, a parametric optimization analysis was conducted to identify the forebay storage capacity that provides the greatest hydropower benefit. Storage volumes ranging from 0 to 20 Mm^3 were evaluated. For each tested volume, the storage simulation was performed using the complete inflow time series, and the corresponding annual energy production was estimated.

The marginal energy benefit associated with an incremental increase in storage capacity was quantified using the derivative of energy with respect to storage volume:

$$\Delta E = E_{storage} - E_{ref}. \tag{9}$$

The relative energy gain was determined using:

$$\eta_E = (E_{storage} - E_{ref})/E_{ref} \cdot 100. \tag{10}$$

Additionally, the total spilled water volume was quantified in order to assess storage utilization efficiency and identify potential losses associated with limited storage capacity.

The hydropower potential of the La Vega SHPP under existing operating conditions was evaluated using the complete observed daily inflow record for the period 2017–2025. Turbine operation was simulated considering an environmental flow requirement of 0.15 m^3/s, a minimum turbine operating discharge of 0.20 m^3/s, and an installed turbine discharge of 1.50 m^3/s. For each time step, the available discharge for power generation was determined and converted into energy production using the hydropower equation.

Based on the observed inflow series, the annual usable water volume available for electricity generation was estimated at approximately 6.91 Mm^3/year. Considering a gross hydraulic head of 183.5 m and an overall turbine–generator efficiency of 0.85, the corresponding average annual energy production was estimated at 2935.8 MWh/year.

This baseline scenario represents the reference case against which all forebay storage configurations were evaluated in the subsequent analyses.

4 Results and discussion

This section presents the results obtained from the integrated hydrological–energy analysis of the La Vega Small Hydropower Plant (SHPP) under the baseline operating condition and the proposed forebay storage scenarios. The influence of forebay integration on water-resource utilization, spill reduction, turbine operation, and energy production was evaluated through comparative scenario analysis.

The hydrological analysis of the La Vega catchment revealed a highly variable flow regime during the period 2017–2025. The mean inflow discharge was 0.453 m^3/s, while the maximum and minimum recorded discharges were 4.418 m^3/s and 0.000 m^3/s, respectively. These values indicate substantial seasonal and interannual variability, which directly affects the operational performance of the RoR hydropower plant.

Under the existing operating conditions, considering an environmental flow requirement of 0.15 m^3/s, a minimum turbine operating discharge of 0.20 m^3/s, and an installed turbine discharge of 1.50 m^3/s, the annual usable water volume available for electricity generation was estimated at approximately 6910 th.m^3/year. This corresponded to an average annual energy production of approximately 2935.82 MWh/year and a turbine-operating frequency of 32% of the analyzed days.

The introduction of a forebay storage system improved the utilization of the available water resource by temporarily retaining excess inflows during high-flow periods and releasing stored water during low-flow conditions. As a result, annual energy production increased for all investigated storage scenarios. Among the predefined regulation periods, the 30-day scenario, corresponding to a storage volume of 1175 th.m^3, produced the highest annual energy generation, reaching approximately 3520 MWh/year.

Table 3 summarizes the effect of increasing forebay regulation duration on the hydropower performance of the La Vega SHPP.

Table 3. Performance of the La Vega SHPP under different forebay regulation durations.

Regulation duration [days]	Storage volume [th.m^3]	Annual energy production [MWh/year]	Improvement with respect to S0 [%]	Improvement with respect to previous S [%]	Operating time (%)
No	0	2935.82	-	-	32.00
1	39	3360.09	14.45	14.45	43.02
3	117	3386.10	15.34	0.77	43.02
7	274	3424.14	16.63	1.12	43.05
15	587	3464.71	18.02	1.18	43.08
30	1174	3520.24	19.91	1.60	43.17

Under baseline conditions (S0), without storage, the plant generates approximately 2936 MWh/year and operates during 32% of the analyzed period. The introduction of even a small forebay corresponding to a 1-day regulation period (39 th.m³) significantly improves plant performance, increasing annual energy production by 14.45% and raising the operating time to 43.02%.

Further increases in storage volume led to additional gains in energy production; however, the incremental benefits become progressively smaller. Annual energy generation rises from 3360 MWh/year for the 1-day scenario to 3520 MWh/year for the 30-day scenario, corresponding to a total improvement of 19.91% relative to the baseline condition. In contrast, the additional energy gain between consecutive scenarios remains relatively modest, ranging from 0.77% to 1.60%.

The operating time remains nearly constant for all storage scenarios, varying only from 43.02% to 43.17%. This indicates that the principal benefit of forebay storage is not a substantial increase in the number of operating days, but rather a more efficient redistribution of available flows within the turbine operating range. Consequently, relatively small storage volumes can capture a large proportion of the achievable hydropower benefits, while larger forebay capacities provide diminishing returns in terms of additional energy production. A storage optimization analysis identified an optimum forebay volume of approximately 600 th.m³, corresponding closely to the 15-day regulation scenario (exactly 15.33 days). At this storage capacity, annual energy production increased from 2936 MWh/year under baseline conditions to approximately 3466 MWh/year, representing an improvement of 18.05%. Beyond this threshold, additional storage volume produced only marginal energetic benefits, indicating diminishing returns associated with larger forebay capacities.

Figure 5 illustrates the temporal evolution of natural inflow, turbine discharge, and forebay storage for the optimum storage volume (600 th.m³).

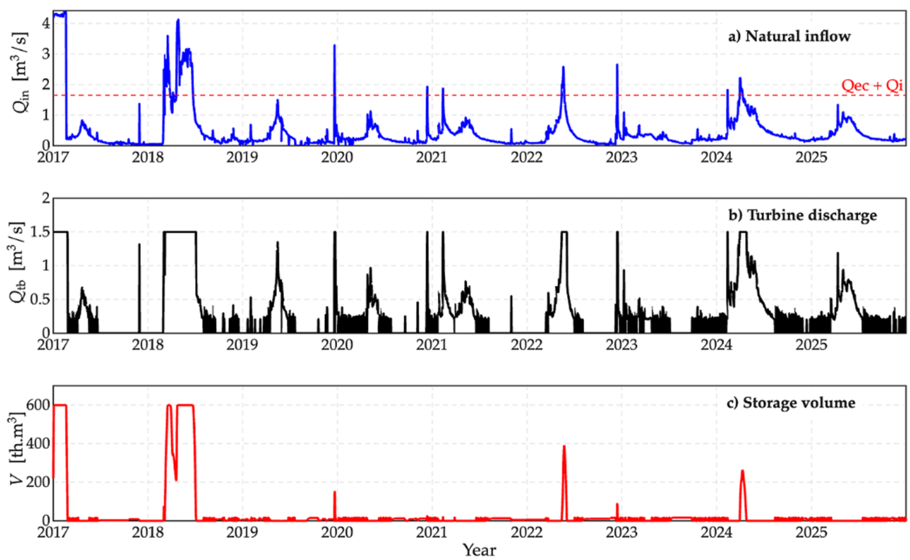

Fig. 5. Temporal evolution of a) natural inflow (Q_{in}), b) turbine discharge (Q_{tb}), and c) forebay storage volume (V) for the optimum forebay capacity, 600 th.m³, corresponding to the 15.33 days inflows regulation, during the period 2017–2025.

For the 1-day flow regulation scenario (forebay volume = 39 th.m³), Figure 6 illustrates the temporal evolution of natural inflow, turbine discharge, and forebay storage at the La Vega SHPP during the period 2017–2025.

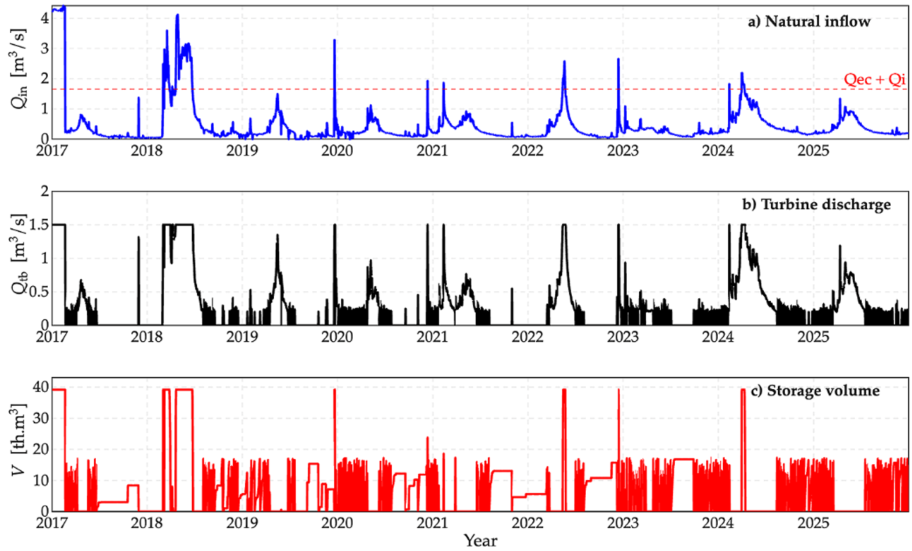

Fig. 6. Temporal evolution of natural inflow (Q_{in}), turbine discharge (Q_{tb}), and forebay storage volume (V) for 39 th.m³, 1 day inflows regulation, during the period 2017–2025.

Figure 5, corresponding to optimum forebay capacity, shows that the forebay is filled only during relatively infrequent high-flow events, while remaining nearly empty during most of the simulation period. Major storage events occurred during 2018, 2022, and 2024, when excess inflows exceeded the installed turbine discharge. The stored water was subsequently released during lower-flow periods, increasing turbine utilization and reducing spill losses. This behavior confirms that the proposed forebay operates as a temporary flow-regulation structure rather than a conventional reservoir, improving the temporal distribution of available water resources.

In Figure 6, the upper panel shows the natural river discharge, characterized by significant seasonal variability and several high-flow events exceeding the installed turbine capacity. During these periods, excess inflows are temporarily retained within the forebay instead of being immediately spilled. The middle panel presents the turbine discharge, which is constrained by the installed flow rate of 1.5 m³/s and the minimum operating discharge. The forebay allows part of the excess water stored during peak-flow events to be released during subsequent lower-flow periods, thereby maintaining turbine operation for a longer duration. The lower panel shows the storage volume within the forebay. Owing to the relatively small storage capacity associated with the 1-day regulation scenario (0.039 Mm³), the storage volume increases rapidly during high-flow events and is subsequently depleted shortly afterward. The forebay therefore operates as a short-term balancing structure, capturing brief flow surpluses and redistributing them over the following days. Although the storage capacity is limited, the regulation effect increases annual energy production from approximately 2935.82 MWh/year under baseline conditions to 3360 MWh/year and raises the plant utilization rate from 32 % to about 43 %.

To further illustrate the forebay operation at a finer temporal scale, Figure 7 presents a representative high-flow event observed during 2018.

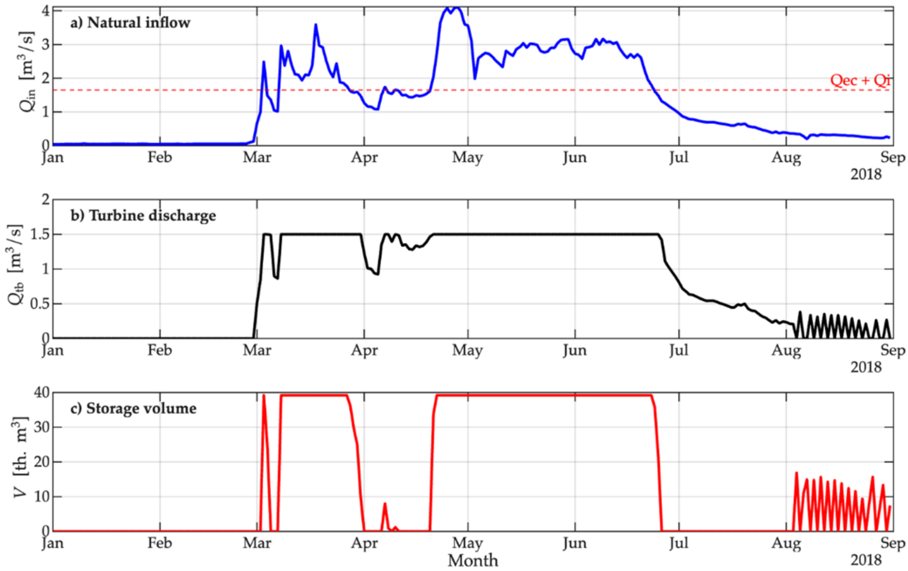

Fig. 7. Detailed view of a representative high-flow event during 2018 illustrating (a) natural inflow (Qin), (b) turbine discharge (Qtb), and (c) forebay storage volume (V) for the 1-day forebay regulation scenario (39 th.m³).

The enlarged view clearly shows the interaction between natural inflow, turbine discharge, and forebay storage. During periods when the inflow exceeds the installed discharge, the excess water is temporarily stored within the forebay. Subsequently, the stored water is gradually released as river discharge decreases, allowing the turbine to continue operating close to its rated discharge for a longer period. This representative event clearly demonstrates the short-term regulating function of the proposed forebay and complements the long-term analysis presented in Figure 6.

These results indicate that even a relatively small forebay can significantly improve the temporal distribution of available water resources, reduce spill losses, and enhance the overall performance of a RoR SHPP.

5 Conclusion

This study investigated the influence of a hypothetical upstream forebay storage system on the hydrological and energetic performance of the La Vega Small Hydropower Plant (SHPP), operating as a run-of-river (RoR) hydropower scheme in southern Spain. The analysis was based on measured inflow discharge data for the period 2017–2025 and evaluated the effects of multiple forebay storage scenarios on hydropower generation.

The results demonstrated that forebay storage can improve the utilization of available water resources by temporarily retaining excess inflows during high-discharge periods and releasing stored water during lower-flow conditions. This operating strategy contributed to a more stable turbine inflow regime and increased the availability of flows suitable for hydropower generation.

Compared with the baseline condition, all investigated storage scenarios resulted in increased annual energy production. The optimization analysis identified an optimum forebay storage volume of approximately 0.60 Mm³, which increased average annual energy generation from 2935.8 to 3465.9 MWh/year, corresponding to an improvement of 18.05%. The optimum volume was found to be very close to the storage capacity associated with the

15-day regulation scenario (0.588 Mm^3), indicating that relatively small storage capacities can provide substantial energetic benefits.

The analysis further showed that increasing storage capacity beyond the optimum threshold yielded progressively smaller energy gains. Although larger storage volumes improved flow redistribution, the additional increase in hydropower generation became marginal, suggesting diminishing returns from further storage expansion.

The study highlights the potential role of small forebay storage systems in improving the operational performance of run-of-river hydropower plants located in Mediterranean mountain catchments characterized by strong seasonal discharge variability. Within the environmental constraints of the Sierra Nevada region, the proposed forebay concept represents a potentially low-impact solution for increasing hydropower generation without requiring large reservoir infrastructure.

The proposed methodology provides a practical framework for evaluating storage-enhanced hydropower operation using observed discharge data and energy-based performance indicators. Consequently, the approach may be applied to other small run-of-river hydropower systems facing similar operational limitations associated with variable inflow conditions.

Future research should focus on the optimization of forebay operating rules, real-time storage management strategies, economic feasibility assessment, and the evaluation of storage performance under projected climate variability scenarios.

Overall, the results demonstrate that small forebay storage systems can represent an effective strategy for improving the flexibility, resilience, and energy efficiency of run-of-river hydropower plants operating under highly variable hydrological conditions.

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