International Validation of FDC as a Sizing tool for Small Hydropower Plants: Study case in Romania and Spain

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***Abstract*— This study presents and validates an international hydrological evaluation framework for run-of-river small-scale hydropower plants under contrasting environmental regimes. The proposed methodology evaluates optimal design flows and takes advantage from the use of Flow Duration Curves (FDC). The framework is empirically validated using the regulated cascade system of the Bistrița River in Romania, where a modeled facility capacity of 24 MW aligns precisely with physical operational parameters. Conversely, the model is applied to the prospective Puente de la Cerrada facility in the highly fluctuating Mediterranean basin of the Upper Guadalquivir River in Spain using an 18-year daily historical record. The results contrast a single base-year baseline approach against a multi-year continuous synthesis model (6,519 daily points). While both frameworks yield a consistent physical infrastructure sizing of approximately 8.0 m³/s and 2.0 MW, the single-year base framework introduces a critical 27.9% underestimation in long-term annual energy production due to its vulnerability to seasonal hydrological extremes. Ultimately, the proposed methodology is successfully validated through these two distinct case studies, establishing a robust and reliable technical baseline to accurately size the prospective Puente de la Cerrada small hydropower plant.**

Keywords—small hydropower plants, run-of-river sizing, flow duration curve, dynamic turbine efficiency, hydrological uncertainty, cascaded systems.

I. Introduction

The evaluation of small-scale hydropower plants (SHPs) requires robust methodologies to accurately determine design flow and nominal power [1-3]. This study proposes a validation framework by contrasting two distinct hydrological environments in Romania and Spain.

A. Case Study Framework: The Bistrița and Guadalquivir Basins

The primary focus area in Romania comprises the middle section of the Bistrița River, stretching from the outlet of the Bicaz dam down to Bacău, where it intercepts the Siret river. This specific reach hosts nine of the 12 cascade hydropower plants belonging to the comprehensive Bistrița-Siret hydro-technical project. Hydrological data from this middle section have been gathered to evaluate small-scale hydropower exploitation and establish a comparative baseline.

Conversely, the methodology is applied to the Upper Guadalquivir River basin, located in the province of Jaén, Andalusia (Spain).

Specifically, an evaluation will be conducted for a prospective small-scale hydropower facility named Puente de la Cerrada.

B. Methodological Validation

The proposed Puente de la Cerrada plant shares structural and operational similarities with the nine operating cascade hydropower plants located between Piatra Neamț and Bacău in the Moldova region of Romania. Consequently, analyzing these existing Romanian structures serves to validate the proposed evaluation methodology. This comparative approach aims to: Quantify the hydraulic potential of the active cascade system along the Bistrița River. Estimate the energy potential of prospective small-scale developments in the Upper Guadalquivir River. Generate comparative analytical models, including energy production and river flow distribution graphics.

II. Context and Study Areas

A. The Bistrița River Basin (Romania)

The middle reach of the Bistrița River, located in the Moldova region of northeastern Romania, serves as a premier reference for cascaded hydro-energetic systems [4-6]. The specific spatial boundary established for this methodology spans from the tailrace outlet just below the Bicaz dam down to the geographical confluence where the Bistrița River joins the Siret River, downstream of Bacău. This operational corridor features a complex hydraulic infrastructure consisting of approximately 78 km of total watercourse length, which is primarily composed of artificial diversion canals.

The macro-system overcomes a total gross head of 200 m, descending from an initial elevation of 350 m above sea level at the upper section to 150 m at the lower confluence. Due to the extended development of the diversion channels, a continuous hydraulic slope of 0.1% (0.001 m/m) is present along the structures. This slope introduces a cumulative linear head loss of 70 m across the entire canal network. Consequently, the total effective net head (H_n) available for power generation across the cascade is reduced to 130 m. This hydraulic resource is exploited sequentially by 9 small-scale and medium hydropower plants clustered within this specific reach, which deliver a combined nominal capacity (P) of 196 MW (196,000 kW) to the regional grid. To validate the overarching hydrological sizing framework, the collective design flow (Q_d) for the cascade can be verified through the fundamental hydropower potential formulation:

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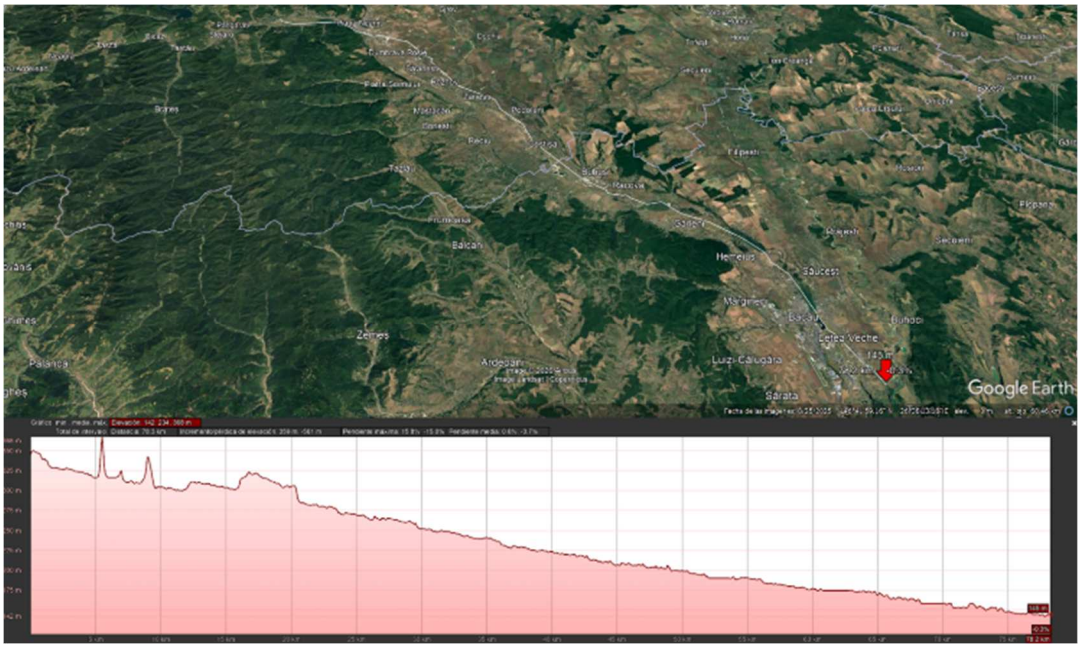

Fig. 1. Elevation profile downstream Bicaz dam until Siret basin.

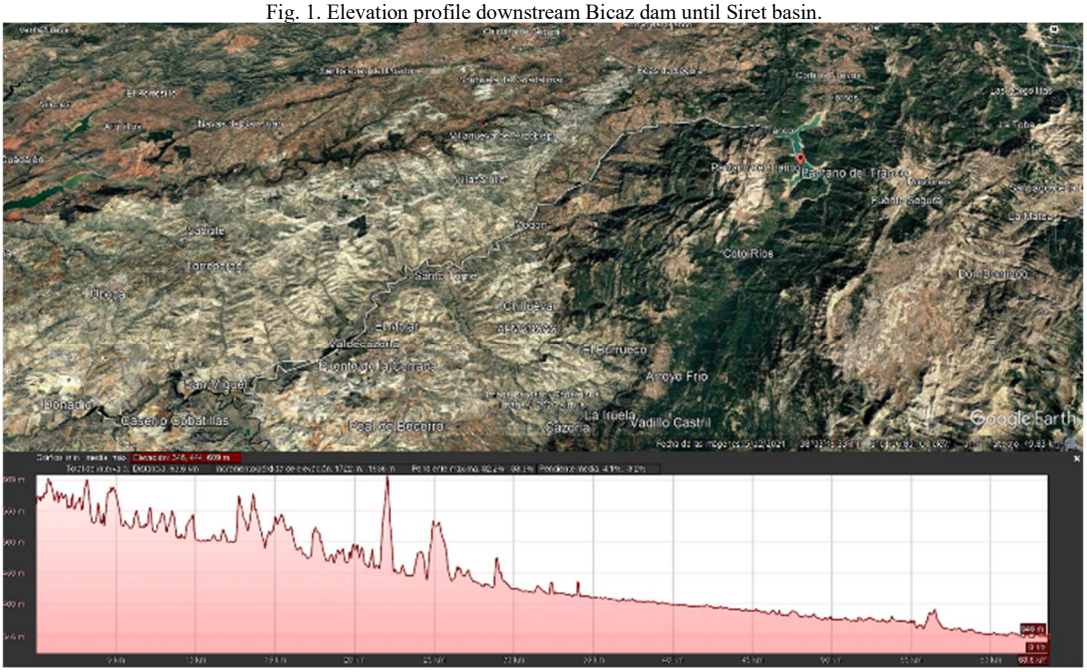

Fig. 2. Elevation profile downstream El Tranco until Puente de la Cerrada - San Miguel.

$$P = 9.81 * H_n * Q_d * \eta \quad (1)$$

where P represents the nominal power in kilowatts, 9.81 is the specific weight of water (9.81 kN/m^3), H_n is the net head in meters (m), and Q_d is the design flow in cubic meters per second (m^3/s). Assuming an ideal system envelope for baseline macro-assessment, the total required design flow is isolated by rearranging the parameters, as a result it is needed at least this flow:

$$Q_d = 196{,}000 \text{ kW} / (130 \text{ m} * 9.81 \text{ kN/m}^3) = 154 \text{ m}^3/\text{s}$$

Extrapolating these system-wide metrics to evaluate a representative standard medium plant within the 9-installation cascade yields a mean net head per facility of approximately 14.44 m. For the mathematical modeling and comparative validation purposes of this study, this operational parameter is rounded to a normalized standard net head of 15 m per plant. This representative facility configuration provides the baseline empirical framework against which the prospective Spanish infrastructure models are benchmarked [9], [11-12].

B. The Upper Guadalquivir River Basin (Spain)

In contrast to the highly regulated, large-scale cascaded systems of northeastern Europe, the southwestern Mediterranean region offers a distinct hydrological environment [7-8]. The secondary study area is located in the province of Jaén, Andalusia (Spain), focusing on the high-altitude headwaters known as the Upper Guadalquivir. The specific river reach evaluated in this study extends from the regulated outlet of the Tranco de Beas reservoir, situated in the Sierra de Cazorla, Segura y Las Villas natural park, down to San Miguel, which serves as the evacuation point for the prospective Puente de la Cerrada hydropower plant. This total evaluated reach covers a river course length of approximately 60 km. The morphological layout of this macro-system drops

through an altitudinal gradient descending from an initial elevation of 563 m above sea level at the Tranco reservoir outlet down to 348 m at the final evacuation boundary. This topography overcomes a total gross head of 215 m. Considering a continuous hydraulic channel slope of 0.1 percent along the 60 km of river course development, a linear elevation drop of 60 m is introduced. Furthermore, accounting for localized hydraulic head losses within auxiliary conduction structures, penstocks, and control valves, the total effective net head (H_n) available for global power generation across this entire unexploited reach is established at 165 m.

Within this geographical and technical framework, the specific infrastructure of the prospective Puente de la Cerrada facility consists of a water intake or diversion structure located at an elevation of 373 m above sea level. From this intake point, a localized diversion canal extending over a length of 5.44 km conveys the water to the penstock forebay. Finally, after passing through the turbines, the water is discharged back into the river at the tailrace evacuation point located at an elevation of 345 m above sea level. This specific plant layout allows the facility to exploit a local gross head of 28 m, which provides a useful net head of approximately 25 m for the localized asset.

To execute a precise hydrological evaluation, a rigorous analysis of available gauging stations was performed. A nearby station located at Santo Tomé was initially considered, but it was discarded due to an incomplete historical series, containing barely three or four complete years of data. Similarly, gauging station 5002, located precisely at Puente de la Cerrada, had to be ruled out because no data has been registered since the decommissioning and dismantling of the old hydropower plant in the year 1994.

Consequently, gauging station 5001, situated on the Guadalquivir River at the Arroyo María confluence, was selected as the sole reliable data source [13], [33-34]. This station is located at an elevation of 538 m above sea level, strategically positioned downstream of the Tranco reservoir outlet and upstream of the intake structure designed for the Puente de la Cerrada plant. The continuous historical records from station 5001 provide the necessary baseline data to implement the proposed evaluation methodology and model the river flow distribution.

III. Methodology and Results

A. *Hydrological Sizing and Evaluation of the Bistrița River Cascade Hydropower plants*

The implementation of the technical evaluation methodology for the middle reach of the Bistrița River is executed through a sequential framework based on the available single-year mean hydrological data series.

The first stage of the assessment consists of representing the annual hydrograph of the river course. This hydrograph illustrates the continuous daily or monthly flow fluctuations throughout the selected representative hydrological year, establishing the baseline behavior of the regulated river reach. Fig. 1 illustrates the complete annual hydrograph of the middle reach of the Bistrița River.

Based on the temporal distribution of this hydrograph, a Flow Duration Curve (FDC) was constructed to analyze the cumulative frequency of the available water resource [14-15]. Within this Flow Duration Curve, the specific operational design flow threshold was identified at the Q100 point, which corresponds to an exceedance duration of 100 days.

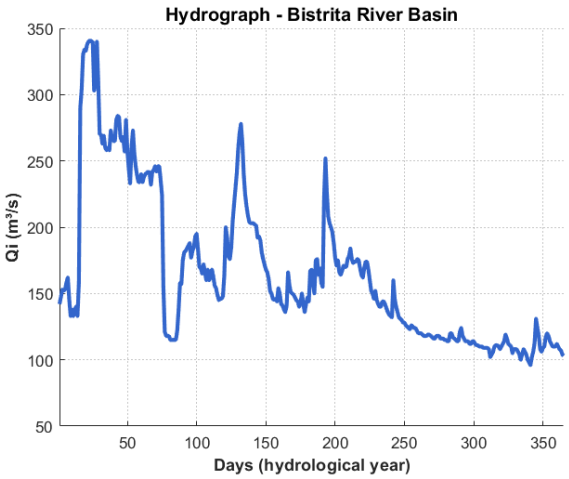

Fig. 3. Hydrograph - Bistrita River Basin.

For the analyzed section of the Bistrița River, this point establishes an available design flow (Q_d) equal to 173.85 m^3/s. This value defines the maximum exploitable limit for the run-of-river infrastructure framework.

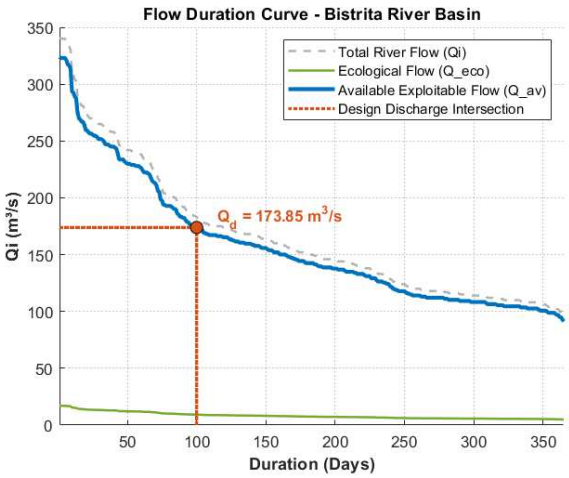

Fig. 4. Flow Duration Curve (FDC) - Bistrita River Basin.

Following the determination of the operational design flow, the methodology advances to the calculation of the nominal power capacity for both the individual hydraulic turbines and the global generation facility [16-18]. For this case study within the Romanian cascade, the engineering model considers a normalized net head (H_n) of 15 m and the identified design flow (Q_d) approximated to 174 cubic meters per second.

The mathematical formulation applied to estimate the gross potential capacity of the turbine system is defined as:

$$P_t = 9.81 * H_n * Q_d * \eta \quad (2)$$

Accounting for mechanical and generator efficiency losses, the total nominal power capacity assigned to the turbine units is established at 25.4 MW. Consequently, the net nominal power capacity of the complete hydropower facility is determined to be approximately 24 MW. To optimize operational flexibility and maintain high efficiency across fluctuating seasonal regimes, this total capacity is structurally

distributed into two identical generation groups of 12 MW each.

Once the nominal capacity of the facility is established, the daily power output profile is modeled throughout the entire hydrological year based on the daily flow availability from the initial hydrograph.

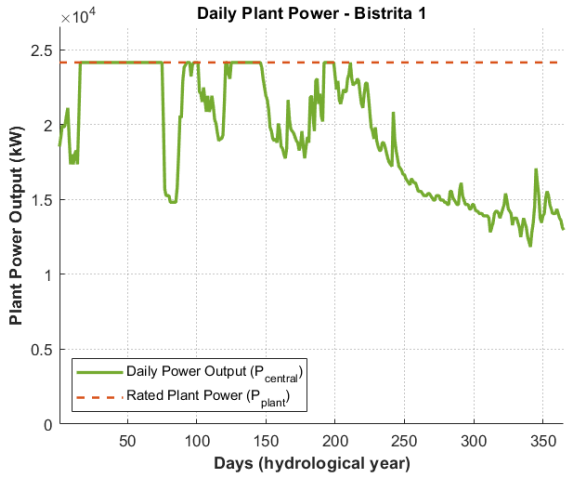

Fig. 5. Daily Plant Power - Bistrita 1 hydropower plant.

Additionally, an Energy Duration Curve (EDC) is constructed and appended to the analysis. This specific curve illustrates the cumulative distribution of the power output, graphically demonstrating the long-term electrical generation potential and reliability of this cascaded facility under the evaluated single-year regime.

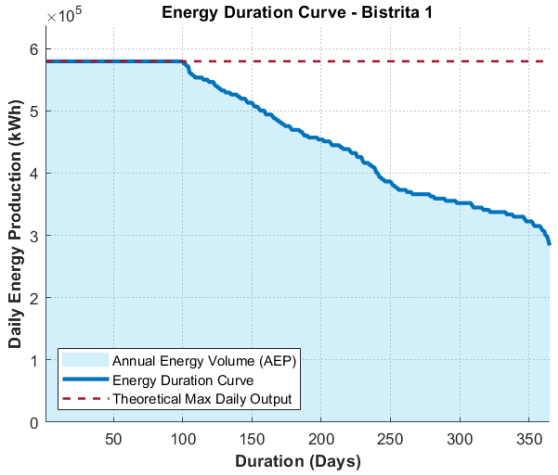

Fig. 6. Energy Duration Curve (EDC)- Bistrita 1 hydropower plant.

The operational analysis reveals that these cascaded units achieve a highly stable generation performance, resulting in a capacity factor of approximately 80 percent.

TABLE I. SIZING AND OPERATIONAL METRIX FOR BISTRIȚA RIVER CASCADE HYDROPOWER PLANT 1

Rated Turbine Power (P_turb)	25,411	(kW)
Rated Plant Power (P_plant)	24,140	(kW)
Annual Energy Production (AEP)	169,784,155	(kWh)
Full-Load Hours (FLH)	7,033	(h/year)
Capacity Factor (CF)	80.29	(%)

This high utilization rate translates into more than 7,000 equivalent full-load operating hours over the yearly cycle. The specific engineering parameters, energy dimensions, and operational metrics derived from this sizing implementation are synthesized in Table I.

B. Hydrological Sizing and Single-Year Base Evaluation of the Puente de la Cerrada Hydropower Plant

The proposed evaluation methodology was implemented for the Upper Guadalquivir River basin at the prospective Puente de la Cerrada facility. The historical database contains continuous river flow records spanning a 20-year operational period, specifically from the 2001/2002 to the 2020/2021 hydrological years. In accordance with regional standard criteria, each individual hydrological year begins on October 1 of every consecutive calendar period.

To guarantee high structural reliability and reduce scientific biases, a data filtering process was conducted. A specific annual period is classified as a valid year only if it contains more than 330 daily mean flow data points. This threshold restricts the maximum structural uncertainty of any individual year to less than 10%. Following this criteria, 18 fully valid years were isolated from the initial 20-year historical series.

The daily mean flow values were calculated for each single validated year to establish the baseline distribution. To identify a representative single period to act as the primary benchmark, the 35th, 50th, and 65th percentiles of the daily mean discharges were calculated across the entire 18-year valid framework. The 50th percentile (the median discharge) was identified as the most critical parameter, establishing an average river flow of 5.34 m^3/s. Fig. 7 illustrates the annual daily mean discharge for all validated historical years, explicitly highlighting the trend of the selected single-year base model against the complete series.

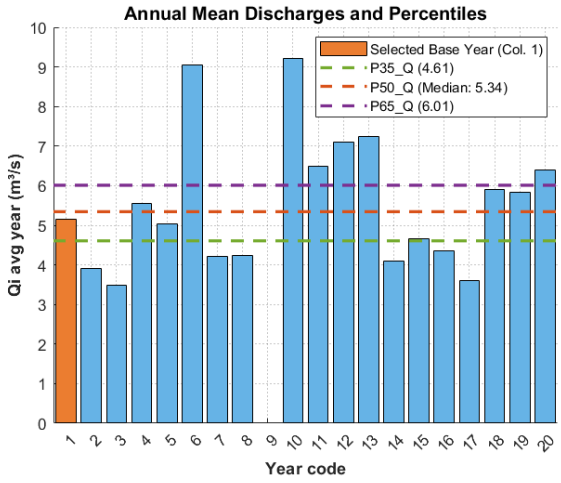

Fig. 7. Annual Mean Discharges and Percentiles - Puente de la Cerrada.

A comparative validation against the individual years indicated that the first historical period, identified as hydrological year 01 (2001/2002) in the records, represents the closest numerical proximity to the multi-year median. Hydrological year 01 presents an empirical daily mean discharge equal to 5.14 m^3/s.

Consequently, this specific period was selected as the representative single-year base framework for the primary

sizing stage. Fig. 8 illustrates the annual hydrographs for each year and for the selected base year.

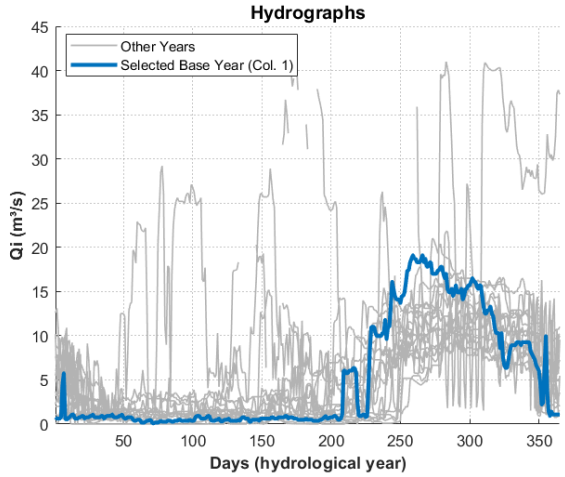

Fig. 8. Hydrographs - Puente de la Cerrada.

Based on the daily flow records of the chosen base year, a Flow Duration Curve (FDC) was constructed. For this Mediterranean-mountain environment, the model incorporates the local environmental constraints. The current legislation for the Guadalquivir River basin requires an ecological reserve flow equal to 10 percent of the average baseline discharge [19-20]. By subtracting this mandatory volume from the gross river flow series, the useful curve representing the available net exploitable flow was derived.

Within this net available Flow Duration Curve, the physical sizing of the plant is determined by isolating the Q100 point, which represents the specific discharge threshold that is equaled or exceeded during exactly 100 days of the yearly cycle. For the Puente de la Cerrada base model, this point establishes an operational design flow (Qd) equal to 8.33 m^3/s. Fig. 9 displays the constructed base-year Flow Duration Curve (FDC), showing both the total river flow and the net available flow curve, indicating the location of the design flow (Qd) at the Q100 point.

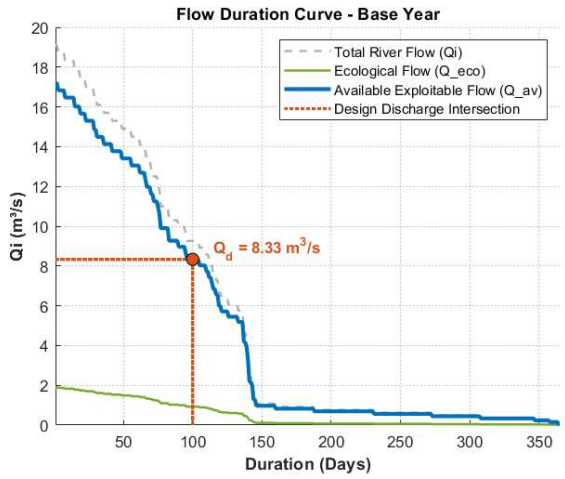

Fig. 9. Base-year Flow Duration Curve (FDC) - Puente de la Cerrada.

Following the isolation of the design flow, the methodology proceeds to calculate the nominal power capacity of the facility. The mechanical sizing model considers a useful local net head (H_n) of 25 m and the determined design flow (Q_d) of 8.33 m^3/s. To achieve a realistic energy simulation, the evaluation avoids a static efficiency coefficient and instead implements a mathematical model introducing the dynamic efficiency curve of the hydraulic turbine.

The instantaneous efficiency of the turbogenerator group varies daily as a function of the operational load ratio, which is directly determined by the ratio of the incoming net turbine flow to the nominal design flow. The mathematical expression utilized to determine the daily power generation capacity of the facility is defined as:

$$P = 9.81 * H_n * Q_d * \eta.$$

Through this daily computational routine, when the available river flow matches or exceeds the design flow threshold of approximately 8 cubic meters per second, the turbine operates at a 100 percent load ratio, achieving its maximum efficiency and delivering the maximum rated plant capacity of 2.0 MW (or 2,000 kW). Conversely, on days with lower water availability, the system calculates the corresponding reduction in both flow and turbine efficiency, mapping a highly accurate power output profile.

Fig. 10 illustrates the daily average power production profile of the facility over the evaluated base-year base framework.

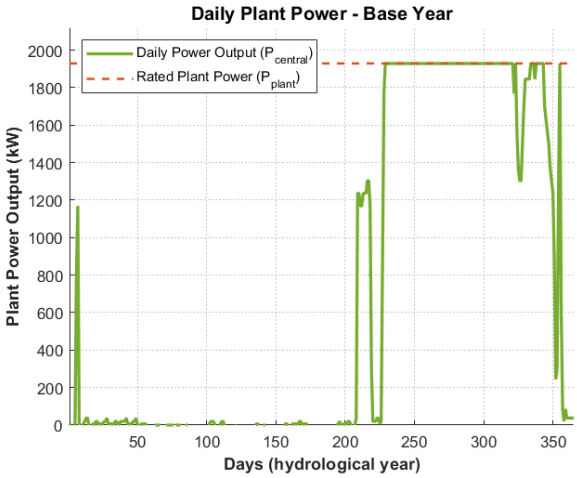

Fig. 10. Daily average power production profile - Puente de la Cerrada.

The operational simulation indicates that under this single-year envelope, the facility operates with a capacity factor of 35.8%. This production rate translates into 3,133 equivalent operating hours at full-load capacity over the yearly cycle. Finally, an Energy Duration Curve (EDC) was constructed to analyze the distribution and reliability of the electricity supply during this specific period.

TABLE II. SIZING AND OPERATIONAL METRICS FOR PUENTE DE LA CERRADA HYDROPOWER PLANT (SINGLE-YEAR BASE MODEL)

Rated Turbine Power (P_turb)	2,030	(kW)
Rated Plant Power (P_plant)	1,928	(kW)
Annual Energy Production (AEP)	6,044,481	(kWh)
Full-Load Hours (FLH)	3.133,95	(h/year)
Capacity Factor (CF)	35,78	(%)

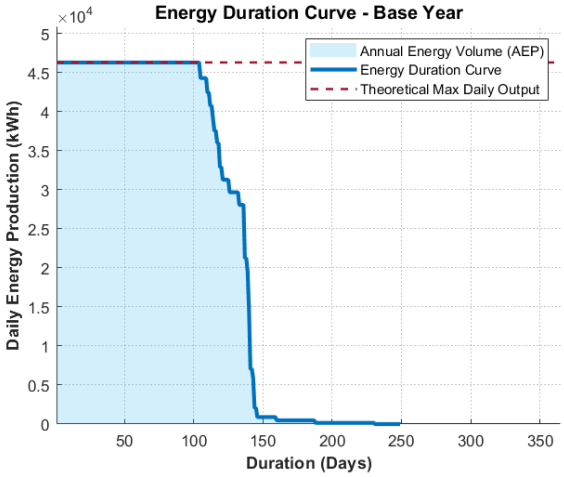

Fig. 11. Base-year Energy Duration Curve (EDC) - Puente de la Cerrada.

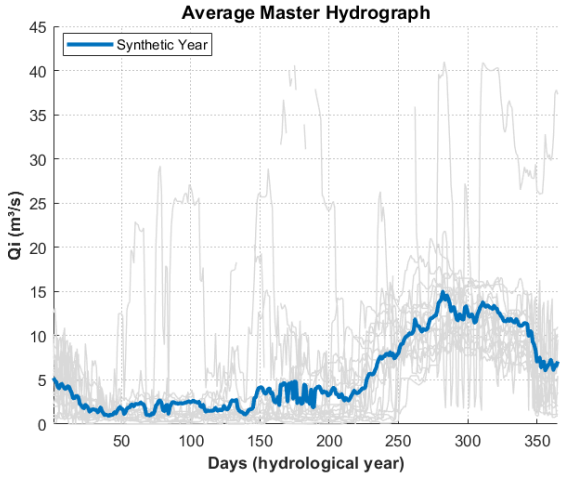

Fig. 12. Synthetic mean annual hydrograph - Puente de la Cerrada.

Fig. 11 presents the base-year Energy Duration Curve (EDC) for the Puente de la Cerrada plant.

The engineering dimensions, operational boundaries, and generation parameters derived from this single-year base analysis are synthesized in Table II.

C. *Hydrological Sizing and Multi-Year Synthesis Evaluation of the Puente de la Cerrada Hydropower Plant*

For this phase of the technical evaluation implements a long-term multi-year synthesis framework for the Puente de la Cerrada facility, applying the same operational and dynamic turbine efficiency principles established in the single-year base model. However, instead of limiting the evaluation to a single isolated period, this approach integrates the complete historical dataset to smooth out seasonal anomalies and capture the comprehensive hydrological behavior of the Upper Guadalquivir basin.

The first stage of this multi-year methodology consists of generating a synthetic mean annual hydrograph. This representative model is constructed by calculating the statistical average for each specific calendar day across the entire series of validated historical years. By plotting this synthetic year against the background of all annual hydrographs, the model provides a stabilized baseline of the river course.

Fig. 12 illustrates the synthetic mean annual hydrograph of the Puente de la Cerrada site, displaying the average daily flow distribution with the individual historical annual hydrographs plotted in the background.

In the second stage, a multi-year Flow Duration Curve (FDC) was constructed by direct integration of the extensive historical series, which compiles a total of 6,519 daily mean discharge data points. Due to the high density of this multi-year dataset, the curve is mathematically parameterized [21-23], [35]. Consequently, rather than isolating a fixed chronological day such as the Q100 threshold, the operational design flow (Q_d) is identified by locating a specific exceedance probability. For this evaluation framework, the design flow is established at a 27.4% probability of exceeding the target discharge throughout the historical series. Applying this parameterized baseline, the operational design flow (Q_d) for the prospective facility is determined to be 7.8 m^3/s.

Figure displays the parameterized multi-year Flow Duration Curve (FDC) derived from the 6,519 daily flow records, highlighting the design flow (Qd) at the 27.4% exceedance probability threshold.

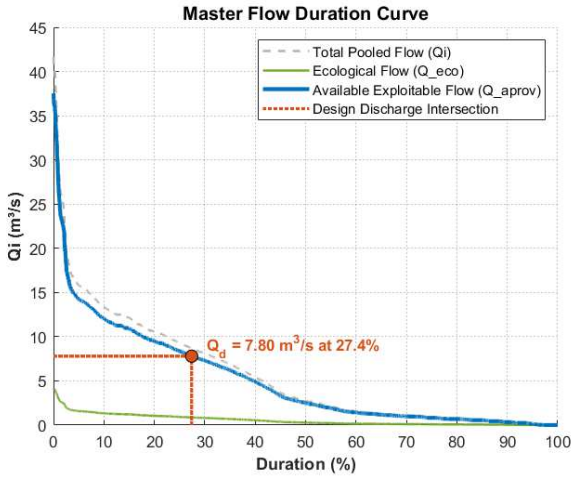

Fig. 13. Parameterized multi-year Flow Duration Curve (FDC) hydrograph - Puente de la Cerrada.

Following the determination of the multi-year design flow, the technical routine executes the daily power simulation. The engineering model considers the useful local net head (H_n) of 25 m and the parameterized design flow (Q_d) of 7.8 m^3/s. As established in the previous section, the power calculations are performed dynamically by introducing the turbine efficiency curve into the simulation. The instantaneous power output varies daily based on the operational load ratio computed from the incoming river discharge. When the available flow reaches or exceeds the 7.8 m^3/s limit, the group achieves a 100 percent load ratio, delivering its maximum rated plant capacity of approximately 2.0 MW.

Fig. 14 illustrates the annual daily power production profile of the facility modeled under the multi-year synthetic hydrological year framework.

Additionally, a multi-year Energy Duration Curve (EDC) was constructed and appended to the analysis to illustrate the cumulative distribution of the simulated electrical power output and demonstrate the long-term reliability of the system under a stabilized mean hydrological regime.

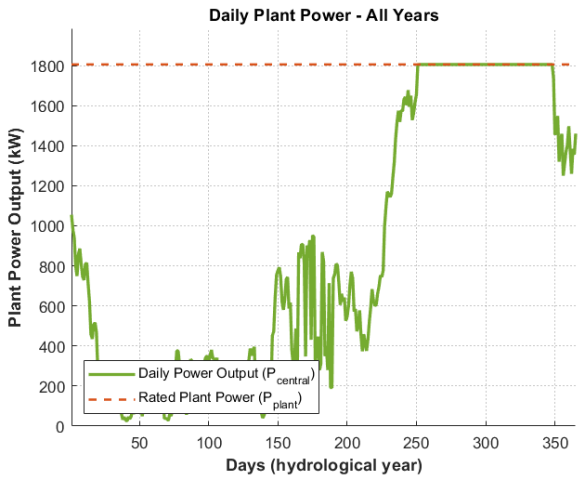

Fig. 14. Daily average power production profile Multi-Year Synthetic Model - Puente de la Cerrada.

Fig. 15 presents the Energy Duration Curve (EDC) derived from the multi-year synthetic hydrological year model at Puente de la Cerrada.

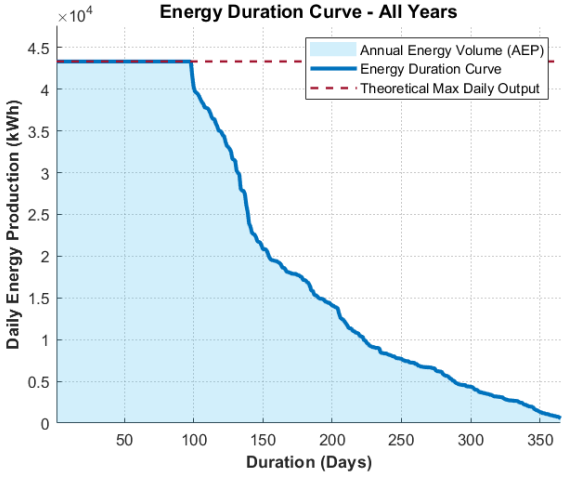

Fig. 15. Energy Duration Curve (EDC) - Multi-Year Synthetic Model - Puente de la Cerrada.

The operational analysis reveals that by integrating the complete historical data series into a synthetic mean year, the modeled facility achieves a higher performance stability compared to the single-year base approach.

This multi-year framework results in an increased capacity factor and a greater total annual energy production, proving that long-term daily data integration prevents the technical underestimation of small-scale run-of-river assets.

The operational metrics, and generation parameters derived from this multi-year synthesis are summarized in Table III.

TABLE III. SIZING AND OPERATIONAL METRICS FOR PUENTE DE LA CERRADA HYDROPOWER PLANT (MULTI-YEAR SYNTHETIC MODEL)

Rated Turbine Power (P_turb)	1,900	(kW)
Rated Plant Power (P_plant)	1,805	(kW)
Annual Energy Production (AEP)	7,731,183	(kWh)
Full-Load Hours (FLH)	4,283	(h/year)
Capacity Factor (CF)	49	(%)

IV. DISCUSSION OF RESULTS

The comparative analysis across the distinct hydrological frameworks of the Bistrița River in Romania and the Upper Guadalquivir River in Spain provides critical insights into small-scale hydropower asset sizing and performance evaluation methods. The integration of empirical operational data from an established cascade system alongside simulated prospective scenarios allows for a validation of methodology scaling limitations based on historical data density.

A. The Bistrița River Cascade System (Romania)

The single-year baseline methodology implemented for the middle reach of the Bistrița River demonstrated a high technical coherence when evaluated against real infrastructure parameters. By selecting a representative hydrological year that mirrors a mean regional flow regime, the calculated operational benchmarks achieved an exact match with the physical reality of the installed cascade. Under a normalized net head of 15 m and an isolated design flow of 173.85 m^3/s at the Q100 threshold, the derived plant capacity converged precisely at 24.14 MW. The high capacity factor of 80.29% and the achievement of 7,033 full-load hours reflect the highly regulated nature of these northeastern European channels, proving that single-year series remain computationally valid for infrastructure design under stabilized, non-torrential flow distributions.

To further reinforce the empirical validation of this mathematical framework, the technical field visit conducted to one of the operational generation assets within the active Bistrița cascade provides definitive proof of the model's accuracy [4]. The inspected facility features a well-established industrial configuration characterized by two identical turbogenerator units, where each individual group is designed to operate with a discharge capacity of 90 m^3/s, yielding a collective plant design flow of 180 m^3/s under an operational net head range between 12 m and 17 m. This operational layout delivers a total rated plant capacity of 23 MW. The direct verification of these physical dimensions demonstrates a remarkable similarity to the parameters derived in the mathematical model (24.140 MW plant capacity modeled with a 15 m net head and 173.85 m^3/s design flow). This narrow margin of convergence between the functioning infrastructure and the analytical simulation successfully validates the reliability and precision of the proposed methodology.

Extrapolating this empirical configuration across the macro-system, multiplying the 23 MW capacity of this standard facility by the 9 cascaded plants evaluated in this reach yields a cumulative potential of 207 MW. This calculated value presents a remarkable convergence with the 196 MW currently installed throughout the actual hydro-technical asset. The narrow margin of discrepancy between the real-world operational infrastructure and the analytical simulation successfully validates the reliability, scalability, and precision of the proposed methodology.

B. The Puente de la Cerrada Hydropower Plant (Spain)

The evaluation of the Puente de la Cerrada plant along the Upper Guadalquivir River exposed the specific risks and sensitivities associated with structural modeling in highly fluctuating Mediterranean-mountain basins. When applying the single-year base framework, a design flow of 8.33 m^3/s was isolated at the Q100 mark, resulting in a rated plant power of 1.93 MW. This single-period simulation yielded an annual

energy production of 6,044,481 kWh, corresponding to 3,133.95 full-load hours and a capacity factor of 35.78%.

However, when the methodology was expanded to the multi-year synthetic framework integrating 6,519 daily mean points over 18 valid historical years, a significant parametric rebalancing occurred. Due to the high density of the continuous dataset, the curve was parameterized using an exceedance probability of 27.4 percent instead of a fixed calendar day. This multi-year optimization model adjusted the design flow to 7.8 m^3/s, which corresponds to a rated plant capacity of 1.81 MW.

The core scientific finding emerges from the comparison of the energy yield simulations between both Spanish models. Despite having a slightly lower rated plant power (1.81 MW in the multi-year model versus 1.93 MW in the single-year model), the multi-year synthetic model achieved an annual energy production of 7,731,183 kWh, a capacity factor of 49%, and 4,283 full-load hours. This represents a substantial increase of approximately 27.9% in total energy yield compared to the single-year model. This divergence is explained by the integration of the dynamic turbine efficiency curve computed on a daily load ratio routine, which was successfully implemented across all evaluation models in this study. The single isolated base year captures seasonal extremes and prolonged dry periods that skew the performance curve downward, penalizing the turbogenerator groups on sub-optimal flow days [24-27]. Conversely, the synthetic multi-year model captures the stabilized flow distribution, smoothing out extreme annual anomalies and demonstrating that the turbine operates at a more favorable partial load profile over the multi-decadal timeline [28-32].

V. Conclusions and Future Work

The This study has successfully developed and validated an international hydrological evaluation framework for run-of-river small and medium-scale hydropower assets, contrasting the regulated Bistrița cascade system in Romania against the unregulated Upper Guadalquivir headwaters in Spain. The mathematical model provides a robust engineering tool capable of precisely calculating both the optimal operational design flow and the parameters of the required electromechanical turbine-generator equipment necessary for small-scale hydropower exploitation. The physical and operational validity of the baseline sizing framework was definitively confirmed through its application on the middle reach of the Bistrița River, expanding from the Bicaz dam outlet through Piatra Neamț down to Bacău. The empirical findings derived from the technical field visit and historical data verify that these active facilities were excellently planned and currently operate under an optimal functional regime. This cascade system demonstrates high engineering efficiency, generating a substantial volume of clean, renewable energy annually in a strategic, distributed generation format along the river course.

The application of the proposed methodology to the prospective Puente de la Cerrada facility in Spain demonstrates that both the single-year base approach and the multi-year continuous synthesis method are highly valid for run-of-river asset planning. Both computational models achieved an excellent physical convergence regarding initial infrastructure sizing, establishing a consistent design flow of approximately 8.0 m^3/s and a matching electromechanical capacity of around 2.0 MW. This dual-scenario validation justifies the implementation of the methodology to determine the total installed capacity of the prospective facility, providing the essential technical baseline required to execute future detailed techno-economic evaluations and financial viability studies.

However, from the perspective of uncertainty and sensitivity analysis, the study exposes critical operational distinctions between both approaches. While a single representative base year is computationally sufficient for initial machinery sizing, it remains highly vulnerable to seasonal hydrological extremes and climatic anomalies that can bias performance simulations. Conversely, by consolidating an extended evaluation framework spanning a 20-year period—which corresponds to the standard minimum operational life cycle of these hydropower assets—the generation of a synthetic mean year successfully smooths out short-term fluctuations. This multi-year integration allows engineers to evaluate the long-term, multi-decadal interannual behavior of the river course on an averaged baseline, ensuring a significantly more precise estimation of annual energy yields and capacity factors under realistic fluctuating Mediterranean regimes.

Future lines of work derived from this research will focus on the integration of climate change projection series into the parameterized multi-year models to simulate how future variations in Mediterranean precipitation trends might impact the exceedance probability threshold.

Additionally, the methodology can be expanded by introducing multi-basin optimization routines to analyze the downstream cumulative impact if a cascaded system, structurally analogous to the Bistrița reference model, were to be implemented along the entire 165 m of effective available net head identified across the 60 km Upper Guadalquivir reach.

Finally, a detailed techno-economic and viability study will be conducted specifically for the prospective Puente de la Cerrada facility to evaluate the engineering requirements, capital investments, and financial returns necessary for its structural remodeling and final operational commissioning.

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