

Article

Hydrological Assessment of Run-of-River Hydropower Plants Under Ecological Flow Constraints: The Ambi River Basin Case, Ecuador

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Abstract

Hydrological variability affects the operational sustainability of run-of-river hydroelectric plants, particularly in Andean basins with marked climatic seasonality. This study evaluated the effective water availability of the Ambi River basin in Ecuador for the La Algodonera and Atuntaqui hydroelectric plants, integrating hydroclimatic analysis, water balance, flow duration curves, ecological flow estimation using the Tennant method, and hydrological projections from the LSTM network. The results showed marked seasonality in the hydrological regime and allowed the identification of characteristic values of $Q_{20} = 6.98 \text{ m}^3/\text{s}$, $Q_{50} = 4.29 \text{ m}^3/\text{s}$ and $Q_{95} = 0.98 \text{ m}^3/\text{s}$, with Q_{50} being adopted as the design flow because it represents a reliable average condition for the system. The incorporation of the ecological flow established thresholds of $0.471 \text{ m}^3/\text{s}$ in the dry season and $1.413 \text{ m}^3/\text{s}$ in the rainy season, demonstrating that gross water availability is not equivalent to effective availability for generation. Under current conditions, peak power reached 1.92 MW, and monthly energy production ranged between 1.2 and 1.4 GWh during the months of highest availability. The hydrological projection indicated future flows between 0.9 and $9.60 \text{ m}^3/\text{s}$, while territorial suitability analysis identified favourable areas for future photovoltaic integration, broadening system planning under an integrated water–energy perspective.

Keywords: hydrological variability; environmental flow; run-of-river hydropower; flow duration curve; LSTM streamflow forecasting



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1. Introduction

The variability of the hydrological regime, intensified by climatic heterogeneity and alterations in precipitation patterns, directly affects the operational reliability and sustainability of run-of-river hydroelectric power plants. In this context, the hydrological characterisation of the water supply, the determination of the ecological flow and the

quantification of the technically usable flow are fundamental elements for evaluating hydroelectric potential, as they allow for the integration of availability, permanence and environmental constraints into the planning and operation of water resources.

The evaluation of hydrographic basins is a foundational process for understanding the behaviour of hydrological regimes and their influence on water resource availability. Rivers are dynamic systems in which physical, biological, and climatic processes interact, determining the stability of fluvial ecosystems and the sustainability of water uses, including hydropower generation [1]. In this context, the increasing pressure on water resources due to population growth, climate variability and energy demand has intensified the need for integrated and sustainable watershed management approaches.

Hydrological studies, as they pertain to the management of water resources, generally entail the examination of hydrometeorological data obtained over extended periods [2–4]. This data encompasses precipitation levels, ambient temperatures and the volume of water discharged by streams. These variables facilitate the characterisation of temporal variability in river regimes and provide a foundation for defining reference hydrological conditions, particularly for the estimation of ecological flow requirements [5]. Ecological flow is of critical importance in maintaining the functionality of riverine ecosystems. This includes the availability of habitat, the transport of sediment and the maintenance of biological connectivity.

Conventionally, ecological flow estimation has been executed through the utilisation of hydrological methodologies, prominently exemplified by the Tennant method. This method delineates environmental flow as a proportion of the mean annual flow [6]. Despite their widespread use, due to their simplicity and low data requirements, these approaches have been the subject of criticism. Critics contend that these approaches are limited in their capacity to represent the natural variability of river systems and that they lack integration with ecological and climatic processes. In contrast, more recent approaches, particularly those developed in Europe, propose an ecohydrological perspective in which ecological flow is defined as a dynamic component of the natural flow regime, incorporating seasonal variability and climate sensitivity [7,8]. This has given rise to a divergence between traditional hydrological methods and integrated ecohydrological frameworks, underscoring the necessity for more comprehensive approaches.

In recent literature, the estimation of environmental flow in hydroelectric systems has evolved from simple hydrological methods, based on percentiles, minimum flows, and duration curves, toward integrated approaches that relate hydrological disturbances, ecological constraints, and energy performance. In run-of-river hydroelectric plants, ref. [9] demonstrated that the selection of the environmental flow method substantially modifies both the river's residual flow regime and the energy generated, showing that there is no universally optimal threshold and that the decision depends on the balance between river conservation and hydroelectric development. By integrating hydrological models with hydroelectric production models, these authors demonstrated that certain environmental flow methods can significantly reduce energy generation or, conversely, conserve it at the cost of greater hydrological disturbance, confirming that the problem cannot be solved with a single fixed threshold. More recently, ref. [10] extended this perspective to the scale of the regulated system, incorporating environmental flow scenarios, ecosystem benefits, and consequences for hydroelectric production, demonstrating that the implementation of environmental flows can be quantitatively evaluated in terms of habitat gain and energy losses. Complementarily, ref. [11] confirmed, through multi-objective optimisation in cascaded hydroelectric plants, that the definition of environmental flow must be analysed in conjunction with system operation, since different hydrological scenarios and ecological conditions produce clear trade-offs between generation, operational reliability, and environ-

mental protection. Taken together, these advances show that the contemporary assessment of ecological flow can no longer be reduced to a fixed value but must be approached as a dynamic hydrological–ecological problem, which depends on the hydrological context and the operational scheme of each basin.

Furthermore, current literature shows a transition towards ecological approaches that seek to represent more realistically the effects of reduced flow in aquatic environments. The research of [12] demonstrates that increases in ecological flow do not always produce proportional improvements in habitat suitability for fish, which underlines the need to incorporate explicit biological criteria in addition to strictly hydrological metrics. In this context, the recent evidence provided by [13] in Ecuador is especially relevant, as it documents the ecological responses of the ichthyofauna and their relationship with hydrological alterations in a run-of-river hydroelectric project, which underlines the importance of conserving flow regimes capable of maintaining habitat diversity and species richness. This perspective aligns with previous studies indicating that reduced or inadequately regulated flow can negatively impact river connectivity, the availability of refuges, feeding and breeding grounds, and the overall stability of aquatic communities. Therefore, modern estimation of ecological flow must integrate not only criteria related to the availability and permanence of water resources, but also the ecological functionality of the river system, so that hydropower planning explicitly incorporates the protection of aquatic habitats alongside energy efficiency.

Concurrently, advancements in computational methodologies have facilitated the implementation of machine learning algorithms within the field of hydrology, particularly in the domain of streamflow forecasting. Among these, Long Short-Term Memory (LSTM) neural networks have garnered considerable attention due to their capacity to capture nonlinear relationships and long-term temporal dependencies in hydrological time series [14–17]. These models have exhibited superior performance in comparison to conventional statistical methodologies, particularly in complex and data-constrained environments, rendering them a valuable instrument for water resource management and hydropower operation.

In Ecuador, particularly in the Ambi River basin, water resources are of strategic importance due to their role in hydropower generation and regional water supply. However, the basin exhibits marked hydrological variability driven by climatic conditions, which poses challenges for sustainable water management and ecological conservation. Despite its significance, there remains a necessity for integrated studies that combine hydrological analysis, ecological flow estimation, and advanced forecasting techniques. In this context, the present study develops a hydrological assessment of the Ambi River basin aimed at determining the effective water availability for the “La Algodonera” and “Atuntaqui” hydroelectric plants. This assessment incorporates an analysis of the temporal variability of the flow, the definition of characteristic and design flows, the verification of restrictions associated with the ecological flow and the estimation of the hydropower potential under current and projected conditions. Beyond a descriptive characterisation, this approach seeks to generate a robust technical and scientific basis for optimising the operational planning of small run-of-river plants in Andean basins, in a scenario where energy efficiency must be evaluated inseparably from hydrological sustainability and the integrity of the river system. In addition, the study incorporates a territorial approach aimed at identifying suitable areas for future photovoltaic–hydroelectric integration within the Ambi River basin, expanding its scope towards a more comprehensive energy planning perspective, in which water availability, ecological limitations and territorial suitability can be analysed in an articulated manner to strengthen the operational sustainability of run-of-river systems in Andean basins.

2. Materials and Methods

Watershed assessment is a fundamental process for understanding the interactions between climatic, hydrological, and environmental variables that determine water availability and ecosystem stability. Watersheds function as integrated systems in which precipitation, evapotranspiration, and runoff interact with topography and land surface characteristics, directly influencing water quantity and quality [18]. In this context, analysing these processes is essential for the sustainable management of water resources, especially in regions exposed to increasing anthropogenic pressures and high climate variability. This highlights the usefulness of basic and semi-distributed hydrological models for basin-scale analysis. Tools such as the Soil and Water Assessment Tool (SWAT) allow for the simulation of hydrological processes by integrating climate data, land use, soil properties, and topographic features. These models are widely applied to assess streamflow generation, sediment transport, and nutrient dynamics under various environmental and climatic scenarios, providing a robust framework for hydrological assessment [19].

Topographic features have been shown to play a fundamental role in controlling watershed dynamics. The use of high-resolution Digital Elevation Models (DEMs) facilitates the precise delineation of watershed boundaries, the identification of drainage networks, and the characterisation of slope and elevation gradients. These parameters are crucial for representing flow paths and understanding the spatial variability of hydrological responses within the watershed [20].

The “Algodonera” and “Atuntaqui” hydroelectric plants are located in the Ontaño sector, along the Ambi River, in the Antonio Ante canton, Imbabura province, Ecuador (see Figure 1). Their main hydraulic components include the intake and the desander, situated at approximately 2205 m and 2287 m above sea level, respectively. The study site is located at approximately 0.33247° N, -78.21371° W. Climatically, the area corresponds to a semi-humid mesothermal equatorial regime of the central Andes, with an average annual temperature in Atuntaqui ranging between 15°C and 22°C , giving it a temperate climate characteristic of the Andean region. Furthermore, the catchment area exhibits a well-defined seasonality, with a rainy season concentrated between May and October.

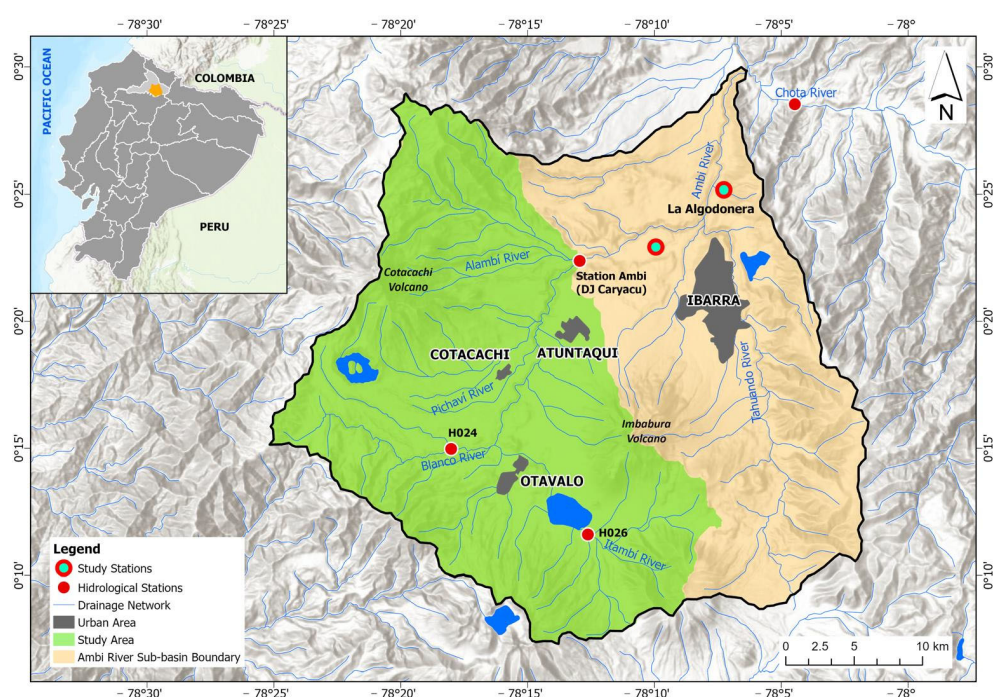


Figure 1. Location of the Ambi River basin, Ecuador, and the “Algodonera” and “Atuntaqui” hydroelectric plants of SERMAA EP.

2.1. Delimitation of the Ambi River Basin

In the case of the Ambi River basin, the hydrological evaluation was conducted through an integrated approach combining geospatial analysis and hydrometeorological data. The delineation of the basin was executed through the utilisation of Geographic Information System (GIS) tools and Digital Elevation Model (DEM) data. This approach facilitated the identification of drainage networks and the delineation of contributing areas. The hydrometeorological data were obtained from the National Institute of Meteorology and Hydrology (INAMHI), with the AMBI-DJ Cariyacu (H0023) station serving as the primary reference point (see Figure 2). The missing data were supplemented using nearby stations, including M315, M326, M105, M0001, and M107C [21,22].

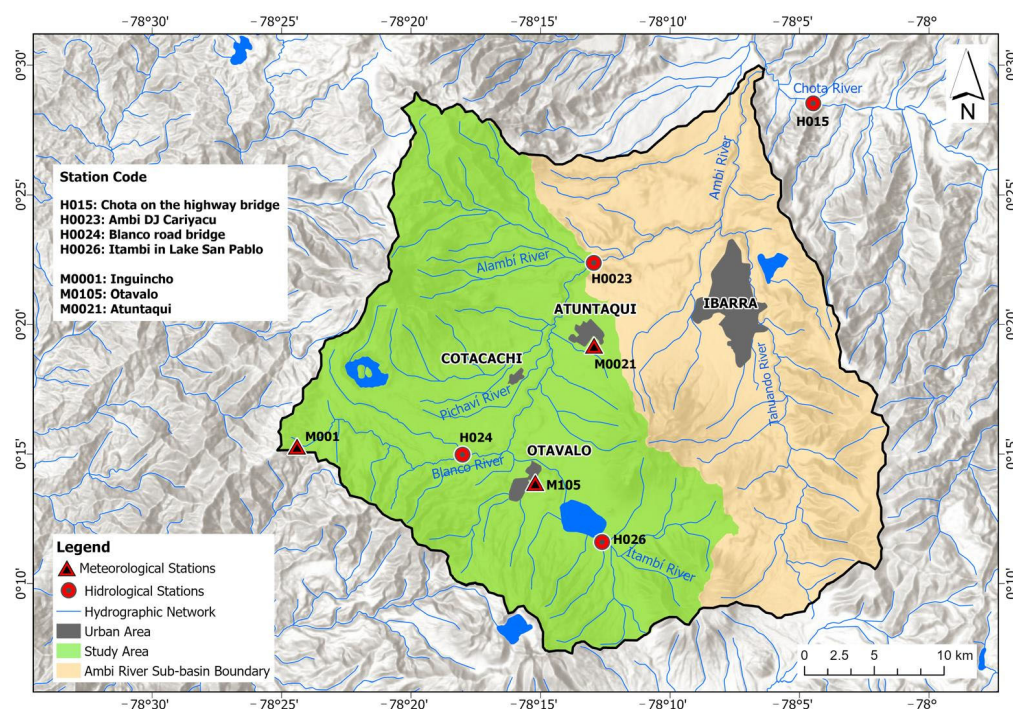


Figure 2. Location of the meteorological and hydrological stations of the Ambi River.

The analysis was based on historical precipitation, temperature, and streamflow data for the period 2010–2025 to characterise the temporal variability of the basin’s hydrological regime. The results revealed a clearly defined seasonality, with peak flows during the rainy season, especially between March and April, and minimum flows during the dry season, primarily in July and August, demonstrating the close dependence of hydrological behaviour on climate variability.

Furthermore, the spatial heterogeneity of the basin was incorporated through an analysis of land use, soil physical properties, and topographic configuration. These elements control key processes such as infiltration, surface runoff, and flow redistribution, and are therefore crucial to the basin’s hydrological response. The integration of these variables allowed for a more robust hydrological characterisation of the system, providing the technical basis for water balance, determination of ecological flow, and predictive assessment of water resources.

For the climate analysis of the Ambi River basin, historical meteorological data from the period 2015–2024 were collected from NASA’s POWER (Global Energy Resources Prediction) platform. This source provides validated satellite data, widely used in energy, hydrological, and climate studies due to its high reliability and spatial coverage. To corroborate these results, additional information was obtained from the National Institute of Meteorology and

Hydrology of Ecuador (INAMHI), specifically the total monthly precipitation records for the province of Imbabura, available on its open data platform for the year 2019.

2.2. Hydrological Simulation and Scenario Modelling

While tools such as WEAP, HEC-HMS, and SWAT are widely used for basin-scale hydrological modelling [23–25], this study opted for a climatological water balance approach due to the limited availability of detailed hydroclimatic data for the Ambi River basin. The hydrological assessment will be based on historical records of precipitation, temperature, potential evapotranspiration, and observed streamflow. In this context, the water balance equation formed the basis of the analysis, describing the dynamics of soil water storage as a function of system inputs and outputs. Its application allowed for a consistent representation of the availability, distribution, and dynamics of water resources in the basin, establishing the basis for evaluating hydrological scenarios and the potential for resource utilisation (Equation (1)).

$$SW_t = SW_0 + \sum_{i=1}^t (P_i - Q_{surf,i} - ET_i - W_{seep,i} - Q_{gw,i}) \quad (1)$$

where:

SW_t : soil water content at the end of day t (mm);

SW_0 : soil water content at the start of the simulation or at the start of the day (mm);

P_i : total precipitation on day i (mm);

$Q_{surf,i}$: surface runoff generated on day i (mm);

ET_i : actual evapotranspiration on day i (mm);

$W_{seep,i}$: water loss due to deep percolation or flow into the vadose zone on day i (mm);

$Q_{gw,i}$: baseflow or groundwater input to watercourses on day i (mm).

The water balance applied in this study was formulated from a basin hydrological perspective and, therefore, did not specifically incorporate sectoral withdrawals associated with irrigation, drinking water supply or urban demand. Based on the analysed hydrological behaviour, representative conditions of normal, wet and dry water availability were defined to evaluate the system's response to different levels of water supply and its possible impact on the use of hydroelectric power.

The Indicators of Hydrological Alteration (IHA) methodology was used to evaluate changes in the flow regime, considering attributes such as magnitude, frequency, duration, and timing of flows. Additionally, the improved indicators hydrological alteration (IIHA) proposed by [26] were used as a reference, as they allow for a more precise evaluation of intra-annual alterations in the hydrological regime, particularly in small and medium-sized rivers. Furthermore, to estimate extreme flows associated with different return periods, hydrological frequency analysis was applied using the Gumbel or Type I extreme value distribution, widely used in hydrological studies for analysing annual maximum flows. The design flow was then included in this distribution, according to the expression presented in Equation (2).

$$Q_T = \bar{Q}_{max} + K_T \cdot S_Q \quad (2)$$

where:

Q_T : design flow rate for a return period T (m^3/s);

$\bar{Q}_{max}$: average annual maximum flow rates (m^3/s);

K_T : frequency factor as a function of return period;

S_Q : standard deviation of maximum flow rates (m^3/s).

The water balance of the basin is utilised as a foundation for the estimation of the potential availability of water resources on an annual scale. In order to arrive at a calculation

of the annual volume of precipitation, the average annual precipitation was related to the basin area using a simplified expression. This relationship is expressed in Equation (3). This method facilitates the estimation of the total water input to the system, thereby serving as a valuable instrument in basin-scale hydrological studies when high-resolution spatial information is unavailable. The procedure is grounded in the depth–area–volume relationship, a widely utilised principle in hydrology for the estimation of the total volume of precipitation over a specified surface [27].

$$V = 100 \cdot \bar{P} \cdot A \quad (3)$$

where:

V: annual precipitation volume (m³);

$\bar{P}$: average annual rainfall (mm);

A: basin area (km²).

To estimate the hydroelectric potential associated with the available flow rate, the theoretical power generated by the hydroelectric plant was calculated. This was achieved by determining the relation between the turbine flow rate, the net head, and the overall system efficiency. This approach facilitates the evaluation of energy availability under varying hydrological conditions, whilst simultaneously enabling the analysis of the generation's sensitivity to fluctuations in the ecological flow rate. The expression for the usable power is given by Equation (4).

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \quad (4)$$

where:

P: electrical power (W);

ρ : water density (kg/m³);

g: acceleration due to gravity (m/s²);

Q: volumetric flow rate of water passing through the turbine (m³/s);

H: net height (m);

η : efficiency.

2.3. Hydrological Forecasting Using LSTM Networks

To provide a complementary hydrological analysis of the basin, a predictive model was implemented, the basis of which are short- and long-term memory (LSTM) recurrent neural networks. The selection of this architecture is predicated on its capacity to embody nonlinear relationships and short- and long-term temporal dependencies in hydrological time series, rendering it especially well-suited for simulating and projecting flows in systems characterised by high temporal variability [28–30]. The LSTM model was employed to analyse flow time series, with the objective of identifying behavioural patterns and generating hydrological forecasting under various water availability conditions. The incorporation of this approach resulted in a significant enhancement of conventional basin analysis, primarily by virtue of its capacity to offer a predictive approach. The primary focus of this predictive approach is the evaluation of future flow trends and their potential impact on water resource availability.

2.4. Territorial Suitability Assessment for Complementary Photovoltaic Integration

As a complement to the hydrological analysis, a territorial suitability assessment was incorporated to identify areas with potential for future photovoltaic–hydroelectric integration within the Ambi River basin. For this purpose, a multi-criteria analysis (MCA) based on the Analytic Hierarchy Process (AHP) was applied to prioritise the relative importance of climatic, geomorphological, hydrological, topographic, land cover, and

accessibility criteria. The criteria considered included global horizontal irradiance (GHI), geomorphology, proximity to rivers, slope, land use, urban areas, and road accessibility.

The relative weighting of these criteria was initiated through pairwise comparisons, and the internal validity of the matrix was verified using the consistency index (CI) and the consistency ratio (CR), yielding a CR value of 0.072, below the acceptability threshold of 0.1, thus confirming the methodological consistency of the adopted scheme. The normalised weights indicated that suitability was primarily determined by site availability (GHI = 0.413), followed by geomorphology (0.240) and river-related constraints (0.144), while slope, land use, urban areas, and road accessibility had a secondary contribution.

To complement this assessment, a comparative analysis of the priority parishes was incorporated using irradiation and temperature data obtained from Meteonorm 8.0, with particular emphasis on global horizontal irradiation, direct normal irradiation, and mean air temperature. This procedure allowed for a comparison of the territorial suitability obtained with the radiometric behaviour of specific sectors within the basin. Under this approach, the photovoltaic suitability assessment was not used as a substitute for hydrological analysis, but rather as a complementary tool to explore the territorial viability of future energy integration strategies within the Ambi system.

The initial concept and draft of the graphical abstract were developed by the authors. ChatGPT (OpenAI, GPT-5.5) was subsequently used to improve its visual presentation. The authors reviewed, edited, and validated the final graphical abstract to ensure its scientific accuracy and consistency with the study.

3. Results and Discussions

3.1. Hydroclimatic and Hydrological Variability of the Ambi River Basin

The Ambi River basin demonstrated significant hydroclimatic variability, characterised by both the temporal distribution of rainfall and the seasonal response of streamflow. At a spatial scale, mean annual precipitation exhibited a heterogeneous pattern within the basin, with higher values recorded in the northwest sector and lower values observed towards the east. This finding suggests a combined influence of topography and altitudinal gradient on the distribution of water input. This spatial heterogeneity is a salient element in the interpretation of the hydrological dynamics of the basin and the availability of the resource at points of use (see Figure 3a,b).

The monthly water balance shows a well-defined seasonality, with months of surplus and deficit that reflect the typical behaviour of an Andean basin with a marked alternation between wet and dry periods. The largest water surpluses were recorded in January, March, April, and June, with values of 138.98 mm, 104.25 mm, 91.76 mm and 105.10 mm, respectively, while the deficits were concentrated in July, August, and September, reaching a minimum of −37.31 mm in July (see Figure 4). This pattern confirms that the basin's water availability decreases significantly during the dry season, reducing the system's operating margin and increasing the sensitivity of hydroelectric power generation to hydrological and environmental constraints.

The flow regime response exhibited a high degree of consistency with the hydroclimatic dynamic. The multi-year average monthly flow exhibited peaks during the rainy season, with a maximum value of 7.29 m³/s recorded in April, followed by 6.30 m³/s in March and 6.25 m³/s in November. Conversely, the lowest values were observed in July and August, at 2.62 and 1.63 m³/s, respectively (see Figure 5). The findings, when considered as a whole, demonstrate a strong dependence of the hydrological behaviour on precipitation patterns, as well as a marked seasonality in the water supply available to the “La Algodonera” and “Atuntaqui” hydroelectric plants. From a management perspective, this variability is a critical factor for water use planning, as it affects both operational relia-

bility and the need to incorporate hydrological sustainability criteria during the months of lowest availability.

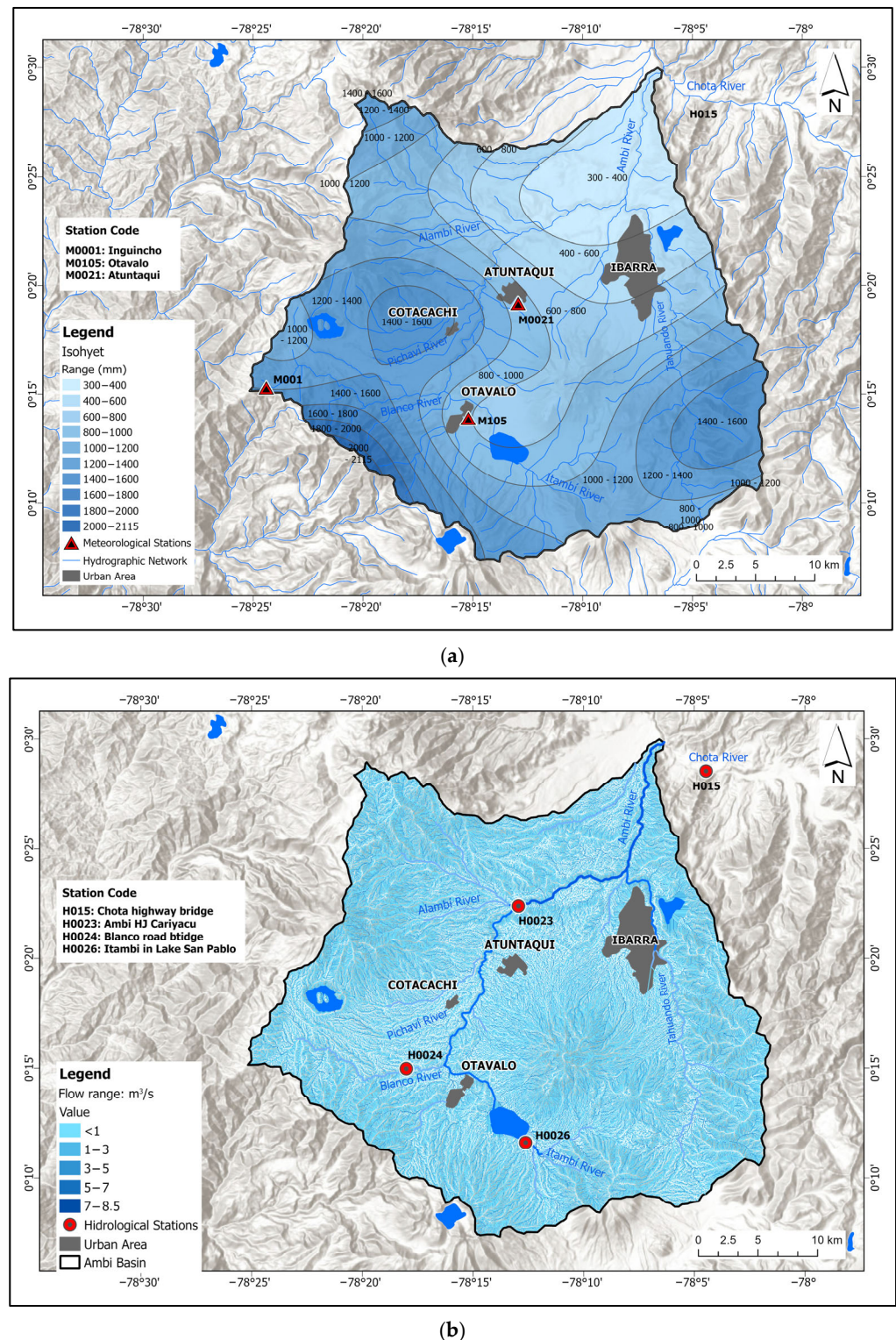


Figure 3. Spatial distribution of precipitation and streamflow in the Ambi River basin: (a) average annual precipitation and (b) average monthly flows.

In summary, the Ambi River basin exhibits a marked hydroclimatic seasonality that controls flow variability and, therefore, water availability for use. This behaviour forms

the basis for determining characteristic flows, defining the ecological flow, and evaluating hydroelectric potential from a hydrological sustainability perspective.

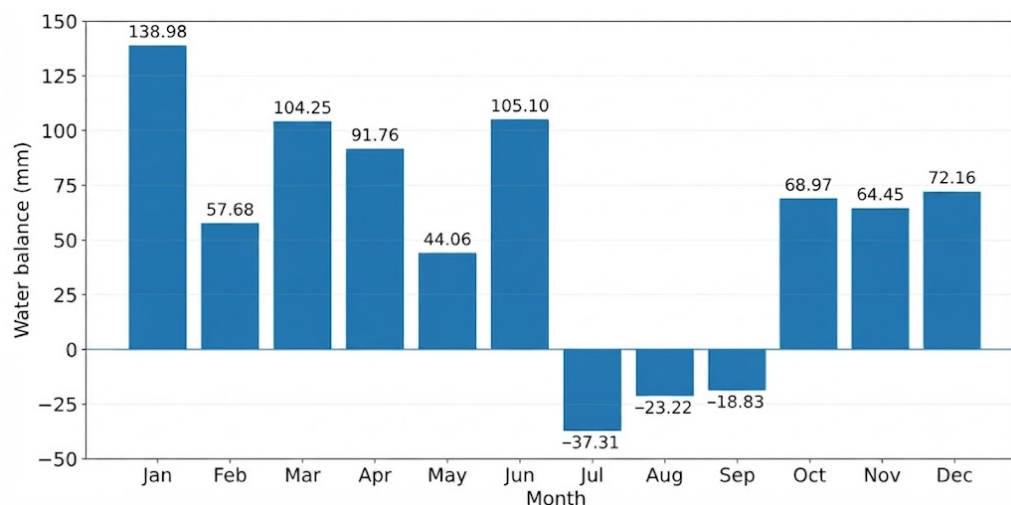


Figure 4. Monthly variation in the water balance in the Ambi River basin.

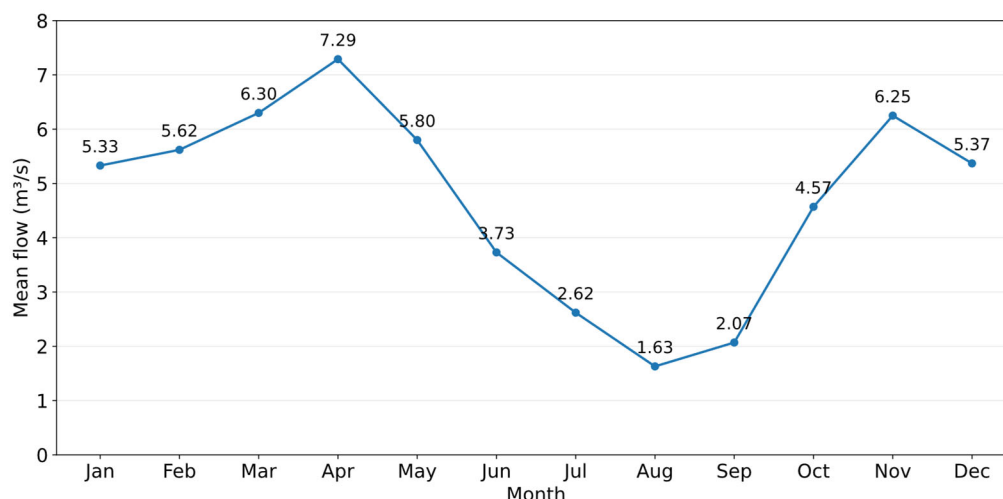


Figure 5. Average monthly hydrological regime of the Ambi River basin.

3.2. Characteristic Flow Rates and Determination of the Design Flow Rate

The flow duration curve facilitated the characterisation of water resource permanence in the Ambi River basin, thereby establishing a technical basis for the hydroelectric evaluation of the system. This analysis revealed marked variability in flow availability, consistent with the previously identified seasonality of rainfall. The differentiation of high-, medium-, and low-water-supply conditions was enabled by the characterisation of the flow regime's percentiles. In this context, the values obtained for Q_{20} , Q_{50} and Q_{95} were $6.98 \text{ m}^3/\text{s}$, $4.29 \text{ m}^3/\text{s}$ and $0.98 \text{ m}^3/\text{s}$, respectively, representing scenarios of high availability, medium system condition, and critical low flow conditions (see Figure 6).

From an operational perspective, Q_{20} corresponds to conditions associated with the rainy season, where water resources are abundant but have a shorter duration, making it unsuitable as a design criterion. In contrast, Q_{95} represents restrictive conditions of low availability, useful for identifying critical scenarios and assessing proximity to restriction thresholds, although insufficient to sustain stable system operation. Between these two extremes, Q_{50} expresses a more consistent balance between resource availability and rela-

bility, as it is exceeded 50% of the time, making it a technically representative parameter of the average operating condition of hydroelectric plants.

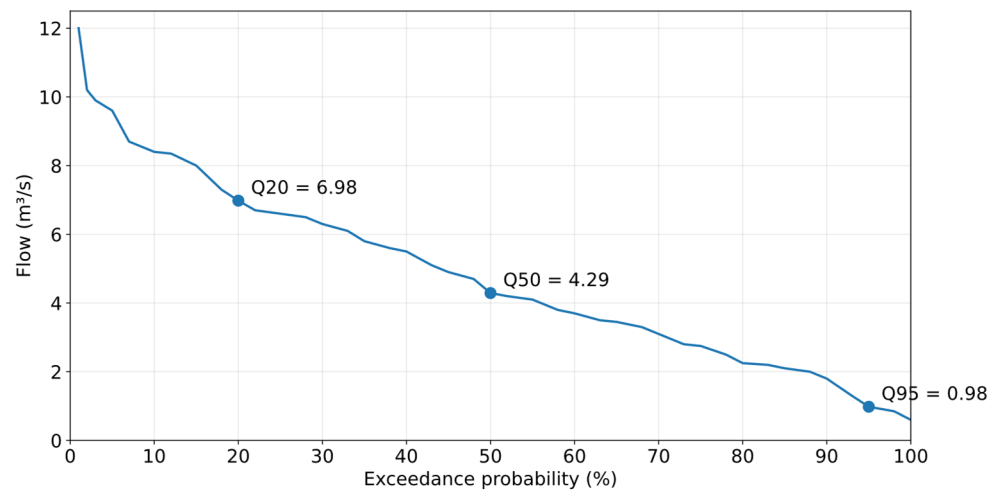


Figure 6. Flow duration curve of the Ambi River showing the characteristic flows Q_{20} , Q_{50} , and Q_{95} .

The design flow rate adopted for the hydroelectric evaluation was $Q_{50} = 4.29 \text{ m}^3/\text{s}$, as this value is equal to or exceeds 50% of the time, making it a representative descriptor of the average hydrological condition of the Ambi River. In contrast, $Q_{20} = 6.98 \text{ m}^3/\text{s}$ corresponds to a condition of higher flow and shorter duration and adopting it as a design criterion could lead to an overestimation of hydroelectric performance. On the other hand, $Q_{95} = 0.98 \text{ m}^3/\text{s}$ represents a highly restrictive condition of low flow, which, while useful for identifying critical periods, would underestimate the typical operating potential of the system. Under these conditions, the selection of Q_{50} provides a more robust balance between resource availability and operational reliability, avoiding both oversizing in wet conditions and under sizing in extreme drought scenarios, and offering a more realistic basis for the subsequent analysis of effective water availability and hydroelectric potential.

3.3. Ecological Flow and Effective Water Availability for Generation

The ecological flow was incorporated into the analysis as an appropriate hydrological and operational constraint to preserve the basic functionality of the Ambi River ecosystem without disproportionately compromising the operation of the hydroelectric plants. Based on an average annual flow of $4.71 \text{ m}^3/\text{s}$, the Tennant method [31–33] allowed for the estimation of values of $0.471 \text{ m}^3/\text{s}$ for the dry season (10%) and $1.413 \text{ m}^3/\text{s}$ for the rainy season (30%), demonstrating that the environmental requirement varies seasonally according to the hydrological regime of the system (see Figure 7). Under this approach, water availability for generation cannot be evaluated solely based on flow, since a portion of the resource must remain in the riverbed to guarantee minimum conservation conditions. Consequently, the gross water availability is not equivalent to the effective availability for generation, particularly during the dry months, when the natural decrease in flow reduces the operational margin and increases pressure on the system.

In this context, the usable flow represents a more realistic estimate of the effectively usable resource, as it subtracts the environmental requirement associated with the ecological flow from the total hydrological supply. In the case analysed, the difference between the design flow of $4.29 \text{ m}^3/\text{s}$ and the ecological flow during the dry season shows that, although the potentially usable volume is reduced, the operation of the power plants remains technically viable. This distinction is pivotal for a consistent hydropower assessment, as it prevents the overestimation of the system's potential and enables the potential

hydrological availability to be translated into an effective availability compatible with the sustainability of the riverbed. From this perspective, the incorporation of the ecological flow not only strengthens the environmental consistency of the analysis but also furnishes a more robust foundation for the subsequent estimation of power and energy under real operating conditions.

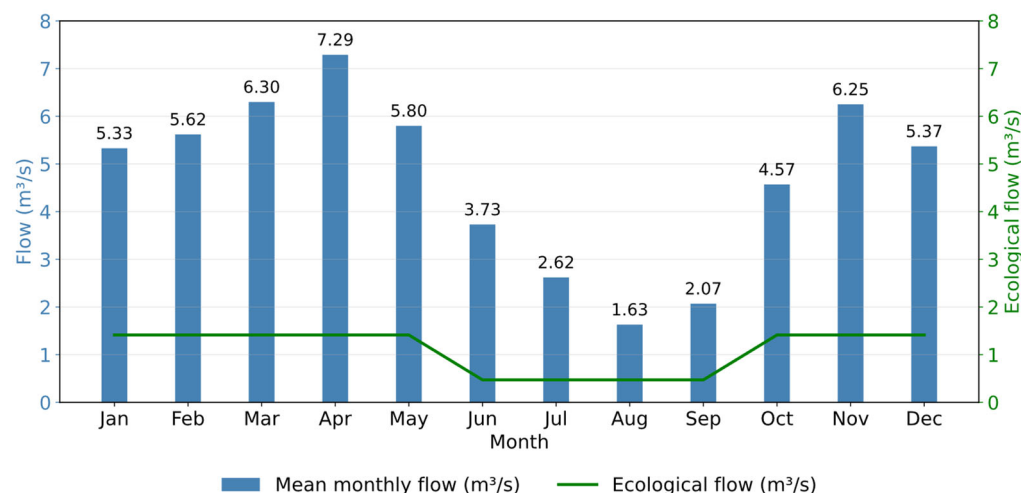


Figure 7. Comparison between the mean monthly flow regime and the ecological flow threshold in the Ambi River basin.

To further assess the robustness of the ecological flow thresholds derived from the Tennant method, a simple sensitivity analysis was performed by varying the mean annual flow used as reference by $\pm 5\%$ and $\pm 10\%$ around the baseline value of $4.71 \text{ m}^3/\text{s}$. Under this range, the ecological flow for the dry season varied between 0.424 and $0.518 \text{ m}^3/\text{s}$, whereas the rainy-season ecological flow ranged between 1.272 and $1.554 \text{ m}^3/\text{s}$. This analysis was included because the Tennant method directly expresses ecological flow as a fixed proportion of mean annual discharge, meaning that any variation in reference hydrological condition propagates linearly into the estimated environmental thresholds. In this sense, the sensitivity analysis provides a more robust interpretation of the ecological flow by showing that these values should be understood as hydrologically conditioned thresholds rather than as fixed limits independent of basin variability. These results reinforce that ecological flow thresholds in the Ambi River basin should be interpreted within the context of hydrological variability and effective water availability.

3.4. Hydropower Implications Under Current Conditions

The hydroelectric response of the system was found to be closely conditioned by the seasonal variability of the Ambi River basin's hydrological regime, thereby confirming the structural dependence of run-of-river hydroelectric plants on the temporal availability of water resources. Utilising metrics such as average monthly flows, net head, and overall system efficiency, the study estimated the power and energy generated under prevailing conditions. The findings indicated a direct correlation between periods of optimal water availability and maximum energy production. This finding suggests that the system's performance cannot be interpreted solely in terms of its hydraulic configuration, but rather because of the interaction between flow duration and its intra-annual distribution.

The highest generation values were recorded in March, April, and November, with outputs between 1.62 MW and 1.92 MW and monthly energy production ranging from 1.2 GWh to 1.4 GWh , peaking in April (see Figure 8). Conversely, during the dry season, reduced flow significantly limited generation capacity, demonstrating the system's reduced operational robustness under low-water-availability conditions. From a hydrological-

operational perspective, these results show that energy production should be understood as an expression of effective water availability, not as an abstract installed capacity. In this sense, the current hydroelectric assessment not only quantifies system performance but also identifies periods of greatest operational limitation, providing a technical basis for resource management and operational planning under hydrological sustainability criteria.

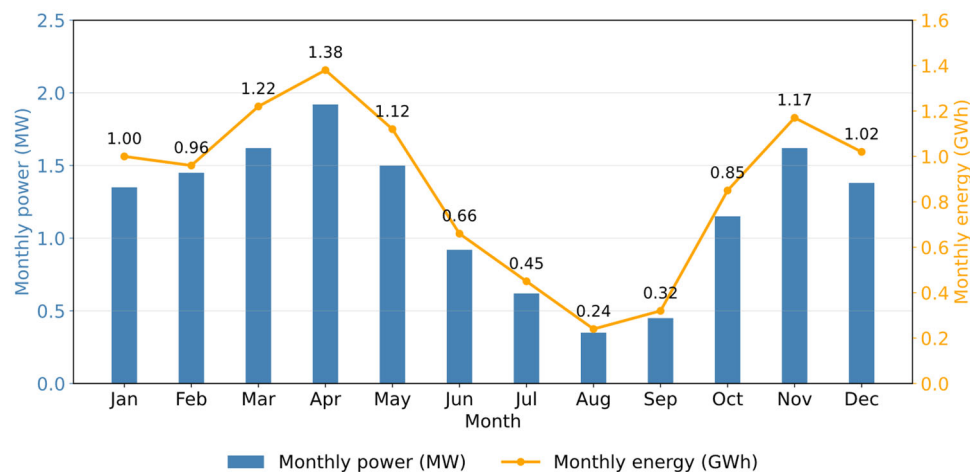


Figure 8. Monthly variation in power and energy generation under current hydrological conditions in the Ambi River system.

3.5. Hydrological Forecasting and Its Effect on Future Use

To incorporate a prospective dimension into the hydrological analysis, a prediction model based on short- and long-term memory (LSTM) recurrent neural networks was applied to the time series of flows in the Ambi River. This approach enables the exploration of the predicted evolution of water availability within a framework of temporal variability, providing a complementary tool for the future assessment of hydroelectric development. As demonstrated in Figure 9, the model displays a consistent capacity to replicate the prevailing trend in the flow series, while concurrently preserving the seasonal variability signal. This attribute renders the model a valuable foundation for prospective analysis of the system.

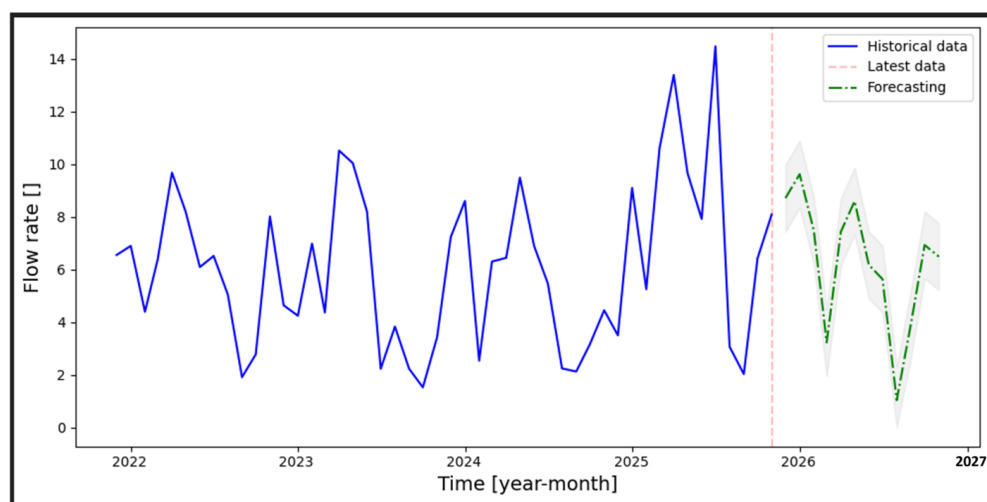


Figure 9. Comparison between the projected average monthly flow and the ecological flow in the Ambi river basin.

A comparison of the projected flow with the ecological flow reveals that the hydrological seasonality of the Ambi River is projected to persist in future scenarios, with increased availability in November, December, March and April, and more restrictive conditions during the dry season, particularly in July and August (see Figure 10). Although the projected flow exceeds the ecological threshold for most of the year, the discrepancy between the two is considerably diminished during the dry months. This has a significant impact on the potential for hydroelectric power generation. In this sense, the figure demonstrates that the future availability of the resource must be evaluated in terms of effective water availability. This evaluation should take place in conjunction with the projected supply and the environmental limitations of the river system.

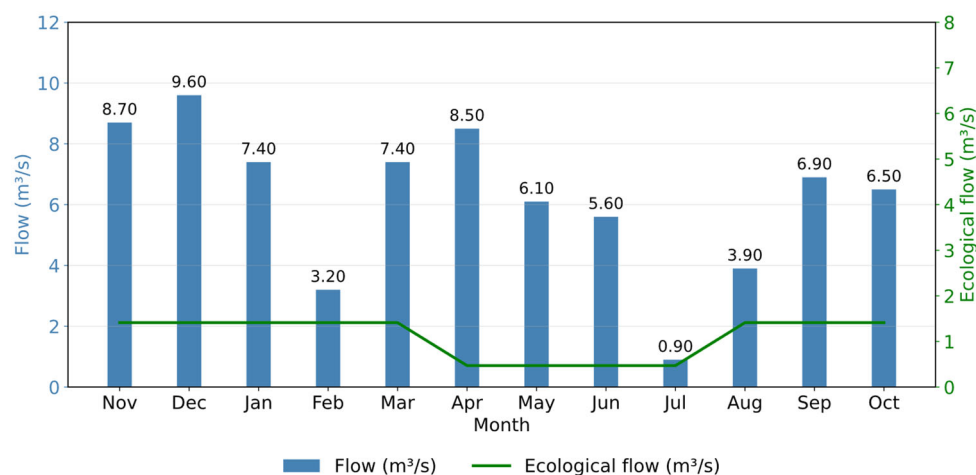


Figure 10. Projected monthly variation in hydropower generation under future flow conditions.

This forecast indicates that the flow rates will vary between 0.9 and 9.60 m³/s. This is significant because it suggests that the supply of water will be subject to considerable variability in the basin under the analysed scenario (see Figure 10). From a hydrological perspective, these results suggest that the seasonality observed in the historical series would continue to influence the magnitude and duration of the available resource. Operational comparisons between the projected average flow rate and the ecological flow rate facilitate the identification of future periods in which pressure on the system could intensify, particularly during the months of lowest availability. In this sense, the hydrological forecasting should not be interpreted as a deterministic prediction, but rather as an approximation that can support planning processes and facilitate anticipation of potential limitations in usable flow and the hydroelectric performance of the system.

3.6. Ecological Implications of Ecological Flow in Run-of-River Hydroelectric Power Plants

In run-of-river hydroelectric plants, flow availability is the main constraint for power generation; however, the fraction of water that remains in the channel plays a crucial role in maintaining the ecological functionality of the river system. When the ecological flow regime does not adequately represent the river's natural dynamics, the affected reach can experience alterations in depth, flow velocity, hydraulic connectivity, habitat availability, sediment transport, and the water's physicochemical conditions. These alterations may affect aquatic and riparian ecosystems through changes in habitat availability, connectivity and ecological stability [13,34]. For this reason, the definition of ecological flow must integrate hydrological and ecological criteria that allow for maintaining the health of the river ecosystem without neglecting the operational requirements of hydroelectric generation [35].

From an ecohydrological perspective, ecological flow should not be limited to a minimum permanence value but rather interpreted as a regime capable of sustaining functional processes associated with hydrological variability. In this sense, excessively uniform ecological flow schemes can reduce the variability necessary to preserve habitat diversity, connectivity, and ecological integrity, especially in basins with marked hydrological seasonality [9,36].

In the Ambi River basin, this problem is directly related to the results obtained in this study. The marked hydroclimatic seasonality identified showed that water availability decreases significantly during the dry season, while the estimated ecological flow thresholds remain at $0.471 \text{ m}^3/\text{s}$ for the dry season and $1.413 \text{ m}^3/\text{s}$ for the rainy season. Under these conditions, during the dry season, the margin between available flow and the minimum flow required for the conservation of the river system narrows, simultaneously increasing the ecological and operational sensitivity of the system. In this sense, periods of low flow represent the condition of greatest vulnerability, since any further reduction in the available resource can intensify alterations in connectivity, habitat stability, and the ecological functionality of the river.

This consideration is particularly relevant for Ecuador, where climatic and hydrological heterogeneity conditions water availability in the inter-Andean basins, with clearly distinguishable rainy, dry, and transitional periods. In these types of systems, ecological flow management must respond to seasonality and operate as a mechanism for reconciling renewable energy generation with river conservation, rather than as a static restriction on energy use. The selection of the ecological flow method directly impacts both the remaining flow allocated to ecosystem conservation and hydroelectric production; therefore, dynamic and proportional approaches offer a more robust alternative for reducing hydrological disturbance without disregarding the energy viability of run-of-river power plants [9,36]. Likewise, methods that incorporate intra-annual variations in precipitation, temperature, and ecological conditions allow for adjusting the ecological flow to the environmental change's characteristic of each hydrological period [37].

Consequently, for inter-Andean basins such as the Ambi River basin, applying an ecological flow variable, whether monthly or seasonal, is more consistent with the natural dynamics of the river system than a uniform allocation scheme. This approach reduces impacts on habitats, connectivity, and aquatic biodiversity, while facilitating a more realistic estimate of the flow effectively available for hydroelectric generation. Furthermore, its relevance increases in climate variability scenarios, where temporal changes in water availability can modify both the ecological requirements and the energy potential of the system [38]. Therefore, incorporating ecologically variable regimes does not limit run-of-river hydroelectric development; on the contrary, it strengthens its environmental sustainability by aligning energy production with the conservation of the ecohydrological processes that maintain the integrity of the river.

3.7. Territorial Suitability for Complementary Photovoltaic–Hydroelectric Planning in the Ambi River Basin

As a complement to the hydrological and hydroelectric power assessment of the Ambi River basin, the territorial suitability analysis showed that there are areas with favourable conditions for potential complementary photovoltaic integration. The suitability map (see Figure 11) shows a differentiated spatial distribution of photovoltaic potential within the basin, resulting from the interaction between the availability of solar resources and a series of physical and environmental limitations. The applied AHP-MCDA scheme demonstrates adequate methodological consistency, with a consistency index (CI) of 0.072, which supports the validity of the adopted weighting process. The normalised weights indicated that territorial suitability was primarily dominated by overall horizontal irradiance (0.413), followed by geomorphology (0.240) and river-related constraints (0.144), while slope,

land use, urban areas, and road accessibility had a secondary influence. In terms of interpretation, this result shows that photovoltaic suitability in the basin depends not only on the availability of solar resources but also on territorial and environmental factors that modulate the spatial feasibility of complementary energy infrastructure.

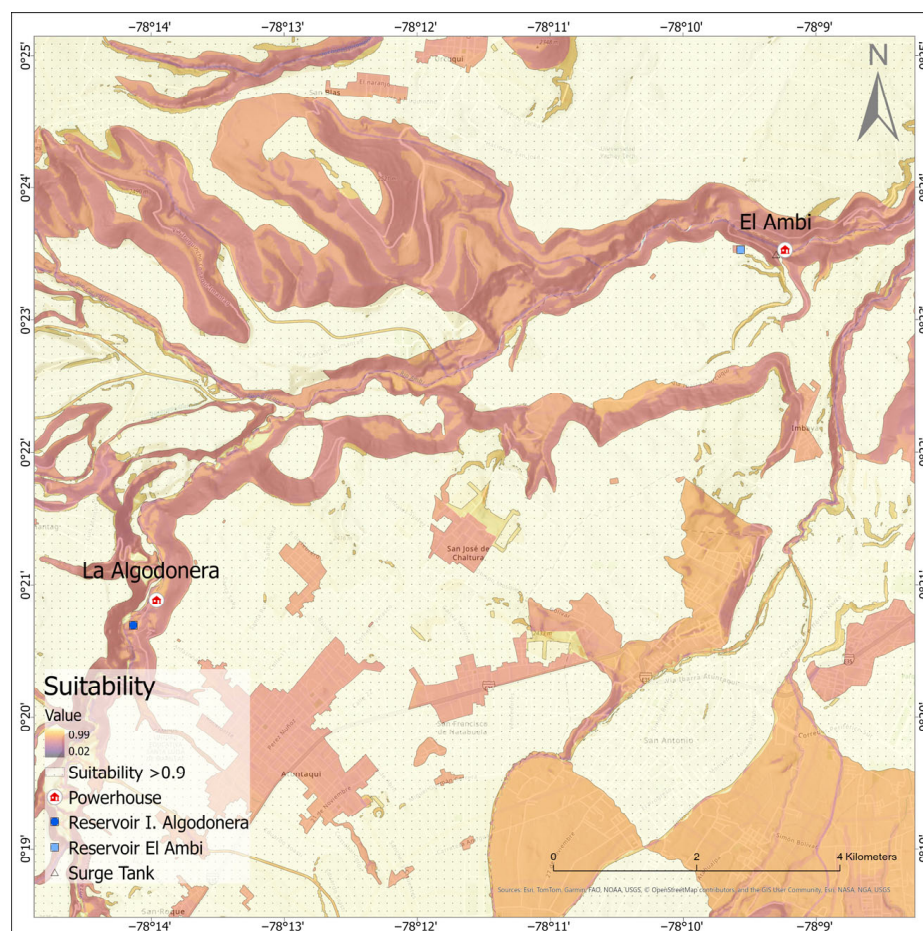


Figure 11. Photovoltaic suitability map of the Ambi River basin and priority areas for complementary photovoltaic planning.

The comparison of priority parishes using Meteonorm 8.0 reinforced this spatial interpretation by revealing significant differences between territorial suitability and radiometric potential. Quiroga presented the highest annual irradiation values, with approximately $1856 \text{ kWh/m}^2/\text{year}$ for H_{Gh} and $1536 \text{ kWh/m}^2/\text{year}$ for H_{Bn} , together with the lowest mean air temperature (14.3°C), indicating favourable radiometric and thermal conditions for photovoltaic performance. San Juan de Ilumán and San José de Chaltura also showed strong solar behaviour, with annual H_{Gh} values of approximately 1821 and $1812 \text{ kWh/m}^2/\text{year}$, respectively, and high suitability indices, suggesting a more balanced relationship between territorial suitability, solar resource, and thermal performance. In contrast, Salinas maintained high spatial suitability (0.987), although with lower annual irradiation values ($1784 \text{ kWh/m}^2/\text{year}$ for H_{Gh}) than other priority areas. This interpretation is further supported by the monthly comparison of global horizontal irradiation among the priority parishes (see Figure 12), which shows that the most suitable sectors also maintain comparatively stable solar resource conditions throughout the year.

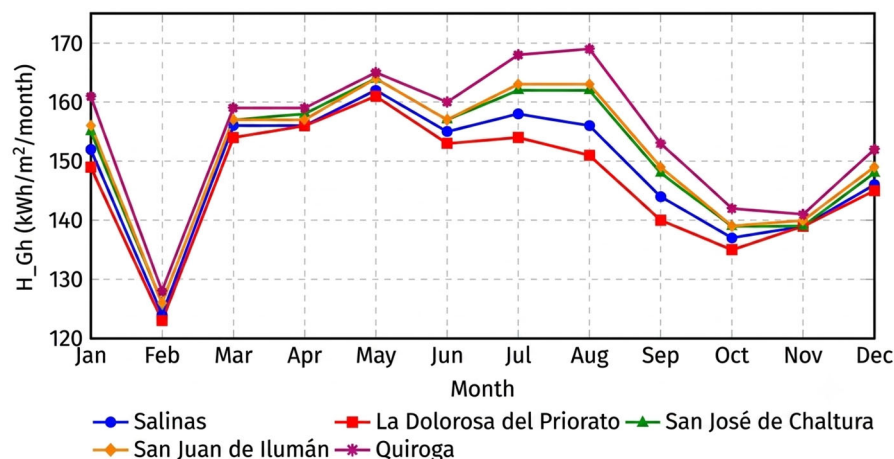


Figure 12. Monthly comparison of global horizontal irradiation (H_{Gh}) for priority parishes in the Ambi River basin.

4. Conclusions

The Ambi River basin demonstrated high hydroclimatic seasonality, with maximum flows occurring during the rainy season and minimum flows during the dry season. This finding serves to confirm the hypothesis that the availability of water for the evaluated run-of-river hydroelectric plants is controlled by the temporal variability of the hydrological regime. In this context, the water supply cannot be considered constant; rather, it is a resource strongly influenced by the intra-annual distribution of pressure and flow.

The utilisation of the duration curve for the characterisation of flow rates facilitated the establishment of a consistent technical basis for the system evaluation, thereby emphasising $Q_{50} = 4.29 \text{ m}^3/\text{s}$ as a design flow rate that is representative of the average condition of the Ambi River. This proved to be a pivotal factor in avoiding two main issues. Firstly, it ensured that the flow did not exceed the capacity during periods of high, short-duration selection flows. Secondly, it ensured that the flow did not fall below the capacity during periods of extreme low-flow conditions. This provided a robust hydrological criterion for the hydropower analysis.

The incorporation of the ecological flow concept demonstrates that gross water availability is not equivalent to effective availability for generation. The estimation of ecological thresholds was based on an average annual flow of $4.71 \text{ m}^3/\text{s}$. Thresholds of $0.471 \text{ m}^3/\text{s}$ were thus estimated for the dry season, and $1.413 \text{ m}^3/\text{s}$ for the rainy season. The analysis of current conditions showed peak generation to be between 1.62 MW and 1.92 MW, with monthly energy outputs ranging from 1.2 GWh to 1.4 GWh in the months of highest availability. In accordance with the LSTM scenario, future flows were projected to range between $0.9 \text{ m}^3/\text{s}$ and $9.60 \text{ m}^3/\text{s}$. This finding indicates that hydrological variability will persist in dictating the usable flow and, consequently, the hydroelectric performance of the system. The results of this study demonstrate that the planning of small run-of-river hydroelectric plants in Andean basins should be based on an integrated approach. This approach should consider the availability of ecological flow, effective water resources, and the resource under operational sustainability, and environmental criteria.

The hydrological assessment indicates that future climate conditions may substantially affect water availability, environmental flows, and hydropower generation within the Ambi River basin. These findings underscore the necessity of incorporating considerations pertaining to climate change into long-term water and energy planning. Conducted as a complementary assessment, the photovoltaic suitability analysis identified several areas with favourable solar resource conditions. While the exploratory analysis does not impact the hydrological results presented in this study, it suggests potential opportunities for future

diversification of Ecuador's energy mix through the integration of additional renewable energy sources.

The assessment of potential operational disruptions associated with extreme reception events, hydraulic safety conditions linked to flooding and to explicit uncertainty analysis in LSTM-based hydrological projections, will be addressed in future work, to complement hydropower planning under operational resilience criteria.

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Abbreviations

DEM	Digital Elevation Model
GIS	Geographic Information System
HEC-HSM	Hydrologic Engineering Center–Hydrologic Modeling System
IHA	Indicators of Hydrologic Alteration
IIHA	Improved Indicators of Hydrological Alteration
INAMHI	Instituto Nacional de Meteorología e Hidrología
LSTM	Long Short-Term Memory
NASA POWER	National Aeronautics and Space Administration Prediction of Worldwide Energy Resources
NSE	Nash–Sutcliffe Efficiency
PBIAS	Percent Bias
Q20	Flow Exceeded 20% of the Time
Q50	Flow Exceeded 50% of the Time
Q95	Flow Exceeded 95% of the Time
SWAT	Soil and Water Assessment Tool
WEAP	Water Evaluation and Planning System

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