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Articles

Decision support system for the hydrological management of the Guayas River

Sistema de ayuda a la decisión para la gestión hidrológica del río Guayas

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Abstract

The Guayas River basin in Ecuador is the largest on the Pacific slope of South America, with an area of 34 500 km^2 (12.57 % of the national territory). Within the basin, the Daule-Peripa reservoir constitutes the largest water reserve in the country, guaranteeing water for the consumption of more than eight million people, in addition to irrigation and hydroelectric generation. A Hydrological Decision Support System (SHAD) has been developed to efficiently manage water resources in the Guayas river basin, improve the energy production of hydroelectric plants and provide early warning of floods downstream of the plants. SHAD integrates a real-time data acquisition module, with the hydrological model of tanks in charge of estimating the inflows to the reservoirs on an hourly scale, and the control module on which the managers interact. The hydrological model has been calibrated separately for the Daule-Peripa and Baba basins with hourly data from the period 2019-2021. For the Baba basin, the Nash-Sutcliffe coefficient for validation at daily and hourly scales were 0.77 and 0.71, respectively, as well as 0.62 and 0.49 for Daule-Peripa. The preliminary comparative analysis of the management of the water resources of the basin, carried out since the commissioning of SHAD shows evidence of significant improvements.

Keywords: Guayas River, hydrological decision support system, basin management, hydrological model, real-time data, flood.

Resumen

La cuenca del río Guayas en Ecuador es la más grande en la vertiente Pacífico de Suramérica, con un área de 34 500 km^2 (12.57 % del territorio nacional). Dentro de la cuenca, el embalse Daule-Peripa constituye la mayor reserva de agua del país, garantizando agua para consumo de más de ocho millones de personas, además de riego y generación hidroeléctrica. Se ha desarrollado un Sistema Hidrológico de Ayuda a la Decisión (SHAD) para gestionar eficientemente los recursos hídricos en la cuenca del río Guayas, mejorar la producción energética de las centrales hidroeléctricas y alertar tempranamente de inundaciones aguas abajo de las centrales. El SHAD integra un módulo de adquisición de datos en tiempo real, con el modelo hidrológico de tanques encargado de estimar los ingresos a los embalses en escala horaria, y el módulo de control sobre el que interaccionan los gestores. El modelo hidrológico se ha calibrado separadamente para las cuencas Daule-Peripa y Baba con datos horarios del periodo 2019-2021. Para la cuenca de Baba, el coeficiente Nash-Sutcliffe para la validación a escala diaria y horaria fue 0.77 y 0.71, respectivamente, así como 0.62 y 0.49 para Daule-Peripa. El análisis preliminar comparativo de la gestión de los recursos hídricos de la cuenca realizada desde la puesta en operación del SHAD muestra evidencias de mejoras significativas.

Palabras clave: río Guayas, sistema hidrológico de ayuda a la decisión, gestión cuenca, modelo hidrológico, datos en tiempo real, inundación.

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Introduction

The Ecuadorian hydroelectric sector is a strategic pillar for the economic and social development of the country. According to data from the National Electricity Operator (Cenace, 2022), the electric energy production in Ecuador in 2021 was 27,659 GWh, of which 92.0% was of hydroelectric origin. This sector faces various challenges related to meteorological and climatic variability, with the El Niño Southern Oscillation being the phenomenon that has the most significant influence on precipitation and available flows in the different regions of Ecuador (Bendix, Gämmerler, Reudenbach, & Bendix, 2003; Recalde-Coronel, Barnston, & Muñoz, 2014), especially in the coastal region (De Guenni *et al*., 2017). In addition to the usual historical challenges, there are new challenges such as the growing demand in consumption (Cenace, 2022) or its vulnerability to climate change (Paz *et al*., 2019).

In the case of the Daule-Peripa (the largest water reserve in Ecuador) and Baba reservoirs and their respective hydroelectric plants Marcel Laniado de Wind and Baba, the main problem in managing the water resource is maximizing energy production while guaranteeing the water supply for over 8 million people and irrigation water in the provinces of Guayas, Manabí, Los Ríos, and Santa Elena. The Daule-Peripa reservoir is a crucial part of the most important hydraulic system on the Ecuadorian coast, which also includes the aforementioned reservoirs, the La Esperanza and Poza Honda Dams, the transfer system and reservoirs of the province of Santa Elena, and the Daule-Vinces transfer (Figure 2 and Figure 3).

In addition to guaranteeing the water resource and hydroelectric generation, the Daule-Peripa and Baba reservoirs are fundamental for controlling or mitigating floods downstream of the reservoirs in the Daule and Quevedo rivers, respectively. Consequently, optimizing the operation of the reservoirs and hydroelectric plants involves multiple water demands both in the Guayas basin and outside it, energy demands within the National Interconnected System, and other functions such as controlling floods downstream, all of this along with meteorology and climate highly dependent on various oceanic and atmospheric variables with a significant influence from the El Niño phenomenon (De Guenni *et al.*, 2017). This is a complex system where access to quality hydrometeorological information in real-time represents a significant advance for the optimal management of the reservoirs.

The SHAD (Sistema Hidrológico de Ayuda a la Decisión, for its acronym in Spanish) developed in this study has multiple objectives, focused on maximizing the use of available data sets. This data comes from both the internal bases of the hydroelectric plants and from external sources, including meteorological models. The integration of this information aims to provide useful real-time data that can be applied in the operation of hydroelectric plants and drainage bodies.

The specific objectives of the SHAD are:

- Optimization of Water Resource Management in the Guayas River Basin: The SHAD is designed to enhance water resource management, thereby contributing to more sustainable water usage in the basin.
- Early detection and mitigation of flooding events: The system aims to minimize risks associated with floods downstream of the hydroelectric plants, providing tools for early detection and response.
- Optimization of energy production in hydroelectric plants: Through the integration and real-time analysis of data, and by operating the plants more efficiently, energy production is increased.

In general terms, a Decision Support System (DSS) is a computational infrastructure designed to assist in decision-making activities. This system facilitates the judgment process of decision-makers without actually making the decision itself (Hersh, 1999). Its development involves various disciplines, including computer science, statistics, psychology, and decision theory (Mysiak, Giupponi, & Rosato, 2005).

Since the late 1970s, there has been considerable development in the implementation of DSSs in water resource management (Johnson, 1986). This growth has accelerated to date due both to improvements in understanding the processes involved in hydrological and meteorological cycles, as well as significant advances in computing, sensor technology, and communications. Additionally, the growing urgency caused by the effects of climate change on water availability has intensified the need for such systems. These evolutions have expanded both data availability and computing capacity, currently offering various tools and options for their development (Wardropper & Brookfield, 2022). An essential component of DSSs in water resource management is hydrological models. Among other uses, these models allow for the early detection of flood events by transforming precipitation data into water flows (Smith *et al*., 2016).

One of the main challenges in managing water resources is reconciling the availability of stored water with flood protection, where under normal conditions, there is usually a conflict (Ahmad, El-Shafie, Razali, & Mohamad, 2014). The optimization of both will depend on the ability to anticipate inflow rates into reservoirs before they occur.

The available surface flow will be determined by the hydrological cycle and its different components; in summary, it will be the precipitation that neither infiltrates the soil nor evaporates, and flows through slopes, streams, rivers, lakes, or reservoirs (Sitterson *et al*., 2018).

One of the main reasons for developing hydrological models is to extrapolate measured hydrometeorological data into the future and thus assess the impact of future hydrological change (Beven, 2011). Based solely on the measurement of meteorological variables up to the present moment, the future prediction frontier for surface runoff will be the basin's concentration time, with the model's predictive capacity being maximum for the present moment and minimum at the end of the concentration time, where only subsurface and deep flows will be reflected (Chow, 1964).

The development of weather models in the last two decades means that a 5-day forecast is now as accurate as a 1-day forecast from 1980, with useful forecasts now reaching 9 or 10 days (Alley, Emanuel, & Zhang, 2019). Seasonal forecasts have also improved, primarily through the incorporation of oceanic models.

Weather prediction using numerical models is based on the ability of an adequate representation of initial conditions along with adequate capacity to model the different interactions that occur in the different layers of the atmosphere, land, and oceans and the interconnections between them. This requires a large amount of resources for monitoring the atmosphere, oceans, and land, a significant scientific community dedicated to the study and numerical modeling of the various ocean-land-atmosphere interactions, and a large computing capacity for calculating these complex systems (Mariotti, Ruti, & Rixen, 2018). Great advances have been made in the accuracy of forecasts, mainly from numerical prediction centers that have had numerous monitoring, development, and computing resources, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Oceanic and Atmospheric Administration (NOAA). The easy access and spatial and temporal homogeneity of these models have favored their use in hydrological modeling (Raimonet *et al*., 2017).

The process of modeling flows from rain and other meteorological variables is a process that involves various phases, starting with the perceptual model of the hydrologist in charge of its development, which will depend on their training and previous experiences, as well as their perception of the behavior of the basins to be modeled. From this perceptual model, the conceptual model or equations to be used will be decided, which will give way to the procedural model or code to run the model on a computer. With the developed model, it will be calibrated and then validated if appropriate, or if not, the previous steps will be reviewed

(Beven, 2011). The whole process will be determined by many factors interacting with each other, such as: input meteorological variables and physical characterization of the basin, the objectives of the model that will determine the need for spatial and temporal accuracy of its output, the algorithms used for its calibration, or the computing capacity and expected response times.

The integration of real-time weather forecasts with hydrological models specifically developed to optimize the exploitation of hydroelectric resources is a fundamental part of the implementation of a Hydrological Decision Support System (SHAD), designed to collect, process, model, and present hydrometeorological data aimed at improving the operation of the Daule-Peripa and Baba reservoirs and Marcel Laniado de Wind and Baba hydroelectric plants within the water system of the Guayas river basin and its transfers.

This paper describes the tool developed and the results obtained both in relation to the behavior of the hydrological models and the improvement in the management of reservoirs and hydroelectric plants.

Materials and methods

The options available for implementing the system are numerous, with multiple interactions and incompatibilities among different options; type of hydrological model, equations used, statistics used for calibration and validation, use of commercial applications versus in-house development, type of graphic application, incorporation of databases, incorporation of weather forecasts, interaction between different modules and databases, etc. Therefore, the adopted solution has been adjusted to ensure the system's proper functioning and the capability for future developments.

As a final solution, the Hydrological Decision Support System has been programmed entirely in Python (Rossum, 1995) and mainly consists of three components/modules that automatically run according to the following scheme in Figure 1.

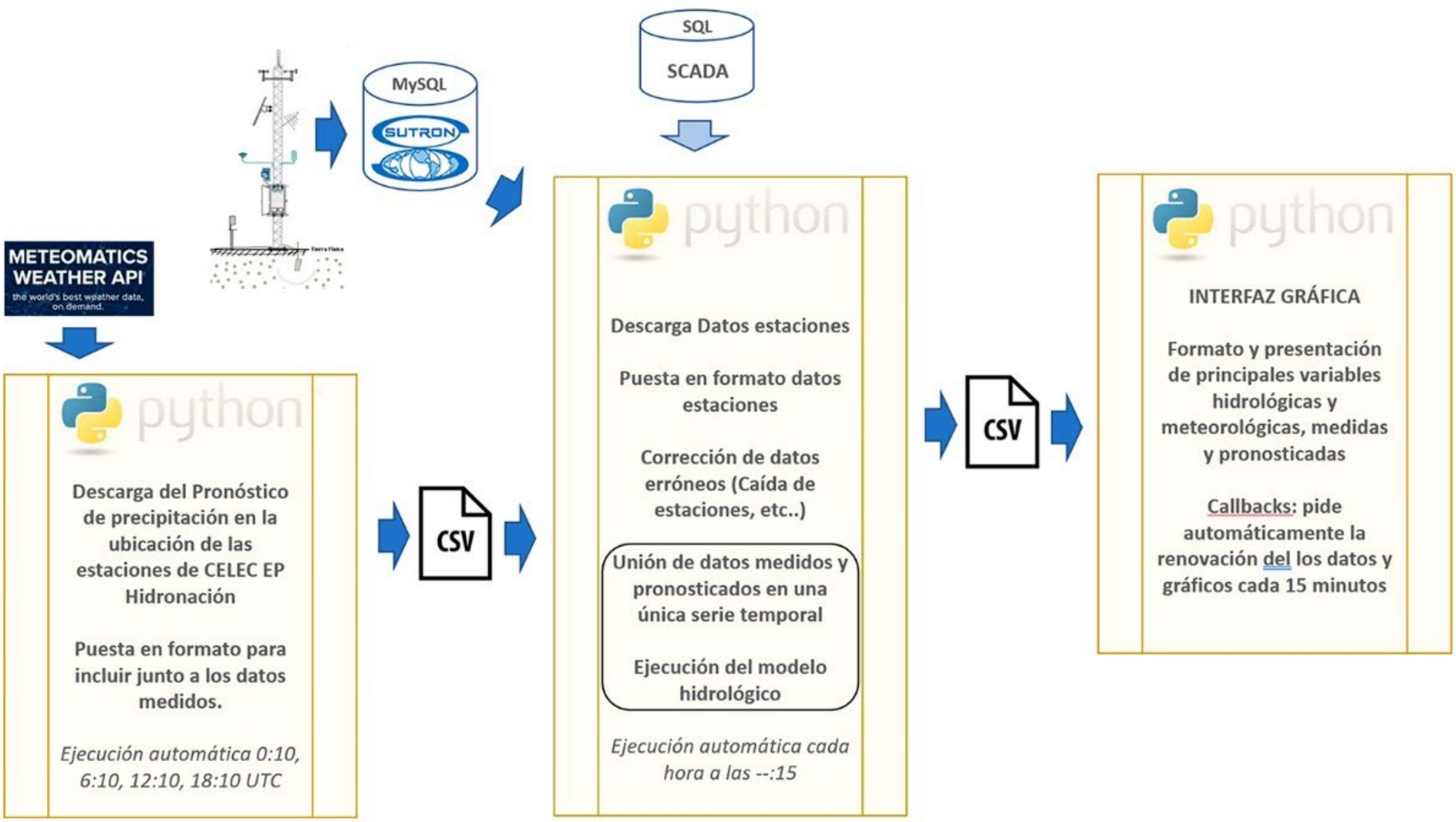

Figure 1. Operation scheme of the SHAD.

The first component/module performs the download and formatting of point precipitation forecasts at the available pluviometric stations.

As a result of this component/module, a file is created that includes forecasts on an hourly scale and local time.

The next component/module, executed hourly once the data from the meteorological stations are received, performs the following functions:

- Incorporates data from different sources: .csv file output from the first code, MySQL database from meteorological stations, and SQL database from the SCADA.
- Corrects erroneous data from down meteorological stations.
- Performs the union of measured and forecasted data in a single time series.
- Executes the hydrological model and obtains the expected inflow rates in the reservoirs. This component/module is run three times for each plant, for the different meteorological precipitation models used (MIX, ECMWF-Ensemble quantile 0.1, and ECMWF-Ensemble quantile 0.9), obtaining the inflow rates in the Daule-Peripa and Baba reservoirs. As a result, another file is created with the output of the hydrological model for each of the meteorological models used.

The third component/module is the graphical interface that reads the output of the second code, formatting and graphically representing the main registered and forecasted hydrometeorological variables upstream and downstream of the plants. An interface is available for the operation of Daule-Peripa and another for Baba.

Study area

The Guayas River basin is the largest hydrographic basin on the Pacific coast of South America, covering an area of 34 500 km^2 and playing a crucial role in supplying water for human consumption and irrigation to more than eight million people and 300 000 hectares of crops in the provinces of Guayas, Manabí, Los Ríos, and Santa Elena. This supply is carried out through different transfers: Conguillo - La Esperanza transfer, La Esperanza-Poza Honda transfer, Daule Vinces transfer, and Santa Elena transfer. Figure 2 includes a scheme of the main hydraulic installations.

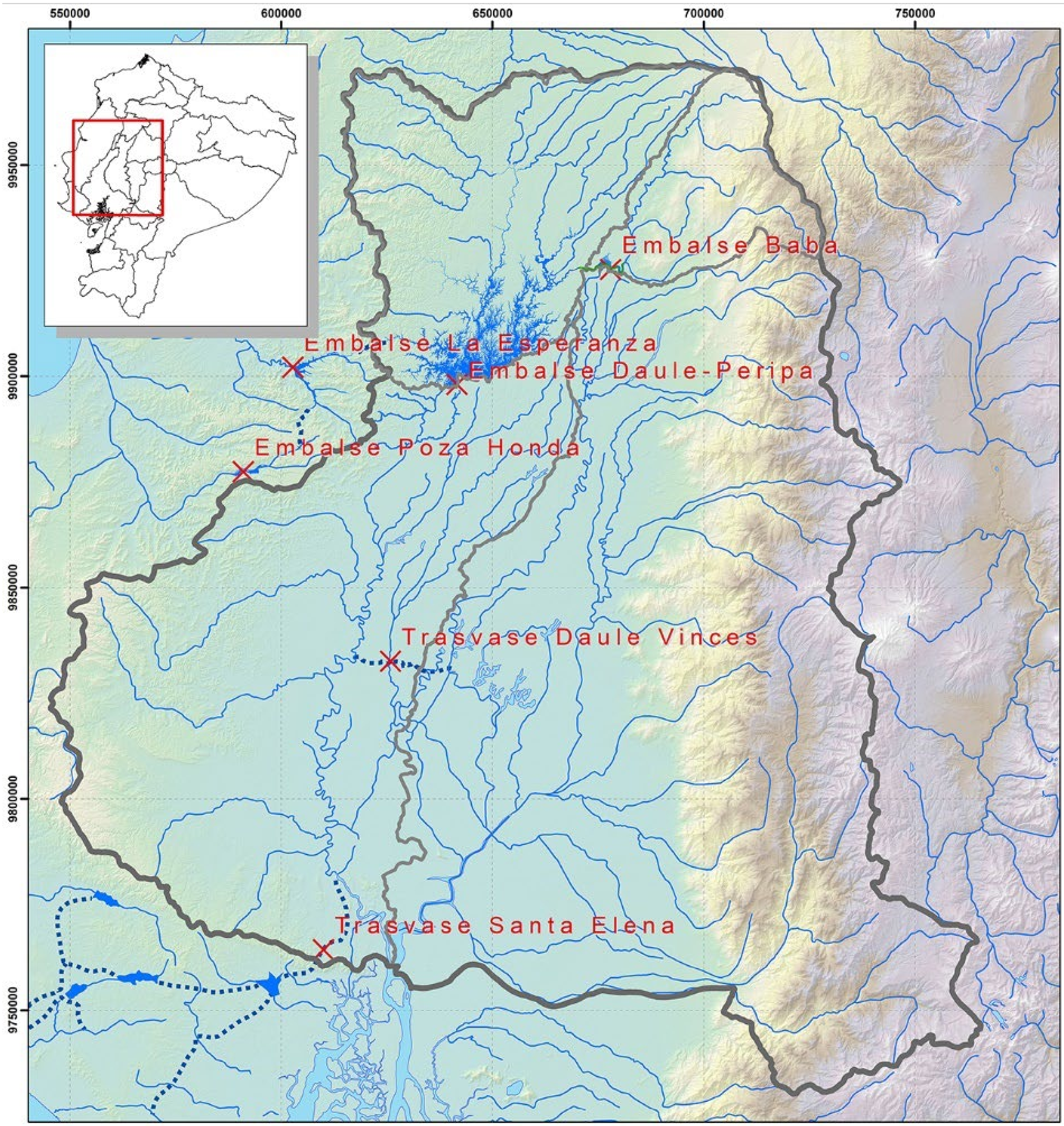

Figure 2. Main reservoirs and transfers in the Guayas River basin.

CELEC EP HIDRONACIÓN operates and maintains the Marcel Laniado de Wind and Baba hydroelectric power stations, located in the Daule-Peripa and Baba reservoirs, respectively, both situated in the Guayas River basin (Figure 3).

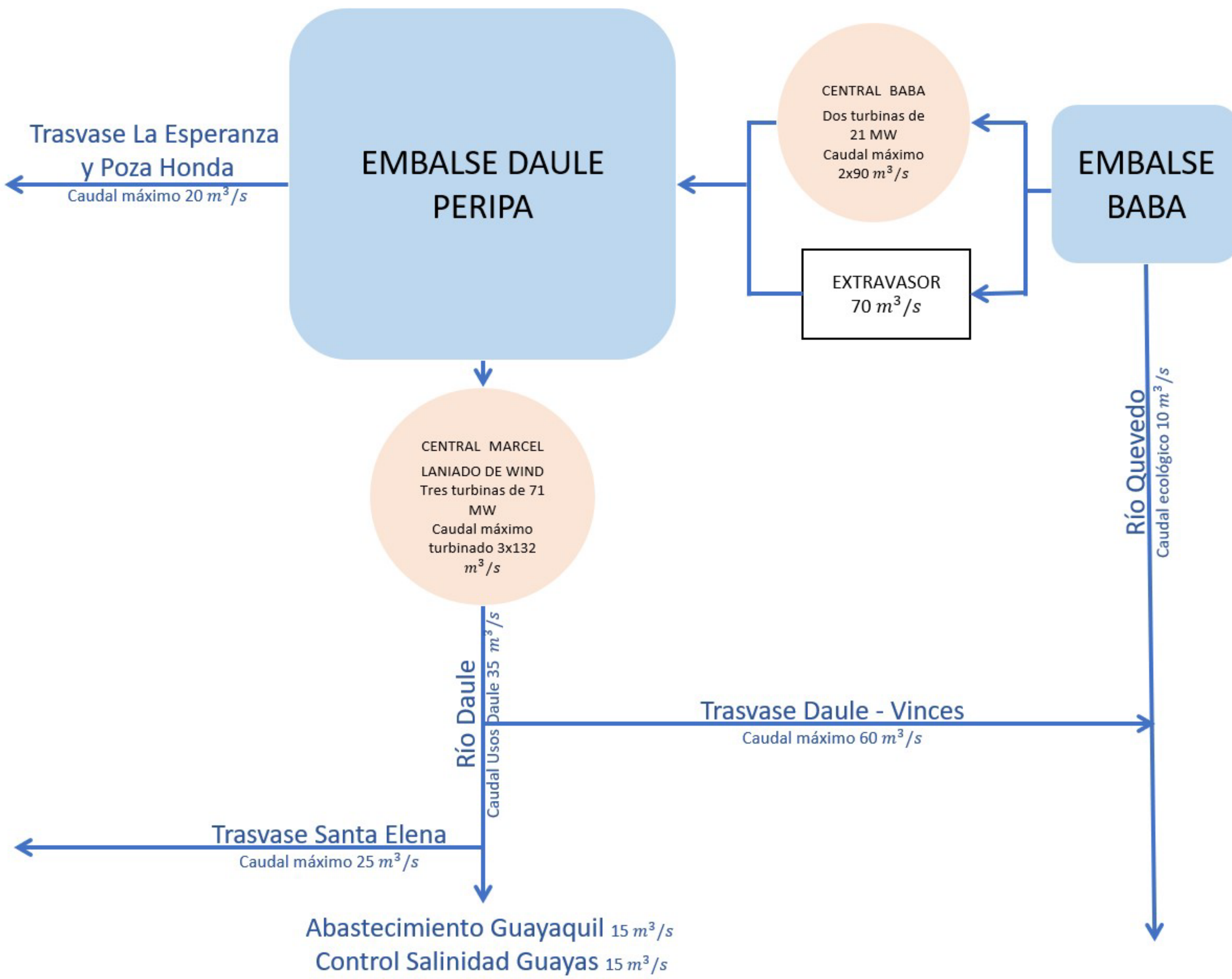

Figure 3. Scheme of maximum demands and hydraulic installations in the Guayas river basin (Ecuador).

The Guayas basin and, generally, the coastal area of Ecuador have a unimodal precipitation regime with a maximum precipitation in the months of February-March and a dry period with minimal precipitation between the months of August-September (Hidalgo-Proaño, 2017). The historical average (1965-2017) of annual precipitation in the Guayas basin is 1932 mm/year, having doubled in years with the East Niño (Wang, Deser, Yu, DiNezio, & Clement, 2012).

The Daule-Peripa reservoir, with a maximum normal capacity of 5 200 Hm^3 and a flooding area for this level of 264 km^2, is Ecuador's main water reserve, guaranteeing access to water resources on the coast during the dry season (July to December). Its main functions are:

- Supplying water for consumption to the provinces of Guayas, Manabí, Los Ríos, and Santa Elena, and water for irrigation.
- Supplying water for irrigation to the province of Los Ríos through the Daule Vinces transfer (2016) and to the province of Santa Elena through the Santa Elena transfer.
- Controlling flooding in populations downstream of the reservoir.
- Controlling saline intrusion in the Guayas River.
- Hydroelectric Generation, through three turbines of 71 MW each, approximately 1 015 GWh/year, being the country's second most important energy reserve.

The Baba reservoir, with a maximum capacity of 100 cubic hectometers, has become a fundamental element for capturing water towards the Daule-Peripa reservoir since it began operations in 2013, through the transfer of water from the Quevedo River basin to said reservoir. Its main functions are:

- Contributing to the filling of the Daule-Peripa reservoir, through the transfer of water from the Quevedo River.
- Mitigation of rising levels by transferring up to 250 m^3/s to the Daule-Peripa basin.
- Hydroelectric Generation, through two turbines of 21 MW each, with an average annual production of 150 GWh/year.

Available information

Hydrometeorological network

The real-time recording of meteorological and hydrological conditions is facilitated by a network of 25 hydrometeorological stations spread across the basins flowing into and downstream of the reservoirs, with precipitation measurements taken at all 25 locations. Water levels in rivers and reservoirs are measured at 7 of them, and 6 have comprehensive weather stations (measuring temperature, wind, radiation, barometric pressure, and humidity) (Figure 4).

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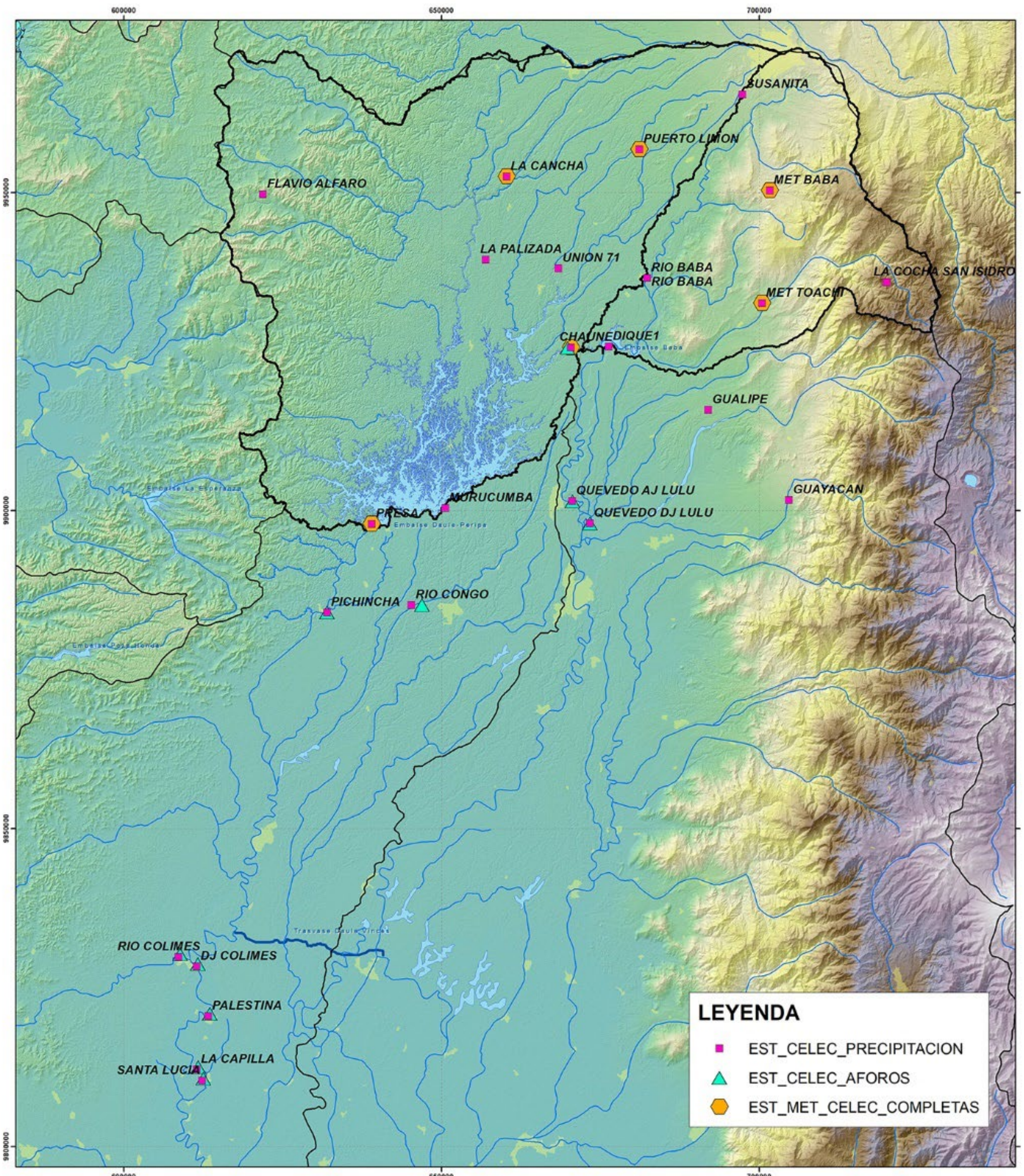

Figure 4. Network of hydrometeorological stations operated by CELEC EP Hidronación.

Different stations communicate via radio with the central station located at the Daule-Peripa Dam. Although the temporal resolution of the data varies between 5 and 30 minutes depending on the sensor type, the data are sent to the base station hourly. This information is integrated into a MySQL database using SUTRON software.

SCADA Integration Database

Concurrently with the development of the SHAD, integration of various data sources from different manufacturers, located on networks scattered throughout the hydroelectric plants, has been performed on a single server (Perez-Suarez & Cedeño-Villarroel, 2021).

The different data to be integrated include:

- **Gross generation**: The gross generation meters of the three units are monitored by the Marcel Laniado de Wind Central SCADA system, and their data will be accessed using the OPC server.
- **Discharge level**: This is monitored by the SCADA system of the Marcel Laniado de Wind Central, and its data will be accessed using the OPC server.
- **Reservoir level**: The reservoir level is monitored in the SUTRON meteorology system, and communication is established with the BDD to access it. Since the information stored in the database has a delay of at least 10 minutes, the option of connecting directly to the Meteorological Network is considered, using an analog-to-

ModbusOnTcp converter to obtain the reservoir level data in real-time, i.e., directly from the sensor.

- **Net generation**: This is obtained directly from the ION energy meters via Modbus, consuming data directly from the device.

Upon integrating the various systems present in the CELEC EP Hidronación plants, the need to share data from an SQL-type database became evident, facilitating access to the flow data required for SHAD operation.

Meteorological forecasts

To enhance the predictive capacity of the hydrological model for future flows and to have reliable predictions beyond the basins' time of concentration, the incorporation of meteorological forecasts into the system, mainly precipitation, has been deemed advisable. Various options have been evaluated for this, considering the reliability of the models as well as their spatial and temporal resolution, which in turn has influenced the hydrological model ultimately adopted.

To have the maximum temporal resolution of hydrological models with the greatest future forecast range, the MIX model provided by METEOMATICS will be used. The Mix model uses, for the first 10 days, the ECMWF model developed by the European Centre for Medium-Range Weather Forecasts (Persson, 2001) with a temporal resolution of 1 hour (up to the 2nd day), 3 hours (up to the 6th day), and 6 hours (up to the 10th day). From the 10th day onwards, the NCEP model developed by the NOAA (Saha *et al*., 2006) is used up to the 14th day; after the 14th day, the ECMWF is used again, which has a range of 46 days with a temporal resolution of 6 hours. From this model, precipitation will be downloaded with hourly resolution, in addition to temperature and solar radiation flow (direct + diffuse) in W/m^2.

Efficient management of reservoir operation is crucially dependent on both the expected income and its uncertainty (expected maximum and minimum flow). For this, along with the modeling of future precipitation, the modeling of the ECMWF-Ensemble meteorological model (Molteni, Buizza, Palmer, & Petroliagis, 1996) will also be carried out, which, unlike the ECMWF-IFS (deterministic) model, is a probabilistic model composed of 50 members (50 different modelings) with slight differences in the initial conditions. By incorporating quantiles 0.1 and 0.9 of this model into the system, the estimation of uncertainty in flow forecasts is improved, thus being able to hydrologically model the expected inflow flows for different probabilities (Dion, Martel, & Arsenault, 2021) (Figure 5).

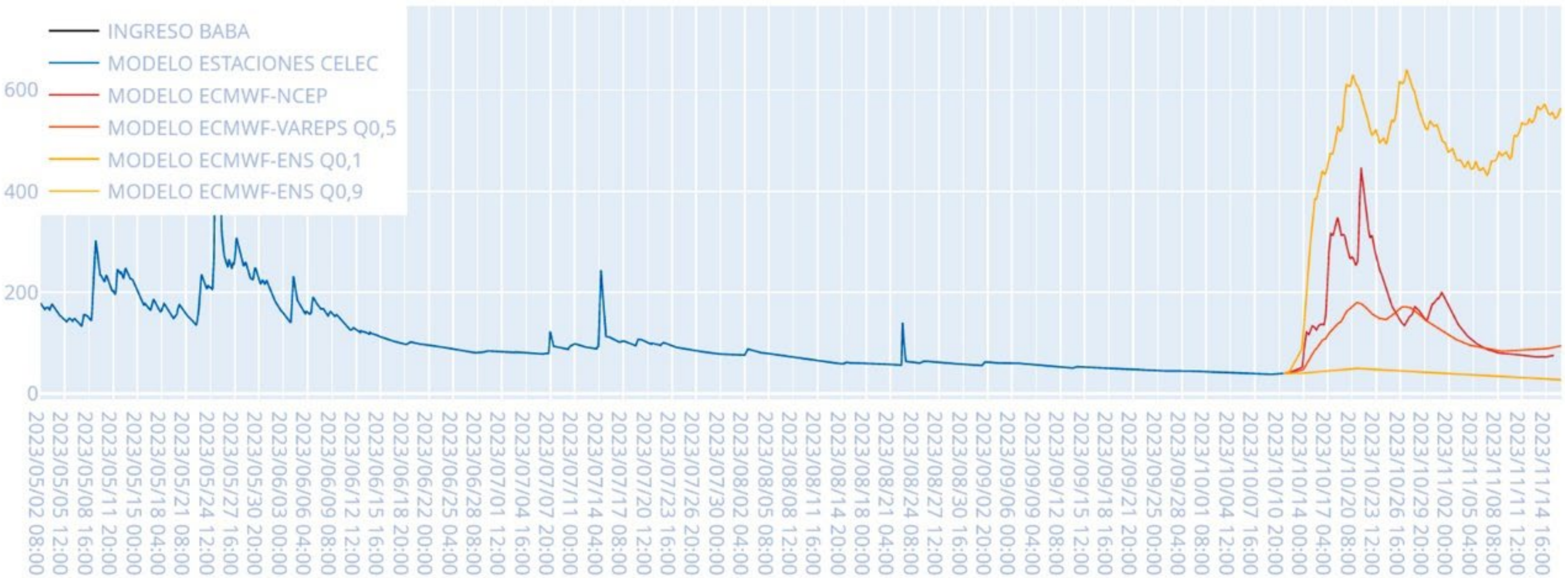

Figure 5. Output in SHAD of hydrological models of income to the Baba reservoir in m3/s. Estimation up to the present through the station network and in the future through the incorporation of MIX and ECMWF Ensemble models, quantiles 0.1 and 0.9.

Precipitation-runoff Model

Standard components of a hydrological model include inputs, boundary conditions, parameters, model equations, and outputs. Models can be classified in various ways (Jajarmizadeh, Harun, & Salarpour, 2012) depending on their structure, such as abstract or mathematical and physically-based (Chow, 1964). Mathematical models can further be divided into black-box or empirical models, which establish the relationship between inputs and outputs without trying to understand the various physical processes occurring in the hydrological cycle, e.g., the Curve Number method (Bosznay, 1989) or models based on artificial neural networks (Dawson & Wilby, 2001). On the other hand, there are conceptual and deterministic or physical models which, more or less simplistically, try to represent the physical processes occurring in the basin.

Based on spatial variability, they can also be classified as aggregate, semi-distributed, and distributed.

A semi-distributed, physically-based conceptual model was chosen for the problem at hand since this type of approach enhances its adjustment capacity in different types of basins with varying densities of pluviometric stations, in addition to reducing the model's calculation and calibration times (Knudsen, Thomsen, & Refsgaard, 1986).

Furthermore, due to the characteristics of the study area, it was a significant requirement to have a model of high temporal resolution.

This model must perform well in high flows beyond the range of calibration or training data, so black-box type models, like those based on artificial neural networks, will be discarded due to the risk of overfitting these models (Kingston, Maier, & Lambert, 2005).

Two models were developed and calibrated for the basins feeding the Daule-Peripa and Baba reservoirs. Although the code used in both cases will be the same, the number of sub-basins and river sections used for each will differ and will be included in the calculation via an external file to the model containing the particular data of each sub-basin.

The sub-basins have been drawn up based on the topographical characteristics of the basins and the available pluviometric stations, so that the model can adequately evaluate the spatial distribution of precipitation captured by the stations. For the Baba basin, 7 sub-basins

(Table 1) and for the Daule-Peripa basin, 10 sub-basins (Table 2) are considered.

Table 1. Characteristics of the sub-basins considered in the hydrological income model to the Baba reservoir.

Sub-basin	C_B_01	C_B_02	C_B_03	C_B_04	C_B_05	C_B_06	C_B_07
Area (km^2)	88.81	75.50	307.64	156.67	200.61	274.81	390.58
Weather transit river (h)	0.00	0.99	0.99	2.33	3.13	3.45	5.11
Weather Punta Cuenca (h)	12.22	11.12	12.34	8.52	20.15	10.78	14.90

Table 2. Characteristics of the sub-basins considered in the hydrological income model to the Daule-Peripa reservoir.

Sub-basin	C_DP 01	C_DP 02	C_DP 03	C_DP 04	C_DP 05	C_DP 06	C_DP 07	C_DP 08	C_DP 09	C_DP 10
Area (km^2)	402.11	374.32	78.11	379.75	273.31	145.35	297.40	1033.33	672.73	494.11
Weather transit river (h)	0.00	2.13	2.13	5.19	5.19	10.37	10.37	12.96	12.13	10.37
Weather Punta Cuenca (h)	0.55	3.07	2.60	5.24	5.54	10.27	10.59	12.63	11.90	10.36

Following, brief descriptions of the solutions adopted for the modeling of the different processes involved in transforming precipitation into runoff are presented.

Precipitation distribution

For the areal distribution of precipitation, the Thiessen coefficient method is employed (Rhynsburger, 1973). This method is deemed most suitable because it combines simplicity with adequate precipitation distribution, avoiding the underestimation effect of extreme values at points situated between stations (increasing minimums and decreasing maximums), which can occur with other straightforward interpolation methods like IDW, spline, or Kriging with poorer results for higher temporal resolutions (Dirks, Hay, Stow, & Harris, 1998), where antecedent moisture conditions are more critical.

This distribution (Figure 6) achieves an accurate representation of soil and vegetation moisture content, which is essential for a proper estimation of infiltration and evapotranspiration over short time intervals.

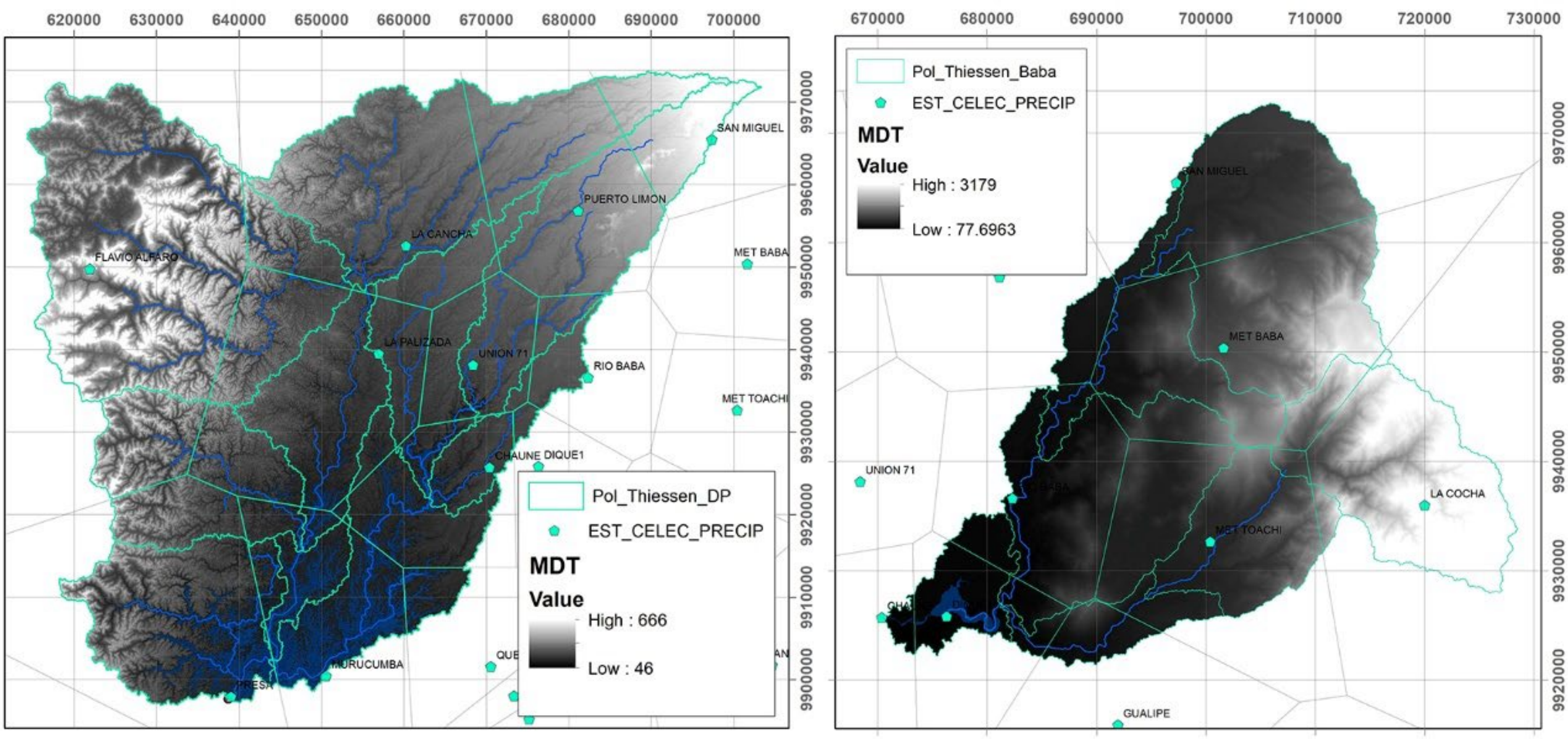

Figure 6. Thiessen Polygons for the sub-basins considered in the hydrological models of Daule-Peripa and Baba with a Digital Terrain Model (DTM) in meters above sea level (masl).

Potential evapotranspiration

Potential evaporation is calculated using the Thornthwaite method (Palmer & Havens, 1958), adapted for calculating the potential hourly evapotranspiration from the average hourly temperature:

$$ETP = 0.02192982 * \left(\frac{10 * T}{I}\right)^{a}$$

Where:

T = average hourly temperature in °C

$a = 675 * 10^{-9} * I^3 - 771 * 10^{-7} * I^2 + 1792 * 10^{-5} * I + 0.49239$

$I = Indice\ de\ calor\ anual\ Annual\ Heat\ Index = \sum_{month=1}^{month=12} \left(\frac{t}{5}\right)^{1.514}$

$t = historical\ average\ monthly\ temperature\ in\ °C$

For the calculation of potential evapotranspiration in the basins (Daule-Peripa and Baba), temperature data from three meteorological stations available in each basin are utilized, weighted by Thiessen coefficients. This weighted data will be applied to all sub-basins.

Tank model

A hydrological tank model has been developed to perform continuous simulation of the inflow rates into the Daule-Peripa and Baba reservoirs with hourly resolution. Tank models have proven their ability to represent flow rates in different types of basins, achieving high precision in predictions with low computational requirements (Kuok, Harun, & Chan, 2011). These models consist of sets of tanks with outputs to the channel or to other tanks (Suryoputro, Suhardjono, Soetopo, & Suhartanto, 2017), and depending on the complexity of the basin responses to precipitation, typically between 2 and 4 connected tanks are used (Song, Her, Park, & Kang, 2019). In the current model, three tanks have been used to represent water behavior in different soil layers, and one to represent water interception by vegetation (Figure 7).

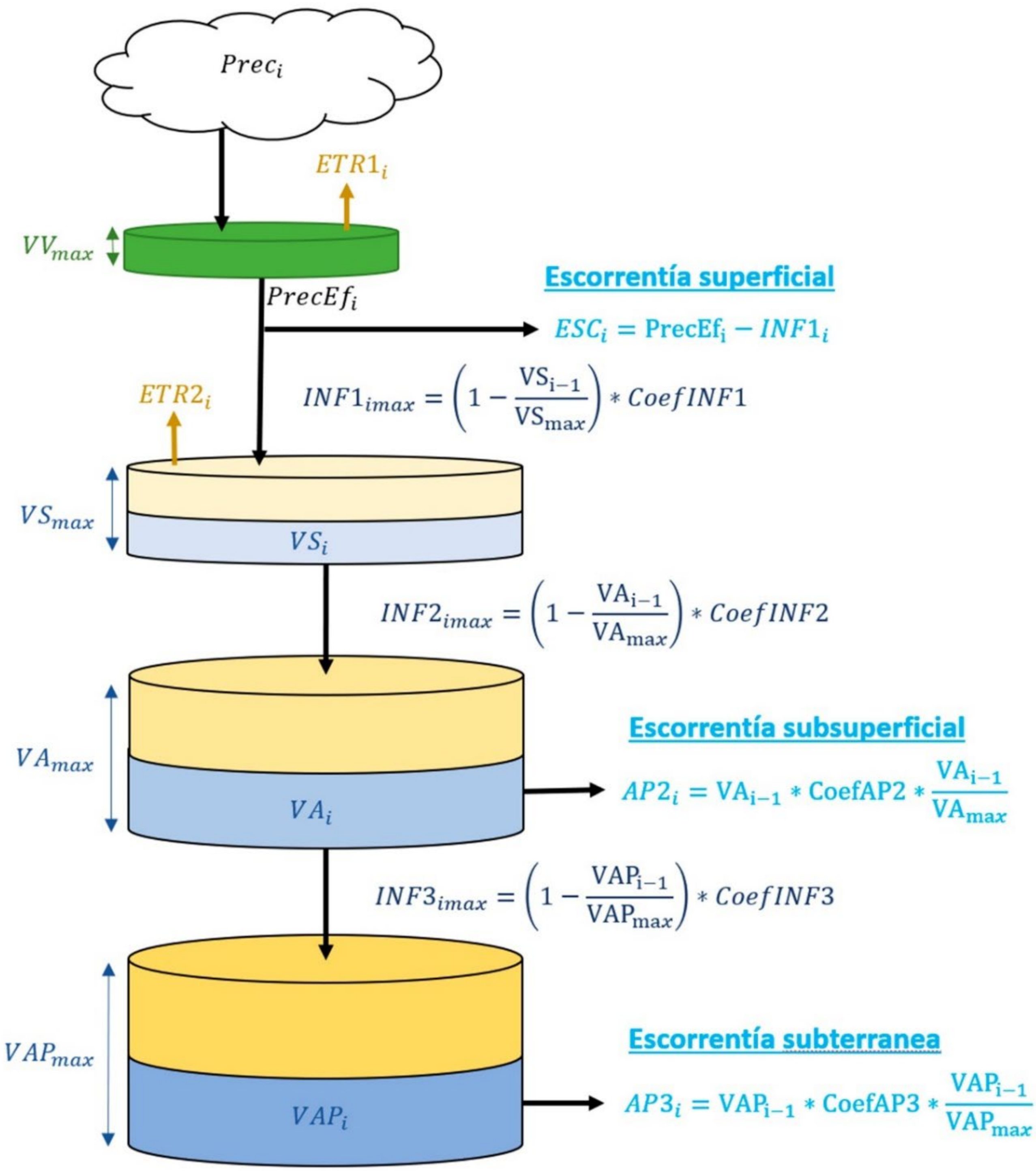

Figure 7. Model scheme used for transforming precipitation into runoff.

The first tank (*VV*) represents the interception of precipitation occurring in the vegetation. For each time interval, effective precipitation (*PrecEf*) will only occur through excess water over the tank volume (*VVmax*), taking into account for each time interval the initial volume, precipitation, and evapotranspiration (*ETR1*).

The next tank (*VS*) represents the soil's surface layer where the vegetation roots are located. Part or all of the effective precipitation will infiltrate (*INF1*), and the remainder will become surface runoff (*ESC*). Infiltration (INF1) will depend on the water volume available in this surface soil layer at the start of the calculated time interval. Evapotranspiration (*ETR2*) also occurs in this tank.

The third tank (*VA*) represents the subsurface flow throughout the basin; inputs are represented as INF2 and will depend on the water volume available at the start of the calculated time interval (*VAi*) and the water available in the previous tank (*VSi*). Outputs occur in the form of subsurface runoff according to linear discharge (AP2) and as infiltration (*INF3*) to the next tank (*VAP*).

The last tank (*VAP*) represents the deep aquifer where infiltration inputs from the previous tank (*INF3*) will depend on the water volume available in this deep aquifer at the start of the calculated time interval (*VAPi*). The output, considered as the base flow of the sub-basin (*AP3*), will be calculated based on the available water volume and the filling percentage.

Both basins have been calibrated at the closing point of the reservoirs through the water balance in these. The calibrated parameters are unique for all the sub-basins flowing to each reservoir, 7 in the case of Baba, and 10 in the case of Daule-Peripa.

Output hydrographs

The calculation of the output hydrograph in the sub-basins is carried out through the triangular unit hydrograph proposed by the Soil Conservation Service (Tschantz, n.d.), a solution widely used in hydrological modeling. The program calculates it based on the concentration time of each sub-basin, included in the external parameter file of each model.

Channel flow

For each sub-basin, the transit time of the channels to the reservoir (Works, 1995) has been calculated, which will be applied to the output hydrograph of the sub-basin.

In order to consider the lamination along the channel, the transit time along the channel, multiplied by a calibration coefficient, has been added to the Concentration Time of the synthetic hydrograph calculated for each basin (Figure 8).

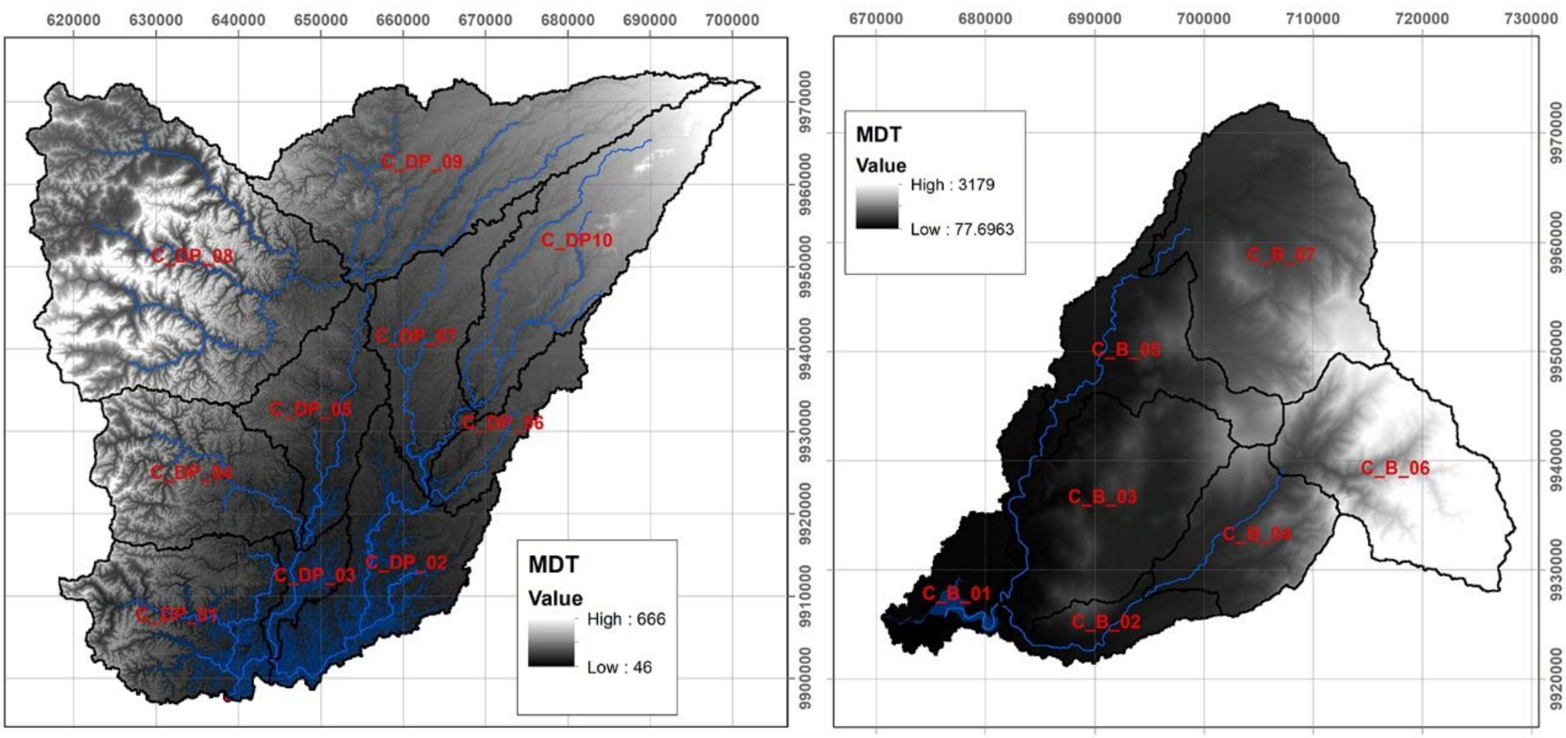

Figure 8. Sub-basins and river segments of the semi-distributed hydrological model applied in the Daule-Peripa and Baba basins with DEM (meters above sea level).

Graphical interface

The graphical interface has been designed to clearly display in real-time the main hydrological and meteorological parameters most important for hydroelectric generation and operation of the discharge mechanisms of the Power Plants operated by CELEC EP Hidronación, such as reservoir level, inputs from the hydrological model for different meteorological models (Figure 4), levels in the main watercourses downstream of the power plants, or precipitation recorded by meteorological stations (Figure

9 in blue) or forecasted with the highest resolution available in the ECMWF and NCEP meteorological models, Figure 9 in red. Precipitation is displayed for each basin, having already obtained the average using Thiessen polygons, or for each station separately in order to detect possible errors.

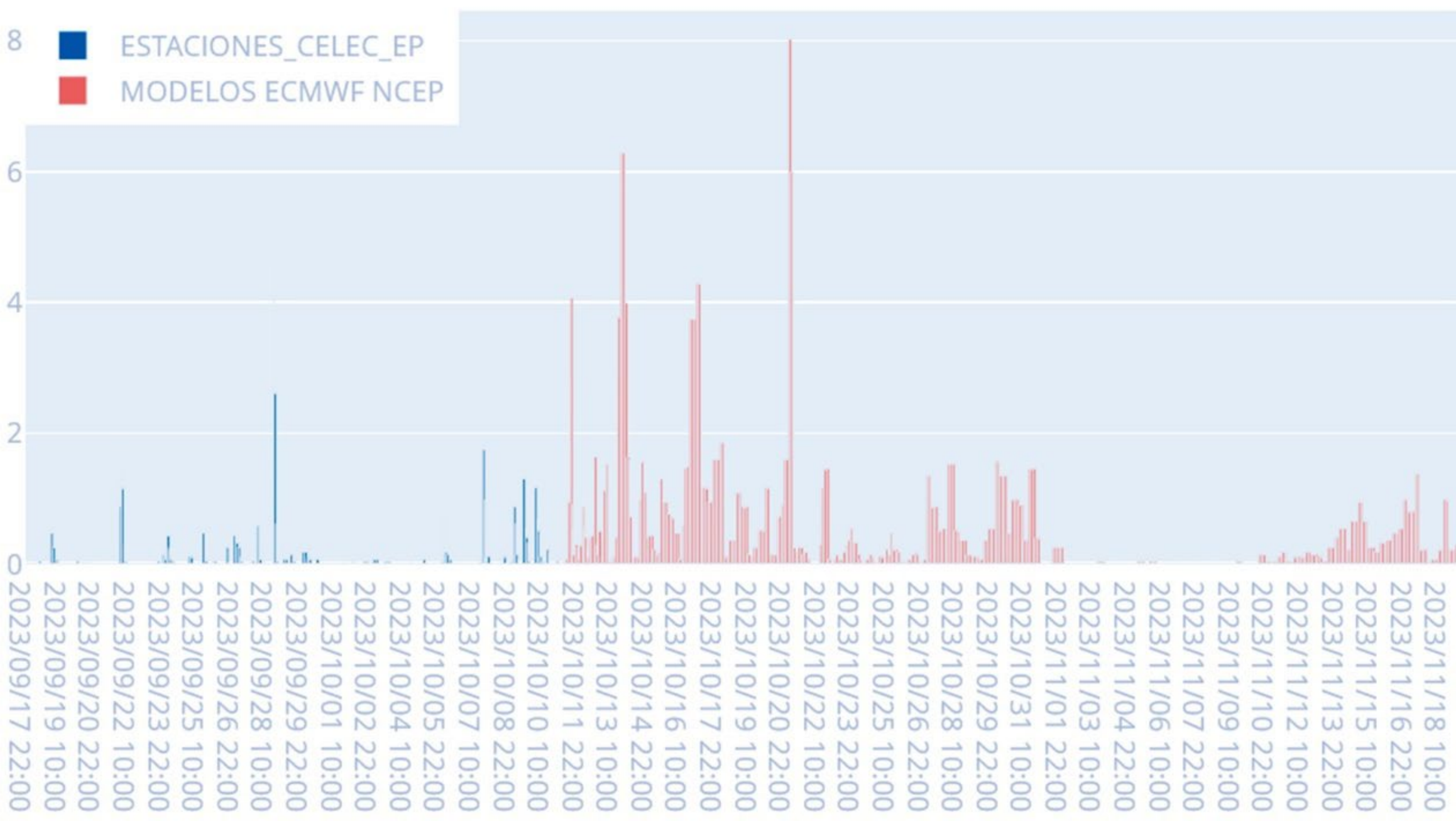

Figure 9. Example of graphical interface output made for the operation center of the Baba plant.

It has been programmed using the Dash library in Python, which allows sharing the interface via URL with several users, allowing each user to interact with the graphs independently since rendering is performed in the browser itself. The Dash library, through Callbacks, allows the automatic update of information in the browser and interaction between different graphs. In this way, continuous visualization of updated information is ensured without the need for the operator to refresh the screen.

Through interactivity with the graphs and the possibility of printing them, their analysis is facilitated and quick reports can be created under abnormal or sudden variation circumstances.

Results

Calibration and validation of the model

Initially, the calibration and validation periods were the same for the Daule-Peripa and Baba basins (October 11, 2020, to July 11, 2021, and November 27, 2019, to July 7, 2020, respectively). However, the validation results for the Daule-Peripa reservoir were not adequate. This was due to a very marked phenomenon of decreased precipitation that occurred in the year 2020 (Initial Validation) and was not as pronounced in the year 2019 (Initial Calibration). This phenomenon occurs due to the southward movement of the Intertropical Convergence Zone in Ecuador and is more marked depending on the year. Therefore, it was decided to calibrate the Daule-Peripa reservoir with the year 2019-20 and validate it with 2020-21.

The parameters obtained in the calibration process for all sub-basins are presented in Table 3.

Table 3. Calibrated parameters for the sub-basins contemplated in the hydrological model of inflows to the Baba and Daule-Peripa reservoirs.

Sub-basin	Baba	Daule-Peripa
VVmax	1.5	1.5
VSmax	6	6
VAmax	225	225
VAPmax	750	400
VV_0	0	0
VS_0	0	0
VA_0	0	0
VAP_0	4.76	10
CoefINF1	20	4.3
CoefINF2	18.5	29.7
CoefINF3	0.35	0.148
CoefAP2	0.013	0.009
CoefAP3	0.0022	0.0004

Calibration was carried out at the drainage point of both basins, on an hourly scale in both cases. Expertly, initial, minimum, and maximum values were set for all parameters. An exhaustive search algorithm was performed through which more than 100,000 simulations were carried out, initially with coarse adjustments of different groups of parameters simultaneously, to finally make adjustments through several groups of simulations of a single parameter repeatedly.

The Nash-Sutcliffe Efficiency Index (NSE) (Nash & Sutcliffe, 1970), was used as the objective function for the calibration and validation of the model, always seeking to maximize the objective function.

For the determination of the initial parameters corresponding to each sub-basin, geospatial information on topography, land uses, and soil types available has been used, which have subsequently been calibrated and validated (Results3). The Table 4 include the Nash-Sutcliffe Efficiency Index (Nash & Sutcliffe, 1970), along with other customary quality metrics.

Table 4. Calculation of hydrological model coefficients on an hourly scale.

Model	calibration-validation	Period	Correlation	Nash Sutcliffe	Mean Squared Error	Volume difference	Mean Flow Rate
Baba	Calibration	11 Oct 2020 a 11 Jul 2021	0.89	0.80	69.76	1.41%	177.33
	Validation	27 Nov 2019 a 7 Jul 2020	0.86	0.71	72.40	-5.87%	177.74
Daule-Peripa	Calibration	27 Nov 2019 a 7 Jul 2020	0.73	0.54	183.17	-0.26%	213.48
	Validation	11 Nov 2020 a 17 Jun 2021	0.72	0.49	285.27	-20.82	327.26

The Nash-Sutcliffe coefficient can vary in the range from -∞ to 1. A coefficient of 1 means a perfect fit between observed and simulated data; a coefficient of 0 means the model does not provide better predictions than the observed data themselves. The results obtained for the hourly calculation interval of the model are as follows (Table 4).

Below are included the calibration and validation graphs for the Baba reservoir, both conducted throughout the entire rainy season with the objective of obtaining a valid model for flow forecasting throughout the year, achieving a Nash-Sutcliffe coefficient of 0.80 for calibration (Figure 10) and 0.71 for validation (Figure 11).

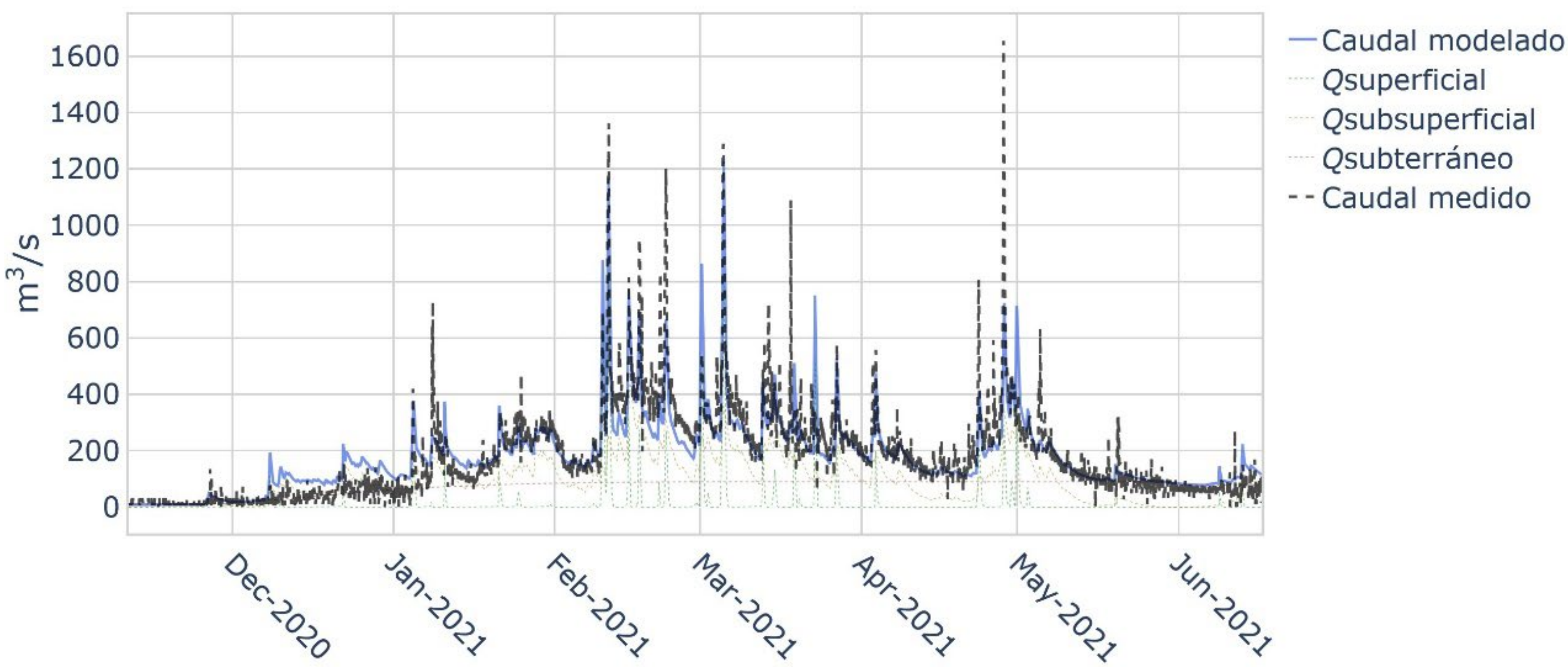

Figure 10. Model calibration results for inflow to the Baba reservoir on an hourly scale.

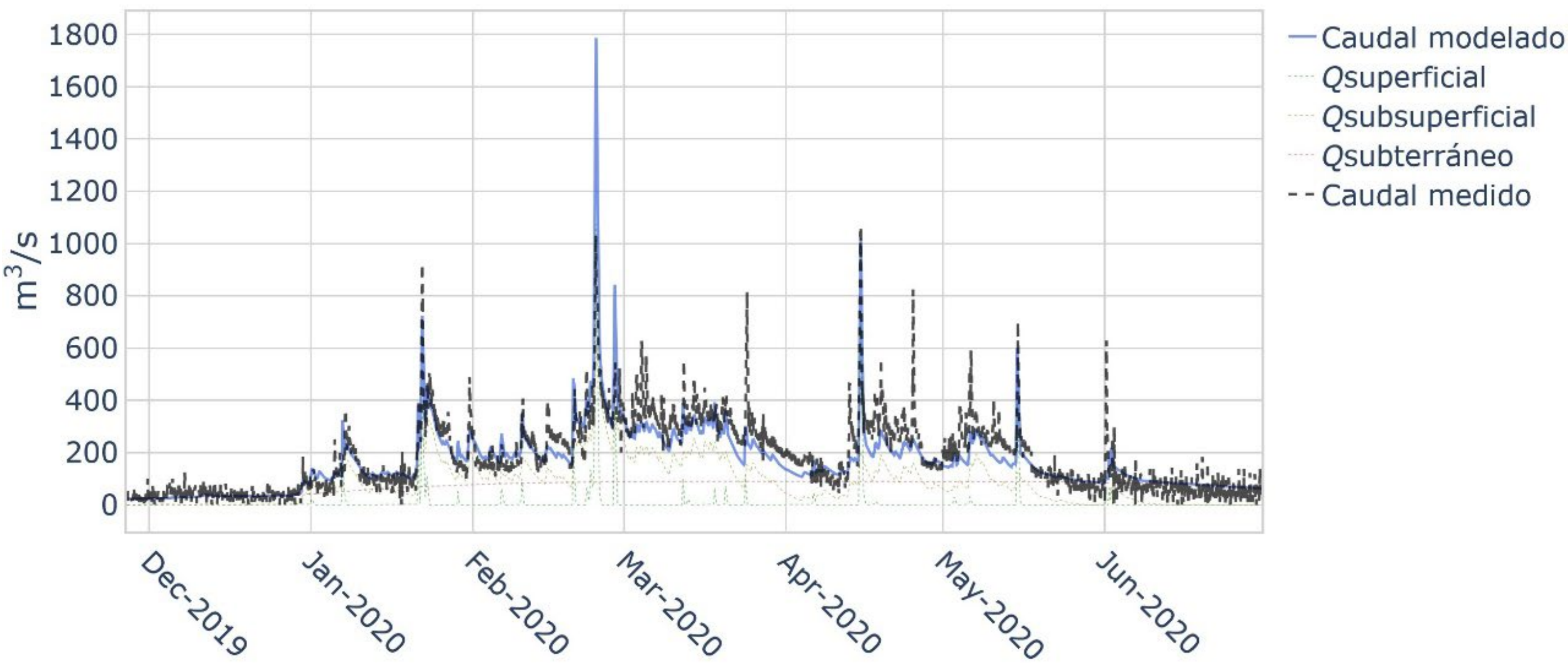

Figure 11. Model validation results for inflow to the Baba reservoir on an hourly scale.

In the case of the Daule-Peripa reservoir, a Nash-Sutcliffe coefficient of 0.54 and 0.49 was obtained for calibration (Figure 12) and validation (Figure 13), respectively (Table 3).

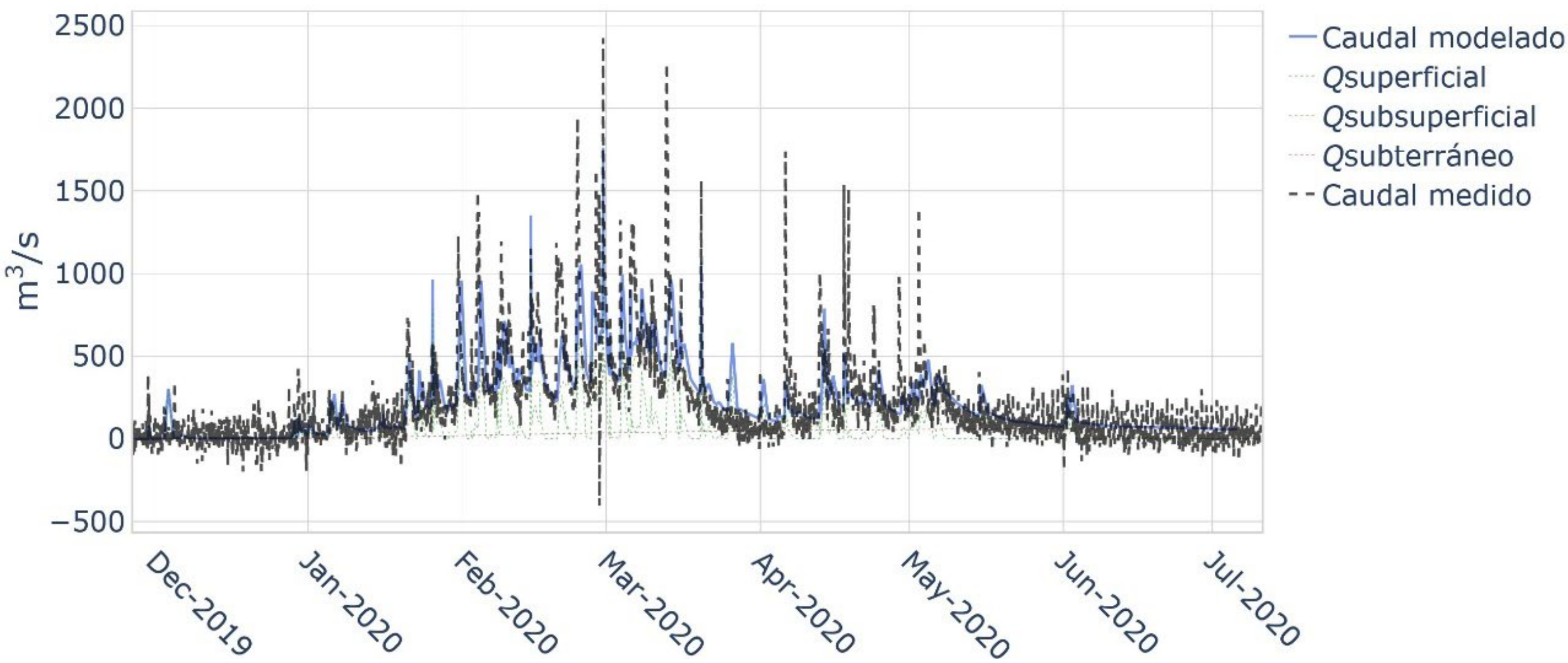

Figure 12. Model calibration results for inflow to the Daule-Peripa reservoir on an hourly scale.

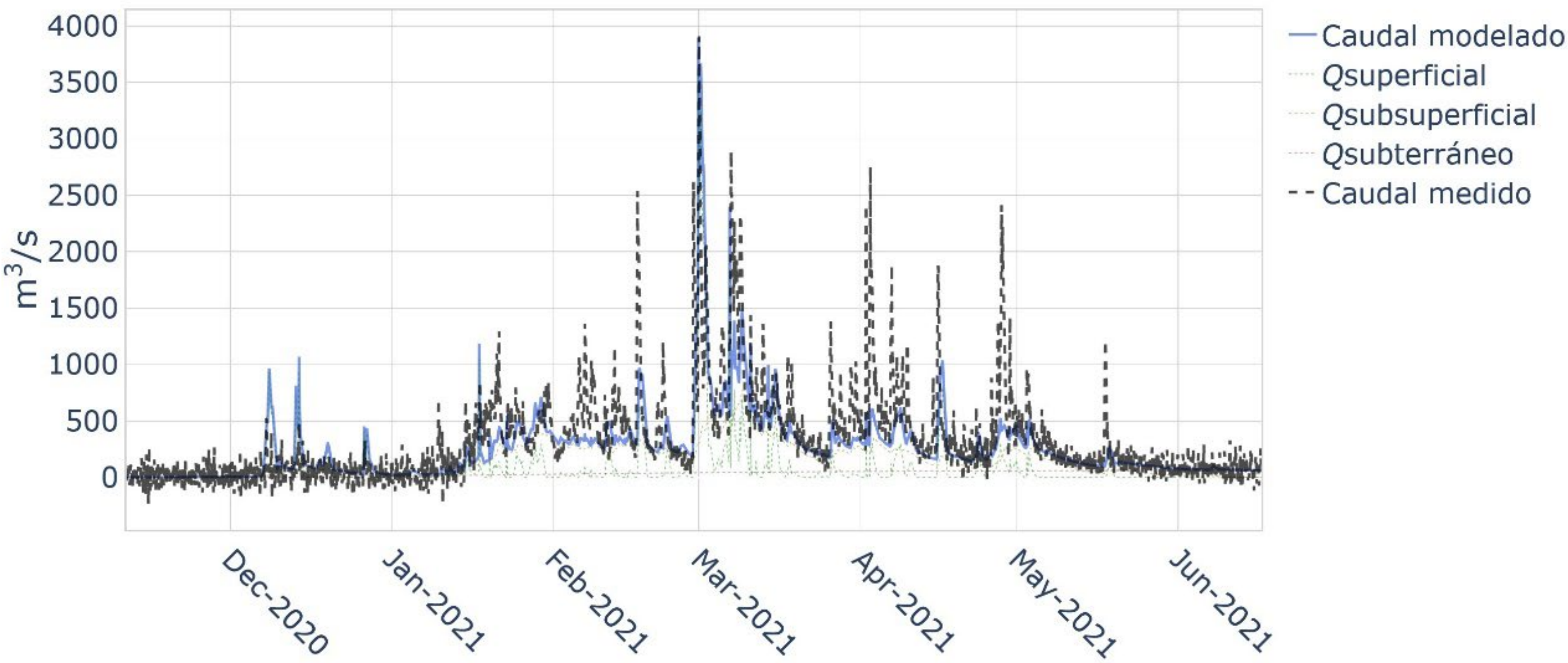

Figure 13. Model validation results for inflow to the Daule-Peripa reservoir on an hourly scale.

The daily mean of the outputs from the hourly model has been analyzed to assess its fit quality at this daily temporal scale, obtaining metrics shown in Table 5.

Table 5. Calculation of coefficients of the hydrological model on a Daily scale.

Model	Calibration-validation	Period	Correlation	Nash Sutcliffe	Mean Squared Error	Volume Difference	Mean Flow Rate
Baba	Calibration	11 Oct 2020 a 11 Jul 2021	0.93	0.85	56.8	1.4 %	177
	Validation	27 Nov 2019 a 7 Jul 2020	0.89	0.77	60.2	-5.9 %	178
Daule-Peripa	Calibration	27 Nov 2019 a 7 Jul 2020	0.87	0.75	115.6	-0.3 %	213
	Validation	11 Nov 2020 a 17 Jun 2021	0.81	0.62	224.2	-20.8 %	327

Following are the graphs of the model on a daily temporal scale for the Baba reservoir, obtaining a Nash-Sutcliffe coefficient of 0.85 for calibration (Figure 14) and 0.77 for validation (Figure 15) on a daily scale.

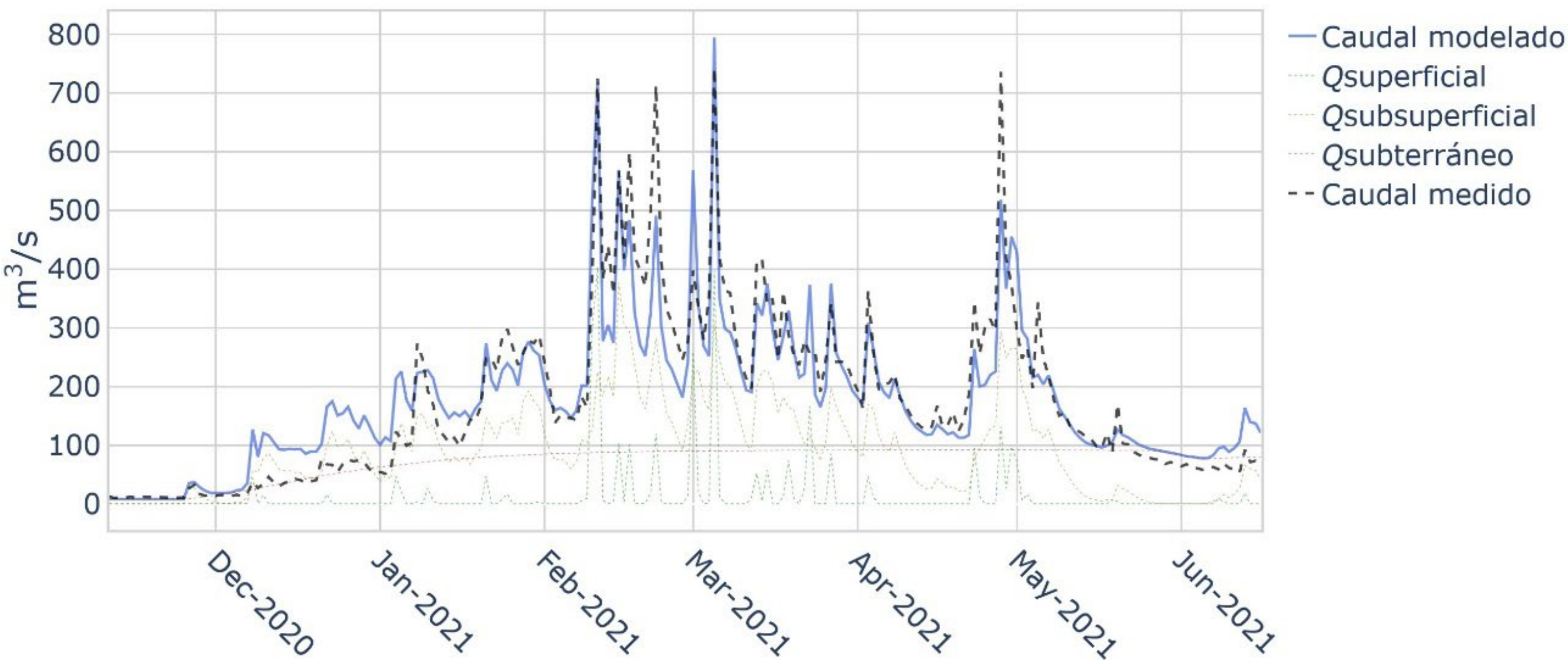

Figure 14. Daily model calibration results for Baba.

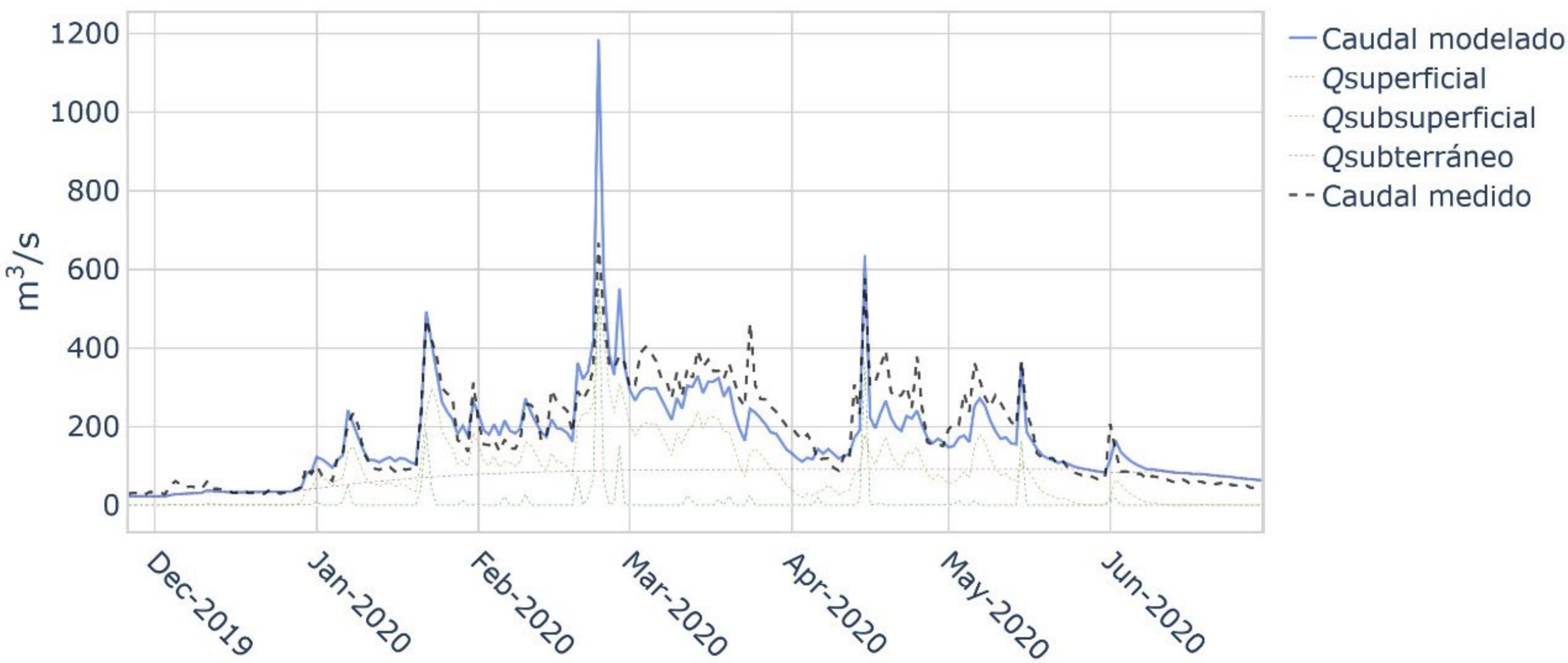

Figure 15. Daily model validation results for Baba.

In the case of the Daule-Peripa Reservoir, a Nash-Sutcliffe coefficient of 0.75 for calibration (Figure 16) and 0.62 for validation (Figure 17) has been obtained.

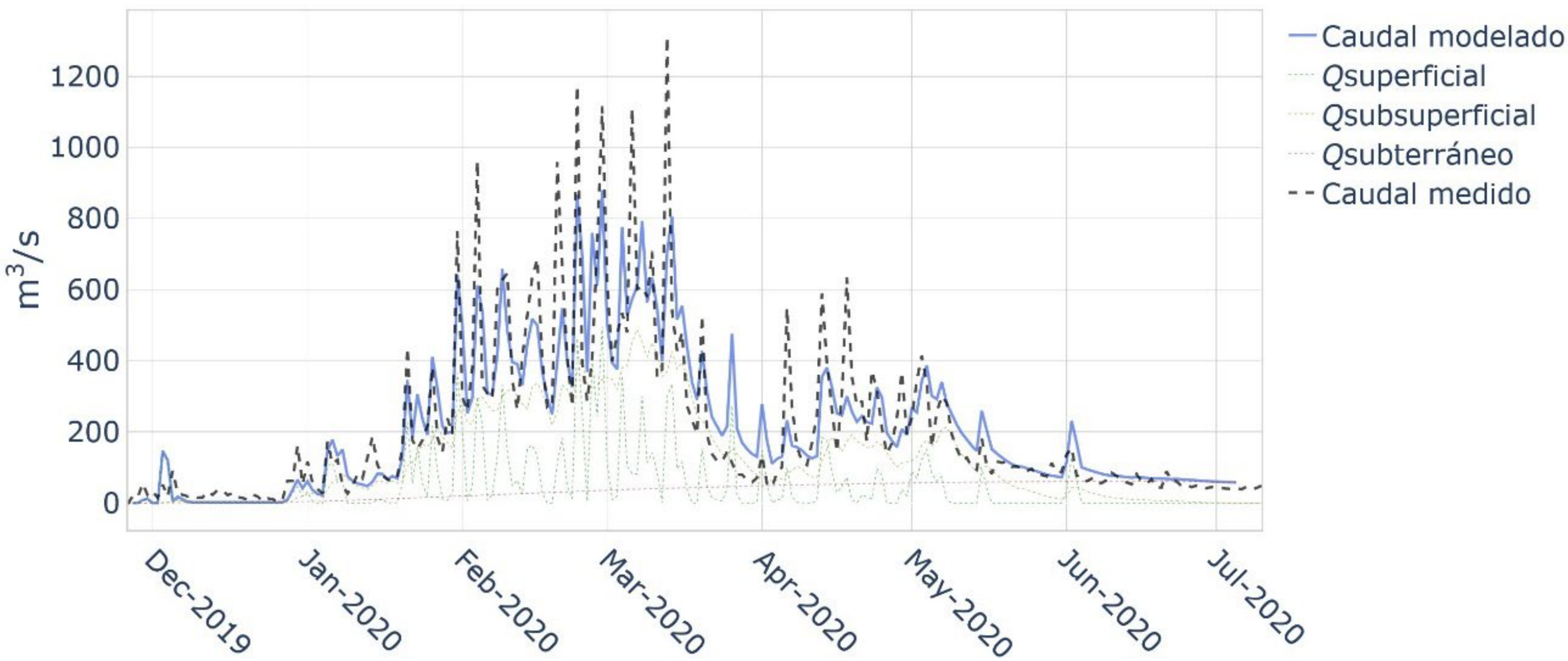

Figure 16. Daily model calibration results for Daule-Peripa.

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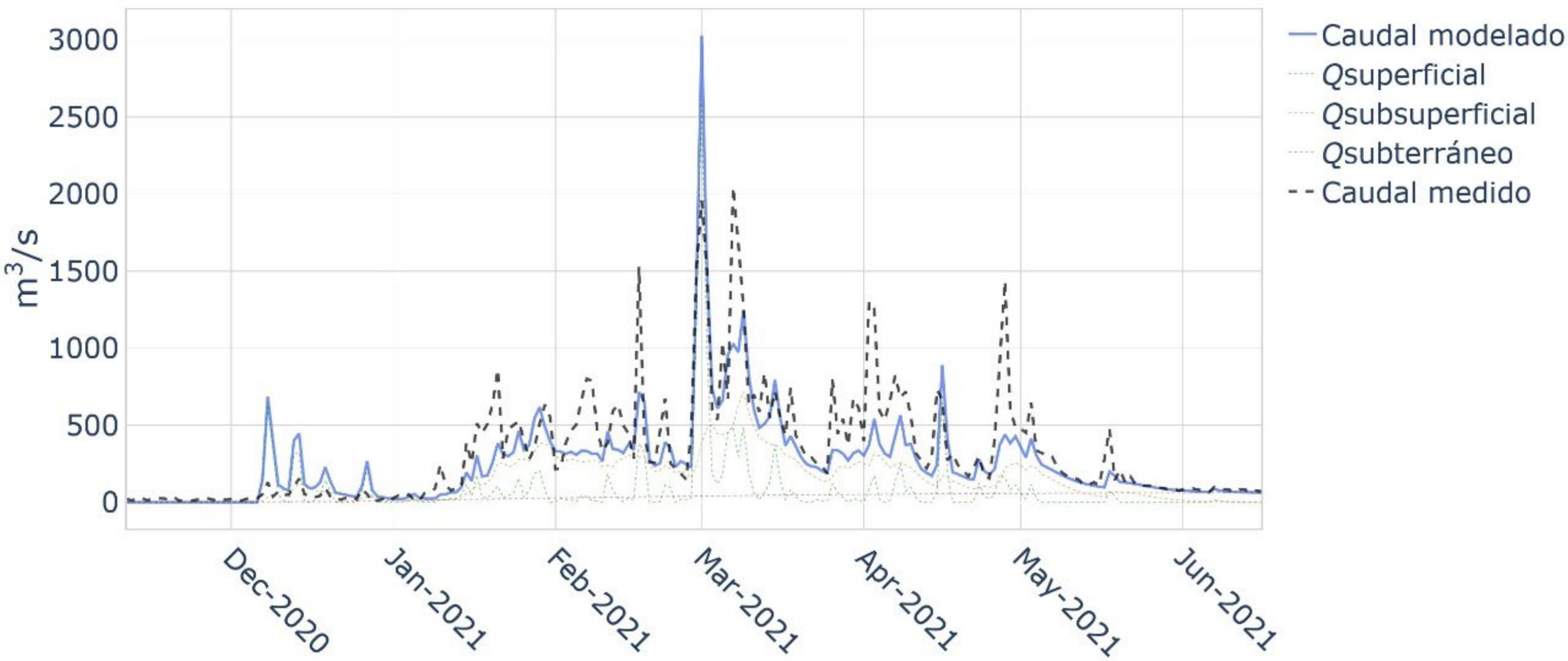

Figure 17. Daily model validation results for Daule-Peripa.

Operation of the system

The SHAD has been operational for both power stations since January 2021, coinciding with the start of the rainy season on the coast of Ecuador. During this period of use, the contribution of the SHAD to improve the operation of both Power Stations has been verified.

Concerning this improvement, it has so far met three of its main objectives.

Management of water resources

In the case of the Daule-Peripa and Baba reservoirs, the optimization of water resource management occurs by minimizing unnecessary spills, and in the case of Baba, maximizing the transfer from Baba to Daule-Peripa, allowing even in drought situations, the filling of the reservoir.

This maximization of the transfer is difficult to evaluate in general terms since it depends on multiple factors, such as inflow rates, availability of generation units, or the need for maximization itself, which, with high levels of the Daule-Peripa reservoir that guarantee its filling, ceases to be a priority. During the first part of the rainy season (January-February), due to uncertainty in the future inflow rates to the reservoirs, every year there is an attempt to maximize the transfer. Taking into account the incidence of many other factors, it can be seen in Figure 18 the maximization and lower variability in the daily transferred flows during the years of SHAD operation (2021 and 2022).

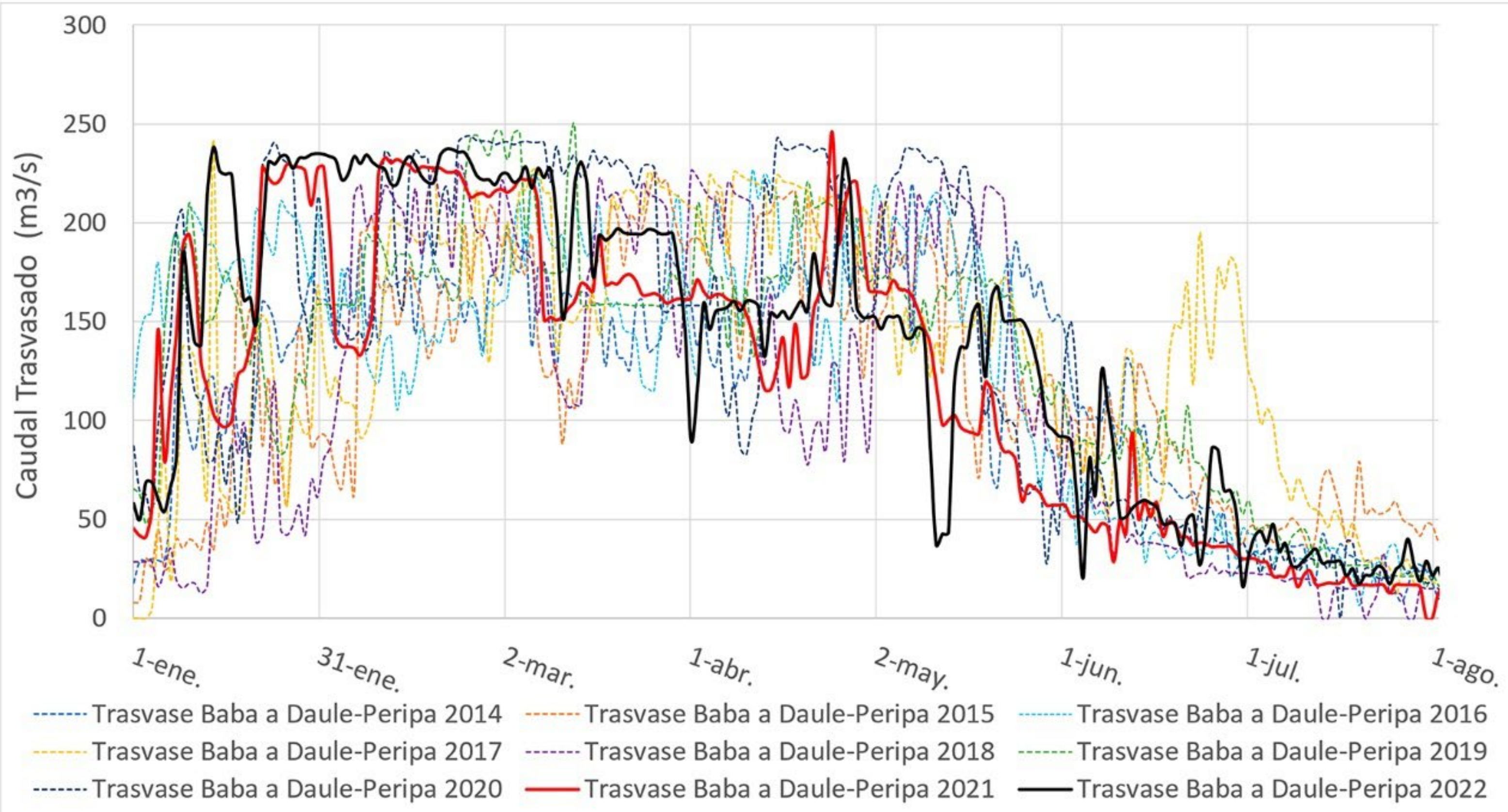

Figure 18. History of daily flows transferred from Baba to Daule-Peripa during the rainy season.

As previously mentioned, although lower daily variability in the transferred flows during the first months of the year might indicate better transfer management, many other factors must be considered. For instance, in 2022, the inflows from January 1st to May 19th were the highest since the hydroelectric power station became operational (317.16 m^3/s), whereas, in the case of 2021, the inflows for the same period were average (256.14 m^3/s), below those of 2016 (267.25 m^3/s), 2017 (275.15 m^3/s), and 2019 (278.60 m^3/s).

This improved management of resources is evident when analyzing particular events, in which, thanks to access to real-time data, the optimization of discharges was possible, avoiding unnecessary and/or excessive spills. An example of this is collected in Table 6; avoiding in 2021 compared to 2019, the spill from the Daule-Peripa reservoir of approximately 32.80 Hm^3. Volume that could have been avoided spilling in 2019 if the inflow forecast had been available at that time. This, in addition to mitigating or preventing possible flooding in the "lower" populations of the Daule river basin and those close to its margins, contributes to the water and energy reserve that represents the unspilled water and the consequent compliance with consumptive uses.

Table 6. Events with Similar Characteristics in Daule-Peripa, Years 2019 (Without SHAD) and 2021 (With SHAD).

Date	Reservoir level 24 h 00 (masl)	Flow rates m^3/s			
		Income	Transferred Baba	Turbined	Dumping
23-may-19	85.298	471.37	163.90	404.40	126.74
24-may-19	85.270	449.05	162.97	405.29	126.52
25-may-19	85.245	419.23	148.67	366.76	126.32
7-may-21	85.286	467.31	166.02	406.51	0.00
8-may-21	85.275	391.43	164.05	405.28	0.00
9-may-21	85.255	349.49	159.92	402.76	0.00

Increase in generation

This increase can be carried out in two ways: with the increase of the transfer from the Baba Power Station to the Daule-Peripa reservoir or as an increase in generation at either of the two Power Stations.

For example, in Table 7, we will take February 9, 2021. At 22:00, the operating conditions at the Baba Power Station were: maximum power (approximately 17.5 MW per Unit), reservoir level at the 116.00 m.a.s.l., no spillage through the Pico de Pato spillway, bypass closed. Through SHAD monitoring, a forecast increase in inflow was detected, proceeding to fully open the bypass to transfer an additional 70 m^3/s to Daule-Peripa beyond the turbined flow. Thanks to the ability to make decisions before the flow increase, it was possible to maximize the transfer with the consequent increase in generation at the Marcel Laniado de Wind Power Station.

Table 7. Events of February 9 and 10, 2021, at the Baba dam.

Date	Time	Reservoir level (masl)	Flow rates m^3/s			
			Income	Landfill	Turbined	Extravasor
9-feb	22:00	116.00	207.44	0.00	151.07	0.00
	23:00	116.04	326.07	8.00	151.07	70.00
	0:00	116.08	337.10	19.00	151.07	70.00
10-feb	4:00	116.43	653.83	206.00	153.90	70.00
	5:00	116.51	695.66	270.00	153.94	70.00
	6:00	116.53	569.66	287.00	153.93	70.00

Early detection of flooding events

During the season of highest rainfall in the Costa region, through SHAD monitoring, it has been possible to detect early all events with the possibility of causing flood damage upstream and downstream of the reservoir at least three hours in advance (generally 8 hours), thus facilitating the early generation and communication of (internal) Alert bulletins. Thanks to the hydrological model, it has also been possible to identify with an accuracy of +/- 2 hours the arrival of "peak" flows to the reservoirs.

Discussion and conclusions

A system (SHAD CELEC EP Hidronación) has been developed to assist in the management of water resources for the basins that feed the Daule-Peripa and Baba reservoirs. This tool has been implemented as the system managing the hydroelectric resources of the Marcel Laniado de Wind and Baba hydroelectric plants.

The tool integrates systems for collecting and storing real-time data from both the hydrometeorological station network and a meteorological module, a hydrological model specifically developed for the basin, and graphic interfaces that greatly facilitate the tasks of technicians managing the reservoirs. The tool integrates software and hardware components to fully automate the processes of capturing and incorporating data from various sources: weather stations, flow stations, meteorological models, hydrological models. It also integrates storage services for such information securely, with the possibility of integrating new features or improving these in the future.

Baba reservoir, with a volume of 100 Hm^3 and an average daily inflow during the rainy season of 253 m^3/s, becomes a daily-regime reservoir during this period (with flows similar to the transfer capacity to Daule-Peripa), making it essential to have quality hourly-scale forecasts. In the case of Daule-Peripa, with a maximum volume of 3 000 Hm^3 and an average inflow of 280 m^3/s, it is an annual regime reservoir where a daily scale model is considered sufficient for its management, both in terms of hydroelectric production and flood management.

The model of the basin flowing into the Baba reservoir has a NSE of 0.8 for calibration and 0.71 for validation, while for the Daule-Peripa basin, NSEs of 0.75 and 0.62 were obtained for calibration and validation, respectively. Therefore, the adjustments of both models can be considered satisfactory. The lower coefficients obtained for Daule-Peripa are due both to the lack of precipitation data in the southwest of the basin and to the difficulty of performing the water balance in the reservoir due to its large volume and length (in some branches of more than 70 km). It should be noted that work is underway to improve the Daule-Peripa model by installing new rain gauges.

Even while waiting for these latest improvements, the hydrological model has been adequately integrated into the management system, making this SHAD a tool that automates the processes of collection, treatment, and meteorological and hydrological prediction.

The preliminary comparative analysis of the management of the basin's water resources, carried out since the SHAD was put into operation, shows evidence of significant improvements in terms of the efficiency in managing the hydroelectric plants, as well as improvements in managing water resources for purposes other than hydroelectric production or the automatic early detection of potential flood events.

The SHAD will allow the implementation of Early Warning Systems for flooding downstream of the plants, by incorporating effective communication systems with the population.

It is also an important tool for the process of developing Basin Management Plans in the Autonomous Decentralized cantonal and provincial Governments, using the developed hydrological models for the technical validation of proposals and as aid for the implementation of territorial planning measures, which are fundamental to strengthen the adaptive capacity to climate change, extreme weather events, droughts, and floods.

As previously mentioned, work is currently underway to install new rain gauges to improve the hydrological model forecast. Also, having automatic records of flows from drainage structures such as gates and spillways will be a notable improvement, so that the total discharges and water balance in the reservoirs can be automatically calculated by the system.

For the improvement of the meteorological models, more active participation at the country level in international meteorological modeling projects would also be desirable, registering and sharing meteorological data that allow predictive improvement of these models in our areas of interest.

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