ORIGINAL ARTICLE

Evaluation of hydrological factors of the Chambas Basin for hydroenergy and agricultural use

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Evaluación de factores hidrológicos de la Cuenca Chambas para uso hidroenergético y agropecuario

Noidys Quirós-Martín[I*], Oscar Brown-Manrique[I], Carlos Miguel Sánchez-Monteserín[I], Maiquel López-Silva[II]

[I]Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Ciego de Ávila, Cuba.
[II]Universidad Ricardo Palma, Lima, Perú.

ABSTRACT: The evaluation of hydrological factors in hydrographic basins is essential for the sustainable management of water resources and the detailed planning of productive activities in a given area. The present study was developed in the Chambas River Hydrographic Basin with the objective of evaluating different hydrological factors of the basin and their contribution to the generation of hydropower and the supply of water to the agricultural sector. The methodology used consisted of constructing the flow probability curve, estimating the ecological and equipment flow; as well as evaluate the hydroenergy potential and agricultural use of the water stored in the reservoir. The results demonstrated that the daily river flows adequately adjusted the probability of occurrence using a second-order polynomial model. The turbine flow rate of the Francis turbine is 2,08 m^3 s^{-1} and has an absolute frequency of occurrence of 170 times. The ecological flow of the river determined by the wetted perimeter method was 0.038 m^3 s^{-1}. The turbine power with the turbined flow rate of 11.30 m^3 s^{-1} offers higher values in relation to the flow rate of 2.08 m^3 s^{-1}; However, this last result responds to the hydrological study carried out in the basin. 39% of the water stored in the reservoir is used for food production.

Keywords: Ecological Flow, Turbined Flow, Surface Runoff, Turbine Power.

RESUMEN: La evaluación de factores hidrológicos en las cuencas hidrográficas es esencial para la gestión sostenible del recurso hídrico y la planificación detallada de actividades productivas en un área determinada. El presente estudio se desarrolló en la Cuenca Hidrográfica del Río Chambas con el objetivo de evaluar diferentes factores hidrológicos de la cuenca y su contribución en la generación de hidroenergía y el abasto de agua al sector agropecuario. La metodología utilizada consistió en construir la curva de probabilidad de los caudales, estimar el caudal ecológico y de equipamiento; así como evaluar el potencial hidroenergético y el uso agropecuario del agua almacenada en el embalse. Los resultados demostraron que los caudales diarios del rio se ajustaron adecuadamente la probabilidad de ocurrencia mediante un modelo polinómico de segundo orden. El caudal turbinable de la turbina Francis es de 2,08 m^3 s^{-1} y presenta una frecuencia absoluta de ocurrencia de 170 veces. El caudal ecológico del río determinado por el método del perímetro mojado fue de 0,038 m^3 s^{-1}. La potencia de la turbina con el caudal turbinado de 11,30 m^3 s^{-1} ofrece valores superiores en relación con el caudal de 2,08 m^3 s^{-1}; sin embargo, este último resultado responde al estudio hidrológico realizado en la cuenca. El agua almacenada en el embalse se utiliza en un 39% para la producción de alimentos.

Palabras clave: caudal ecológico, caudal turbinado, escorrentía superficial, potencia de la turbina.

*Author for correspondence: Noidys Quirós-Martín, e-mail: noidysquirosmartin@gmail.com

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INTRODUCTION

Currently, the world is facing new challenges to solve the problems derived from traditional energy systems; among these problems are the increase in energy demand, the increase in generation costs and the need to replace the oil resource with renewable energy sources, where around 20% of electricity is produced using hydraulic energy or hydropower (Monirul *et al.*, 2021; Pérez *et al.*, 2022).

The agrarian transformation of Cuba has been based from its beginnings on the vision of an alternative model that included the recovery and use of water and energy resources, the construction of new plants for the use of hydroenergy, the installation of windmills and the dissemination of new agroecological technologies for the transition towards a new organizational technological model in the agricultural sector Arias, (2009); as well as the preservation of the environment and sustainable development (Paneque *et al.*, 2015).

Hydroelectric energy is a type of renewable energy that produces negative environmental impacts in the case of water impounded in dams; however, the use of this technology offers the advantage of energy diversification and the possibility of development of communities where the energy generated supports productive activities (Reyna *et al.*, 2017). This energy is related to hydrological factors of a hydrographic basin, essential in the generation of electrical energy; especially the flow duration curve (Gallego & Carvajal, 2017). The objective of this work was to evaluate different hydrological factors of the Chambas Basin and their contribution to the generation of hydroenergy and the supply of water to the agricultural sector.

MATERIALS AND METHODS

The research was carried out in the Chambas River Hydrographic Basin, located on the northern slope of Cuba in the province of Ciego de Ávila; It covers the municipalities of Florencia and Chambas with an area of 384.374 km^2. The coordinates are included according to the North Cuba Coordinate System GCS_NAD27-CU in: Upper: 286754.723900 m; Left: 700995.360200 m; Right: 720785.727100 m; Lower: 248273.406300 m.

In this basin is the Florencia Liberation Hydraulic Complex, of Ciego de Ávila, made up of the Chambas I (Cañada Blanca) and Chambas II reservoirs; as well as the Small Hydroelectric Power Plant "Alzamiento de Jagüecito" with a generation capacity of 1.2 MW with the use of Francis type turbines.

In the investigation, the diagnostic technique was used to obtain all possible information related to precipitation, the filling volume of the reservoir and energy production for 10 years (2008-2018) with the use of different tools such as documentary analysis. of technical reports, from the Hydraulic Use Company and the Electrical Union respectively.

The probability curve of the Chambas river flows was constructed from the recorded flow values, the calculation of the probability of exceedance with the empirical Weibull function and the construction of the graph with the flow data on the ordinate axis. and the respective probability values on the x-axis (Gallego & Carvajal, 2017).

The ecological flow (Q_{eco}) was estimated using the Wet Perimeter method Benetti *et al.* (2003); Brown *et al.* (2016), was found at the inflection point of this curve. This procedure requires knowing the height of each vertical (h), the average instantaneous velocity in each vertical, the partial flows, the total flow, the average velocity and the hydraulic radius for the simulation of the expected depths in each vertical of the section. transversal by varying the average flow of the river (Q_m) and the functional relationship between Δ_v and ΔA.

The equipment flow (Q_e) and the minimum technical flow (Q_{mt}) of the turbine were estimated according to Castro (2006). In the case of the minimum technical flow, a proportionality factor (K) of 0.35 was selected for the Francis turbine. The equations used were:

$$Q_e = Q_m - Q_{eco} \quad (1)$$

$$Q_{mt} = KQ_e \quad (2)$$

The evaluation of the hydroenergy potential was carried out based on data on the turbine flow (Q_e), the characteristic curves of the reservoir and the turbine location elevation. This information allowed us to calculate the difference in level at each topographical elevation of the volume of water in the reservoir and finally the power of the turbine with the use of the following equations:

$$P = \frac{\rho g Q_e H_n \eta}{1000} \quad (3)$$

$$H_n = (C_{NA} - C_{IT}) - \left(\frac{10.67 L Q_e^{1.852}}{C^{1.852} \quad D^{4.87}}\right) \quad (4)$$

Where P is the turbine power (kW), ρ the density of water (kg m^{-3}), g the acceleration of gravity (m s^{-2}), Q_e the turbine flow (m^3 s^{-1}), H_n the height of the net head (m), η the efficiency of the turbine (dimensionless), C_{NA} the topographical elevation of the water level in the reservoir (m), C_{IT} the installation dimension of the turbine (m), L the length of the pressure pipe (m), C the roughness coefficient of the pipe, D the diameter of the pipe (m).

The evaluation of hydropower production consisted of analyzing the behavior of the variables rainfall, reservoir filling volume and energy production in each of the months of the evaluated period. Using the data, the behavior graph of the variables in the evaluated period was constructed and the facility's energy production trend curve was drawn up.

The evaluation of the use of the runoff stored in the dam's reservoir for agricultural purposes was based on the behavior of the volume of water delivered by the dam to be used in food production in the area served by this important hydraulic work.

RESULTS AND DISCUSSION

In the Figure 1 the probability curve of the average daily flows corresponding to the Chambas River in the Ciego de Ávila province is shown. In the figure it is possible to obtain the value of the daily flow of the river for any characteristic year desired. In this sense Rivera & Penalba (2018) carried out studies in regions of Cuyo and Patagonia in Argentina to select the probability distribution with the best fit to the observed flow frequencies; however, in this study it was achieved that the daily flow values of the river adequately adjusted the probability of occurrence (P_r) through a second-order polynomial model with a high coefficient of determination (R^2) that in this case reached a value of 0.9903:

$$Q_m = 0.0004Pr^2 - 0.105Pr + 6.529 \qquad (5)$$

The analysis of the time series of the daily flows of the Chambas River allowed us to determine the average flow (Q_m) with a value of 2.12 $m^3\ s^{-1}$. This parameter constitutes the basis for the design of the Francis turbine; obtaining a turbine flow (Q_e) of 2.08 $m^3\ s^{-1}$, an ecological flow (Q_{eco}) of 0.038 $m^3\ s^{-1}$ and a minimum technical flow (Q_{mt}) of 0.73 $m^3\ s^{-1}$; which indicates that this is the lower limit for the installed hydraulic turbine to generate electrical energy.

In the Figure 2 shows the histogram of flow frequencies of the Chambas River. It is verified that the flow rate of 2.12 $m^3\ s^{-1}$ presents the highest absolute frequency with an occurrence of 170 times, very close to six months, which confirms that this value corresponds to the probability of 50%.

In the Figure 3 The cross section of the Chambas River is shown, which is used as a starting point for subsequent simulations of the flow velocity and the expected depths in each vertical of the cross section when varying the average flow of the river. The functional relationship between the average instantaneous velocity in each vertical (Δv) and the partial areas (ΔA) in the cross section of the river responded to a linear model with a high coefficient of determination (R^2) of 0.9989, as shown in the following equation:

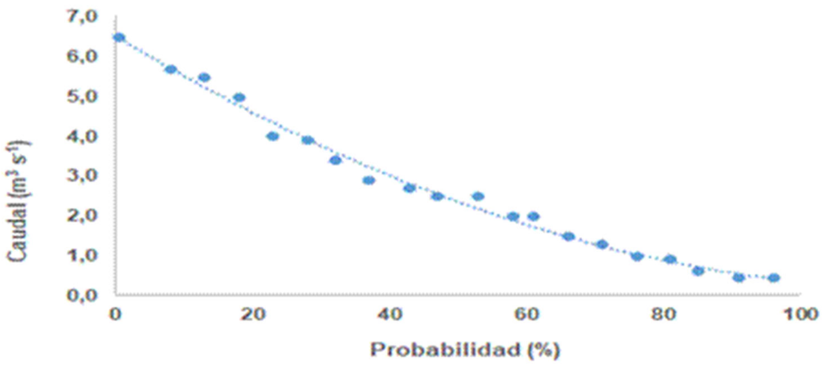

FIGURE 1. Probability curve of the Chambas River flows.

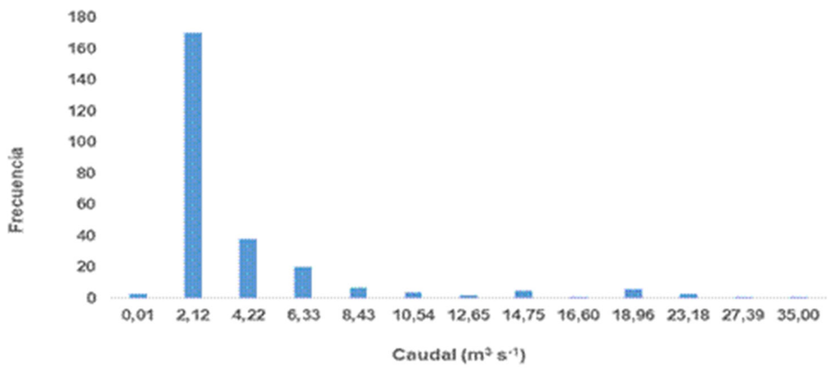

FIGURE 2. Histogram of relative frequencies of flows of the Chambas River.

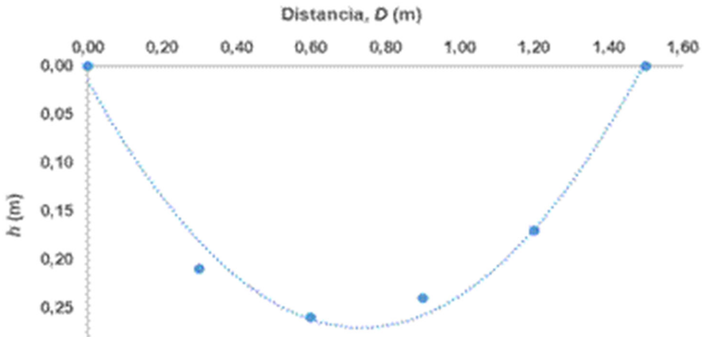

FIGURE 3. Cross section of the Chambas River.

$$\Delta v = 8.366\Delta A + 0.002 \quad (6)$$

The cross section can be simulated from the second-order polynomial type model and coefficient of determination (R^2) of 0.9812. This model allows the determination of the depth of each vertical (h) in the river cross section as a function of the distance from the left bank of the cross section.

$$h = -0.472D^2 + 0.695D + 0.015 \quad (7)$$

With the flow and perimeter data, the curve shown in the figure was drawn Figure 4, which shows an inflection point from which the ecological flow of the river was found. This flow reached the value of 0.038 $m^3 s^{-1}$; being close to the average minimum flow of the river; therefore, the Wetted Perimeter method can be considered an acceptable estimator of the ecological flow under the conditions of the Chambas River.

The values of the characteristic curve of the Chambas I dam (Cañada Blanca), offered by the Hydraulic Use Enterprise, allowed us to relate the water levels of the reservoir, H (m) with the volume of water impounded, V (hm^3); obtaining a polynomial function of the second degree with a high coefficient of determination R^2 of 0.9925.

$$H = -0.581V^2 + 104.31V - 4635.30 \quad (8)$$

Table 1 shows the gross power of the Francis turbine for a reservoir power plant, calculated with the design flow and the turbined flow in the range of the normal water level and the turbine location elevation (84.00 and 57.00 m) for the Chambas I dam (Cañada Blanca), which made it possible to find the generation height (H_n) for each of the water level levels (H).

The estimation of the power with the turbine flow of 11.30 $m^3 s^{-1}$ (50% of the maximum flow of the taking work) and efficiency of 93%, which is recommended for this type of turbine, values were obtained that were higher in relation to the calculation taking into account the gross power of the Francis turbine in the case of a run-of-river plant, calculated with the turbine flow of 2.08 $m^3 s^{-1}$ (respecting the river ecosystem) and a minimum technical flow rate of 0.73 $m^3 s^{-1}$, which represents the lower limit for the turbine hydraulic power can generate electrical energy under the conditions evaluated.

The simulated result for the case of the run-of-river plant responds to the hydrological study carried out in the basin. In this way, hydroenergy use guarantees better protection of the environment based on the planning and operation of hydroelectric projects aimed at minimizing the negative impacts due to the effects of global climate change and extreme weather events (Bedoya & López, 2015).

The generation of hydroelectric energy is produced by converting the kinetic energy of water into electrical energy using hydraulic turbines, taking into

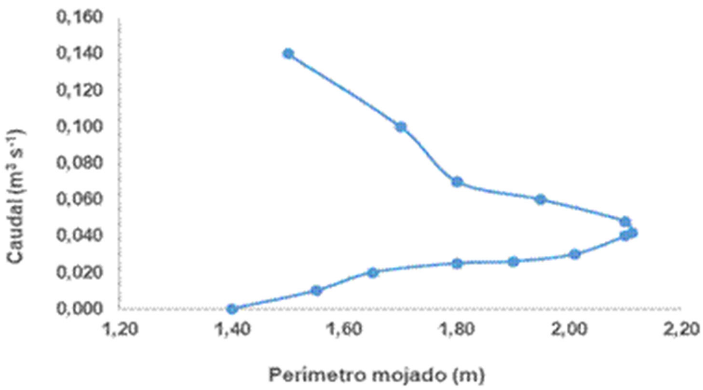

FIGURE 4. Ecological flow by the Wet Perimeter method.

TABLE 1. Turbine power calculated with the design and turbine flow rates.

Water level, C_{NA} (m)	H (m)	Q_e = 11,30 m³ s⁻¹	Q_e = 2,08 m³ s⁻¹
		P (kW)	P (kW)
84	27.00	2769.60	509.80
80	23.00	2359.29	434.28
76	19.00	1948.98	358.75
72	15.00	1538.67	283.22
68	11.00	1128.36	207.70
64	7.00	718.04	132.17
60	3.00	307.73	56.64

account several factors, such as the amount of water available in the basin, generation height, the type of turbine installed, the flow that reaches the turbine and especially the ecological flow so that the hydroenergy project (Meza & Aparicio, 2018).

Figure 5 shows the behavior of the variables energy production, precipitation and reservoir filling volume on a monthly time scale. The behavior of precipitation reflects that between the months of May and October the highest accumulations are obtained and between November and April there is a considerable decline in this meteorological parameter.

Regarding the accumulated volume, it is observed that, in all months of the year, high percentages are not achieved in filling the reservoir, which influences the production of electrical energy due to the reduction in the generation height, the turbine flow and turbine power. From the month of November to March, considerable decreases in the reservoir volumes occur; However, the volume increases from May to October; being the most favorable period in energy production to satisfy the demand for energy consumption for the different sectors of the economy, especially the population and agriculture.

The analysis of the use of the runoff stored in the dam's reservoir for agricultural purposes reveals that the largest consumer of the Florencia Hydraulic System release is the generation of electrical energy through the Small Hydroelectric Power Plant with 37.7%, followed by the Group AZCUBA Business with 20.5% for activities related to the production of sugar cane and its derivatives; as well as in self-consumption. The Ministry of Agriculture employs 13.9% in livestock farming, rice cultivation, various crops and vegetables; For its part, the Ministry of the Fishing Industry uses 4.6% for aquaculture production.

The remaining consumers are the population that receives 1.4% for supplies and the Ministry of Construction in the construction materials industry. This result indicates the importance of reservoirs for securing water resources for the use of their waters in periods of water deficit, which contributes to the food security of the area.

Studies carried out by Mendoza & Campos (2021) demonstrated the need to assess the precipitation and runoff of the basin as it constitutes a contribution to the solution of the problem of the existing water deficit in an area; which contributes to the determination of water potential, its storage in the rainy season and its subsequent use in times of drought to satisfy water needs, both for irrigation and human consumption.

There are contradictions between the water used for hydroelectric generation and agricultural irrigation. These contradictions are manifested in the distribution of water resources between different uses, which makes it difficult to satisfy the demand for water for both purposes and requires making decisions and actions of a comprehensive, transdisciplinary and participatory nature, principles that are related to water management and the Integrated Management of Water Resources (Cazorla, 2003).

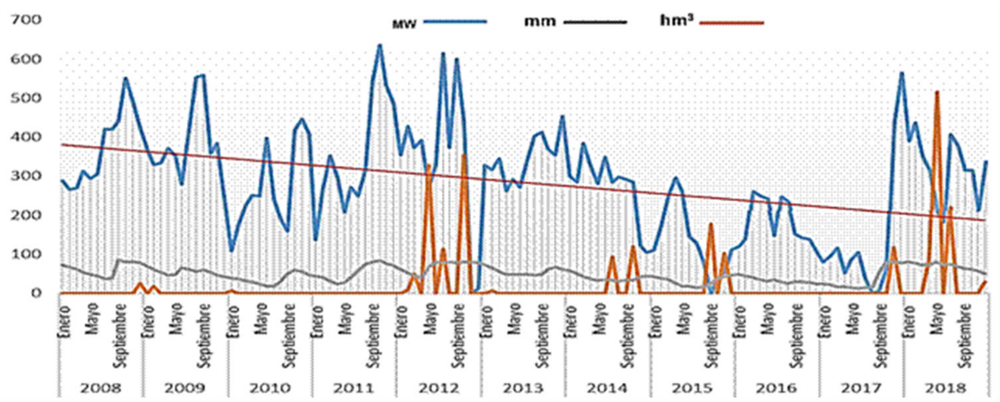

FIGURE 5. Energy production according to rainfall and filling volume.

CONCLUSIONS

- The daily river flows were adjusted for the probability of occurrence using a second-order polynomial model with a coefficient of determination of 0.9903. The turbine flow rate of the Francis turbine is 2.08 $m^3 s^{-1}$. The minimum technical flow rate is 0.73 $m^3 s^{-1}$ and the ecological flow rate determined by the Wetted Perimeter method is 0.038 $m^3 s^{-1}$.
- The estimation of the turbine power with the turbine flow rate of 11.30 $m^3 s^{-1}$ offers higher values in relation to the flow rate of 2.08 $m^3 s^{-1}$. The latter responds to the hydrological study carried out in the basin and guarantees hydroenergy use with environmental protection.
- The water stored in the Florencia Hydraulic System is released for food production by the following consumers: AZCUBA Business Group, Ministry of Agriculture and Ministry of the Fishing Industry.

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Noidys Quirós-Martín. M.Sc., Prof. Auxiliar, Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Departamento de Mecánica Aplicada, Ciego de Ávila, Cuba.

Oscar Brown-Manrique. Dr.C., Prof. Titular, Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Centro de Estudios Hidrotécnicos (CEH), Ciego de Ávila, Cuba. e-mail: obrown@unica.cu.

Carlos Miguel Sánchez-Monteserín. Dr.C., Prof. Titular, Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Departamento de Mecánica Aplicada, Ciego de Ávila, Cuba. e-mail: monte@unica.cu.

Maiquel López-Silva. Dr.C., Prof. Titular, Universidad Ricardo Palma, Perú. e-mail: maiquel.lopez@urp.edu.pe.