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Hydroelectric potential in mountain hydrographic basins subject to Cuban environmental regulations: notes for its use

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Abstract: Benefiting and improving the electrical service to residents in intricate and mountainous areas exposed to environmental regulations is a complex task due to the necessary care that must be taken in minimizing the environmental impacts that hydroelectric projects can generate. The main objective of this research is to determine and characterize the hydroelectric potential of the upper basin of the "La Magdalena" river in the Guamá Municipality, in the province of Santiago de Cuba, located in an area environmentally protected by the Cuban State. For this, a basic procedure was designed that had, as fundamental results, the general characterization of the Basin, the determination of the ecological flow and optimal usable flow; as well as the hydroelectric potential of the basin and the recommendations regarding the type of hydraulic turbine to be installed in the area to guarantee electrification.

Key words: Hydroelectric potential; mountain hydrographic basins; environmental regulations; exploitation; La Magdalena

1 Introduction

Today, hydropower provides nearly one-fifth of the world's electricity, with China, Canada, Brazil, the United States, and Russia being the top five producers of this type of energy in 2020 (IRENA, 2021) (Table 1) (Figure 1).

Table 1. The largest producer of hydropower in 2020 (Source: Irena, 2021)

Country	Hydroelectric	Installed	Capacity factor	% of world	%Household
China	1,232	352	0.37	28.5%	17.2%
Brasil	389	105	0.56	9.0%	64.7%
Canadá	386	81	0.59	8.9%	59.0%
Estados	317	103	0.42	7.3%	7.1%
Rusia	193	91	0.42	4.5%	17.3%
India	151	49	0.43	3.5%	9.6%
Noruega	140	33	0.49	3.2%	95.0%
Japón	88	50	0.37	2.0%	8.4%
Vietnam	84	18	0.67	1.9%	34.9%
Francia	71	26	0.46	1.6%	12.1%

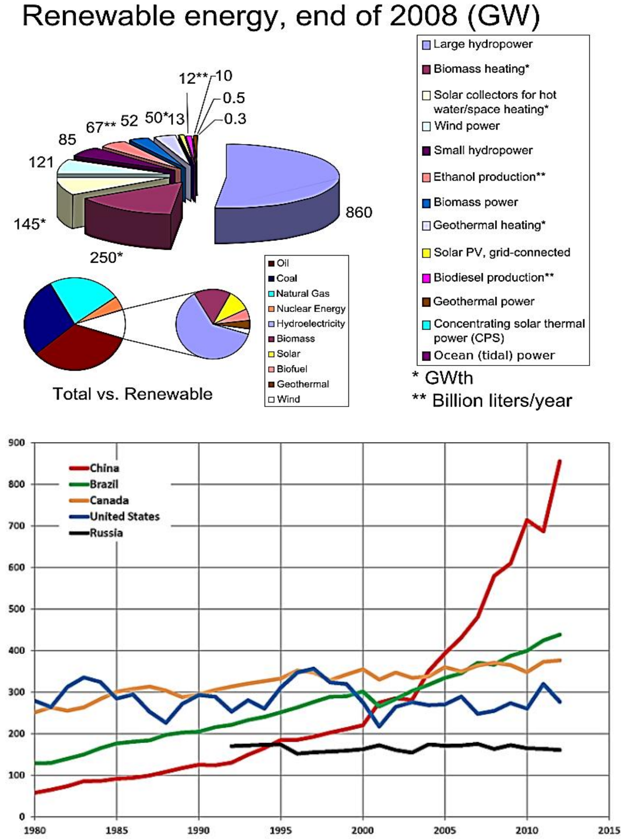


Figure 1. The global distribution of renewable energy production (as shown in the figure above), the growth trend of hydropower production in the largest producing country (below)

Source: Ren21, 2016

Hydropower stations are usually located in areas where rainfall and geological slopes are appropriately combined to facilitate dam construction. Hydraulics is obtained from the potential and kinetic energy of river water bodies brought about by rainfall and melting. When water descends between two layers of riverbed, it passes through a water turbine, which transfers energy to an AC generator, which converts it into electrical energy (Figure 2). Another method is to build a small dam in the river and divert some of the flow through channels with a smaller slope than the river, so that after a few kilometers, they will create a certain water level difference with the riverbed and pour water into the riverbed through pipelines with special turbines. This form of energy is the key to developing in a sustainable and green way to meet the growing energy demand of the post industrial world. Hydropower and other forms of renewable electricity are increasingly seen as necessary choices for the future world. (Galileo. edu, 2017).

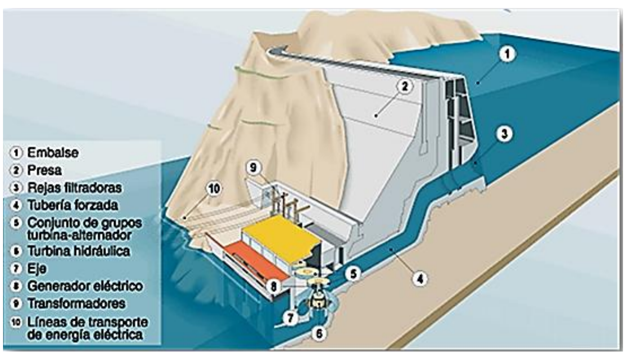


Figure 2. The classic scheme for water supply in hydropower stations under dams Source: Sanchez, 2019

Cuba had a small number of facilities before the 1980s, including the Hanabanira hydroelectric power station, Guaso and San Blas hydroelectric power stations, as well as some small hydroelectric power stations. Based on the development of the will for water aimed at maximizing the utilization and acquisition of water resources and protecting the people, the construction of hydropower stations, mainly small and micro hydropower stations, has begun with the aim of providing this energy to residents in mountainous areas. There are currently 162 hydroelectric power plants in the country with a total installed capacity of 71.9 megawatts. In 2017, they generated 83 gigawatt hours of electricity, of which 34 are connected to the national power system, and 128 provide services for 8,486 housing units and 416 economic and social goals. The largest power plant is the Hanabanila hydropower station, with an installed capacity of 43 megawatts. It is estimated that the current technological potential is 135 megawatts, of which 13.7 megawatts are in Transvases. (Minem, 2022) (Figure 3)

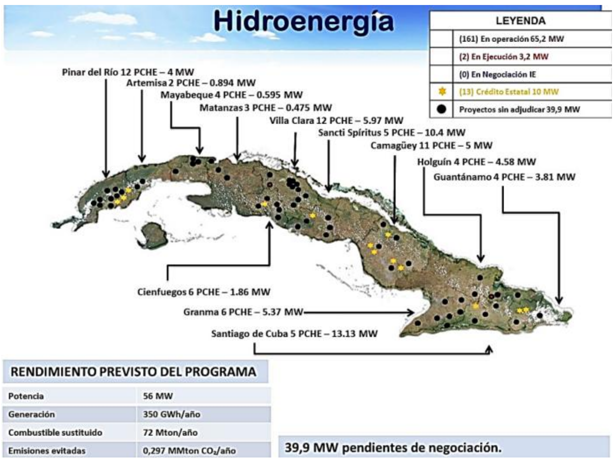


Figure 3. Distribution of hydroelectric production in Cuba by province

Source: Minem, 2022

Cuba has a production structure in the Cuban steel industry, namely the Aguilar Noriega factory (mechanical plant) in Santa Clara, which specializes in manufacturing, repairing, and assembling water turbines, governors, mechanical gates, and pipe forming. On the other hand, an ambitious plan is being implemented to gradually replace other forms of electricity production using renewable energy with fuel cell energy matrices. The plan includes goals such as building new dams and energy storage devices. The country is modernizing existing facilities, most of which have been in operation for over 20 years and are technologically outdated. (Minem, 2022)

In the installation of mini hydroelectric plants it is necessary to know the hydroelectric potential of the basin in which it will be located, so it is essential to make a detailed study of this parameter, due to the commitment in the use of renewable energies, in this case hydroelectric energy, either for the care of the environment, or to respond to problems such as meeting the demand for electricity in areas that are not connected to the national electricity system, and also its viability due to the low economic cost that presupposes the exploitation of these plants (MINEM. 2022). This study becomes a complex situation when the planned hydroelectric developments are located in mountain watersheds subject to environmental regulations, especially because of the subsequent impacts on the environment. In this sense, the following impacts can be generated (Méndez, 2012):

- Floods in large ecosystems are usually fertile and highly valuable in tropical regions.
- In most cases, the extinction of local flora and fauna.
- The displacement of population and human settlements.
- Parasitic diseases have increased in the created reservoir.
- Change the hydrological cycle or flow in the region.

- The water quality has undergone significant changes due to contamination by biological, herbicide, and insecticide elements from crops and agricultural production.
- Changes in fish migration when the normal riverbed is interrupted.
- According to the local geological conditions, the main erosion is the steep riverbank and the erosion of the reservoir riverbank.
- Changes in the living conditions of organisms in rivers and reservoirs.
- Sediments, nutrients, and water contribute less to estuaries and oceans, requiring ecological flow to sustain life downstream of reservoirs.
- The groundwater level rises and appears in unpopular places.

In this case, it is necessary to conduct detailed hydrological studies that take into account the ecological and landscape factors; Afterwards, other international considerations for optimal utilization of flow, as well as hydraulic calculations. This study proposes a general procedure for determining the hydroelectric potential of the La Magdalena River basin located in the Sierra Maestra Large National Park, which is today a special sustainable development area. In addition to several locally significant protected areas, it also includes national parks such as Granma, Turkino, and Bayamasa landings. (Decree No. 331 of 2015)

2 Materials and methods

For hydropower generation in the upper Magdalena river basin, the following steps must be taken:

① Study the general characteristics of basins and the selection of closure coordinates.

② Update the current and future electricity demand of the community.

③ Determine the optimal flow rate available for hydroelectric power generation.

④ Select the closure type based on the determined terrain and flow characteristics.

⑤ Choose the motor that will generate energy.

⑥ Projection of the basic steps for the construction of the dam and hydropower production station.

In this case, previous hydrological research had three stages:

① Determine the natural flow rate at the designated closure site for hydropower station construction.

② Determination of ecological river flows.

③ Determine the optimal available flow rate for hydropower production.

It must be pointed out that in order to determine the optimal flow rate for hydropower generation, hydrological studies were conducted using different direct and indirect methods, including:

- Reasonable methods
- Numerical curve method
- The third variant of Jose Luis Batista
- The classic formula
- Hydrometeorological formula
- Apart from others

In order to achieve greater accuracy, it is recommended to choose an average flow rate between the methods applied and their rectification with direct methods.

The concept of environmental flow or ecological flow refers to the amount and quality of water that must be maintained in a river to protect its ecological functions and ensure the life cycle of the organisms living in the river. It is related to the protection, adjustment, or restoration of the ecological functions and environmental services provided by natural systems, such as water quality, flood control and drought resistance, protection and preservation of biodiversity, aesthetics, and the flow of natural chemical elements. (Salas and Mendoza, 2021)

Ecological flow must maintain appropriate habitat, temperature, dissolved oxygen, and chemical properties of aquatic organisms, drinking water for terrestrial animals, and soil moisture for plants. The determination of ecological flow is concentrated during dry and humid periods, as ecosystems are considered excess water during the rainy season. Before treating the dam and diversion canal, it is necessary to estimate the average flow rates during dry and wet periods in the study area, which are similar to the initial conditions of the basin.

This ecological flow can be calculated using the "distributed hydrological model" method (Mendoza et al., 2002), which considers the distribution of temperature and precipitation. It can predict the impact of climate change and changes in the annual average flow of rivers; In addition, values from watersheds and sub watersheds can also be used for calibration. (Figure 4)

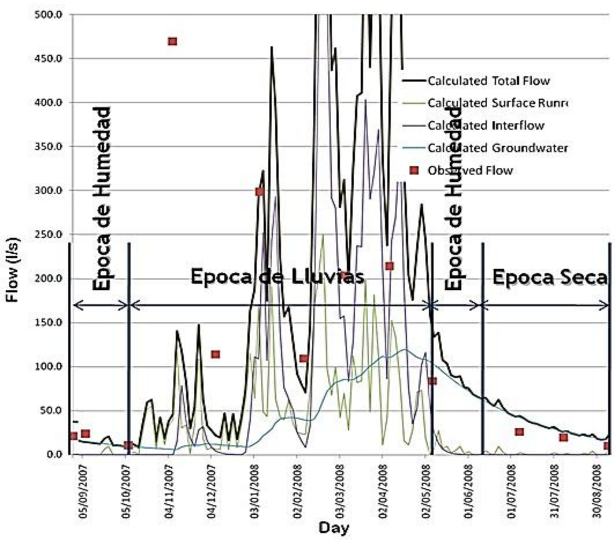


Figure 4. An example of the "distributed hydrological modeling" method, which determines the flow during the rainy and dry seasons through the decay curve after rainfall

Source: http://gidahatari.com/ih-es/caudal-ecologico

The method generally proposes that the calculation of the ecological flow rate can be carried out considering the following elements:

More accurate and complex calculations. Considering the distribution of temperature and precipitation. It can predict climate change and its impacts. It can be calibrated using values from watersheds and sub watersheds.

Total Hydrological Modeling (LUMP): A simpler and faster calculation that can only be calibrated on one watershed. It did not take into account the distribution of temperature and precipitation.

Another method defines ecological flow and its evaluation methods. The main calculations to be carried out are (according to document number) (Cavero, 2013):

✓ For watercourses with average annual flow rates of less than 20 m^3/s, the ecological flow rate shall be at least 10% of the average monthly flow rate for the avenue season, and for the summer season it shall be 15% of the average monthly flow rate.

✓ For waterways with an annual average flow rate equal to or greater than 20 m^3/s and less than or equal to 50 m^3/s, the ecological flow rate should be determined as a percentage of the monthly average flow rate, with a flood period of 10% and a storage period of 12% of the monthly average flow rate.

✓ For watercourses with average annual flow rates greater than 50 m^3/s, the ecological flow rate will correspond to 10% of the average monthly flow rate for all months of the year.

Once the ecological flow and average flow of the watershed are selected, the author suggests determining the optimal hydraulic development flow as follows:

$$Qop = Qm - Qec \quad (1)$$

Among them:

Qop--Best available traffic

Qm--Average flow rate of the watershed

Qec--Ecological flow

3 Results and discussion

The La Magdalena River originates from the Maestra Mountains at an altitude of 880 m.s.n.m and flows into the Caribbean Sea, where the community of the same name is located in Guama City, Santiago Province, Cuba (Figure 5).

Figure 5. Geographical location map of La Magdalena community in Guama city

3.1 General characteristics and selection of closure coordinates for the "La Magdalena" river basin

The climate of the territory is tropical, although dry conditions dominate due to its location south of the Maestra Mountains. The largest mountain range in Cuba is a natural barrier against the humid trade winds from the Atlantic Ocean. When they encounter these mountains, they are forced to rise, so they condense and settle on their northern slopes, and when they dry down along the southern slope where the town of La Magdalena is located, they lead to drier conditions. The southern slope of the Maestra Mountains faces the sun all year round, which exacerbates these low humidity conditions. The average temperature is 26 degrees Celsius, slightly lower in the highlands. (Figure 6)

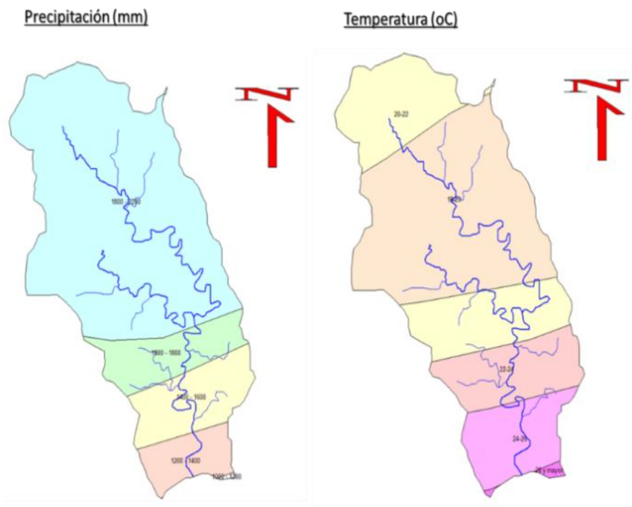
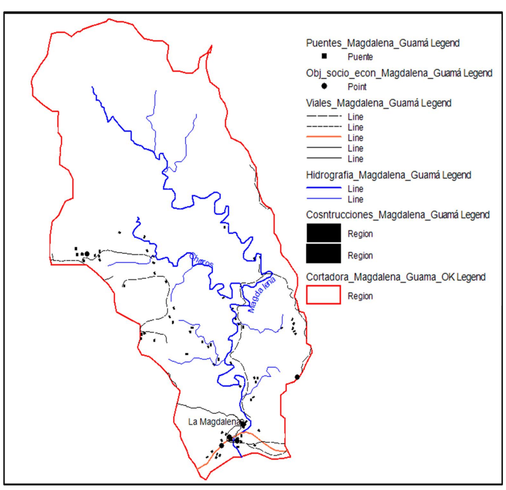


Figure 6. Map image of rainfall and temperature in the La Magdalena River basin in Guama city
(Geography of Cuba. 2010)

The La Magdalena River is one of the most important rivers in the city of Guama, with a drainage area of 138 square kilometers, running north-south and having 15 tributaries. The steep slopes form a canyon, with an average slope of 184% and softening towards the mouth of the river. The average height of the river is 144 meters. The river is 27 kilometers long, with an average slope of 9.9% and a drainage density of 1.06 kilometers per square kilometer. Its waters are used to supply the scattered inhabitants of the area. The hydrological network is very small, and sometimes small micro watersheds belonging to intermittent tributaries may appear. Due to its location in an area dominated by arid climate conditions, it is classified as a short and low flow river based on its length. During the rainy season (especially during cyclone season), the height of the water column increases to 5 meters above the normal water level (especially in low-lying areas near river mouths), which can be dragged anytime and anywhere to isolate various communities upstream of the watershed (Figure 7). (Duran, 2018)

In 2020, the population of the basin was approximately 1,419 people, distributed in three rural settlements. The Magdalena community was established from 1992 to 1993. The town's economy is mainly based on animal husbandry, such as cattle raising, miscellaneous grains, and forestry. The terrain of the territory is mountainous, with elevations ranging from 75 meters to 220 meters. The vertical and horizontal anatomy of the territory, as well as the dominant position of steep slope areas, have a decisive impact on the possibility of mechanization, production costs, working conditions, limitations of agricultural machinery, irrigation systems, and operating costs. (Figure 7)



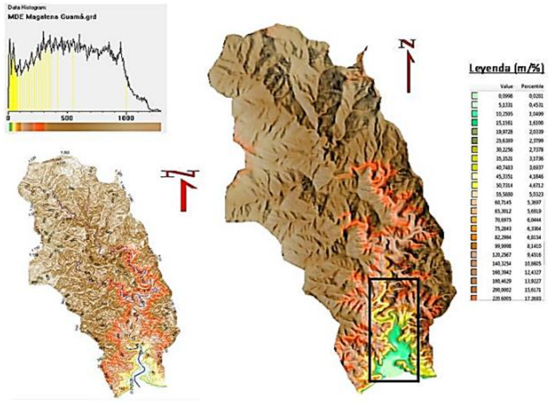


Figure 7. The La Magdalena River basin in Guama city

Above: Hydrological and socio-economic features located within it. Below: Watershed topographic map image and digital elevation model, specify the project work area of the same named community in the box (Geography of Cuba. 2010)

3.2 Current electricity demand in La Magdalena town

The electricity demand in La Magdalena town varies throughout the day. This change is a function of many factors, among which the most important are: the existing industrial types and their production schedules in the region, extreme cold or hot climates, the most commonly used types of household appliances, the type of water heater you install at home, the season of the year and the time of day when demand is considered.

Power generation must follow the demand curve, and as the demand for power increases, the power provided must also increase. This means that additional units located in the same power plant or reserved for these periods must be used to start generating electricity. (Minem, 2021)

When calculating the electricity demand of a given community, taking into account the above factors, calculate the specific demand of each factor, and then add up all these specific demands to determine the overall electricity demand of the community. (Minem, 2021)

According to data from the Cuban Ministry of Energy and Mines, in 2020, the average consumption of the residential sector in Cuba was 185 kilowatt hours per month, equivalent to an average daily consumption of 6.16 kilowatt hours. These are typically distributed in the average consumption of household appliances, lighting fixtures, and internal costs of wiring systems (Minem, 2021).

As for the community, Magdalena currently has 225 housing units and a population of 1,419 people. There are currently no industrial consumers who need electricity. Therefore, calculating the daily electricity demand of the community is achieved by multiplying the housing demand by this number:

$$Ddc = Cv * 6.16 \text{ kW/h} = 1{,}386 \text{ kW/h} \qquad (2)$$

Among them:

Ddc--Daily needs of the community

Cv-- Number of houses

6.16 kWh-- Cuba's daily demand for housing

This work approximates the calculation of future demand, as in communities like today, once electrified, other isolated residents in mountainous areas will migrate there, increasing local electricity consumption. For this, they calculated the average population growth and linked it to the future housing demand. As for the Nieto community (2020) analyzed using arithmetic methods, it was determined that over a period of 20 years, the community would have 3,690 residents. Therefore, the future number of housing units will be:

$$\text{Vcf(20 años)} = \frac{\text{Vca}*\text{Pf}}{\text{Pa}} = 585 \text{ viviendas} \quad (3)$$

Among them:

Vcf (20 años)--The future housing of the community in 20 years

Vca-- Current housing

Pf --Future population

Due to economic and social development, estimates of future electricity demand have increased over time. This prediction is uncertain, but it is necessary for evaluating the sustainability of hydropower projects during the design process. Similarly, multiplying the current demand for housing by the calculated future housing quantity:

$$\text{Ddfc} = \text{Cvf} * 6.16 \text{ kw/h} = 3{,}603.6 \text{ kw/h} \quad (4)$$

Among them:

Ddc -- Daily needs of the community

Cv -- Number of houses

kWh -- Cuba's daily demand for housing

3.3 Determine the optimal available flow rate for hydropower production

The specific sub basin corresponds to the closure of the La Magdalena River located in the upper part of the basin. Considering the location of the hydropower station, characterized by being a protected area declared as Special Region of Sustainable Development that contains the national parks Desembarco del Granma, Turquino and La Bayamesa, in addition to several other protected areas of local significance, as it is an area subject to environmental regulations, it is necessary to use the following formula 1 to determine the optimal hydropower development flow according to the above ideas.

For the average flow of rivers, different methods must be used. This study chose the classical formula method, which is a widely used and reliable hydrological research method internationally, as follows:

Substitute the values of runoff coefficient, basin average precipitation coefficient, and basin area into equation 5 to obtain the average runoff (Figure 8):

$$\text{W} = \frac{\text{C}*\text{P}*\text{A}}{1{,}000} \quad (5)$$

Obtain the flow rate by replacing the runoff value in equation 6:

$$\text{Qo} = \frac{\text{Wo}}{31.54} \quad (6)$$

The runoff modulus is determined by replacing the flow and area values of the watershed according to equation 7:

$$\text{M0} = (\text{Q0}/\text{Ac})*1{,}000 \quad (7)$$

Replace the runoff and watershed area values in equation 1.8 with the runoff table:

$$\text{Y0} = (\text{W0}/\text{Ac})*1{,}000 \quad (8)$$

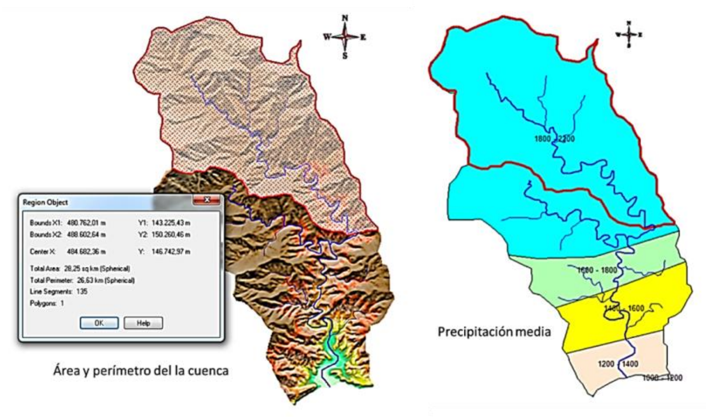


Figure 8. Directly using geographic information systems to obtain preliminary data images: watershed area, perimeter, coordinates; Closing the sub basin means the location of the hydropower station.

Obtain the value of runoff coefficient (c) from Table 2 based on soil type, land use type, and slope. When the drainage area presents different types of soil, vegetation, and average slope. The runoff coefficient (c) should be obtained for each partial area, and then the weighted average value should be calculated and applied to the equation.

Table 2. Runoff coefficient value Source: Forcadell, 1994

Uso del suelo y pendiente del terreno	Textura del suelo		
	Gruesa	Media	Fina
Plano (0-5% pendiente)	0.10	0.30	0.40
Ondulado (6-10% pendiente)	0.25	0.35	0.50
Escarpado (11-30% pendiente)	0.30	0.50	0.60
Plano (0-5% pendiente)	0.10	0.30	0.40
Ondulado (6-10% pendiente)	0.16	0.36	0.55
Escarpado (11-30% pendiente)	0.22	0.42	0.60
Plano (0-5% pendiente)	0.30	0.50	0.60
Ondulado (6-10% pendiente)	0.40	0.60	0.70
Escarpado (11-30% pendiente)	0.52	0.72	0.82

From this, the ecological flow rate and the optimally exploitable flow rate are calculated:

Input data:

- Annual average rainfall (P) = 2,000 millimeters
- Watershed area (a) = 28.25 square kilometers
- Drainage coefficient (c) = 0.30 (Thick soil with tropical forest vegetation)

$$W = \frac{2{,}000 * 0.30 * 28.25}{1{,}000} = 16.95$$

$$Qm = 16.95/31.54 = 0.54\ m^3/s$$

$$M0 = (0.54/28.25)*1{,}000 = 19.11$$

$$Y0 = (16.95/28.25)*1{,}000 = 600$$

Due to the annual average flow rate of the basin being less than 20 m^3/s, according to the Kawero method (2013) mentioned above, the ecological flow rate during water storage will be 15% of the monthly average flow rate, and the optimal hydropower development flow rate has been obtained based on this concept.

$$Qec = (15\%)\ 0.54 = 0.081\ m^3/s$$

$$Qop = 0.54 - 0.08 = 0.46\ m^3/s$$

Table 3. Preliminary hydrological calculation summary of La Magdalena sub basin in hydropower shutdown area using classical formula method

Área (km^2)	Perímetro (km)	Precipitación (mm)	W	Qm (m^3/s)	Mo	Yo	Qec (m^3/s)	Qop (m^3/s)
28.25	26.63	2,000	16.95	0.54	19.11	600	0.081	0.46

3.4 Select the closure type based on the determined terrain and flow characteristics

As for the water intake project of the hydropower station, considering the current energy utilization potential of the river, it is recommended to evaluate the use of three variants. These variants plan to construct a concrete rock dam and lift the river's suspension rod to approximately coordinates (486.779; 141,380), 200 meters away from the confluence with the tributary "El Cato", which will have derivative functions (Figures 9 and 10). The shortcomings of these variants lie in the distance to be covered upstream and the investments to be made to build an access road that does not exist today in an area with irregular mountainous relief.

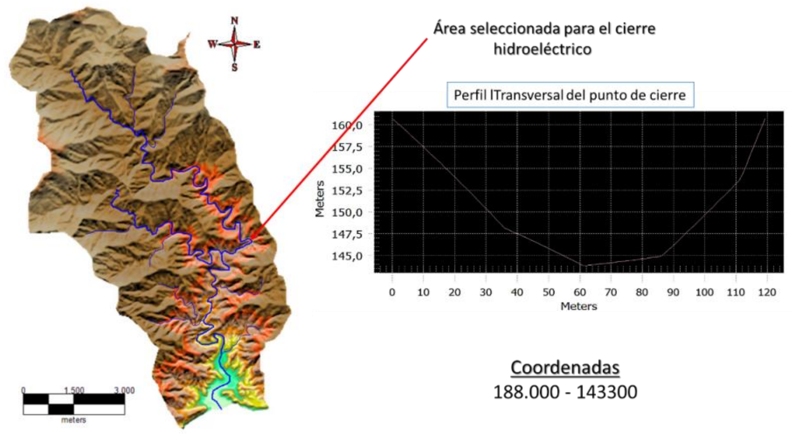


Figure 9. Display the cross-sectional profile of the closed area of the hydropower station

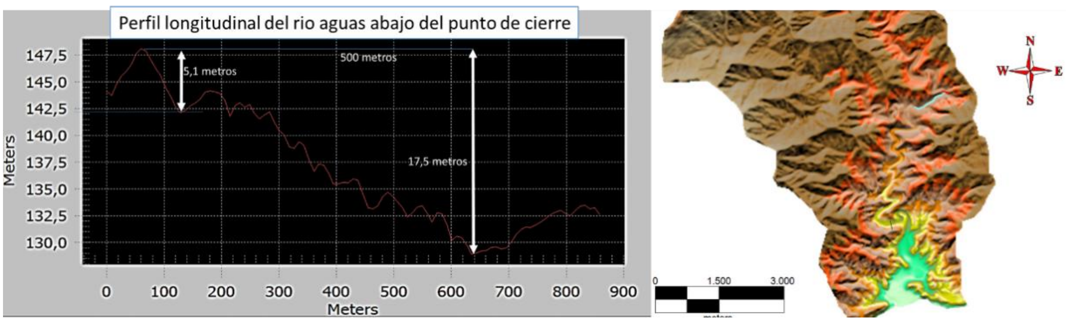


Figure 10. Longitudinal profile of the river downstream of the closing point

3.5 Selection of generator motor

As mentioned above, for the variant that uses regulated runoff to shut down and utilize hydroelectric power, the first exposed variant, namely regulated shutdown, can be selected and transmitted downstream to the plant room. Then use the previous data and select the turbine based on its position on the international abacus (Figure 16) (Table 6):

Qop = 0.45 kW/h

Altura del salto (H) = 17.5 m

This led to the selection of mixed flow turbines

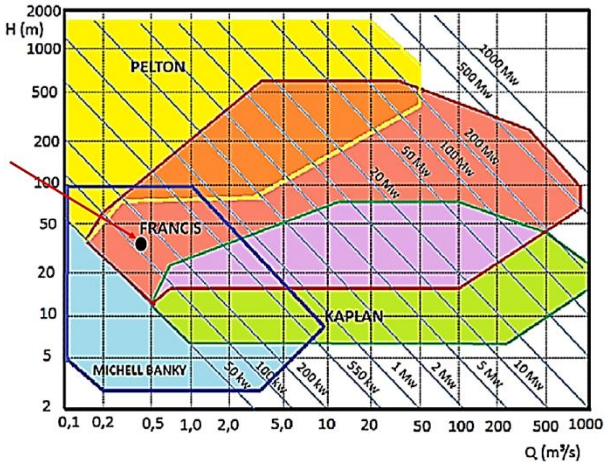


Figure 11. ABACO determines the type of turbine to be used based on preliminary calculations and points out the main selected locations Source: ESHA, 2006

Table 4. Select turbine type based on specific speed ns

Specific speed Ns	Turbine Type
De 5 a 30	Pelton con un inyector
De 30 a 50	Pelton con varios inyectores
De 50 a 100	Francis lenta
De 100 a 200	Francis normal
De 200 a 300	Francis rápida
De 300 a 500	Francis doble gemela rápida o express
Más de 500	Kaplan o hélice

3.6 Small scale hydroelectric power generation

The two main characteristics of a mini hydropower plant, from the point of view of its power generation capacity are:

- ✓ Power is a function of the imbalance between the average water level of the reservoir and the average water level below the micro hydropower station, as well as the maximum turbidity flow and the characteristics of the turbine and generator.
- ✓ The guaranteed energy for a certain period of time, usually within one year, depends on the effective capacity, annual rainfall, and installed capacity of the reservoir.

The power of small hydropower stations is usually measured in kilowatts (kW) and calculated according to the following formula:

$$P= 9{,}81.\ \rho\ \eta t\ .\ Q.\ H$$

Among them:

- ✓ P = Power (kW)
- ✓ P = fluid density (kg/m³)
- ✓ η t = turbine performance (0.75 to 0.94)
- ✓ Q = turbidity flow rate (m³/s)
- ✓ H = available slope between the inlet and downstream machine room entrance, in meters

In small hydropower stations, the definition is as follows:

Average power: the power calculated according to the above formula, taking into account the average available flow and average available slope.

Installed power: the rated power of the generator sets installed in the mini hydropower plant.

For the closure proposed at the conceptual level, the average power value is:

$$P = 9{,}81.\ \rho\ \eta t\ .\ Q.\ H$$

Among them:

Ht = 0,80 (Applicable to domestic mixed flow turbines)

Q = Qop = 0.46 m^3/s

H = 17,5 m

P = 9,81. 0,80. 0.46. 17,5

P = 63,2 Kw/h

It is necessary to analyze whether it will supplement the needs of the community based on the latest defects in the electrical equipment it possesses, which is currently impossible to do, although reducing the location of the data center will increase the load and power to be generated.

4 Conclusion

① For communities located in intricate and mountainous areas exposed to Cuban environmental regulations, especially the La Magdalena community in the municipality of Guama, the electricity service can be solved from the production of hydropower that can be extracted from the river of the same name, designing hydroelectric projects that adequately take into account the ecological flow in the initial basic hydrological study that is carried out for this purpose.

② Based on this concept, a procedure was developed that detailed the steps to be followed in order to understand the ecological flow, optimal hydraulic utilization flow, and other basic parameters of the upper reaches of the La Magdalena River basin in Guama City. These parameters make it possible to select the turbine type for the project: QEC=0.081 m^3/s, QOP=0.46 m^3/s. The current electricity demand in La Magdalena town is 1,386 kW/h. The low-speed mixed flow turbine serves as a generator with a maximum power of 100kW.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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