Methodology for Hydroelectric Potential Evaluation in High Jungle Area with Scarce Topographic and Hydrological Information Using GIS and Algorithm MATLAB

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***Abstract*—Due to scarcity of topographic and hydrological information in high jungle areas, many times projects based on water management are not developed. This is of interest because they involve hydroelectric generation projects. The latter are considered important because of their capacity to satisfy the energy demand of a population and to minimize environmental impact of energy generation. In this sense, we propose a methodology for hydroelectric potential evaluation in high jungle areas that considers the following steps: (a) develop an algorithm in MATLAB in charge of searching geographical conditions for hydroelectric power plant's location, (b) definition of restrictions: political delimitation, environmental and demographic, (c) generation of average flows based on rainfall-runoff models, estimation of hydroelectric potential and economic evaluation of selected points. The high jungle area studied was Utcubamba basin, in department of Amazonas, Peru, where 2 possible locations with hydroelectric power of 5.33 and 6.09 MW were located.**

***Index Terms*—hydroelectric potential, renewable energy, algorithm, geographic information system, hydrological model**

I. Introduction

Electric energy is a resource of high need worldwide [1]. Since it was discovered, it has been used for development of different environments such as health, education, housing, among others. In addition, electricity facilitates development of daily tasks. Therefore, it is considered an essential element for development of technology, and therefore for economy of a country [1]. Therefore, it is sought that all communities, populated centers, rural areas, among others, can access this resource and satisfy the needs that associate it.

Since 2016, 25% of world's population (approximately) doesn't have access to electricity, especially those countries that are developing [2]. On the other hand, as stipulated by the EIA (Energy Information Administration), world energy consumption is expected to increase by 28% between 2015 and 2040 [3]. This is in addition to complying with the objectives of the United Nations (UN), specifically item 07 "Ensure access to affordable, reliable, sustainable and modern energy for all".

In Peru, energy consumption has increased at an average annual rate of 5.8% since 1995 [4], while energy production decreased. According to 2021 national electricity sector indicators report, electricity market decreased by 7% and energy production for own use by 17% [5]. Similarly, production of electrical energy per area has decreased by 7.5% [5].

In 2020, it is stated that 17.8% of rural population don't have a public lighting network [6], causing dangerous situations for community such as crime [1].

Department of Amazonas is located in northeast of Peru, is an area with little electricity production. According to 2021 national electricity sector indicators report, this is positioned in twentieth place in energy production. In addition, this department has presented a decrease in energy production of 31% [5]. The largest source of electrical energy production is thermal [5]. That is why it seeks to increase production of hydroelectric energy. Being this one of the largest sources of energy and considered the most used renewable energy [7].

The case study will be Utcubamba river basin, belonging to Department of Amazonas, there are 220048 inhabitants, it is in the high jungle area, it currently has an installed power of 4.89 MW there are eight hydrological stations and does not have information topographic detailed.

The present research seeks to evaluate hydroelectric potential of the area in order to increase the production of this energy, using hydroelectric run of river system, because these types of plants are not very invasive and generate fewer environmental problems. In addition, reduces emission of greenhouse gases, complying with objectives of the United Nations. For this, Geographic Information System and an algorithm in Matlab will be used.

II. Methodology

A. Matlab Algorithm, Model Constraints and Conditions

Designed algorithm has a conditional structure due to setting of initial tentative variables such as flow rate

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(m3/s), channel length (m) and elevation difference (m). It also has a search behavior, since algorithm itself must find within the storage matrices values of fall and length initially set as shown in Fig. 1.

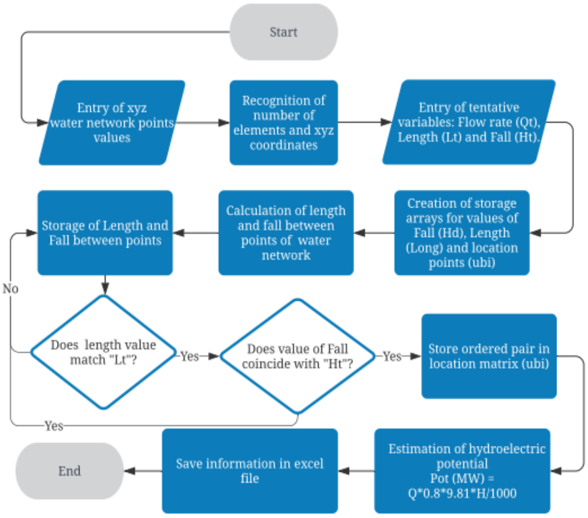

Figure 1. Algorithm for hydroelectric potential estimation in Matlab.

For algorithm developed in Matlab, first the political, environmental and demographic restrictions were established in study area. This was done in order to reduce the work area and discard those places where it is not possible to design hydraulic projects. In this case, as shown in Fig. 2, restrictions included 1516 population centers, 26 Natural Protected Areas (24 Private Conservation Areas and 02 Buffer Zones) and 77 archaeological sites.

For model conditions, we proceeded with estimation of tentative flows at 85% persistence in basin. Based on this flow, variables of fall (m) and channel length (m) that hydroelectric power plants should have to reach a power of 10 MW were calculated. These variables were varied according to estimated slope, 03 slopes were proposed: 2, 1 and 0.5%. Table I shows the sub-basin identifiers (ID Basin) and their respective tentative flow rates. Based on these flow rates, the required drops to obtain 10MW of power were defined. For each sub-basin, the length of the channel was estimated based on the slopes mentioned above.

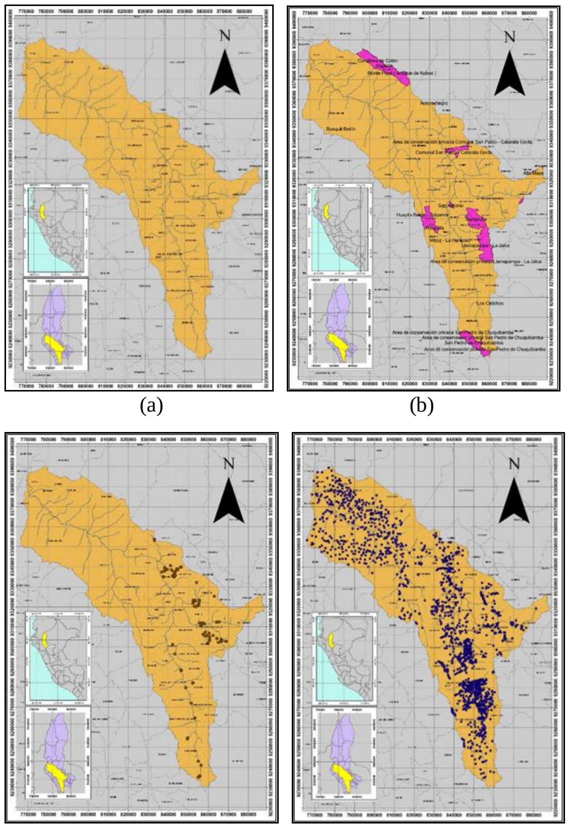

Figure 2. Restriction maps of Utcubamba watershed. Political delimitation (a), Environmental – Natural Protected Areas (b) Archaeological Sites (c) and Demographic (d).

TABLE I. SUMMARY OF FLOW RATE, HEAD AND CHANNEL LENGTH VARIABLES IN THE UTCUBAMBA WATERSHED

Basin			Hydroelectric power (MW)	Slope %	Slope %	Slope %
Utcubamba			10	0.02	0.01	0.005
Item	ID Basin	Flow Rate 85% (m^3/s)	Height (m)	Channel lenght (m)	Channel lenght (m)	Channel lenght (m)
1	3482 - 1977	456.3	2.79	139.62	279.25	558.5
2	1975 - 1953 - 2000 - 1985	71.5	17.83	891.49	1782.98	3565.97
3	1988 - 3488	44.8	28.45	1422.74	2845.49	5690.98
4	2047 - 2035 - 2142	24	53.03	2651.66	5303.32	10606.63
5	2057	10.2	124.92	6246.13	12492.26	24984.51
6	2027 - 2054	11.3	112.76	5638.1	11276.19	22552.39
7	2042 - 2067	3.1	411.04	20551.77	41103.55	82207.1

With these variables, the execution of the algorithm in Matlab was started. Finally, pairs of points that met the established conditions were obtained.

B. Flow Generation

For generation of annual mean flows, GR2M hydrological model was used, which was chosen after carrying out a previous evaluation together with Temez and Lutz Scholz models. In this evaluation, it was observed that GR2M model presents a better fit compared to the other models, and to arrive at this assumption the Nash, PBIAS and R^2 coefficients were taken into consideration. Fig. 3 shows the flow chart used for the generation of average flows through 03 water balance models.

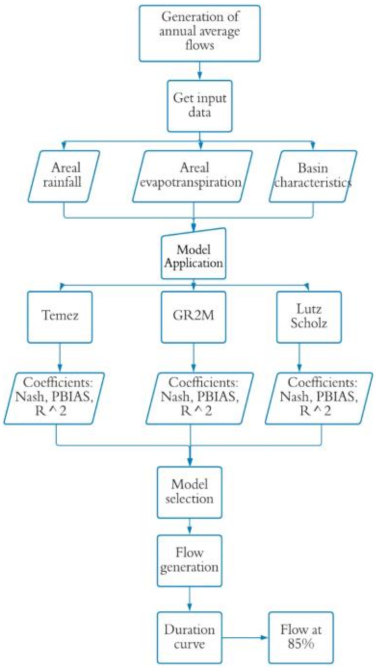

Figure 3. Flowchart of annual average flows generation.

A comparative analysis between the observed and simulated data was then performed by means of a hydrograph as shown in Fig. 4.

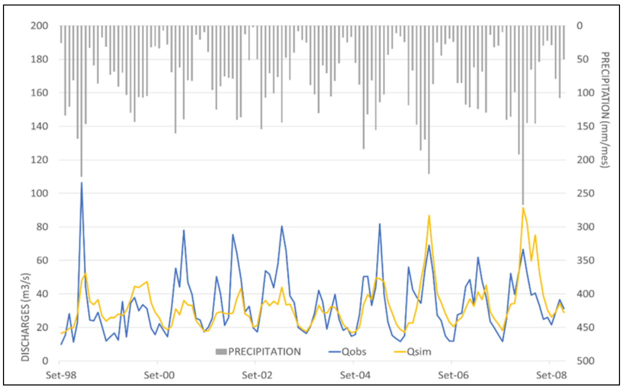

Figure 4. Hydrogram of annual average flows.

The variables required for generation stage are defined as follows.

Precipitation and evapotranspiration: Areal rainfall and evapotranspiration corresponding to each sub-basin of Utcubamba basin, were obtained by applying an algorithm in R in conjunction with PISCO product. Input data required by the algorithm were shapefiles of sub-basin areas, determined by the points obtained from the algorithm in Matlab, and rainfall products (PISCOpm.nc) and evapotranspiration (PISCOmpe_oudin_v1.1.nc), obtained from the SENAMHI website.

Characteristics of Basin: For generation of average annual flows, GR2M model requires certain characteristics and initial data. Characteristics that model requires are area of sub-basin, maximum storage capacity of soil reservoir and underground exchange coefficient, and initial data correspond to initial filling level.

Observed flow rates: Two types of observed flow rates were used. For calibration and validation, the flows recorded by Maguncha1 hydrometeorological stations were used from 2002 to 2007. After models's selection, flows obtained from research A Model of Monthly Water Balance in Peru (1981-2020) were used.

Calibration and Validation: For both, Calibration and Validation of GR2M model, it was sought to comply with satisfaction range established for the Nash, PBIAS, R ^ 2 and KGE coefficients.

Fig. 5 shows the validation ranges and their level of fit for the evaluation of the hydrological models.

GOODNESS OFFIT	NASH	PBIAS	R^2	KGE
Very Good	$1.00 \geq NASH > 0.75$	$PBIAS < \pm 10$	$R^2 \geq 0.85$	$1.00 \geq KGE > 0.70$
Good	$0.75 \geq NASH > 0.65$	$\pm 15 > PBIAS \geq \pm 10$	$0.85 \geq R^2 > 0.75$	$0.70 \geq KGE > 0.60$
Satisfactory	$0.65 \geq NASH > 0.50$	$\pm 25 > PBIAS \geq \pm 15$	$0.75 \geq R^2 > 0.60$	$0.60 \geq KGE > 0.40$
Unsatisfactory	$0.50 \geq NASH$	$PBIAS \geq \pm 25$	$R^2 < 0.60$	$0.40 \geq KGE$

Figure 5. Ranges of validation and calibration coefficients.

For the selection of the hydrological model, a comparative analysis of their respective validation coefficients was carried out. As shown in Table II and III, the GR2M hydrologic model obtained a better fit in the calibration and validation stage. In the calibration it obtained the following coefficients: Nash = 0.53, PBIAS = 2.46, R^2 = 0.47 and KGE = 0.42. In the validation, the results were Nash = 0.71, PBIAS = 2.31, R^2=0.69 and KGE=0.74. Thus, it was chosen to work with the GR2M model for the generation of average flow rates.

TABLE II. Validation Coefficients Obtained for the Temez, GR2M and Lutz Scholtz Hydrological Models

Model	Coefficients			
	Nash	PBIAS	R^2	KGE
Temez	0.50	1.55	0.40	0.57
GR2M	0.71	2.31	0.69	0.74
Lutz Scholtz	0.39	26.02	0.50	0.22

TABLE III. Calibration Coefficients Obtained for the Temez, GR2M and Lutz Scholtz Hydrological Models

Model	Coefficients			
	Nash	PBIAS	R^2	KGE
Temez	0.42	17.26	0.43	0.46
GR2M	0.53	2.46	0.47	0.57
Lutz Scholtz	0.40	-17.23	0.46	0.42

Persistence at 85%: After obtaining average annual flows from 1981 to 2016, duration curve was performed. In which flow was determined with a persistence of 85%, since it seeks to obtain conservative data close to reality.

C. Evaluation of Hydroelectric Potential

Turbine technical specifications: Fig. 6 shows a graph that helps to choose the type of turbine based on the estimated head and flow rate. Since elevation difference between points varied between 50 and 150 m and the estimated flow rate ranges from 10 to 20 m3/s, a Francis type turbine was considered.

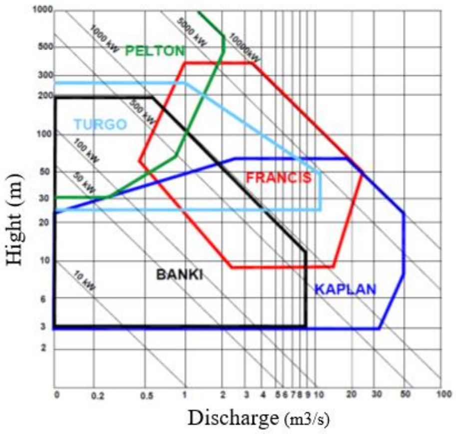

Figure 6. Graph for turbine selection. Adapted from "Small hydroelectric power plants in Uruguay" by CEDECAP, 2010.

Turbine efficiency parameter: Once the turbine was selected, the efficiency parameter of turbine was estimated with help of the graph in Fig. 7. Given that the powers worked are around 10MW, 0.80 was considered as the efficiency parameter.

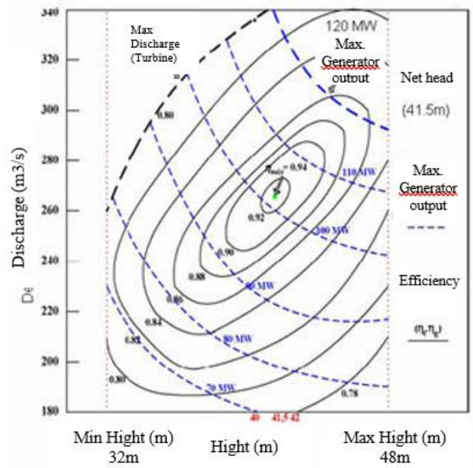

Figure 7. Graph for efficiency parameter selection. Adapted from "Technical efficiency as a new approach to short-term hydroelectric generation", by Javier Diaz, 2009.

TABLE IV. TABLE OF POTENTIAL LOCATIONS

ID	Coord X	Coord Y	Coord Z	Height (m)	Channel Length (m)	Q tentative 85% (m3/s)	Power Tentative (MW)	Q Model GR2M 85% (m3/s)	Final Power (MW)
A	856334.345	9240619.980	3167	56	2698.59	24	10.55	11.33	4.98
A	855194.907	9243066.220	3111						
B	831690.421	9311694.660	2455	54	2670.14	24	10.17	12.57	5.33
B	832594.315	9314207.160	2401						
C	839211.638	9312800.830	2131	53	2654.03	24	9.98	13.85	5.76
C	840115.421	9315296.240	2078						
D	832077.869	9313942.610	2416	52	2698.71	24	9.79	13.05	5.33
D	834542.227	9315042.610	2364						
E	843072.209	9320536.900	1648	56	2673.99	24	10.55	5.34	2.35
E	843640.424	9323149.810	1592						
F	856302.921	9240478.630	3168	57	5339.52	24	10.74	11.33	5.07
F	854402.158	9245468.370	3111						
G	842848.124	9313712.810	1699	51	5351.34	24	9.61	12.57	5.03
G	842602.925	9319058.530	1648						
H	842696.599	9318186.430	1648	56	5347.39	24	10.55	13.85	6.09
H	843640.423	9323449.870	1592						
I	852412.371	9267155.720	2049	55	5344.2	23	9.93	20.78	8.97
I	850890.421	9272278.620	1994						
J	851647.198	9270766.560	2028	55	5255.12	23	9.93	20.75	8.96
J	850627.921	9275921.880	1973						
K	853990.421	9258991.950	2162	51	2626.48	23	9.21	20.65	8.27
K	853777.921	9261609.820	2111						

Hydroelectric Potential Estimation: Finally, with the information obtained (flow rates, waterfalls and efficiency parameters), the hydroelectric potential of the possible locations obtained was calculated. Table IV shows 11 possible locations of run-of-river hydroelectric power plants, also showing their respective flow rates estimated through GR2M model.

III. RESULTS AND DISCUSSION

A. Analysis of Results

Possible Locations: Table V presents the possible locations of the hydroelectric power plants, detailing characteristics such as: elevation difference between the chosen pair of points (m), length of the conduction channel (m), estimated flow at 85% persistence (m^3/s) and Estimated Power (MW).

TABLE V. TABLE OF POTENTIAL LOCATIONS WITH THEIR RESPECTIVE CHARACTERISTICS

ID	Q GR2M 85% (m3/s)	Hydroelectric Power (MW)
A	11.33	4.98
B	12.57	5.33
C	13.85	5.76
D	13.05	5.33
E	5.34	2.35
F	11.33	5.07
G	12.57	5.03
H	13.85	6.09
I	20.78	8.97
J	20.75	8.96
K	20.65	8.27

Economic Evaluation: To calculate the investment required for each plant, the graph in Fig. 8 was used. In this graph, the investment cost per MW was estimated by developing a linear regression with information from different hydroelectric projects. Additionally, it shows the formula used to estimate the investment of the hydroelectric power plants.

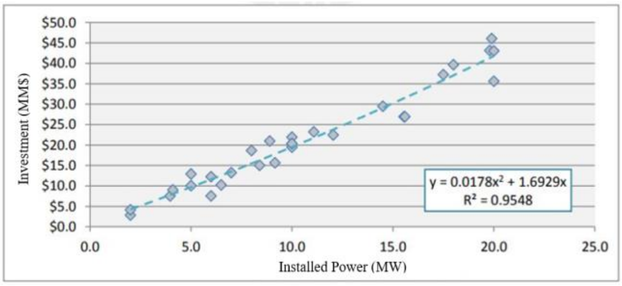

Figure 8. Investment vs installed power graph. Adapted from "Study of development of a hydroelectric generation project" by A. Deyvis and A. Héctor, 2019.

Fig. 9 shows the estimated powers for the 11 alternatives described above.

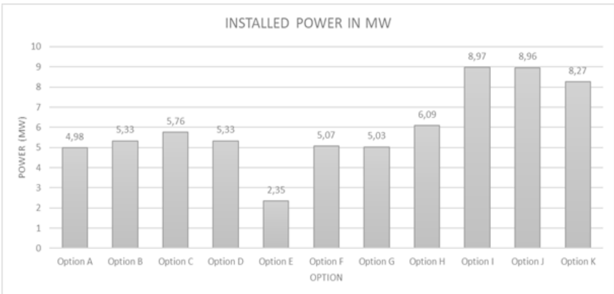

Figure 9. Graph of installed power in MW.

Fig. 10 shows the investment costs for different projects proposed. Among these alternatives, minimum cost was option E with 2.35 MM$ and maximum cost was option J with 8.96 MM$.

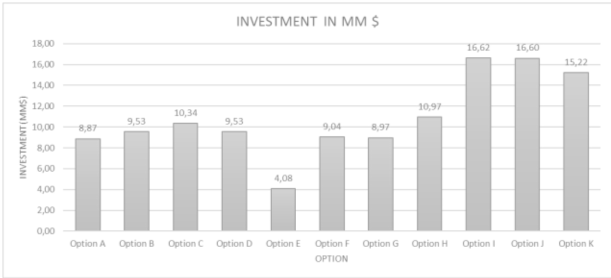

Figure 10. Investment chart in MM$.

In Fig. 11, for maintenance of hydroelectric plants, 2% of investment was considered. Maintenance cost ranged from 0.082 to 0.332 MM $ and an average cost of 0.217 MM $ was obtained among the 11 locations.

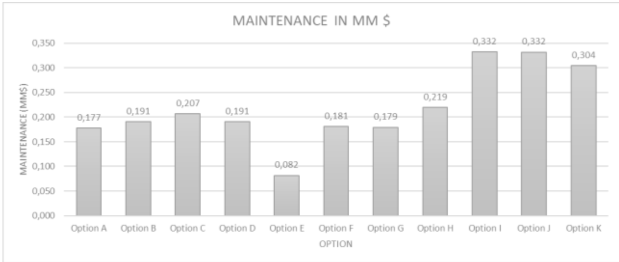

Figure 11. Maintenance chart in MM$.

After conducting economic evaluation, following options were chosen: B and H, which are located in Utcubamba river. Hydroelectric plants that were simulated in these locations have an installed power of 5.33 and 6.09 MW, and operate with flow rates of 12.57 and 13.85 m^3/s respectively.

To perform evaluation between production of simulated hydroelectric plants and existing plants, it was considered that plants operated for eight hours a day. Also, a comparison was made between power plants (simulated and existing) and consumption of the population belonging to Utcubamba basin.

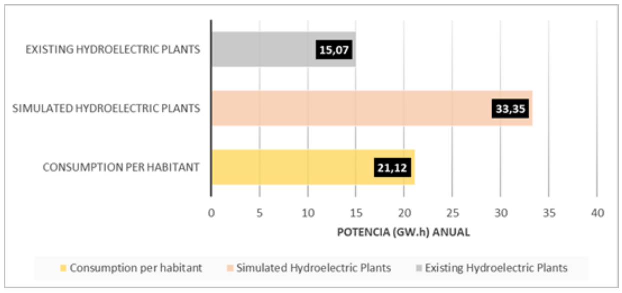

Figure 12. Comparative graph between energy production and consumption.

As can be seen in Fig. 12, simulated stations produce a total of 33.35 GW.h per year; while existing stations generate 15.07 GW.h per year. On the other hand, population's consumption is 21.12 GW.h per year, with an energy deficit by the existing stations of 6.85 GW.h per year.

At present, the application of this hydroelectric potential assessment methodology could help reduce the gap between energy consumption and clean energy production. Satisfying this energy deficit would contribute to the development of rural communities and population centers, which do not have access to energy. In this sense, hydroelectric projects were chosen because of the geographic and hydrometeorological conditions of the Utcubamba basin. In addition, it contributes to reducing the environmental impact because it is considered a clean energy source.

The application of this methodology can be applied at the sub-basin level and even at the national level, with the objective of preliminarily identifying those geographical points suitable for the development of hydroelectric projects. The main difference is the agility in the search for points with help of Matlab algorithm and also the use of satellite information in digital elevation model and hydrological model.

A validation and calibration process were used in digital elevation model and hydrological model with existing projects in the study area. Regarding the geographic location, the algorithm itself located existing hydroelectric power plants with a margin of error of 50 meters. As for flow estimation, satisfactory levels of fit were obtained with GR2M model.

However, the level of detail of the economic evaluation must be improved to consolidate feasibility of proposal, factors such as electromechanical equipment, excavation works, transmission line works, etc. must be considered. Therefore, work is being done to add the recognition of longitudinal profiles within the algorithm, with the objective of improving economic evaluation and obtaining not only preliminary, but also feasible proposals for construction.

IV. Conclusion and Future Research

Final locations chosen were B and H, which obtained 5.33 and 6.09 MW as hydroelectric potential, respectively. These 02 options have a total investment of $ 20.50 million and a total maintenance cost of $ 0.41 million.

Simulated hydroelectric plants based on potential locations estimated with Matlab algorithm manage to satisfy energy consumption of inhabitants of Utcubamba basin, exceeding the energy need by 12.23 GW.h per year. In addition, investment that these require is 20.91 MM $, considering maintenance.

For future research and in order to obtain a more detailed analysis of the project, a survey of topographic information should be done. Likewise, the influence of ENSO on the hydrological model should be used to take the maximum flow rate of the area of study.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both, Carlos Canales and María Gonzales developed the data's collection and processing, and the elaboration of the Digital Elevation Model; Carlos Canales was in charge of the development of code in Matlab for estimation of potential locations; María Gonzales carried out the investigation of Models GR2M and Lutz Scholz, while Carlos Canales investigated model Temez. The analysis of possible locations was developed by both authors and the analysis of results was developed by María González. Both authors wrote the scientific article. Sissi Santos was in charge of advising on the hydrological balance models and the request for hydro-meteorological information from the PISCO - SENAMHI satellite product. All authors had approved the final version.

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