A feasibility analysis of energy harvesting coming from Puerto Rico's rivers

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Abstract - Puerto Rico's location is optimum for receiving constant precipitation all year. It reaches up to 4000 millimeters per year of rainfall and 1000 millimeters of total annual runoff. This precipitation makes Puerto Rico suitable for generating energy from clean sources, such as the sun, air, and water. Currently, the trend is to search for energy alternatives to taking care of the environment, and it should be low costs. Thus, using the flow of rivers will be whether they can generate small amounts of energy without requiring extensive and expensive instruments to access them. Currently, some companies are focusing their efforts on manufacturing small equipment to obtain low-cost energy clean.

Index Terms – water, energy, rivers, Kinetics

I. Introduction

The classification of world climates relies on some climatic parameters, such as temperature and precipitation. As one of the most widely used climate classification systems, the Köppen climate classification divides the world's climates into five primary types: tropical climate, dry climate, temperate climate, continental climate, and polar climate. Puerto Rico is located between 15° to 35° latitude north, and its climate is considered Tropical.

The representative climate in the tropics is warm, humid, and rainy, and this range of areas is received the most significant amount of solar radiation and precipitation. Approximately 40 percent of the land surface is between the earth's tropics. It is home to almost half of the world's population and supports more lives and economic activities in the region. These great attributes of the tropical climate make Puerto Rico a privileged country where great energy resources can be obtained from solar radiation and rainfall [1]. Additionally, Puerto Rico has several water bodies, such as aquifers, rivers, streams, water, and reservoirs.

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Puerto Rico has approximately 47 principal rivers with about 5,385 miles, 224 rivers secondaries, and 553 named streams. These are fed by the high precipitation all year. The mean annual rainfall is 30.0 in/yr (768 mm/yr). Pronounced orographic effects from the Cordillera Central and the Sierra de Cayey mountains in Puerto Rico result in high rainfall amounts occurring on the windward side of the mountains, which is north of the insular hydrologic divide. The high precipitation and shallow water table contribute to the rivers holding up significant flows throughout the year.

This study will allow us to know if there is any possibility of converting the kinetic energy from rivers to electrical energy using a small and simple system and applying lower quantities of potential energy.

II. Study Area

The first step for this feasibility analysis is to study the geomorphological characteristics of the rivers in Puerto Rico. Three (3) of the most important rivers were selected: Rio de la Plata, Rio Grande de Añasco, and Rio Grande de Loiza. The river la Plata extends from Cayey to Dorado with 58.5 miles; Rio de la Plata is Puerto Rico's longest river. It also has the third-largest basin, with a catchment area of 200.2 square miles. The monitor of this river's precipitation, discharge, and water quality is in charge of USGS; this river has six stations, USGS 50045010, 50046000, 50043800, 50043000, 50044000, and 50042500. The first three stations measure water discharge, gauge height, precipitation, and water quality. All stations in Puerto Rico are managed by the CFWSC (Caribbean-Florida Water Science Center). Data from these stations (and all the other stations in the United States of America) are publicly accessible through the USGS (United States Geological Survey) official site.

For this study, data were analyzed monthly from 2010 to 2020. Some products, such as average discharge and gauge height, were analyzed to know if the Rio de la Plata is feasible for energy harvesting. The goal will be to generate at least 25 watts of energy. Station USGS 50046000 was selected because it is the closest to the river's mouth. See Figure 1.

Fig. 1. Río de la Plata´s drainage área (USGS)

Data from USGS station 50043800 (Latitude 18°13'19.77", Longitude -66°13'28.63") Rio de la Plata at Comerio shows the lowest average precipitation readings in the years 2017 to 2020 were in June, May, and February, with rainfall of 2.29, 2.57 and 2.69 inches, respectively. Within this same year, it is observed that the wettest months were the months of September, March, October, and July, with precipitation averages of 10.37, 5.69, 5.48, and 5.1825 inches. The data from the USGS station 50045010 (Latitude 18°20'45.62", Longitude66°14'19.73") Rio de la Plata BLW la Plata Damsite were evaluated. The flow found in the Rio la Plata tends to be lower between January to June, with an average of 140 cubic feet per second, and higher from July to December, with 345 cubic feet per second.

For Río Grande de Añasco, USGS station 50144000 (Latitude 18°17'03.00", Longitude 67°03'03.46") Rio Grande de Anasco NR San Sebastian, the average precipitation readings through the years 2018 to 2020 were the lowest in January, February, and December, with rainfall of 1.65, 1.85 and 2.0 inches, respectively. Within this same period, it is observed that the months with the highest precipitations were those of June, July, August, and September, with precipitation averages of 11.4, 17.6, 13.2, and 13.8 inches. In addition, the flow found in the Rio Grande de Añasco tends to be lower between December to May, with an average of 203 cubic feet per second, and higher in July to December, with an average of 641 cubic feet per second. See Figure 2.

Fig. 2 Río Grande de Añasco drainage área. (USGS)

For Río Grande de Loíza, precipitation data from USGS station 50059050 (Latitude 18°20'32.17", Longitude 66°00'21.51" NAD27) Rio Grande de Loiza BLW Loiza Damsite shows that the lowest average precipitation readings throughout years 2018 to 2020 were in April, May, and June, with precipitation values of 2.8, 3.5, and 1.6 inches. Within this same date, it is observed that the wettest months were the months of July, August, and October, with precipitation averages of 7.5, 6.1, and 6.2 inches. Evaluating the discharge data from the USGS station 50059050 (Latitude 18°20'32.17", Longitude 66°00'21.51" NAD27) Rio Grande de Loiza BLW Loiza Damsite, the flow found tends to be lower from December to April, with an average of 106.4 cubic feet per second, and higher in July to December, with an average of 525.8 cubic feet per second. See Figure 3

Fig. 3 Río Grande de Loíza drainage área. (USGS)

II. KINEMATIC TO ELECTRICAL ENERGY

A great variety of processes have been used for many years to generate electricity from renewable sources. These methods, such as wind energy, use the winds to generate electricity. Solar energy takes advantage of the photovoltaic rays generated by the sun's rays to produce electricity, and hydroelectric energy, takes advantage of most of the water; this system uses kinetic and potential energy generated by the flows of the rivers [2]. The type of electrical energy has been in use for many years. At the end of the 19th century, in 1879, the first hydroelectric power station was built in Niagara Falls. Electrical energy has already managed to suffice almost a fifth of the electricity in the world since it is the cheapest way to generate energy due to the raw material being built. The energy source is clean and renewable throughout the year through de-icing and rainfall; it can be reused, thus reducing the obtaining of energy by methods such as the burning of fossil fuels which generate an increase in the greenhouse effect [2]. However, this hydroelectric system destroys flora and fauna and other natural resources since, by controlling the flow of water, the migrations of fish and other natural systems can be affected, which is harmful to fluvial habitats.

A *hydroelectric system* is a complex system that has begun to be implemented exponentially. It is mainly used to obtain large amounts of electricity, enough to auction a town, city, or country. To obtain large amounts of electricity, area necessary specific characteristics in the body of water and equipment to be used.[3] There is a wide variety of methods for obtaining electrical energy from bodies of water such as rivers. They usually are large dams with construction that obstructs the river's flow, being in total control of the human being. Humans are the ones who control when and how much water they will let flow through the dam.

The hydroelectric giants consist of a large dam that accumulates water and open gates. The water flows with great potential energy. The water collides directly with some turbines, making them rotate, achieving that with this tremendous kinetic and potential energy, mechanical energy (energy of movement) is created. Unlike planning to transform kinetic energy into electrical energy, it is possible to find many methods. However, the most common is a turbine connected directly to a generator that transforms mechanical energy into electricity.[3]

However, the most common method in large installations is that the turbine is directly connected to a generator composed of a rotator covered by some conductive material such as copper. At the same time, this generator is surrounded by magnets creating thus electromagnetic energy formed by induction junction to a series of cables that transfer the residual energy from the generator to a transformer which transforms all the residual energy into electricity. On the other hand, as these hydroelectric systems exist on a large scale, they also exist on a small scale, such as micro-hydroelectric systems. These systems work mainly with bodies of water in which there is no fall, or the waterfall is tiny. The strategies focus on energy production through the flow of the body of water. Of course, there are more hydroelectric systems. They are relatively small systems whose primary function is to obtain electricity in small quantities to satisfy basic needs. These small-scale hydroelectric systems can generate 4 to 12 kWh per day [3].

IV. ELECTRICITY WITHOUT POTENTIAL ENERGY

It is possible to obtain electrical energy from a river depending on its flow or velocity. The river flow provides velocity for the turbine to convert kinetic energy into electrical energy. The turbine activates a generator responsible for converting all residual energy into electricity.

For these small-scale hydroelectric systems to function correctly, a turbine is needed, which is small enough but efficiently effective. The turbine must have the ability to operate efficiently at different depths. The generator must be 100% waterproof since this system will directly contact the water.[3] A converter is needed in which the energy loss in the process is minimal. The Idénergie company has made a breakthrough in the efficiency of these small-scale hydroelectric systems [4]. The ability to operate with a depth of 2 feet with a turbine that is only 66 cm high and feels 32 cm wide makes it portable. This turbine made of aluminum and stainless steel makes it more accessible than cheap materials, which facilitates their maintenance. Referring to this generator, Idénergie created a small generator that is 100% waterproof and highly efficient in rivers with little flow. This sealed generator achieves a longer production of any water.[4]

The company demonstrated that it is possible to obtain electricity efficiently with only the current of the river flow. Those results were that the stronger the current, the more significant the amount of electricity obtained. As seen in Table I [4].

TABLE I
RELATIONSHIP BETWEEN WATER VELOCITY AND DAILY PRODUCTION

Water velocity (m/s)	1	1.5	2	2.5
Daily production (KWH/DAY)	2.3	4.7	7.8	11.6

V. EQUIPMENT USED

In transforming kinetic energy into electrical energy, taking advantage of the flow of rivers, specific equipment is necessary which is as efficient as possible. For a hydroelectric system, a turbine is used, which is responsible for converting all the kinetic energy of the river water that passes through it into mechanical energy. A generator is responsible for converting all that mechanical energy into electrical energy and, depending on the flow and fall of the river, the relevant materials so that the system is stable and efficient [4].

Hydroelectric systems are somewhat expensive due to the enormous raw material and investments required. However, at the same time, it is the cheapest way among all others to generate electricity. This process consists of billions of dollars divided between the creation and maintenance of the system. This system is the most economical since hydroelectric energy is a constant resource compared to solar renewable energy. In contrast, solar energy can only be obtained when the photovoltaic rays emitted by the sun are obtained directly. Therefore, this system is more cost-effective than all the competition. In (fig. 4), there is a particular increasing trend for the different sizes of hydroelectric systems. In contrast, the need for capacity of the hydroelectric plant is greater, and the investment would continue to increase. For example, if the capacity needed is 500 megawatts, the approximate investment for the construction of this plant is 100 to 1000 million dollars, as can be seen in (Figure. 4).

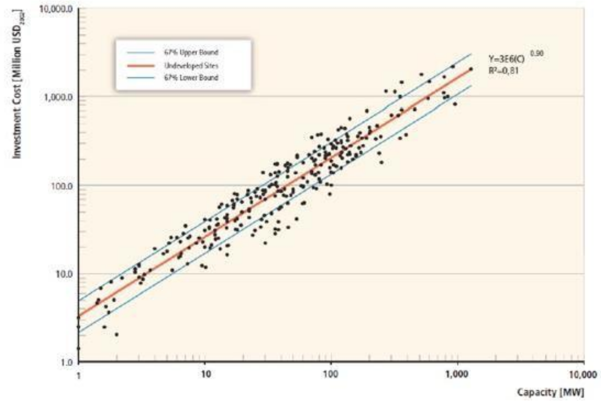


Fig. 4. investment costs of hydroelectric plants as a function of capacity [2]

Likewise, by maintaining control of the rotation speed, this generator has a technological plate responsible for varying the speed within the generator cover, safe since it is fully sealed; this variance oversees starting the automatic turbine and continuous energy optimization. A miniature hydroelectric system and excellent electrical efficiency, which is easy to install, does not need great experts or a great team to install and operate it.[4] As can be seen in the figure below, this system achieves excellent results and expresses that the stronger the flow, the more electricity it can generate; for example, if the flow is 1 meter per second (m/s), the amount of electricity it can generate. It is 2 kWh per day, while if the flow is 3.5 meters per second (m/s), then the amount of electricity it can generate is 14 kWh. see Figure 5.

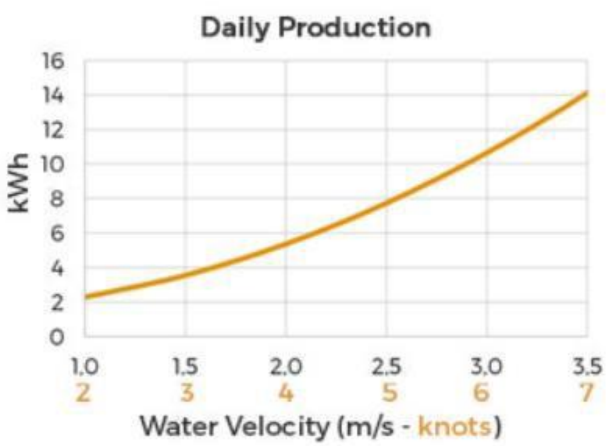
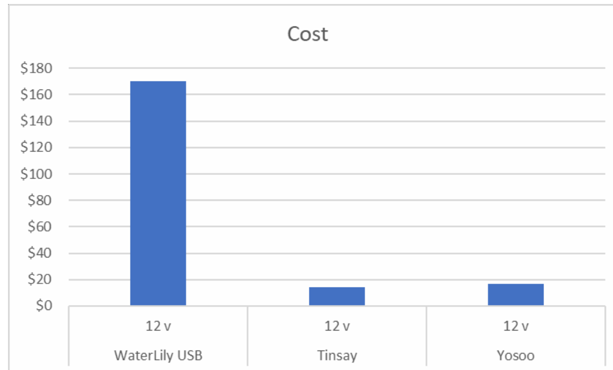


Fig. 5. Daily Production Energy [4]

They know how this company managed to create a hydroelectric system at such a level that it can auction the basic needs of a home. However, all these inventions have given way to hydroelectric generators, which are significantly small, and serve to generate tiny amounts of electricity. The WaterLily USB generator, the Tinsay generator, and the Yosoo generator are waterproof generators and have excellent efficiency.

These generators can obtain small amounts of electricity, but at the same time, they are portable and inexpensive, as can be seen in Table II.[5]

TABLE II
RELATIONSHIP BETWEEN COST ENERGY AND GENERATORS



Puerto Rico has a great diversity of rivers, each of which has its distinctive property; some have a more substantial flow, some have significant falls, etc. These miniature systems can be applied to Puerto Rico with great ease due to their cost and efficiency, and they are all made of eco-friendly materials such as aluminum and stainless steel. The portability of these generators is of the utmost importance since being relatively small does not need heavy machinery to move or install them; a single person can manipulate these systems. Table III shows the components for the elaboration of a microturbine.

TABLE III
MICRO TURBINE COMPONENTS

Turbine	Distributor	It is where the blades are located, responsible for regulating and directing the flow of water.
	rotor	It is the part where the kinetic energy of the water flow is transformed into mechanical energy.
Generator	Stator	Immobile part that is responsible for storing electricity. In the stator there are coils, the coils are responsible for producing electricity.
	coils	Conductive material responsible for generating electric current, through a magnetic flux. Normally it is copper or antioxidant wire.
	Rotor	Rotating part in which several magnets are located necessary so that together with the static bobbins an electromagnetic field can be generated.
bridge	Piece that connects the turbine rotor with the generator rotor, and responsible for transmitting mechanical energy.	
cover	It is what surrounds certain parts of the System, such as the generator, so that it is waterproof.	

Using another alternative is exposed by Maldonado (2005), which uses an inclined rotor with materials of stainless steel and aluminum alloys. This turbine needs a minimum speed of 1 m / s. And with a velocity of 1.8 m / s and a depth of 1.6 m, a hydraulic power of 800 Watts can be obtained. [6].

A comparative graphic of power production was elaborate between Indenergi and the data obtained by Maldonado [7]. The power generated for both was similar. See Figure 6.

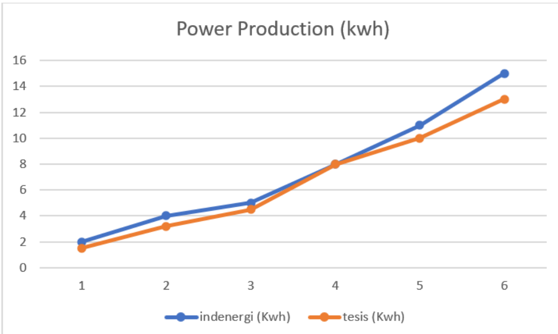


Fig. 6. Power Production

VI. Flow Analysis

Once the tools and equipment used to generate energy are known, the feasibility of producing energy in the rivers of Puerto Rico can be determined by evaluating the available values of flow and gage height provided by the USGS and calculating the cross-sectional area of each river. To obtain the cross-section areas of rivers, these were located by entering the coordinates provided by USGS in Google Earth to estimate the top width. A trapezoid figure was then assumed to calculate the bottom width of the rivers, using the equation for open-channel flow: b = t - 2my, where b is bottom with, t is top width, and m is a slope cross-section (which it is assumed to be 2), and y is gage height. See Table IV.

TABLE IV
Cross-Sectional Equations for Open-Channel Flow

Section Type	**Area (A)**	**Bottom width (b)**
 Trapezoid	$A = (b + my)y$	$b = t - 2my$

For the Rio la Plata station, see Figure 7. The yellow pin marks the station's coordinates, Latitude 18°24'41.72", Longitude -66°15'39.45". The estimated top width corresponding to the base flow is 19.96 meters. Altitude: 21 m. (69ft) msl.

Fig. 7 Río de la Plata USGS 50046000

Figure 8 shown a streamflow representative for a period of six days of La Plata river.

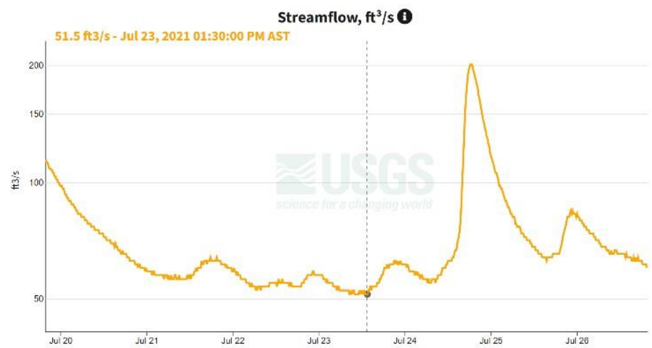


Fig. 8 Río de la Plata streamflow USGS 50046000

Similarly, Figure 9 presents yellow pin marks that mean the coordinates of the station Rio Grande de Anasco, Latitude 18°17'03.00", Longitude -67°03'03.46". The estimated top width corresponding to the base flow is 23.05 meters. Altitude: 29 m. (95 ft) MLS.

Fig. 9 Rio Grande de Añasco USGS 50144000

Figure 10. shown a streamflow representative for a period of 21 days of Rio Grande de Añasco according USGS.

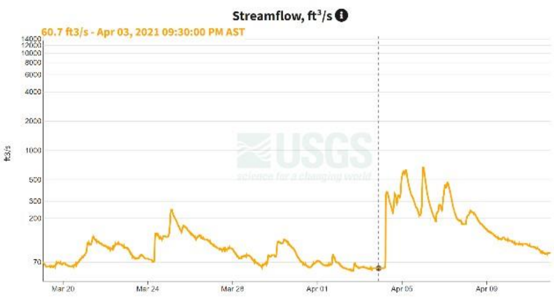


Fig. 10. Rio Grande de Añasco Streamflow USGS 50144000

Another station analyzed was in the Rio Grande de Loiza. The yellow pin marks the coordinates of the station, Latitude 18°20'32.17", Longitude -66°00'21.51". The estimated top width corresponding to the base flow is 23.05 meters. Altitude: 56 m. (184 ft) MLS. See Figure 11.

Fig. 11 Río Grande de Loíza USGS 50059050

Figure 12. shown a streamflow representative for a period of six days of Rio Grande de Loiza, according USGS.

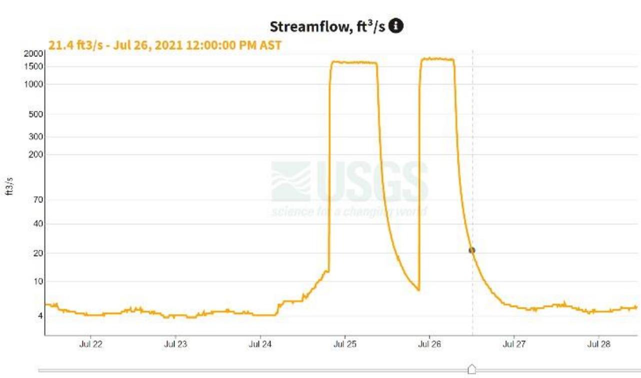


Fig. 12. Río Grande de Loíza streamflow for USGS 50059050

Additionally, for this analysis was selected some days where the rivers reached the peak flow. The next Figures 13, 14, and 15 show the peak flow selected for this study in each river.

For Rio la Plata, the highest registered streamflow in 2020 was on July 30, 5:15 PM AST. It was estimated that for 25000 ft^3/s of flow, the top width would be around 37.76 meters—Figure 13.

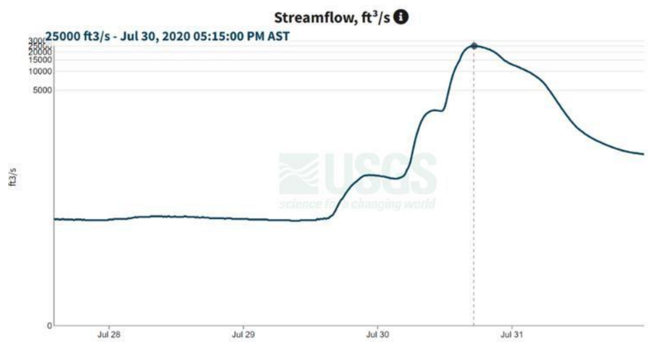


Fig. 13 Río de la Plata peak streamflow in 2020 USGS 50046000

For Rio Grande de Añasco, the highest registered streamflow in 2020 was on July 30, 7:40 PM AST. It was estimated that for 12000 ft^3/s of flow, the top width would be around 36.77 meters. Figure 14.

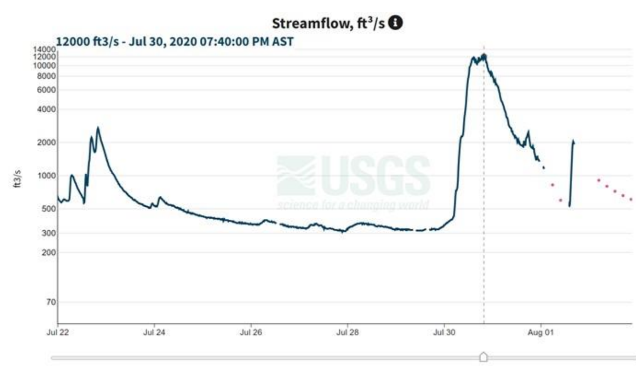


Fig. 14 Río Grande de Añasco peak streamflow in 2020 USGS 50144000

For Rio Grande de Loiza, the highest registered streamflow in 2020 was on July 30, 12:50 PM AST. It was estimated that for 62,700 ft^3/s of flow, the top width would be around 60.29 meters. Figure 15.

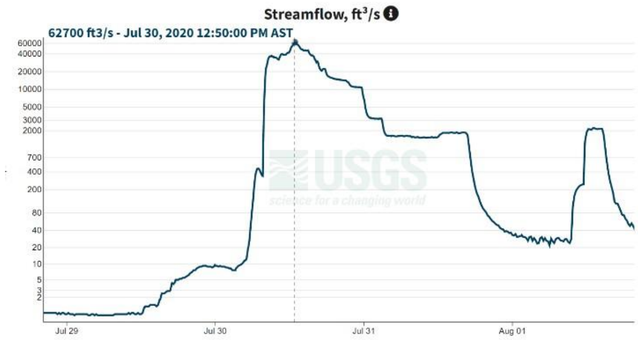


Fig. 15 Río Grande de Loiza peak streamflow in 2020 USGS 50059050

To establish the power generated by the river flow was necessary to apply a series of equations to estimate the factor most important in this case, velocity, and in this way compare with the values of energy found in several alternatives such as Idénergie and the exposed by Maldonado.

All the variables of the cross-sectional area are known, and the velocity was calculated using the equation Q = V * A, where V is the velocity and A is the area, knowing the flow (Q) and area (A). Table V shows the parameter obtained for each river and the velocity calculation results using baseflow.

The economic topic is fundamental for all energy research; a university team worked on new product development to reduce the energy costs associated with general illumination. The research deliverables include the development of a business plan that proposes a substitution of the current energy source with an eolic alternative. The proposed application could result in approximately $ 100 million savings annually [9]; this represents an enormous energy saving.

TABLE V
RIVERS´ PARAMETERS FOR BASEFLOW

Measurements	Rio Grande de la Plata	Rio Grande de Añasco	Río Grande de Loiza
t: TOP WIDTH, ft	65.48876	75.62705	74.44589
Q: DISCHARGE, ft^3/s	51	60.7	21.4
y: HEIGHT, ft	3.2	3.12	5.79
m: SLOPE	2	2	2
b = t - 2my, ft	52.68876	63.14705	51.28589
(b + my) y = A, ft^2	189.084032	216.487596	363.9935031
Q/A = V, ft/s	0.269721348	0.280385579	0.058792258

Table VI shown the parameter obtained for each river and the results of the velocity calculation using peak flow.

TABLE VI
RIVERS´ PARAMETER FOR PEAK FLOW

Measurements	Rio Grande de la Plata	Rio Grande de Añasco	Río Grande de Loiza
t: TOP WIDTH, ft	123.88	120.64	197.81149
Q: DISCHARGE, ft^3/s	25000	12200	62700
y: HEIGHT, ft	19.95	12.16	35.24
m: SLOPE	2	2	2
b = t - 2my, ft	44.08	72	56.85149
(b + my) y = A, ft^2	1675.401	1171.2512	4487.161708
Q/A = V, ft/s	14.92180081	10.41621131	13.97319822

VII. Conclusion

For each river, two different flows were used, based on the maximum and minimum flow, that is, the flow when there is maximum rainfall and the flow only with the base flow of the rivers. As can be seen from the data, the river's baseflow capacity to produce electricity is dim. Thus, it is discarded. However, for maximum flow rates, it is possible to use the instrument proposed by the Idénergie company, which suggests the following power production according to the speed of the fluid.

Considering the comparison between the two possible alternatives to implement in Puerto Rico, it can be observed that both systems have considerable efficiency and can be used in the rivers of Puerto Rico. Now, both have different costs regarding their efficiency. However, suppose it refers to quality and price. In that case, the alternative obtained by Maldonado becomes a viable alternative since the financing of this system is practically 2/3 compared to the system provided by the Idenergie company.

VIII. Acknowledgment

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