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ESTIMATE OF AVERAGE ENERGY GENERATED IN A RIVER BASIN BY STATISTICAL ANALYSIS FOR SMALL HYDROPOWER PLANTS

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Abstract. The estimate average energy generated is one of the important aspects analyzed during the first stage of the deployment of a small hydropower in Brazil, the Estimate of Hydropower Potential. In this scenario, knowledge of water availability is a fundamental part of the hydrologic studies of a river basin, studies pertaining to the stage of the cycle to determine the flow of a river or precipitation in a location or region, including its temporal variability. In this context, this work has the objective to perform a statistical analysis to determine the values of the variables that affect the calculation of the average energy: a reference flow, the average monthly flows and the permanence curve. It was used the data from streamflow time series 1942-2013 of the river Tijuco, in the state of Minas Gerais. In the analysis of the variables, it was necessary to know and study agencies and legislation, a probabilistic model and computational tools to help determine the values. It was found that the statistical hydrology in the process of estimating the average power for hydroelectric projects provide reliable data and that the interpretation of the data can support the decision in the phase of projects.

Keywords

Average energy, Small Hydropower, Statistical analysis, Flow

1. Introduction

To obtain the authorization for hydroelectric project characterized as Small Hydro Power Plant (SHPP) in Brazil, there are some steps to follow. They are: Estimate of Hydropower Potential; Hydropower Inventory; Feasibility; Basic Project; Executive Project [1].

In the Estimate of Hydropower Potential occurs the identification and initial assessment of the utilization of a basin, river, site, section, segment or Local, to obtain permission to proceed to the next step. It aims to contribute to the organization of a structure analysis of technical, social, environmental and economic aspects of a preliminary way.

This step serves as a help to verify of attractiveness of a basin river that SHPP's enterprises need to culminate decisions and advance the studies of Hydropower Inventory. As the analyses of the aspects occur secondarily, based on data from specialized agencies and institutions, there is not necessity of investment in next studies where it was possible to identify some objection or analyse which aspects deserve more investment in the phase of Hydropower Inventory [1].

The hydrologic study is one of the most important sessions at any step of the SHPP's project. In the Estimate of Hydropower Potential, the knowledge and development of a hydrologic study are responsible for checking the hydric availability, in other words, the flow, in m³/s, used to estimate the energy produced in a river basin.

According to [2], the flow (Q) must be estimated of the date from hydrometric stations in the basin and that it can be the minimum flow measured (Q_{min}), the common flow in 95% of the time ($Q_{95\%}$) or the average flow along the critical period of the Interconnected System in Brazil (Q'). These flow values are found after statistical analysis of data from hydrometric station and used to estimate the average energy.

In this context, this work presents a hydrologic study in the step of Estimate of Hydropower Potential in a river basin for the installation of SHPP using statistical hydrology to determine the flow and the estimate the average energy.

2. Hydrologic Study

The hydrologic study appears as a session where one of the variables to calculate the average energy or average power is found to estimate the energy potential of a river basin for the installation of SHPP, the flow or hydric availability, given in (m³/s). The Eletrobras Guidelines for SHPP Project apply some concepts and procedures to determine the flow. They are [2]:

- The flow for the local must be estimated from data of hydrometric stations of the basin/region;
- It must be established for the local a series of monthly average flows derived from a time series of a

station located in the same watercourses or in the same basin;

- It is possible to perform a direct correlation among drainage areas of the same basin, limited the difference among them of 3 to 4 times. The correlation equation is defined by (1):

$$\mathbf{Q_1} = \frac{\mathbf{A_1}}{\mathbf{A_2}} * \mathbf{Q_2} \qquad (1)$$

where
$\mathbf{A_1}$: drainage area of the local [Km²]
$\mathbf{A_2}$: drainage area of the hydrometric station [Km²]
$\mathbf{Q_1}$: flow of the local [m³/s]
$\mathbf{Q_2}$: flow of the hydrometric station [m³/s]

- The historical series must have at least 25 years of registry;
- The flow can be the minimum flow measured (Q_{min}), the common flow in 95% of the time ($Q_{95\%}$) or the average flow along the critical period (Q') of the Interconnected System in Brazil (June/1949 – November/1956).

According to National Water Agency in Brazil, there are 4.543 monitoring stations, strategically located in several Brazilians river basins, capable of measuring volume of rain, evaporation of water, the level and flow of the rivers and water quality [3].

Thus, the application of hydrologic study, from historical series of flows in a river basin, to determine the possible project flows, is characterized as a good method to be applied during the first step to obtain the authorization for hydroelectric project due to the large number of existing stations with data flows in Brazil.

A. Rights of Use of Water Resources

Every building or business that uses or affects water resources is subject to the legislation. The National Water Agency is a Brazilian federal organ responsible for the water resources and its mission is planning and coordinating the management of water resources and to regular the use of water, promoting the sustainable use.

The hydrologic studies need to associate, in its accomplishment, to the regulatory aspects of utilization of water resources that environmental agencies, in the state and federal levels, ensure for environmental licensing, granting and construction of dams. It is important in the hydrologic studies the knowledge of current legislation of the federal agency, and also of the state agencies where the SHPP will be constructed.

B. Hydrology Statistics

The knowledge of water availability is a fundamental part of the hydrologic studies of a river basin, studies pertaining to the stage of the cycle to determine the flow of a river or precipitation in a location or region, including its temporal variability [4]. Therefore, it is necessary to utilize same statistic values that describe the hydrologic behaviour of the river.
As described previously, the flows of reference for SHPP projects are the minimum flow measured (Q_{min}), the common flow in 95% of the time ($Q_{95\%}$) or the average flow along the critical period (Q') of the Interconnected System in Brazil (June/1949 – November/1956). These flow values are found after statistical analysis of the time series at the selected local. With the reported perspectives, the analyses include the calculation of the following statistical variables:

1) *Average Flows.* The average flow or average precipitation is the average of the entire series of flows or precipitation recorded, and it is important in the evaluation of the total hydric availability in a basin. The average monthly flows represent the average flow for each month of the year, and they are important to analyze the seasonality of a river [4].

   The average flow was found by (2) [4]:

$$\mathbf{Q_{ave}} = \frac{\sum_{i=1}^{n} \mathbf{Qi}}{\mathbf{n}} \qquad (2)$$

   where: $\mathbf{Q_{ave}}$ is the average flow [m³/s] (daily, monthly or yearly) and $\mathbf{n}$ is the number of available data (daily, monthly or yearly).

2) *Permanence curve.* The permanence curve relates a value of flow with its probability of occurrence equal to or higher value at a certain time. It can be established based on daily, weekly or monthly values for the entire period of available time series. The elaboration of the curve is one of the most important stats analyses in hydrology and hydropower projects [2].

   The permanence curve assists in the analysis of flow data determining the constancy of its values, percentage of the time that the river presents flows in certain range. In hydropower projects, it can be used to determine the installed the power to be installed. For the calculation, the common flow in 95% of the time ($Q_{95\%}$) is utilized [2].

3) *Flow of seven days with recurrence period of ten years.* The $Q_{7,10}$ flow is the average annual minimum flow of 7 days (Q_7) with a return period of 10 years. It is used in some Brazilian states as reference flow for granting of the use of hydric resources [5].

   For this study the function of the Weibull distribution was applied to be regarded as one of the most common distributions parameters used in calculating minimum river flows [5] – [7]. To use the adjustment of the Weibull distribution, the average and standard deviation of the values of Q_7 were calculated. Then, it was determined the variation coefficient (VC) according to (3) [6]:

$$\mathbf{CV} = \frac{\textbf{standard deviation}}{\textbf{average Q7}} \quad (3)$$

Thus, the parameters of the Weibull distribution α, A(α) e β were calculated by (4), (5) and (6) [6]:

$$\alpha = 1{,}0122 \,.\, \mathrm{CV}^{-1{,}077} \quad (4)$$

$$\mathrm{A}(\alpha) = 0{,}9982 - 0{,}4419 * \mathrm{CV} + 0{,}4360 * \mathrm{CV}^2 \quad (5)$$

$$\beta = (\text{average Q7})/\mathrm{A}(\alpha) \quad (6)$$

The minimum flow for the return time (Tr) required ($Q_{7,10}$) was calculated by (7) [6]:

$$\mathbf{Q_{7,10}} = \boldsymbol{\beta}\left[-\mathbf{ln}\left(\mathbf{1} - \frac{\mathbf{1}}{\mathbf{Tr}}\right)\right]^{\mathbf{1/\alpha}} \quad (7)$$

C. Ecological flow

Coupled with the environmental factor during the hydrologic studies it is necessary to identify which ecological flow required for the preservation of the natural features of the basin.

Ecological or Residual flow is the demand of water to keep in a river in order to ensure the maintenance and conservation of natural aquatic ecosystems, landscape of scientific or cultural interest. It is a reference value that must be kept on the stretch of the river situated downstream from a dam.

In general, the fixing of ecological flows in Brazil has been done mainly through the state legislation at the federal level. It is very important to know the environmental agencies responsible for the hydric resources and the legislations [7].

3. Estimate of the Average Energy

The assessment of the hydropower potential considers two variables as relevant: heading and flow, according by (8) [2]:

$$\mathbf{P_{ef}} = \mathbf{9{,}81} * \boldsymbol{\eta} * \mathbf{Q} * \mathbf{H_{liq}} \quad (8)$$

where
$\mathbf{P_{ef}}$: effective power [KW]
η: efficiency of the units turbine-generator
Q: average flow [m³/s]
$\mathbf{H_{liq}}$: heading [m]

During the step of the estimate of hydropower potential develops the estimate average energy (or average power) that it can be produced on site, relevant aspect in this step. Generally, this estimate is based on historical series of flows, defined in hydrologic studies for the site, and the heading, defined from the perception of the arrangement of the plant.

For this work, a study to the estimate the average energy of a site was applied of preliminary form. The variables used for the calculations, flow and heading, were separated and it was considered only the flow for the calculation. Thus, the average energy was estimated based on the variation of flow and according to the yield curve of hydraulic turbines. The yield curve of hydraulic turbines considers the variation of flow (turbinable flow/ maximum flow) with constant height. Consequently, the average power becomes a variable depending on the height.

Thus, the calculation is in accordance by (9):

$$\mathbf{P_{ave}} = \mathbf{9{,}81} * \boldsymbol{\eta} * (\mathbf{Q} - \mathbf{Q_{eco}}) \quad (9)$$

where
$\mathbf{P_{ave}}$: average power [KW/m]
η: efficiency of the turbine
Q: average flow [m³/s]
$\mathbf{Q_{eco}}$: ecological flow [m³/s]

The separation of variables for calculating the average power was made because the arrangements defined in this first stage are representative, presenting only basic characteristics. Thus, utilizing the hydric availability to verify the energetic potential of the local, object of study of this work.

4. Material and Methods

For the application of statistical hydrology to determine the flow a river basin and the estimate average energy generated for a SHPP was chosen the basin of the river Tijuco, limited to the city of Ituiutaba, Minas Gerais. The choice of the site of application of the methodology was motivated for being a region that already has deployed SHPP, under construction or requires authorization to operate.

The river basin Tijuco, municipality of Ituiutaba - MG-Brazil, with an approximate area of 1.335,1 Km², region of great economic significance to the State of Minas Gerais, located in the Minas Triangle, between the geographical coordinates 18º40 ' the 19º47' S and 47º53 'the 50º13' W [8].

According to the National Information System about Hydric Resources (SNIRH), coordinated by the National Water Agency, within the municipality of Ituiutaba, there are two monitoring stations of hydric resources of the Tijuco river. For this work, it was chosen the Ituiutaba station because it has a historical series with data of the last 72 years (1942-2013) [3].

The Ituiutaba station is located at coordinates 18º56' and 49º26', 563m elevation and drainage area of 6310 km² [3]. It was observed that for some years there was a lack of recorded data at certain times, but that does not compromise the accuracy of the calculations because it is a small percentage, about 1%, compared to the number of recorded data.

The river basin is located in the state of Minas Gerais. In the state, the Mining Institute of Water Management is responsible for planning and promoting measures aimed at preserving the quantity and quality of water of Minas Gerais. So, It was necessary to know the laws of the Institute for the calculations. The main laws will be highlighted during execution.

With the historical series of flows of Ituiutaba station proceeded the calculations to determine the average flow, the permanence curve, $Q_{7,10}$ flow and, subsequently, the estimate of average energy of the Tijuco river and analyzed the hydropower potential through the results.

5. Results and Discussion

From the historical data of the Ituiutaba station was calculated the average monthly flow to represent the minimum expected volume of water in an average year. Table I shows the average global monthly flow of the Tijuco river.

Table I. - Average monthly flow of the river Tijuco

Month	Flow (m³/s)	Month	Flow (m³/s)	Month	Flow (m³/s)
January	160,85	May	75,92	September	40,27
February	164,18	June	60,99	October	56,22
March	149,73	July	51,76	November	78,93
April	113,14	August	42,36	December	125,01

It is observed that the highest flows occur in February and the lowest in September (Table I), a direct consequence of the rainfall seasonality, which occur in concentrated form in the summer (Dec to Feb).

It is also noteworthy that the global average flow (Q_{glo}) is **93,28** [m³ / s] and the average flow along the critical period of the Interconnected System in Brazil (Q') is **44,68** [m³/s]. This period is the interval between June/1949 to November/1956.

The permanence curve was constructed with the average monthly flows (Table I). The values for the permanence curve found are in Table II. Figure 1 shows the graph of the permanence curve of the Tijuco river.

Table II. - Flow values with its respective probability of occurrence over time

Duration	Flow [m³/s]	Duration	Flow [m³/s]
0%	164,18	55%	75,18
5%	162,35	60%	66,97
10%	159,74	65%	60,28
15%	153,62	70%	57,65
20%	144,79	75%	55,10
25%	131,19	80%	52,65
30%	121,45	85%	48,47
35%	114,92	90%	43,30
40%	99,46	95%	41,42
45%	80,64	100%	40,27
50%	77,43		

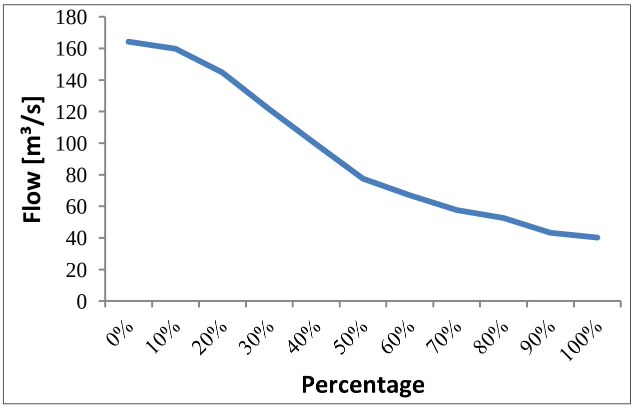

Fig. 1. Permanence curve

Some points of the curve permanence receive more attention. As the aim of the study is for hydroelectric purposes, the point of greatest highlight is the flow $Q_{95\%}$, which it has a value of **41,42** [m³/s]. This flow value can be used to define the assured energy at a hydroelectric project in Brazil.

The values of the lowest moving average of seven consecutive days (Q_7) found for each year are shown in Table III.

Table III. - Values of moving average of seven days

Year	Flow [m³/s]	Year	Flow [m³/s]	Year	Flow [m³/s]	Year	Flow [m³/s]
1942	31,5	**1960**	21,3	**1978**	28,51	**1996**	34,2
1943	31,61	**1961**	19,1	**1979**	33,64	**1997**	33,70
1944	30,41	**1962**	23,21	**1980**	52	**1998**	30,12
1945	-	**1963**	15,6	**1981**	22,2	**1999**	28,31
1946	-	**1964**	-	**1982**	51,99	**2000**	25,50
1947	-	**1965**	-	**1983**	49,63	**2001**	22,30
1948	29,04	**1966**	33,54	**1984**	46,47	**2002**	15,02
1949	20,13	**1967**	36,57	**1985**	40,23	**2003**	31,78
1950	19,44	**1968**	32,13	**1986**	33,43	**2004**	20,51
1951	23,9	**1969**	18,93	**1987**	41,43	**2005**	28,67
1952	21,5	**1970**	25,5	**1988**	37,59	**2006**	42,59
1953	20,13	**1971**	7,41	**1989**	35,93	**2007**	26,2
1954	9,6	**1972**	28,01	**1990**	37,8	**2008**	27,99
1955	6,03	**1973**	28,87	**1991**	43,51	**2009**	51,14
1956	18,93	**1974**	29,1	**1992**	43,09	**2010**	29,14
1957	22,53	**1975**	53,5	**1993**	51,79	**2011**	3,65
1958	34,45	**1976**	35,19	**1994**	40,4	**2012**	29,96
1959	28,7	**1977**	38,1	**1995**	38,7	**2013**	32,51

Some years do not show their values due to the small number of recorded data for that year, previously cited. The $Q_{7,10}$ flow and the variables involved in the calculation are shown in Table IV.

Table IV. – $Q_{7,10}$ flow and variables

Average Q_7	Standard deviation Q_7	CV
30,53 **(**m³/s)	11,25	0,37
α	**A (α)**	**β**
2,97	0,89	34,13
	$Q_{7,10}$ Flow	
	16 (m³/s)	

In the State of Minas Gerais, the ecological flow is 70% of the $Q_{7,10}$. Thus, the ecological flow (Q_{eco}) is **11,2** [m³/s].

To estimate the generated energy, it was first determined to turbinable flow [m³/s], after subtracting the ecological flow of average monthly flow (Table V)

Table V. – Average Monthly, Ecological and Turbinable Flow

Month	Average Monthly Flow [m³/s]	Ecological Flow [m³/s]	Turbinable Flow [m³/s]
January	160,85	11,2	149,65
February	164,18	11,2	152,98
March	149,73	11,2	138,53
April	113,14	11,2	101,94
May	75,92	11,2	64,72
June	60,99	11,2	49,79
July	51,76	11,2	40,56
August	42,36	11,2	31,16
September	40,27	11,2	29,07
October	56,22	11,2	45,02
November	78,93	11,2	67,73
December	125,01	11,2	113,81

After, some flow values was chosen between $Q_{95\%}$, 41,42 [m³ / s] to Q_{glo}, 92.28 [m³ / s] to identify which value would result in a better estimate of energy. If the flow chosen was less than the turbinable flow, it would use the chosen. Otherwise, it would use the turbinable flow (Table VI).

Table VI. – Monthly Flows Applied

Month	Q_{45} [m³/s]	Q_{60} [m³/s]	Q_{75} [m³/s]	Q_{90} [m³/s]
January	45	60	75	90
February	45	60	75	90
March	45	60	75	90
April	45	60	75	90
May	45	60	64,72	64,72
June	45	49,79	49,79	49,79
July	40,56	40,56	40,56	40,56
August	31,16	31,16	31,16	31,16
September	29,07	29,07	29,07	29,07
October	45	45,02	45,02	45,02
November	45	60	67,73	67,73
December	45	60	75	90

For the calculation, it was used the efficiency of the Francis and Kaplan turbine (Fig. 2) [9].

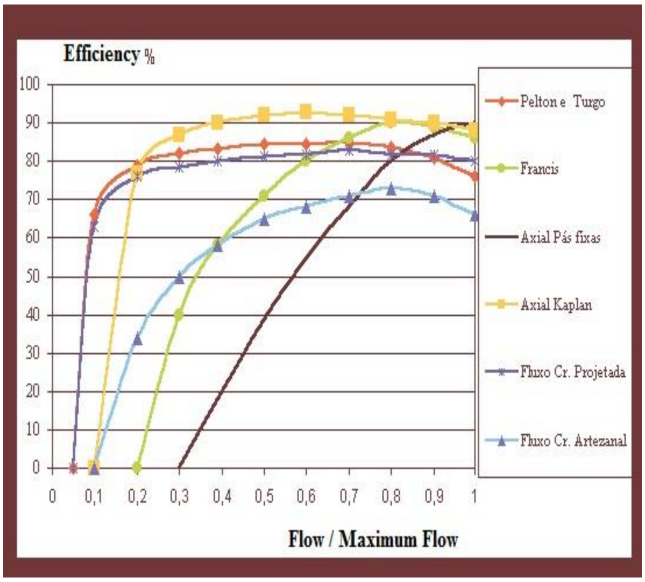

Fig.2. Efficiency of some types of turbines with the variation of flow and constant height.

It was chosen in the calculation of the average power for the Francis turbine efficiency equal to or greater than 0.87, and Kaplan turbines, efficiency equal to or greater than 0.88. These values are the results of the relation flow/maximum flow equal to 1 for each turbine (Fig. 2). To determine the efficiency, it was observed the value of the efficiency in each curve (Fig.2) after making the division between the monthly flows applied by turbinable flows.

With all the variables, the calculation for the average power was realized for each turbine (Tables VII and VIII).

Table VII. - Average Power [KW / m] for the Francis Turbine

Month	P_{45}	P_{60}	P_{75}	P_{90}
January	383,67	511,56	639,45	767,34
February	383,67	511,56	639,45	767,34
March	383,67	511,56	639,45	767,34
April	383,67	511,56	639,45	767,34
May	383,67	511,56	570,95	0
June	383,67	439,28	0	0
July	353,86	0	0	0
August	265,79	0	0	0
September	0	0	0	0
October	383,67	392,72	0	0
November	383,67	511,56	590,83	0
December	383,67	511,56	639,45	767,34
Total	**4072,68**	**4412,93**	**4359,03**	**3836,7**

Table VIII. – Average Power [KW/m] for the Kaplan Turbine

Month	P_{45}	P_{60}	P_{75}	P_{90}
January	388,08	517,44	646,8	776,16
February	388,08	517,44	646,8	776,16
March	388,08	517,44	646,8	776,16
April	388,08	517,44	646,8	776,16
May	388,08	517,44	564,6056	583,63724
June	388,08	439,2836	453,9264	453,92642
July	357,8345	365,7863	369,7623	361,81039
August	281,0693	281,0693	274,9591	268,84889
September	265,0342	259,3345	253,6349	0
October	388,08	401,5472	410,3724	405,95983
November	388,08	517,968	597,4712	610,74835
December	388,08	517,968	646,8	776,16
Total	**4396,658**	**5370,157**	**6158,732**	**6565,7311**

Tables VII and VII provide the following observations:

a) The power is zero for some months. This is due to the relation flow/maximum flow giving a lower efficiency than those chosen for each type of turbine.

b) When the relation decreases, a decrease in the efficiency happens for the Francis turbine and smaller power values. The Kaplan turbine has stability in its efficiency when the relation decreases and has higher power values.

c) They present a better estimate of the power with the flow of 60 [m³/s] for the Francis turbine and 90 [m³/s] for the Kaplan turbine. However, these values would not be viable for some months, according to the monthly average flows (Table V). During the rainy period, the efficiency of the turbines would be used, but not in the dry period.

d) As described previously, the flows of reference for SHPP projects can be the common flow in 95% of the time, 41,42 [m³/s] and the average flow along the critical period of the Interconnected System in Brazil, 44,68 [m³/s]. Considering the statement above and the results of Tables VII and VIII, the flow chosen for this estimate of energy is 45 [m³/s]. This flow presents a good average power too.

e) The selected region has a great hydropower potential and it could be an area of study for the implementation of SHPP projects from the point of view hydrological.

6. Conclusion

The study developed in this work aimed to estimate the average energy generated for a SHPP project, analyzing historical series of flows in a river basin.

Through the results, it is observed that the application of statistical analysis allows a more comprehensive assessment of flow values that can be applied to hydropower projects and the interpretation of their data can help decision making that are needed in the following stages of the project of a SHPP.

In general, this work contributed to some studies and analyzes that can give subsidies to future works, for example, choosing the best type of turbine to a river basin according to the arrangement of the hydroelectric development.

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