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The impacts of transposition methodological decisions on energy and economic analysis for hydroelectric generation projects

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Abstract

Hydroelectric generation is the most widely used form of renewable energy generation in the world. In order to estimate hydroelectric energy potential, transposition of flow data is commonplace, allowing for the transfer of data from one fluviometric station to one or more potential hydroelectric point of interest. Using the relation between drainage areas is among the most used methodologies for flow transposition. In light of this, this article aims to evaluate the impact of flow data transposition through area relation on energy and economic potential for a hydroelectric dam. To do so, three sets of hydroelectric dams were used in three distinct hydrographic areas in Brazil with different distances and drainage areas between them. For each of the dams, hydrologic, energy, and economic calculations relied on permanence curve, maximum net benefit, and levelized cost of electrical energy methodologies. The results emphasize the difficulty in establishing a pattern or correlation for the deviations based on this single analysis parameter, thus indicating that the transposition methodology may lead to errors in the prospecting of hydroelectric dam energy potential.

Keywords: economic feasibility, drainage area relation, flow data transposition, hydrological studies, hydroelectric usage.

INTRODUCTION

The Brazilian National Energy Balance (BEN, 2021) demonstrated that the generation of electric energy from water sources was responsible for almost 65% of the total energy generated in Brazil in 2020. According to the generation information system from the Brazilian Electricity Regulatory Agency (ANEEL – Agência Nacional de Energia Elétrica in Portuguese), Brazil registered 1,498 hydroelectric generation systems in operation in 2020 with a total installed power of 109,393,910kW , with another 124 units under construction. These data show that hydroelectric generation plays an essential role in the Brazilian energy grid. Many studies have been conducted on hydroelectric energy applications in Brazil under myriad aspects (Souza et al., 2017; Costa et al., 2021; Santos et al., 2022). According to ANEEL, a micro hydroelectric powerplant (MHP) has an installed potential of up to 5MW, while a small hydroelectric plant (SHP) runs between 5MW and 30MW, and finally, a large hydroelectric plant (LHP) has an installed power greater than 30MW (ANEEL, 2016). In this work we will consider as SHPs every plant with P<30MW. Several studies must be done before constructing a hydroelectric generation operation, including hydrological studies at the beginning of the project in order to provide data for energy studies, as well as assessing operational and sanitary safety, which are fundamental for establishing key dimensions of such an undertaking (Souza et. al., 2009).

Hydrologic studies are conducted using data collected from fluviometric stations located throughout the river. The choice of these data collection points is essential for successful project implementation. According to Eletrobrás (2000), stations should be considered when there are at least 25 years of flow data history, in the same watershed. There are 22,779 monitoring stations spread throughout 12 hydrographic regions of Brazil, covering an area of 8.5 million km2 (Silva, 2021). While numerous, the monitoring network does not reach the entire territorial expanse and its historic series have flawed or missing data that must be collected (Junqueira et. al., 2018). According to Silva (2021), few stations are free to public access, as only 28% are under federal supervision and therefore in public domain.

Facing the absence of fluviometric data at points of interest for hydrological studies, methodologies for flow data transposition have been created. Based on these methods, it is possible to transpose data from one location with flow gauges to another point of interest without flow data, thus enabling the feasibility assessment for hydroelectric generator installation. One of the simplest transposition methodologies is area relation, which makes it possible to transfer data between data collection stations via Equation 1. The manual for small hydroelectric plants from Brazilian electric power holding company Eletrobrás S.A suggests that, among other factors, this method be conducted utilizing a relation between the drainage areas from 0.25 and 4 for stations in the same river and watershed (ELETROBRÁS, 2000). This method is also quoted by other authors in the international literature, as de Lavenne et al. (2015).

$$Q_A = \frac{A_A}{A_B} . Q_B \quad (1)$$

Where: A_A = Drainage area for the hydroelectric installation in km^2; A_B = Drainage area of the station where data have been collected in km^2; Q_A = Waterflow from the area for hydroelectric installation in m3/s; and Q_B = Waterflow from the station where data have been collected in m^3/s.

Many authors have utilized advanced methodologies for regionalizing waterflow for transpositions, relying on physical characteristics and watershed topography, precipitation, and statistical distributions (Baena et al., 2004; Souza et al., 2009; Lopes et al., 2016; Cassalho et al., 2017). However, the transposition method in function of related areas has been widely applied in hydroelectric projects by multiple authors in recent years in Brazil, including Moreira et al. (2018) and Kanzawa et al. (2021), thus justifying that the uncertainties surrounding this methodology be studied.

Several studies have assessed the impact of uncertainties of hydrological studies on the hydroelectric potential under myriad circumstances and aspects. Costa and Santos (2018) concluded that the differences obtained through the use of average daily and monthly flows in the construction of a permanence curve can be significant, reaching up to 25% of the installed power, having a direct impact on the economic results of the hydroelectric plant. Saliba (2000) conducted a case study with a run-of-river SHP and concluded through confidence interval analysis of permanence curves that the errors in estimative energy increases when waterflow less than Q70% is used (waterflow with 70% permanence).

The relation of climatic changes on hydrology and hydroelectric generation have also been discussed by authors such as Gaudard et al. (2016). As affirmed by Casadei et al. (2014), hydrologic uncertainty due to daily waterflow variations as an effect of climatic changes on water resources is a critical topic in the evaluation of feasibility assessments for hydroelectric projects, especially for run-of-river plants. Vasconcellos et al. (2020) points out that multiple small hydroelectric plants have presented energy generation below expected levels in Brazil. One of the reasons for this generation may come about due to hydrological errors when measuring for hydroelectric plants or accounting for recent climatic changes.

The impacts of transposition methodology on hydroelectric generation have also been investigated by many authors. Meyer (2017) used hydrological data to analyze the influence of errors originating from transposition methodology for energy guarantee in a hydroelectric plant in Brazil; the preliminary conclusion of this study was that, when using the method of drainage area proportion relation, there is a tendency for underestimated values when related to a station with a greater area than that with a smaller area. This is one of the few studies present in the literature on the impact of uncertainty of the transposition by area relation on the hydroelectric potential. This current study expands upon the analysis by Meyer (2017) through the consideration of several dozens of fluviometric stations and evaluating a greater number of energy and economic parameters, thus innovating upon the initial approach.

Given that, in order to assess hydroelectric energy potential, one must use the methodology of flow data transposition and, that transposition per area relation is one of the most used methods due to its simple and easy application, the current study aims to assess the impacts of possible errors in the methodology of flow transposition by area relation on the energy and economic potential in a hydroelectric plant, aside from evaluating the relation between the deviations from physical parameters as well as the relation of drainage areas or distance between stations.

METHODOLOGY

With the aim of comparing results in distinct conditions, three sets of fluviometric stations located in different hydrographic watersheds were utilized for this study. For each data set, one station had to be used as a reference. The transposition methodology was then applied through Equation 1 for the average monthly flows of the other stations in order to transport them to the reference station, and the transposed results could be compared to the results originally measured in a point. The reference station was chosen based on the area relation being from 0.25 to 4 times (as previously explained, as one of the suggestions from ELETROBRÁS, 2000 for application of the transposition methodology) when compared with some stations and, that did not follow this rule when compared to other stations, in order to obtain results that allowed for evaluation of the influence of the area relations.

The first set (Set A) is comprised of eight fluviometric stations whose drainage areas do not exceed 2,000 km2 and are located in the São Francisco River basin. The second (Set B) is made up of eight stations as well and belongs to the Atlantic Basin Eastern Region. The third and final Set C is located in the Paraná Basin and is comprised of 10 measurement stations of which some of them possess intermediate drainage areas when compared to A and B, varying from 2,000 km2 to 10,000 km2. The information on these fluviometric stations in each set can be found in Table 1. A distribution map of the stations is presented in Figure 1. It is worth highlighting that the stations in Set C are distributed along multiple sub-basins, while the other sets are concentrated in two separate but single sub-basins.

Table 1: Summary of stations for Sets A, B, and C

Station	River	Basin	Sub - Basin	Code	Drainage Area [km²]	Distance to the reference station [km]
Set A						
Pari	Itapecerica	São Francisco	São Franciso River Paraopebas	40185000	1,910	34.6
Marilândia (Bridge BR-494)	Itapecerica	São Francisco	São Franciso River Paraopebas	40170000	1,040	39.22

Itaúna Montante (reference station)	São João	São Francisco	São Franciso River Paraopebas	40269900	338	0
Fazenda Laranjeiras Jusante	Mato Dentro Stream	São Francisco	São Franciso River Paraopebas	40810400	11	10.96
Fazenda Pasto Grande	Serra Azul Brook	São Francisco	São Franciso River Paraopebas	40810800	55	14.79
Jardim	Serra Azul Brook	São Francisco	São Franciso River Paraopebas	40811100	113	17.9
Suzana	São Francisco	São Francisco	São Franciso River Paraopebas	40823500	154	25.12
Jaguaruna Jusante	São João	São Francisco	São Franciso River Paraopebas	40300001	1,560	44.46
Set B						
Fazenda Cachoeira das Antas	Doce River	East Atlantic	Doce River	56425000	10,100	191.83
Cachoeira dos óculos Montante	Doce River	East Atlantic	Doce River	56539000	15,900	166.05
Belo Oriente	Doce River	East Atlantic	Doce River	56719998	24,200	154.21
Governador Valadares	Doce River	East Atlantic	Doce River	56850000	40,500	128.36
Tumitiringa	Doce River	East Atlantic	Doce River	56920000	55,100	96.11
Resplendor Jusante	Doce River	East Atlantic	Doce River	56948005	61,200	38.57
UHE Mascarenhas Barramento (reference station)	Doce River	East Atlantic	Doce River	56992400	73,700	0
Colatina-Corpo de Bombeiros	Doce River	East Atlantic	Doce River	56994510	76,400	31.1
Set C						
Fazenda Buriti do Prata	Prata River	Paraná River	Paranaíba River	60850000	2,460	190.14
Tiradentes Port	Mortes River	Paraná River	Rio Grande	61107000	2,720	720.5
São Domingos Bridge	São Domingos River	Paraná River	Paranaíba River	60925001	3,520	143.38
Fazenda Boa Vista	Bois River	Paraná River	Paranaíba River	60715000	4,640	113.83
Prata Bridge	Prata River	Paraná River	Paranaíba River	60855000	5,230	130.86
Ituiutaba	Tijuco River	Paraná River	Paranaíba River	60845000	6,310	135.92

Espanhol Port	Ivaí River	Paraná River	Paraná, Paranapanema Rivers	64645000	8,540	717.97
Fazenda Santa Maria (reference station)	Bois River	Paraná River	Paranaíba River	60772000	17,300	0
São José do Piquiri	Pequiri River	Paraná River	Paraguaí, São Lourenço Rivers	66650000	30,000	655.33
Cárceres (DNPVN)	Paraguay River	Paraná River	Rios Paraguaí, São Lourenço Rivers	66070004	32,400	820.37

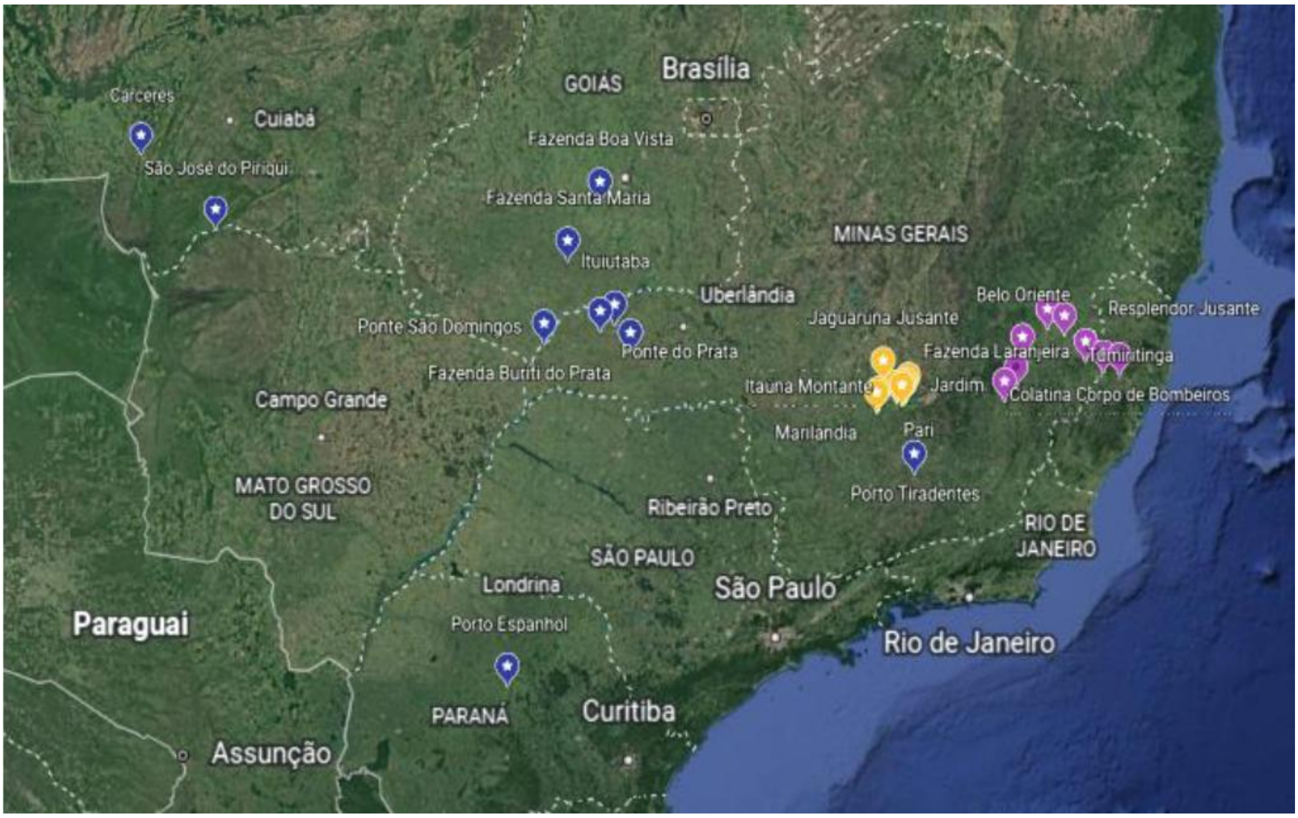


Figure 1: Geographic Dispersion of Station Sets

The stations in Set A, identified by yellow markers, are concentrated in a single region of the São Francisco River basin and the distance between them is the smallest of this study. The purple markers from Set B are farther from each other when compared to Set A. Finally, the stations in Set C, identified by blue markers and located along the Paraná River basin, are the most distant from each other in this study. This more pronounced geographic dispersion could lead one to expect greater deviations in the results. In this set, four stations are located at a distance greater than 200 km, going up to 600 km and 800 km, allowing the authors to evaluate the quality of the transposition for longer distances in which expectations for this methodology to be successfully applied in practical situations are diminished. It should be noted that not all of the studied stations are on the same river, which is a suggestion from ELETROBRÁS (2000) for the transposition results to present fewer errors.

Hydroenergy studies

In order to calculate the optimal potential and economic feasibility for the project, one must determine the annual amount of energy generated by the waterflow. To do this, a permanence curve is defined. Given that the hydraulic potential is related to flow and the permanence of the flow is associated with its time of availability, the hydraulic energy available can be calculated through the use of a river permanence curve (Souza et al., 2009).

According to Vesterna (2012), Brazilian law stipulates criteria for the use of water and each state maintains sanitary regulations for these flows. The flow must pertain to the riverbed and, therefore, cannot count on the calculation of potential energy in plants that have additional flow channels. As the present study does not aim to examine the merits of arranging an eventual hydroelectric plant at the analyzed points, the authors opted to adopt the remaining flow into the studied points, which amounted to flow values equal to 50% of the Q95% due to the fact that this is the value in many Brazilian states, aside from being the methodology adopted by Costa et al. (2021).

$$Q_u = Q - 0.5Q_{95\%} \quad (2)$$

Where: Q_u is the flow used in the project [m³/s]; Q refers to any flow related to the permanence curve [m³/s] and $Q_{95\%}$ refers to the flow of 95% of the permanence curve [m³/s].

Considering that each region has its own particular topography, and that the objective of this article is not to conduct detailed energy analysis of any one particular hydroelectric project, but rather to elaborate a comparison of the energy calculated to verify the errors of transposition by area relation, the authors opted to use a single gross head for each of the analyzed stations. The chosen value was 20 meters. The calculation of available energy for the hydroelectric plant based on a local permanence curve considers the base energy as the energy produced in a permanence flow 100% of the time, which is shown by the energy rectangle in E1 of Figure 2. Obtaining the available energy for any installed flow in the river above this is determined by the sum of the increments in energy (trapezoids) and can be described in Equation 3.

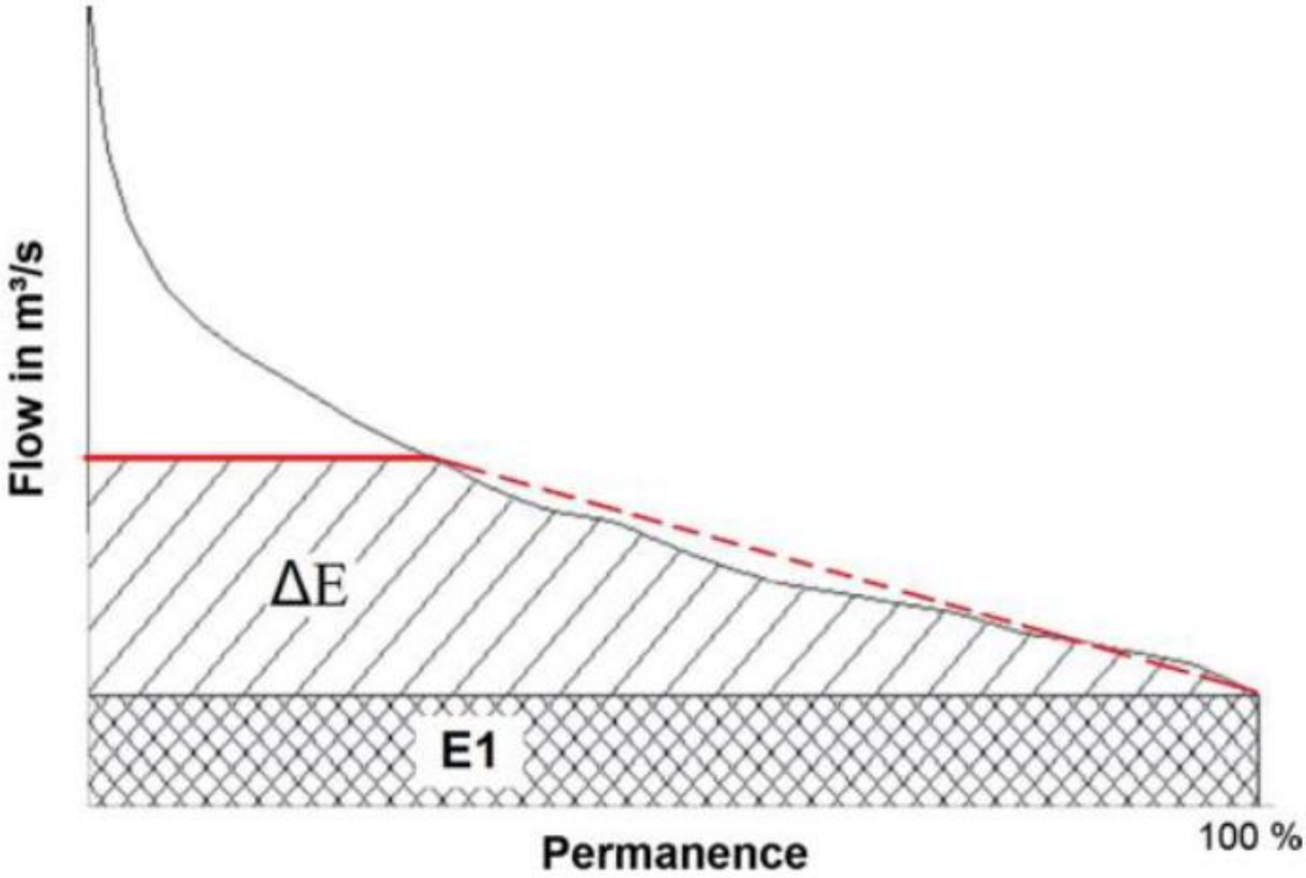


Figure 2: Permanence Curve with Energy. Source: Costa et al. (2021).

$$E\ (n) = E\ (n-1) + \frac{1}{2}[p(n-1) + \rho(n)][P(n) - P(n-1)] \quad (3)$$

Where: n is the order of a given permanence; ρ is the permanence in h/h; P is the potential in kW and E is the energy in kWh

According to Cardoso et al. (2007) and Mensah et al. (2016), to optimize the installed power in a hydroelectric plant, the method of maximum net benefit (MNB) is used. The calculation considers hydrologic variables as well as economic ones, thus attaining a power while also maximizing profitability. The annual net benefit can be calculated through Equation 4. The power that results in the MNB is selected as the optimal installed potential power of the project. This methodology is valid for the run-of-river hydroelectric projects which do not have regularized reservoirs, in turn having lower average reserves (Souza et al., 2009; Singal et al., 2010). Even for the points in this study that can be characterized as large hydroelectric plants (P>30 MW) were considered to be run-off-river projects given that this is a possible arrangement, as is the case of the Belo Monte plant – NORTE ENERGIA 2022.

$$NB = E\,T_m - P(\,C_{un}\,FRC) - C_{om} \quad (4)$$

Where: NB: benefit [BRL/year]; E: energy generated annually [MWh/year]; P: total installed power [kW]; C_{un}: unit cost [BRL/kW]; T_m : average value for the energy sale rate [BRL/MWh]; FRC: the capital recovery factor, given by Equation 5 (Cardoso et al., 2007); i: the annual interest rate in %, set at 10% per year and n: useful life of the project. It is worth noting that a more detailed refinement was not applied in determining the interest rate, such as calculating the weighted average cost of capital or considering real versus nominal rates. However, this simplification will not have a significant impact on the results, as the objective is to compare the outcomes of daily and monthly flow rates, both of which are subject to the same rate.

$$FRC = \frac{(i) * (1+i)^n}{(1+i)^n - 1} \quad (5)$$

The sales rate for the energy utilized varied between the studied scenarios, given that the analyzed points behaved as SHP (P < 30 MW) and, for other plants, as MHP (P > 30 MW). According to ANEEL (2022), the reference price rate for energy in government bidding A-4 in 2022 was 268.4 BRL/MWh for SHPs and 187.7 BRL/MWh for LHPs. Accounting for the tendency of government contracts to have lower values than the ceiling price, the rates for this study were set at 20 BRL/MWh less than the reference above, resulting in values of 248.4 BRL/MWh for SHPs and 167.7 BRL/MWh for MHPs.

The concept of Levelized Cost of Electricity (LCOE) represents the cost per megawatt-hour in monetary costs for a generating plant during its useful lifecycle (Branker et al., 2011). This variable is calculated by the quotient between the sum of the transferred costs in the initial year and the energy discounted through time, according to Equation 6.

$$LCOE = \frac{\sum_{t=0}^{m} \frac{C_n}{(1+i)^n}}{\sum_{t=0}^{m} \frac{E_n}{(1+i)^n}} \quad (6)$$

Where:

Cn = Cost per year (BRL), equal to the investment (I) in the first year and equal to the operational and maintenance costs in the remaining years (Com); E = Energy produced annually (MWh/year); m = Useful life of the project, set at 30 years for this study; i = Annual discount rate and t = year.

Many authors have proposed cost estimation equations for hydroelectric projects in the literature, both for projects in Brazil (Tiago Filho et al., 2017; Souza et al., 2019) as well as for other countries, such as Kaldellis et al., 2005; Singal et al., 2010, for small hydroelectric plants in India; Aggidis et al., 2010 for operations less than 1 MW in the United Kingdom; Buthchers et al., 2022 on hydroelectric generation cost estimates in Nepal). In this study, a cost estimate equation defined based on data from Almeida (2020) was used, which utilized 127 hydroelectric energy projects throughout Brazil (see Equation 7). This equation elaborates an investment estimate I in small and large plants. Furthermore, the correlation coefficient obtained by Almeida was also markedly elevated, greater than 0.9. The operational and maintenance cost was adopted as 2.5% of the initial investment (IRENA, 2012).

$$I\ [R\$] = 9.950{,}47.\, P(kW)^{0{,}953} \quad (7)$$

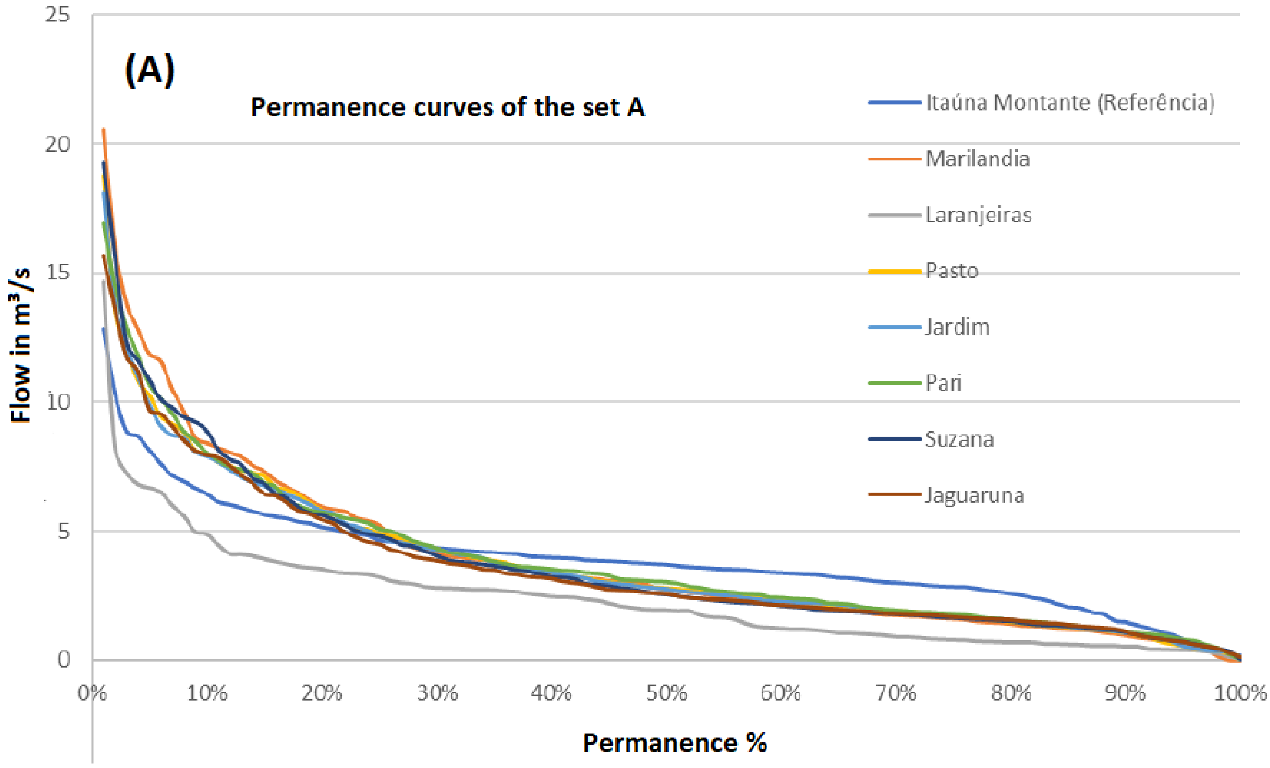
To conduct a robust analysis of the transposition methodology results, the relative percentual deviation (D) was calculated between the transposed values with the reference station in relation to the energy and economic parameters of the hydroelectric project; more specifically, 5%, 50%, and 95% of the permanence, the optimal potential (Pot – identified using the method of maximum benefit) and the LCOE in all three of the sets of the analyzed stations.

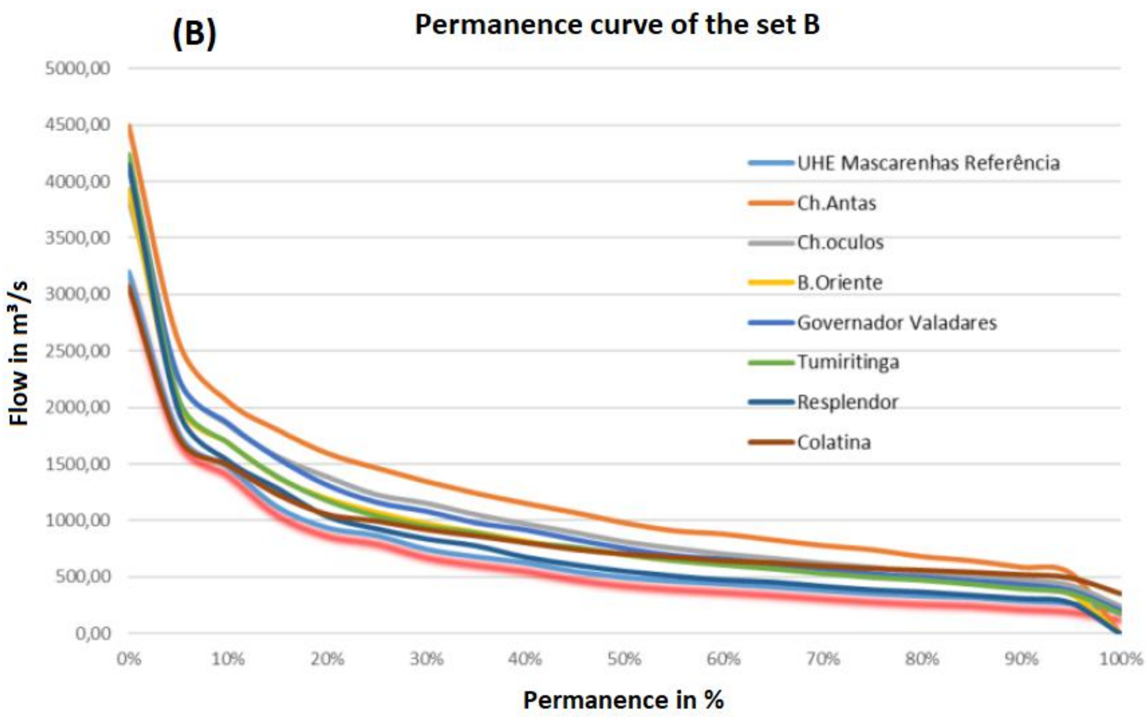
Finally, an analysis of the behavior of the deviations through correlations of the parameters as area relations and distances between the stations. The efficacy of the results will be evaluated in function of the suggestion of the relation of the areas of 0.25 to 4, which is the suggestion from ELETROBRÁS (2000) to minimize the errors of the transposition method, in order to verify the use of this proportion influences the calculated results. Basic statistical analyses were also conducted.

RESULTS AND DISCUSSIONS

Variations in the Permanence Curve due to Transposition Methodology

The results obtained at the reference station were compared to the transposed stations for each set. Upon doing so, some discrepancies were observed between them, influenced by factors that go beyond the analyzed area relation. Figures 3a, 3b, and 3c show the permanence curve for the reference stations and the stations whose data were transposed to the points of study.


(A)
Permanence curves of the set A
Flow in m³/s
Permanence %
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Itaúna Montante (Referência)
Marilandia
Laranjeiras
Pasto
Jardim
Pari
Suzana
Jaguaruna


(B)
Permanence curve of the set B
Flow in m³/s
Permanence in %
5000,00
4500,00
4000,00
3500,00
3000,00
2500,00
2000,00
1500,00
1000,00
500,00
0,00
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
UHE Mascarenhas Referência
Ch.Antas
Ch.oculos
B.Oriente
Governador Valadares
Tumiritinga
Resplendor
Colatina

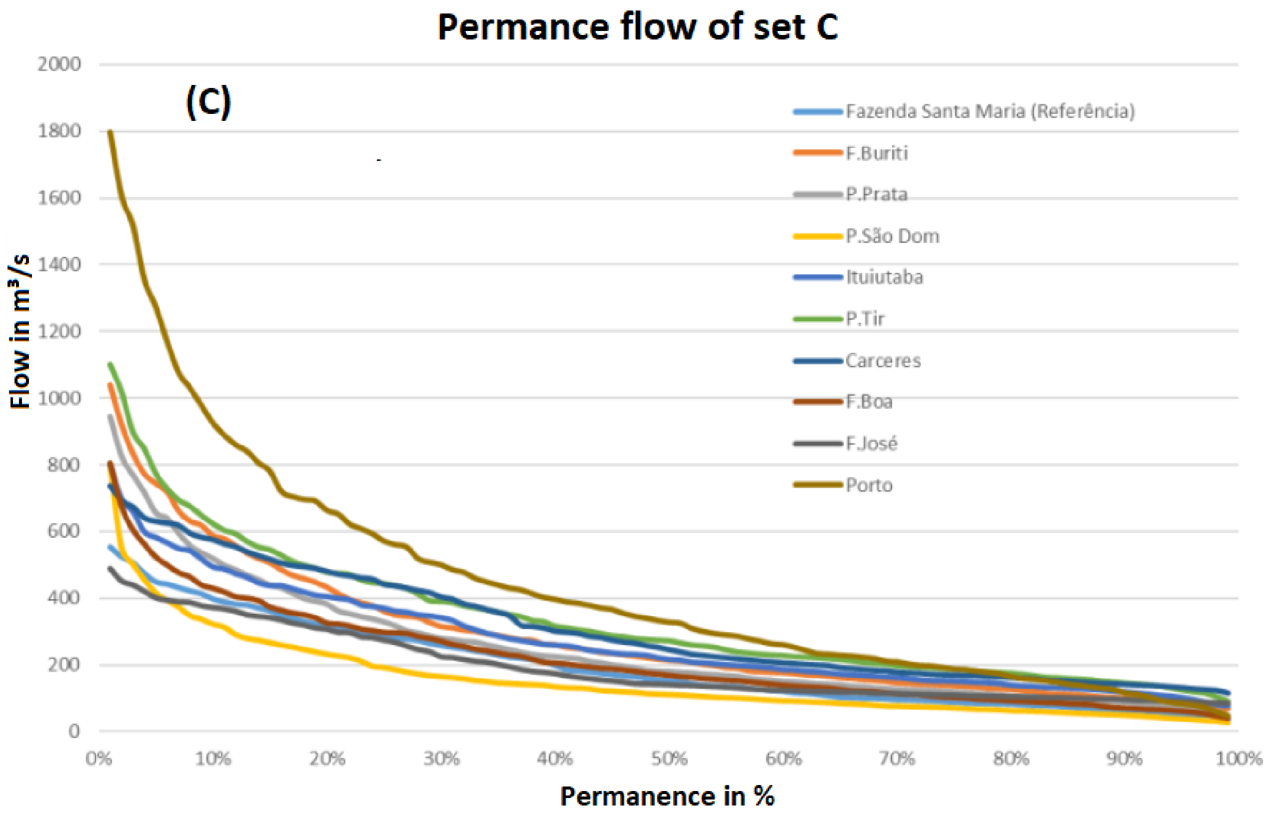


Figure 3: Permanence Curve a) Set A, b) Set B, and c) Set C.

Through Figure 3, it can be seen that the curves not only vary between each other in their flow values, but there are also eventual alterations in the variation profiles themselves. That is, there are distinctions between the original permanence curve profiles that are brought together with the transposition, which naturally only corrects the flow values and not the curve shape because it deals with the multiplication of the curve values by the area relation, which is a constant.

The stations belonging to Set A have a smaller drainage area and therefore the distance between stations is also smaller. Precisely the contrary occurs with Sets B and C. This suggests that this could be one of the reasons for the difference between the curves from Set A and Set C, since a greater discrepancy is seen between the permanence curves for the latter.

These variations between the permanence curves from the reference station and the transposed points are relevant and will have direct impact on the energy and economic results of the hydroelectric project, given that the energy produced by the plant will be calculated by the area below the permanence curve. Figure 4 exemplifies the impacts of the permanence curve variations on the energy curve, which relates power and energy) of the Itaúna Montante stations, which is the reference for Set A, with two stations whose data were transposed, Marilândia and Pari. The behavior of the curve shows that by increasing the power, there is an increase in the energy generated, until it reaches its saturation point. From that point on, there is no alteration in the energy values. It can be seen that the reference station (Itaúna) presents a maximum value for power versus energy greater than the other two sets.

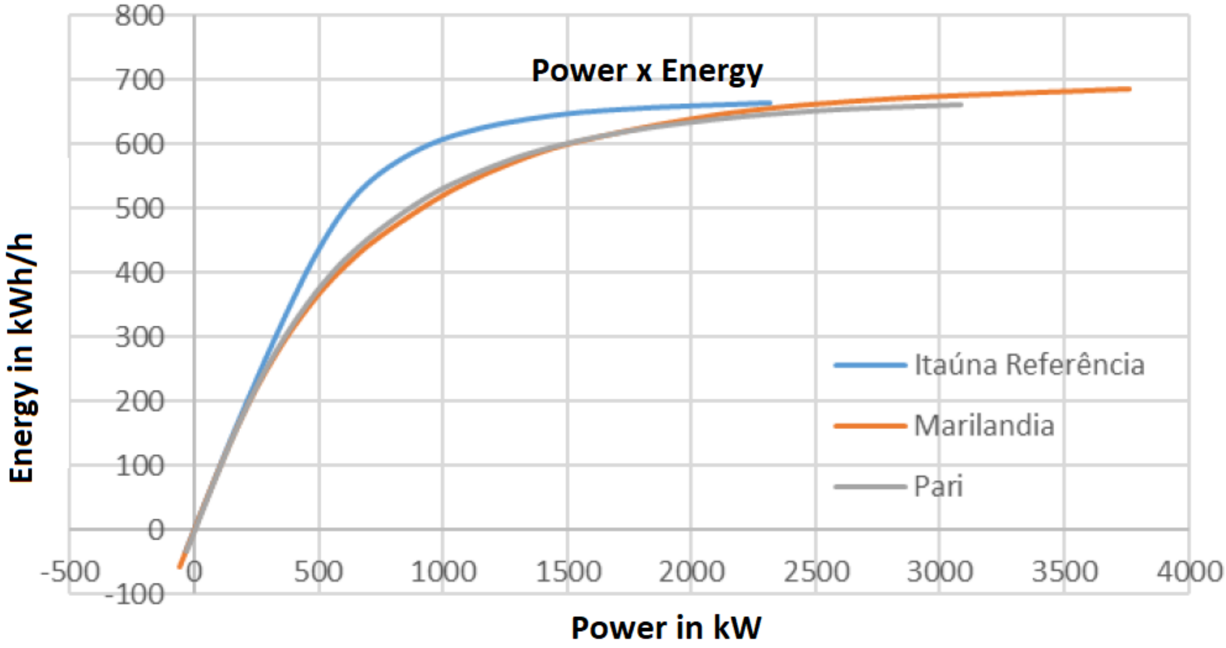


Figure 4: Power versus Energy Curve for Set A Stations.

Analysis of deviations in the power calculations resulting from the permanence curve

In light of the highly discrepant values encountered for the permanence curve, the deviation results between the original results and the associated transposed power values for the three permanence results relevant to the permanence curve are presented: Q95% (a lower value, used when one desires greater certainty in operating a hydroelectric plant – Souza et al., 2009), Q50% (a more elevated value, closer to medium flow) and Q5% (a significantly elevated value, normally not used for turbine operation), for all of the stations.

It was expected that the power for the Q95% flow would show values close to those found, especially for dealing with flow rates below the others. However, they differed significantly among each other, in some cases up to 100% of the difference between the reference station with the stations whose data were transposed. The power for the Q50% flows in general demonstrate discrepancy in their values when compared to the reference station for all of the sets of analyzed stations, as the deviation values were considerably elevated, and many times above 100%. The same behavior was obtained in Set C; it is worth highlighting the deviation of the Espanhol Port station, which was close to 200% in relation to the reference station. These results show the elevated errors that can be obtained through transposition methodology when comparing the transposed powers with those calculated from the original data from a determined location. The results in Table 2 along with Figures 3 and 4 demonstrate the absence of relevant differences in the results in function to the area relation. No significant differences were observed when considering stations between or outside of the proportion of 0.25 to 4, which is the suggestion from ELETROBRÁS (2000).

Table 2: Powers and deviations of the reference stations and transposed stations

Set	Fluviometric Station	Area Relation	Power relative to Q95%[kW]	P95% Deviation from reference	Power relative to Q50% [kW]	P50% Deviation from reference	Power relative to Q5% [kW]	P5% Deviation from reference
A	Pari	5.65	73.64	-1.30	489.81	-20.51	1,918.55	33.10
	Marilândia	3.07	59.47	-20.29	453.39	-26.42	2,150.54	49.19
	Itaúna Montante (Reference)	-	74.61	0.00	616.20	0.00	1,441.43	0.00
	Fazenda Laranjeiras Jusante	0.03	35.76	-52.07	324.69	-47.31	1,208.65	-16.15
	Fazenda Pasto Grande	0.16	52.55	-29.57	468.10	-24.03	1,859.55	29.01
	Jardim	0.33	50.00	-32.98	461.84	-25.05	1,794.90	24.52
	Suzana	0.46	65.34	-12.42	408.72	-33.67	1,958.21	35.85
	Jaguruna Jusante	4.62	64.74	-13.23	413.33	-32.92	1,744.66	21.04
B	Cachoeira das Antas	0.13	49,861.15	104.45	132,884.93	97.13	432,208.07	41.02
	Cachoeira dos Óculos	0.21	39,941.09	63.78	111,529.10	65.45	379,730.58	23.90
	Belo Oriente	0.33	37,667.20	54.45	107,784.62	59.90	371,781.10	21.30

	Governador Valadares	0.55	35,442.46	45.33	105,005.90	55.77	385,902.63	25.91
	Tumiritinga	0.75	33,080.75	35.65	96,801.52	43.60	353,789.10	15.43
	Resplendor Jusante	0.83	25,478.25	4.47	77,555.91	15.05	341,924.32	11.56
	UHE Mascarenhas (Reference)	-	24,387.55	0.00	67,409.06	0.00	306,489.86	0.00
	Colatina Corpo de Bombeiros	1.04	45,933.23	88.35	85,548.34	26.91	277,444.98	-9.48
C	Fazenda Buriti do Prata	0.14	7,401.70	57.42	32,209.33	37.02	130,942.25	65.57
	Prata Bridge	0.3	6,611.90	40.62	26,986.52	14.80	115,740.55	46.34
	São Domingos Bridge	0.2	3,610.42	-23.22	17,163.05	-26.99	74,042.99	-6.38
	Ituiutaba	0.36	9,606.35	104.30	30,952.94	31.67	98,951.64	25.12
	Tiradentes Port	0.15	11,452.05	143.56	38,998.56	65.90	132,320.36	67.31
	Cárceres	1.8	12,395.39	163.62	33,537.39	42.67	105,145.80	32.95
	Fazenda Boa Vista	0.26	5,566.05	18.38	25,570.49	8.78	91,627.14	15.85
	Fazenda Santa Maria (Reference)	-	4,702.02	0.00	23,507.28	0.00	79,087.98	0.00
	São José do Piriqui	1.74	8,318.90	76.92	17,612.24	-25.08	66,113.68	-16.40
	Espanhol Port	0.49	7,750.45	64.83	53,355.42	126.97	229,506.29	190.19

Analysis of optimal power deviations and LCOE

Table 3 presents the results for the maximum net benefit values, LCOE, optimal power, and the percentage of flow failures (months without flow measurements) for the stations from Set A.

Table 3: Comparison of Set A Data.

	Itaúna (reference station)	Marilândia	Pari	Fazenda Laranjeiras Jusante	Fazenda Pasto Grande	Jardim	Suzana	Jaguaruna Jusante
Area relation	-	3.07	5.65	0.03	0.16	0.33	0.46	4.62
Percentage of Flow Failures	0	1.45	0.72	65	0	0.25	0.72	0
Maximum net benefit [10^6 BRL /year]	0.504	0.336	0.333	0.175	0.336	0.336	0.294	0.300
Optimal Power [kW]	659.1	543.8	568.9	401.9	552.8	557.2	486.4	479.2
LCOE [BRL/MWh]	138.4	155.9	154.8	172.3	152.75	153.2	153.3	151.33
Relative deviation between the optimal power values in relation to the reference station (%)	-	-17.5	-20.79	-39.01	-16.12	-15.46	-26.20	-27.29
Relative deviation between the LCOE values in relation to the reference station (%)	-	12.6	11.82	24.50	10.36	10.67	10.75	9.33

With the exception of Laranjeiras, all of the stations presented low failure rates in their flow data, which demonstrated the reliability of the results due to the limited amount of interference in the flow values in the permanence curves. It can be noted that, for Set A, the greatest deviations related to optimal power and LCOE values originated from Fazenda Laranjeiras (outside of the area relation of 0.25 to 4.0), while the lowest deviations are present at Fazenda Pasto Grande (also outside of the 0.25 to 4 relation). Furthermore, it is possible to perceive that the Fazenda Pasto Grande and Jardim stations obtained very similar results, while the former was outside of the area proportion and the latter was within. Finally, it stands out that the stations with relation to areas within the suggested range also presented elevated deviations, such as the Suzana station with optimal power. It can be concluded that the use of the area relation from 0.25 to 4 did not significantly influence the deviations encountered for Set A.

Still on Table 3, it can be seen that the Fazenda Laranjeiras and Fazenda Pasto Grande stations have, respectively, the MNB furthest and closest to the value found for the reference station. Both are outside of the recommended drainage area proportion ratio.

Table 4 presents the results from the stations in Set B, which is characterized by increased drainage areas and, in turn, increased flow and power. Such plants have optimal installation power levels that go beyond the power limit for small hydroelectric plants, thus being considered as run-of-river hydro power plants for the present study.

Table 4: Comparison of Set B Data.

	UHE Mascarenhas Reference Station	Fazenda Cachoeira das Antas	Fazenda Cachoeira dos Óculos	Belo Oriente	Governador Valadares	Tumitiringa	Resplendor Jusante	Colatina
Area relation	-	0.13	0.21	0.33	0.55	0.75	0.83	1.04
Percentage of Flow Failures	0.41	0.41	0	13.75	0	0	50	8.75
Maximum net benefit [10^6 BRL /year]	28.15	60.99	48.71	54.03	44.78	41.25	45.71	26.91
Optimal Power [kW]	67,409.05	141,499.13	116,276.02	113,985.11	107,208.35	98,223.62	77,696.05	85,548.34
LCOE [BRL/MWh]	109.02	106.45	107.87	110.55	108.17	108.12	108.41	101.53
Relative deviation between the optimal power values	-	109.91	72.49	69.09	59.04	45.71	15.26	26.90

in relation to the reference station (%)								
Relative deviation between the LCOE values in relation to the reference station (%)	-	-2.352	-1.05	1.41	-0.77	-0.82	-0.55	-6.86

The data from Set B show optimal power deviations for stations that are within the suggested area relation ratio. However, considerable optimal power deviations are also found in the stations with area relation outside of the 0.25 to 4.0 proportion. Furthermore, stations both between and outside of this indicated range have quite similar optimal power and LCOE deviations, which is the case for Cachoeira dos óculos and Belo Oriente. These results demonstrate the difficulty in defining an adequate distinction of the influence of area relation on the results.

When the LCOE deviations are analyzed, it can be seen that there are stations within the area relation whose deviations are greater than those outside. This occurs with Colatina, which is within the proportion relation; however, it possesses the greatest LCOE of the entire set. The lowest LCOE value belongs to Resplendor Justante, which is within the 0.25 to 4.0 relation. In general, reduced deviations are seen between the calculated LCOE and the reference station for Set B. The elevated values for the power in Group 2 are one of reasons for this, which go beyond the limits of small hydro power plants, which the transposition methodology is suggested, and mean that the identified potentials are of large run-of-river hydroelectric plants, which may imply a tendency for LCOE to stabilize with increasing power. This tendency is verified in the results of Costa et al., 2021.

The results of the deviation for Set C are presented in Table 5.

Table 5: Comparison of Set C Data.

	Fazenda Santa Maria (reference station)	Fazenda Buriti do Prata	Prata River	São Domingos River	Ituiutaba	Porto Tiradentes	Cárceres	Fazenda Boa Vista	São José do Piquiri	Porto Espa-nhol

Area relation	-	0.14	0.30	0.2	0.36	0.15	1.8	0.26	1.74	0.49
Percentage of Flow Failures	0	0	0	0	0	0.75	0	0	6.61	0
Maximum net benefit [10^6 BRL /year]	7.06	11.044	9.39	5.52	11.63	14.49	12.59	8.46	7.23	17.83
Optimal Power [kW]	21,047.58	31,059.62	26,238.79	15,698.83	29,432.68	36,629.99	30,988.22	23,732.84	16,450.4	52,763.22
LCOE [BRL/MWh]	119.01	116.32	116.37	117.84	112.55	112.19	111.60	118.02	110.16	118.14
Relative deviation between the optimal power values in relation to the reference station (%)		47.56	24.66	-25.43	39.83	74.34	47.22	12.75	-21.84	150.68
Relative deviation between the LCOE values in relation to the reference station (%)		-2.25	-2.22	-0.98	-5.42	-5.78	-6.27	-0.83	-7.43	-0.72

Table 5 shows an elevated deviation of 150% for the optimal power for the Espanhol Port gauge, whose area relation is favorable to the suggested proportion, while the deviations for the fluviometric stations that are not within the area relation do not go beyond 75%.

Seeing that the power deviations are elevated, the proximity among the MNB curves diminishes. Figure 5 shows the discrepancy between the curves of the Espanhol Porto and the reference station, while the curves from Fazenda Boa Vista and the reference gauge are similar. In this case, the area relation does not have any influence on the MNB curves versus power, as both of the cited stations are within 0.25 to 4.0. It is worth highlighting that the power limits are superior to the small hydroelectric plants and the stations analyzed present elevated distances between each other. The Espanhol Port station is over 700km from the reference station, which is much farther than most of the studied stations, thus indicating that this factor is responsible for the elevated deviations.

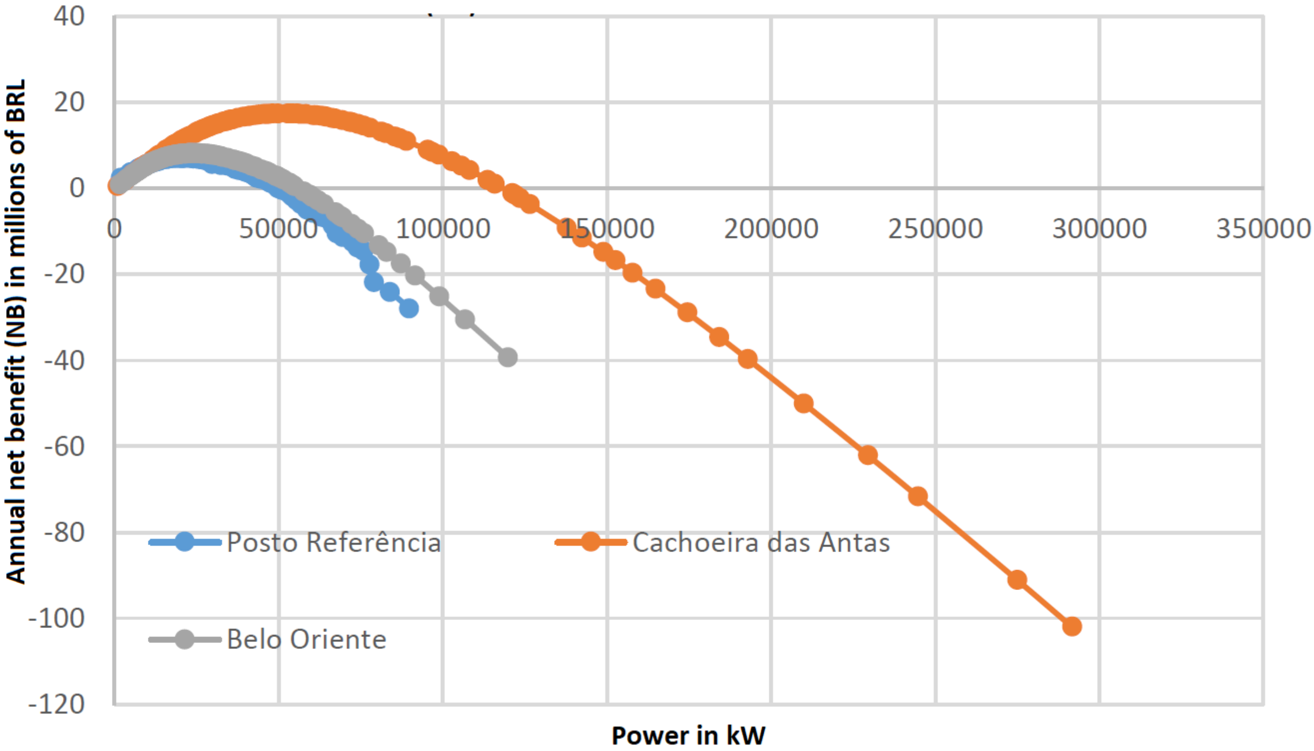


Figure 5: Net Benefit of the reference station and the greatest deviations

The LCOE versus Power in Figure 6 demonstrates the proximity between the curves from the Fazenda Boa Vista station with the reference. For the Set C stations, there was no considerable discrepancy for the for the LCOE deviations on the MNB points between the analyzed stations; they vary in values below 7%. However, the LCOE curves for the Espanhol Port, in relation to the reference, are significantly distant. The probable motive for this is the distance from the reference, as discussed in the previous paragraph.

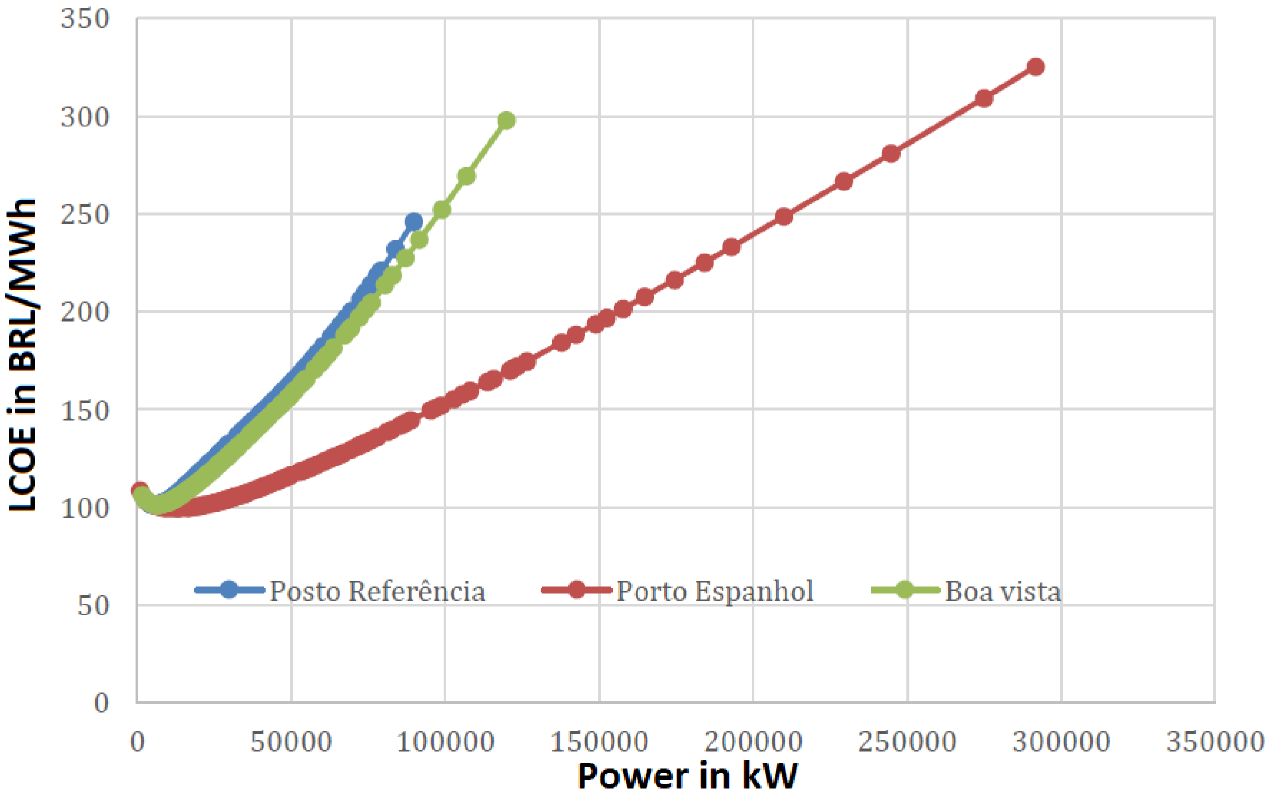


Figure 6: LCOE for the reference station and greatest deviations.

It is worth highlighting that a single energy rate was used for the Set C stations (a typical energy sales rate for LHPs is approximately 170 BRL/MWh), given that the station power for the stations in this region could be considered SHPs or LHPs based on the installed power. However, when using different rates in function of the power, the optimal power of 30 MW (the threshold between SHP and LHP) was the value that resulted in the MNB for multiple options (given that this is the limit for SHPs, which has a greater sales rate for energy than LHPs). Thus, in some points the transposition methodology does not lead to errors; this is not due to the precision in the hydrologic methodology, but rather due to the deviation caused by the distinction between these rates. The contrary is also true, where some points would exhibit a pronounced deviation between transposed and original stations, not due to imprecision in the hydrologic methodology, but rather from the rate differences.

The results for the analyzed sets show difficulties in establishing a relation between the drainage area proportions (between and outside of the 0.25 to 4.0) with quality energy and economic results, given that there are results with small and large deviations for the stations with different area relations. Thus, at the moment of transposition, the area relation is not the only factor that should be considered, seeing that no pattern was observed for the deviations.

Another point to be discussed is the degree of the deviations. In most cases, the deviations between the reference and the transposed value are greater than 50% of the optimal power, which is an elevated value and that could bring about considerable errors in power and feasibility studies for hydro power plants, causing erroneous forecasts and expectations for a region and thus leading to incorrect project dimensions and operational losses. One example of this problem is lower than expected generation (which is a problem for many SHPs, as identified by Vasconcellos, 2018 and Vasconcellos et al., 2020). In the case of LCOE, the deviations were lesser, which shows that the final cost for developing power under these conditions showed themselves to be more inelastic than the optimal power, usually under 10% and diminished in accordance with diminished installed power.

Deviation correlation analysis

The correlation analysis herein aims to verify if a tendency for the deviations to increase along with the distance or the drainage area relation between the stations, regardless of the hydrographic basin under study.

The correlated parameters can be seen in the following graphs. Initially, the distance between the stations with the optimal power are shown in Figure 7. Figure 8 establishes the existing correlation between the drainage area parameters and the optimal power deviation. Figure 9 shows the deviations between the 95%, 50%, and 5% powers in relation to the drainage areas for each of the studied sets. Figure 10 presents the permanence curve deviations in relation to the distance between the stations and the reference.

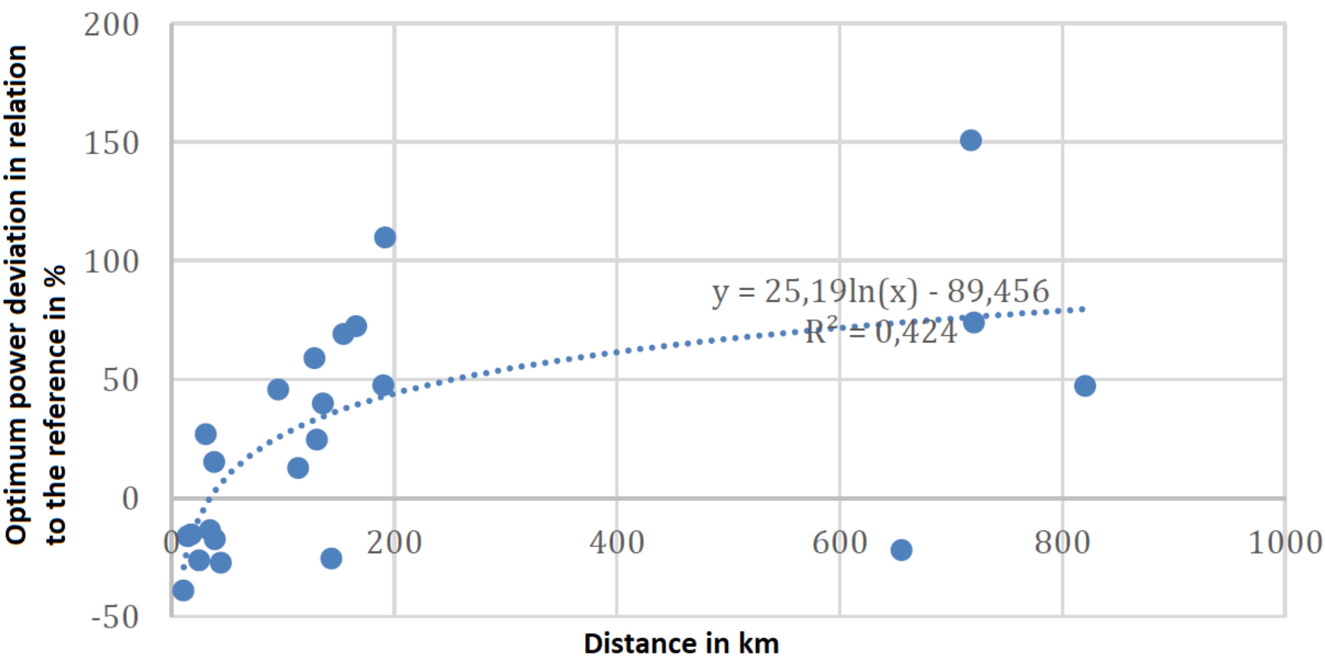


Figure 7: Correlation between Distance and Optimal Power

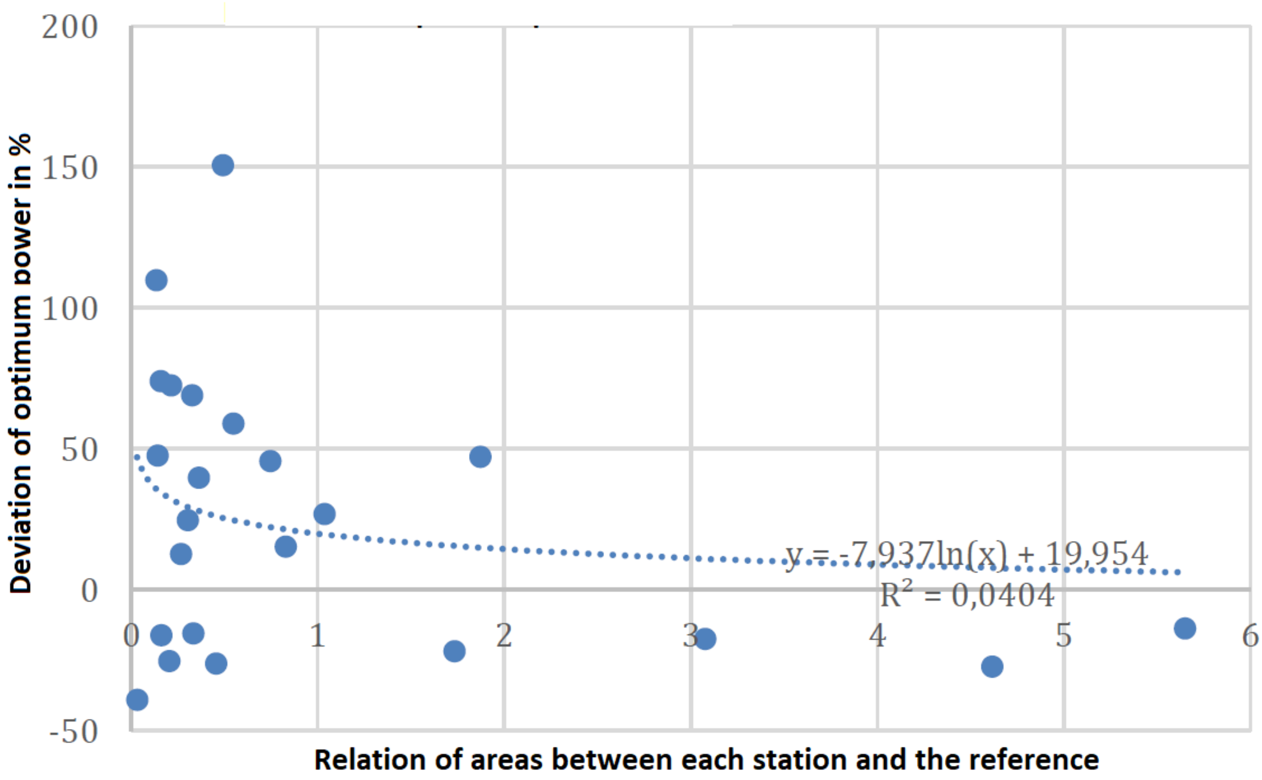
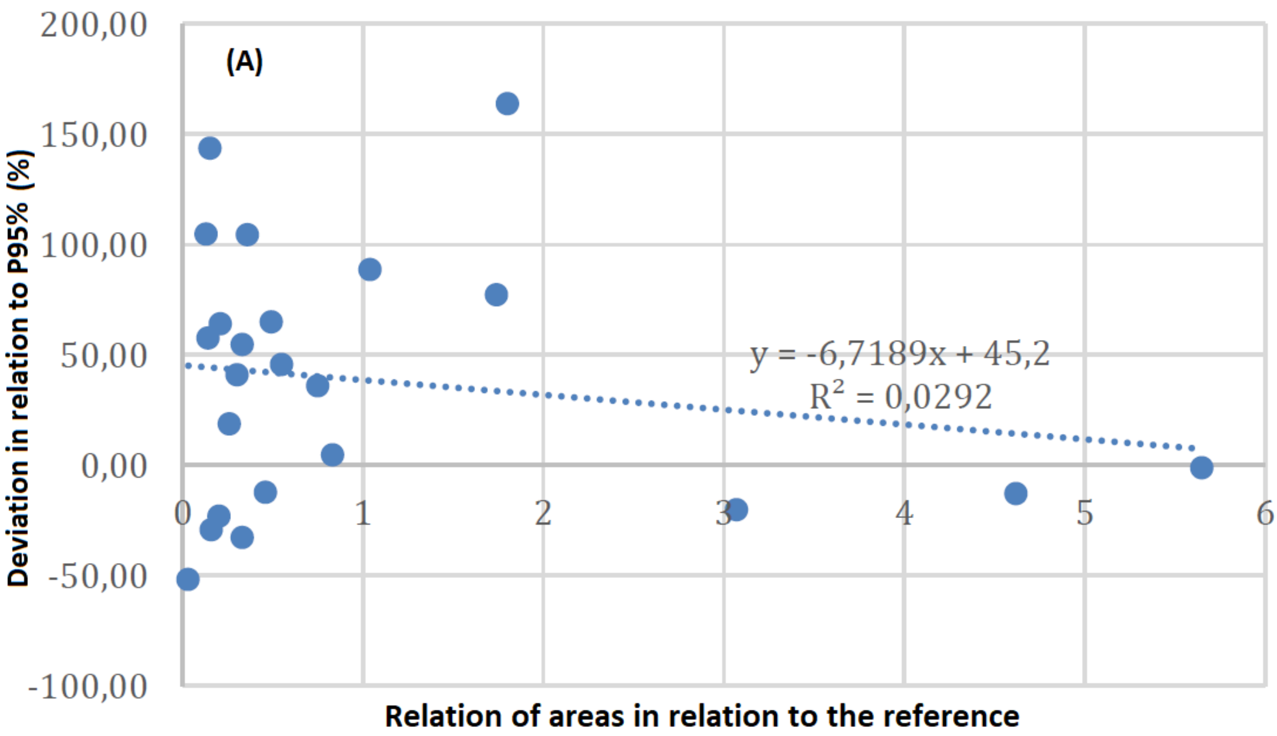
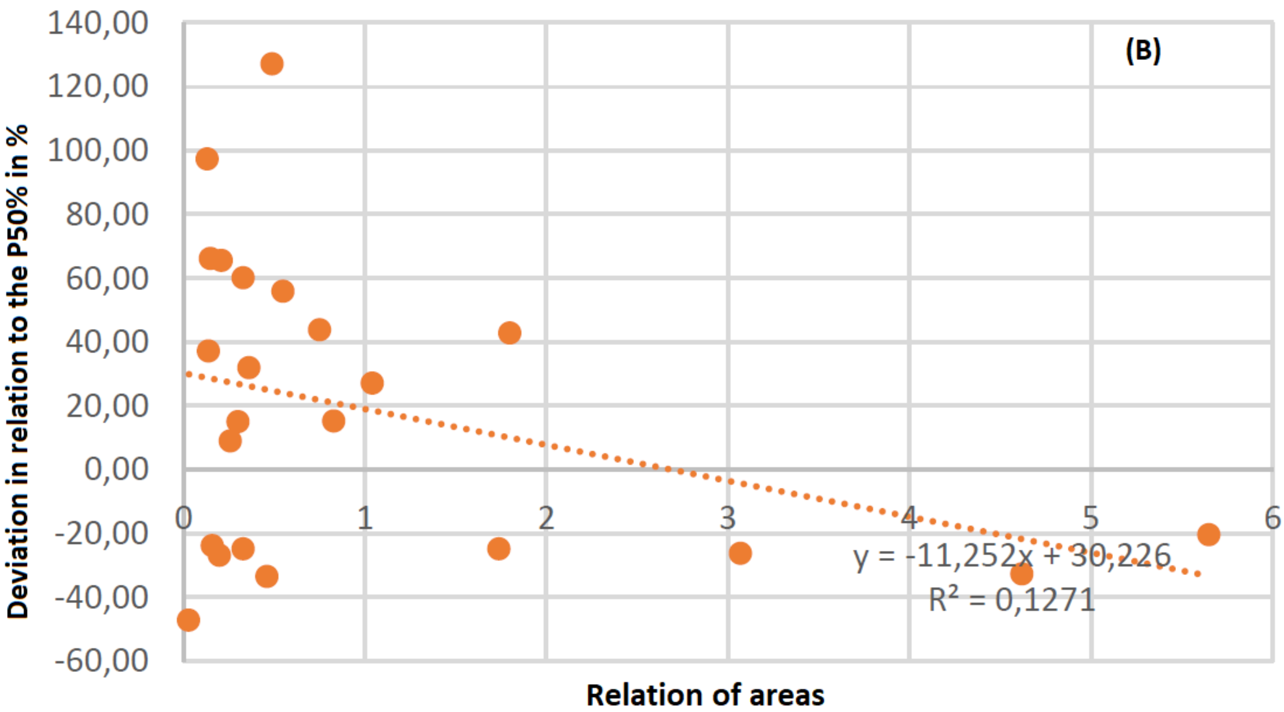


Figure 8: Correlation between the Area Relation and the Optimal Power Deviation


200,00
150,00
100,00
50,00
0,00
-50,00
-100,00
(A)
y = -6,7189x + 45,2
R² = 0,0292
0
1
2
3
4
5
6
Deviation in relation to P95% (%)
Relation of areas in relation to the reference


140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
-20,00
-40,00
-60,00
(B)
0
1
2
3
4
5
6
y = -11,252x + 30,226
R² = 0,1271
Deviation in relation to the P50% in %
Relation of areas

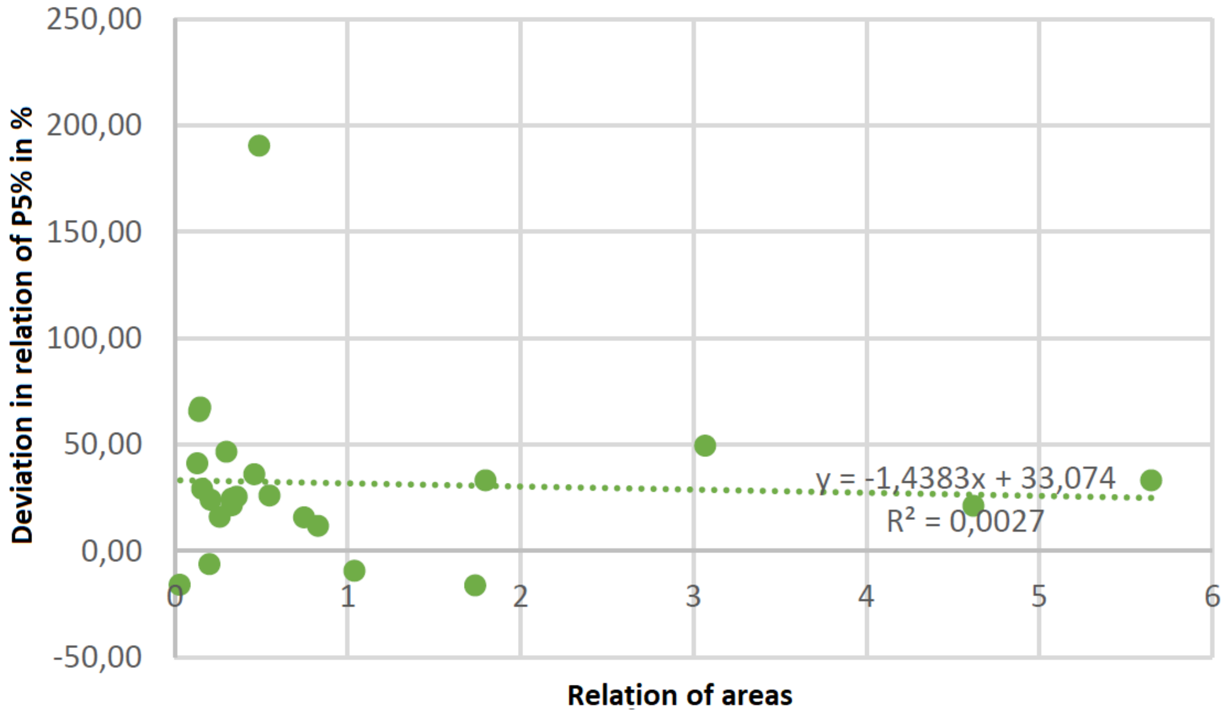
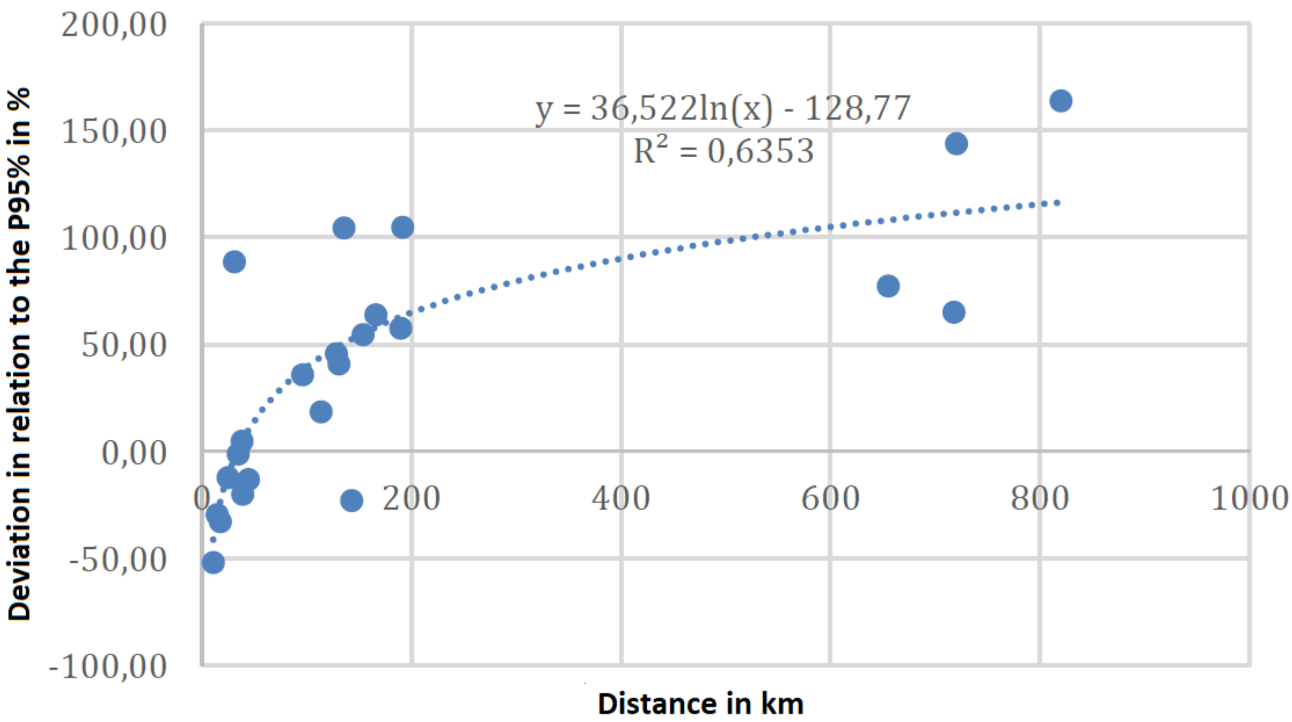
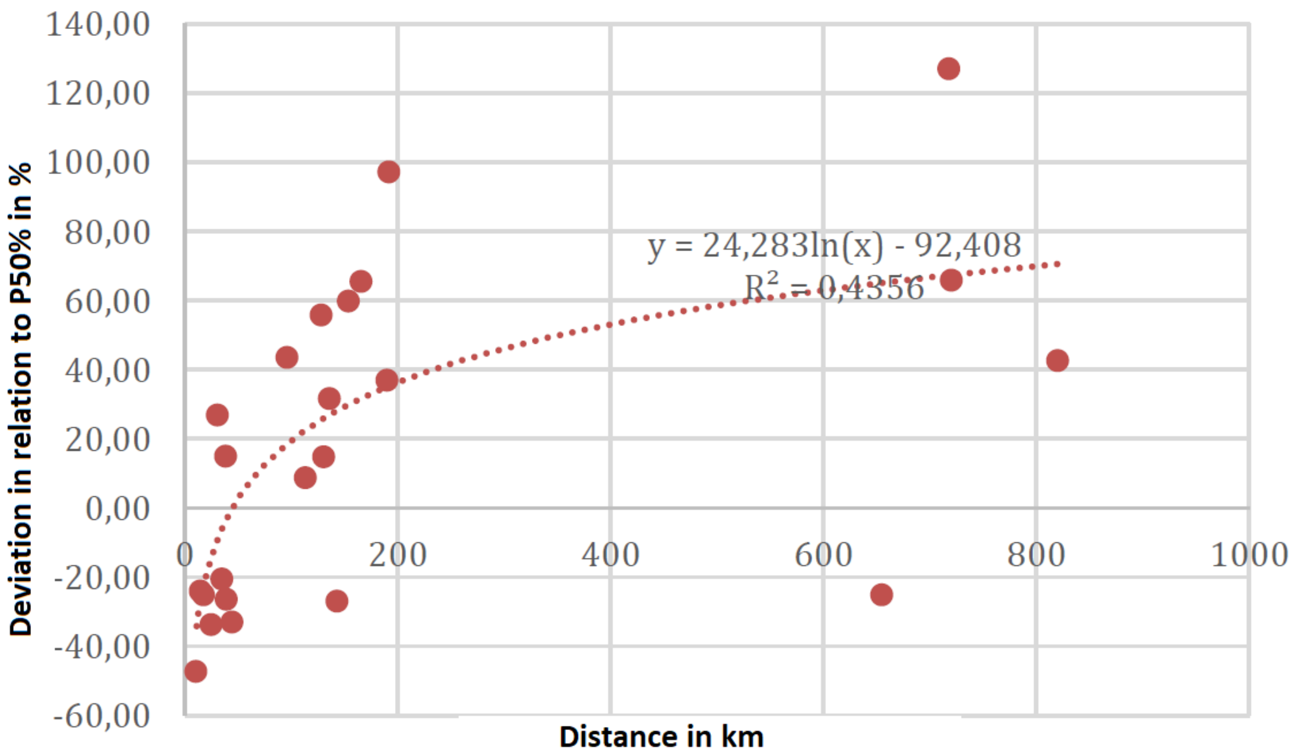


Figure 9: Correlation between Area Relation and the Permanence Curve Power Deviation: (a) P95%; (b) P50% e (c) P5%




Deviation in relation to P50% in %
140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
-20,00
-40,00
-60,00
0
200
400
600
800
1000
y = 24,283ln(x) - 92,408
R² = 0,4356
Distance in km

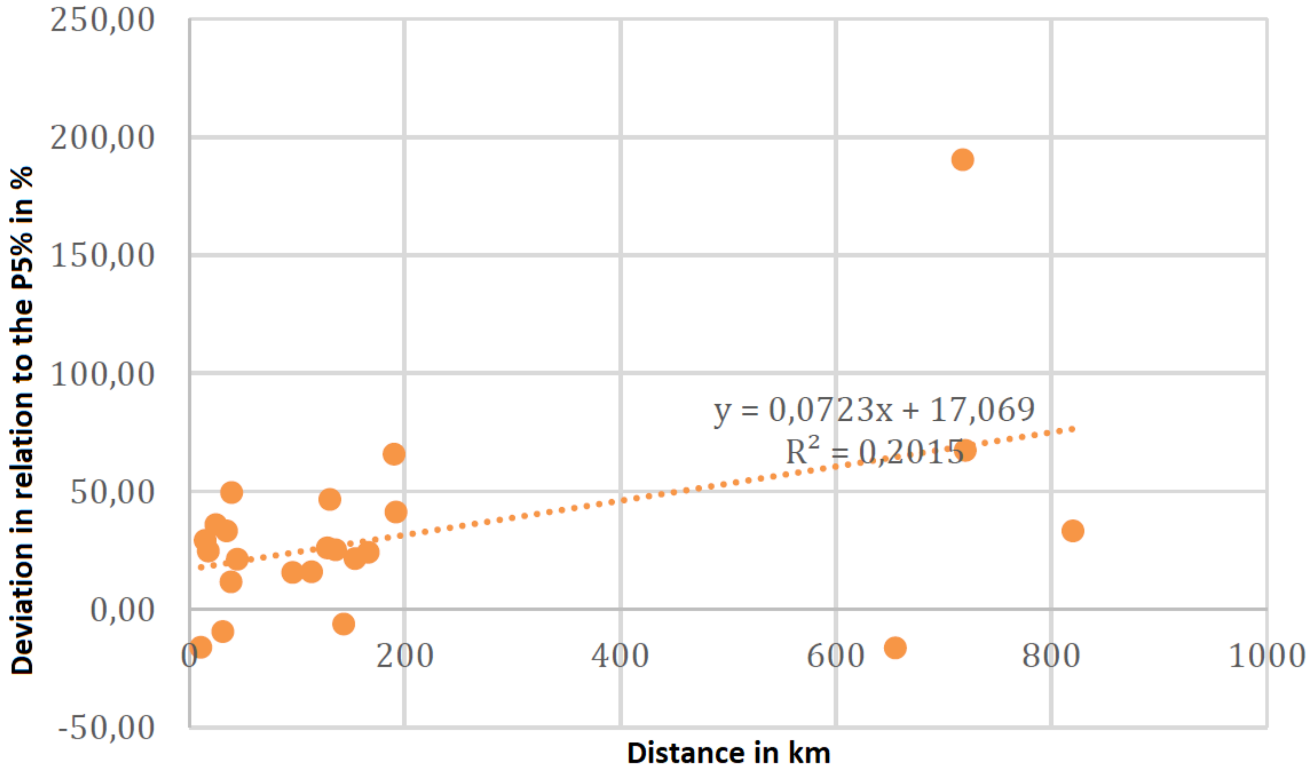

Deviation in relation to the P5% in %
250,00
200,00
150,00
100,00
50,00
0,00
-50,00
0
200
400
600
800
1000
y = 0,0723x + 17,069
R² = 0,2015
Distance in km

Figure 10: Correlation between distance and the Permanence Curve Power Deviation (a) P95%; (b) P50% e (c) P5%.

Figures 7 to 10 suggest that there is no relevant correlation between the analyzed parameters and their area relation, given that the data are disperse and the correlation coefficients are quite reduced for all of the tendency lines evaluated. Thus, it can be concluded that the drainage area relation between fluviometric stations whose data were transposed, and the reference stations exercise some significant influence on the optimal power results found.

Even the correlation analyses with powers of 95%, 50% and 5% of permanence with the relation of areas, which consider only hydrological and non-economic factors, were not successful. Therefore, one can conclude that it is not the economic factors involved in the analysis of net benefit and optimal potency that cause the high deviations and correlations.

Figures 7 and 10 present the correlations between the optimal power deviations and the distance from the reference station. Although the correlations obtained are not yet high (the correlation coefficient is no more than 0.7), there is a clear tendency for deviations to increase as distance increases. This result was intuitively predicted, seeing that, with increasing distance between the stations, naturally the power deviations also increase, since the greater the distance between them, the greater the probability of having variations in the climate or in the use of the soil of the basin that impact the local hydrology.

Considering these complex questions, one must consider all factors to reach reliable conclusions, since there are many factors that influence the results. Several authors have studied different methods to perform regionalization and flows using parameters that go well beyond area relation, such as relief, climate and land use parameters. Souza et al. (2009) stipulates equations that are a function of the average precipitation in mm and the drainage area for the regionalization of the flows. Lopes et al. (2017), uses a series of variables such as drainage area (the only factor considered in the transposition method), basin drainage density, basin length, and precipitation (total, wet months and dry months) in its regionalization process. A joint analysis with such factors may enable a better understanding of the errors associated with the transposition process.

Statistical Analysis

For a better understanding of the calculated deviations between the original and transposed data, an analysis of basic statistical parameters of the results was performed. Deviations were considered in module for the calculation of these parameters. Table 6 shows the values found, separated into groupings of data within and outside the ratio of proportion of areas in module.

Table 6: Deviation values within and outside the area relation

Data outside the area relation of 0.25 to 4				
Area (km²)	Distance (km)	Area relation to the reference Station	D_{Pot} %	D_{LCOE} %
11.00	10.96	0.03	39.01	24.50
55.00	14.79	0.16	16.12	10.36
1560.00	44.46	4.62	27.29	9.33
1910.00	34.60	5.65	13.67	11.82
10100.00	191.93	0.14	109.91	2.35
15900.00	166.05	0.22	72.49	1.05
2460.00	190.14	0.14	47.57	2.26
3520.00	143.38	0.20	25.41	0.98
2720.00	720.50	0.16	74.03	5.78
Data within the area relation of 0.25 to 4.0				
Area (km²)	Distance (km)	Area relation to the reference Station	D_{Pot} %	D_{LCOE} %
113.00	17.90	0.33	15.46	10.67
1040.00	39.22	3.08	17.48	12.65
154.00	25.12	0.46	26.20	10.75
24200.00	154.21	0.33	69.09	1.40
76400.00	31.10	1.04	26.91	6.87
61200.00	38.57	0.83	15.26	0.55
55100.00	96.11	0.75	45.71	0.82
40500.00	128.36	0.55	59.04	0.77
32400.00	820.37	1.87	47.23	6.23
4640.00	113.83	0.27	12.76	0.83
6310.00	135.92	0.36	39.84	5.42
5230.00	130.86	0.30	24.66	2.22
8540.00	717.97	0.49	150.69	0.73
30000.00	655.33	1.73	21.84	7.43

In order to verify whether there are relevant differences between the results obtained, the sets, and the different area relationships, the averages and standard deviation for the data of each set were compared, as well as a division of the data outside (scenario 1 - SC1) and within (scenario 2 – SC2) the range of 0.25 to 4 (Tables 7 to 9).

Table 7: Statistic Analysis of the Optimal Power Deviation

D_{Pot}	Set A	Set B	Set C	SC1	SC2	All Stations
Average (%)	22.18	56.92	49.34	47.28	40.87	43.38
Standard Deviation (%)	9.15	31.53	42.22	32.25	36.08	34.03

Table 8: Statistical Analysis of LCOE Deviation

D_{LCOE} (%)	Set A	Set B	Set C	SC1	SC2	All Stations
Average	12.87	1.98	3.54	7.6	4.81	5.9
Standard Deviation (%)	5.3	2.24	2.65	7.6	4.34	5.83

Table 9: Statistical Analysis of the Permanence Curve Deviation

Deviation (%)	Parameter	Set A	Set B	Set C	SC1	SC2	All Stations
P relative to Q95%	Average	23.12	56.64	76.98	48.86	54.47	54.40
	Standard Deviation (%)	16.7	33.25	51	46.32	42.95	42.98
P relative to Q50%	Average	29.99	51.97	42.21	41.73	38.31	41.46
	Standard Deviation (%)	8.98	26.9	35.84	28.02	29.52	27.65
P relative to Q5%	Average	29.84	21.23	51.79	30.35	37.15	35.81
	Standard Deviation (%)	10.91	10.69	56.22	22.49	45.7	37.37

For the optimal power deviation (Table 7), it can be seen that there is no difference in the average value of the deviation inside and outside the studied area relation (SC1 and SC2), while in SC1 a slightly higher average was observed. However, with the standard deviation, the opposite occurred; that is, the greatest deviation was observed within the area relation (SC2). This indicates that, despite being slightly smaller on average, the relative deviations within the area relation from 0.25 to 4 vary more than those outside, therefore, are more subject to outliers.

In Table 8, which lists the LCOE deviation data, it was observed that the mean and standard deviation inside and outside the area relationship have similar values, being smaller within the area relationship. The LCOE deviations were smaller in sets B and C, probably because of the greater power of these sets. With greater power, there are smaller LCOEs with a greater tendency to stabilize, which also resulted in smaller deviations. The deviations obtained in the LCOE values were much lower than the deviations in the optimal power values.

It is observed that the average of the power deviations is lower in Set A for both the optimal power as well as the powers taken from the permanence curve (see Tables 7 and 9). This is due to the small distance values between the stations in set A, which show an average of 27 km. However, this conclusion is not valid for all cases, since set C, whose average distance exceeds 400 km, has average deviations close to set B, whose average distance does not exceed 120 km, in some cases for optimal power and for P50%. As mentioned before, other factors must be considered for a more comprehensive analysis, such as land use, physical and climatic characteristics of the basin, financial variables, which, in the case of the optimal power determined by the maximum net benefit method, will directly influence the result.

A scenario with a higher rate and closer to the reality of SHPs was analyzed for stations in Set C. The use of a sales rate equal to 227 BRL/MWh (instead of 168 BRL/MWh) would reduce the average deviations of this set of stations to 31.66%. This demonstrates that economic variables affect average deviations obtained in the transposition methodology when the power optimization is applied through the MNB method and reinforces the need for the correct choice of economic variables in hydroelectric potential studies. However, for both rates, the average deviations obtained were high.

The results made it possible to identify the average deviations of optimal power of all 26 stations, being equal to 43.38% ±34.03% for optimal power and 5.9% ± 5.83% for LCOE; thus, demonstrating that the deviations of the transposition process by area relation cause considerable errors in general, especially for the optimal power, while the LCOE parameter proved to be more inelastic under the conditions studied. In the case of the powers of the permanence curve (which are not influenced by economic factors), the average deviations were always between 30% and 50%. Such facts demonstrate that the transposition methodology can lead to errors in the calculated hydroelectric potential and even cause operational problems for hydro power plant projects. This reinforces the importance of using more comprehensive methodologies in the regionalization of flows, which consider more parameters such as relief and different uses and types of soil.

FINAL CONSIDERATIONS

This study sought to analyze the impact of flow transposition methodology on the energy and economic parameters of a hydroelectric plant, sets of fluviometric stations located in different hydrographic basins and with different drainage areas were analyzed. For each set of stations, a reference point was chosen based on the analysis of the proportion of areas that it established with the other stations in the set. It was taken into account that the stations chosen for the same set were in the same hydrographic basin. The impact of the size of the drainage areas of the stations involved in the transposition process was evaluated considering three sets of stations located in different basins.

From the analysis of the permanence curves, variation is seen not only in the shape of the curves, but also in the analyzed flow values. Such values have a direct impact on the energy and economic results of a hydroelectric plant since the energy produced is directly linked to the area below the permanence curve.

The data from the three sets of stations did not establish a reliable or repeatable relationship between the drainage areas that could influence energy and economic results. The errors found in the permanence curves were loaded into the calculation of the MNB and LCOE, and, in the three sets of stations studied, there were cases with high and low deviations both inside and outside the area relation from 0.25 to 4, in turn making it difficult to establish a pattern for understanding the behavior of the problem. This demonstrates that the area relation should not be the only factor considered in order to transpose flow data, since no deviation pattern was observed. A joint analysis with additional variables, such as physical characteristics and climatic conditions of the hydrographic basin would be a more robust approach.

It was not possible to establish a relevant correlation for the power deviations and the area relation for the any of the studied sets. It can be concluded that the relation between the drainage area proportions of the reference station and the transposed station does not exert, for the cases studied here, a significant influence on the optimal power and LCOE results. Regarding the distance between the stations, a trend towards an increase in the relative deviations can be verified as a function of the distance between the stations, although it was not possible to obtain a direct correlation between the parameters. Such a result may indicate that thinking in terms of distance, rather than a relation of areas, may be more appropriate when defining limits for the application of the transposition methodology.

Through statistical methodologies applied to the available data set, it was possible to conclude from the calculation of the average deviations that, in general, these deviations from the process of transposing flow data through the area proportion method cause considerable errors, namely for power, which can cause serious problems, such as incorrect estimation of hydroelectric power, resulting in projects with operational complications and power generation below forecasted levels and erroneous estimates of economic feasibility.

It should be highlighted that there is a need for more studies in the area with a greater number of samples from fluviometric stations. Suggestions for future work include: i) a hypothesis test to verify the statistical differences between the criteria for the relationship of areas; b) a comparison of the transposition methodology by relation of areas with more advanced methodologies that use other climatic and physical factors of the basin; and c) differentiate between SHPs and LHPs in the analyses to verify if the type of hydro power plant impacts the results.

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