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ESTIMATES OF MONTHLY AND ANNUAL EVAPORATION RATES AND EVAPORATED VOLUMES PER UNIT TIME IN THE TUCURUÍ-PA AND LAJEADO-TO HYDROELECTRIC POWER PLANT RESERVOIRS BASED ON DIFFERENT METHODS

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KEYWORDS

lake evaporation,
multiple water uses,
water resources.

ABSTRACT

Evaporation rates in reservoirs influence the volume of water available for multiple uses. Thus, the objective of this study was to estimate the evaporation rates and the evaporated volumes per unit time in the Tucuruí-PA and Lajeado-TO reservoirs based on the methods in Linacre (1993), Kohler et al. (1955), Morton (1983), Bruin & Keijman (1979) and Penman (1948) method was adopted as the standard. The mean annual evaporation rates in the Tucuruí and Lajeado reservoirs, estimated by the Penman method, were similar, with values of 1,784 mm and 1,882 mm, respectively. None of the alternative analyzed methods could be used to estimate the mean annual evaporation in the Tucuruí and Lajeado reservoirs and could not replace the Penman method. However, the Linacre (1993) and Bruin & Keijman (1979) methods could be used to estimate monthly evaporation during the dry season in Tucuruí. The mean evaporated volume per unit time and the mean net evaporated volume per unit time in the Tucuruí reservoir correspond to 120% and 50%, respectively, of the total water demand in the Tocantins-Araguaia region, while the mean evaporated volume per unit time and the mean net evaporated volume per unit time in the Lajeado reservoir correspond to 120% and 50%, respectively, of the total water demand in the basin.

INTRODUCTION

In the current context of water resources and energy scarcity, there is growing concern about the hydrological sustainability of hydroelectric power plants (Herath et al., 2011; Liu et al., 2015). Conflicts among water users are increasing, making it evident that there is a lack of a judicious, balanced and transparent procedure for water allocation. The issue of water distribution between general sectors and, in particular, between the energy sector and other activities, is therefore crucial (Galvão & Bermann, 2015).

As one of the most popular forms of renewable energy, hydroelectric power is often considered a clean and environmentally friendly source of energy. However, the construction of dams can generate a series of negative externalities since it interrupts the continuity of river ecosystems and causes flooding of adjacent areas and terrestrial ecosystems (Stickler et al., 2013; Zhao & Liu, 2015).

In addition, one of the negative impacts caused by reservoirs associated with hydroelectric power plants (HPPs), which has generated debate, is related to the adequate allocation of water resources. An important question, but still without consensus, is whether the use of water resources by HPPs is non-consumptive (Cooley et al., 2011; Mekonnen & Hoekstra, 2012).

The evaporation of liquid off surfaces represents a large component in the reservoir water balance. The impacts of reservoir evaporation on the management of water resources vary significantly with locality, climatic differences, reservoir characteristics and management practices (Wurbs & Ayala, 2014). A better understanding of the relative magnitude of evaporation of liquid off surfaces in the water balances of reservoirs and river systems is relevant to various aspects of the development, allocation, management and use of water resources.

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Estimating evaporation rates in reservoirs is a difficult task compared to estimating other components of the hydrological cycle, such as precipitation and surface runoff. This difficulty is due to the diverse factors involved in this process, such as various time scales and types of measurements required for the application of evaporation estimation methods (Mcmahon et al., 2013).

The importance of better understanding the reservoir evaporation process is clear, and there is a need for more updated and accurate evaporation estimates for reservoirs of Brazilian hydroelectric power plants to help the management of water resources with economic, social, political and environmental value at the national level.

In this context, the main objective of this work was to estimate and compare the monthly and annual evaporation rates as well as the volume of water evaporated per unit time in the reservoirs of Tucuruí-PA and Lajeado-TO using Penman (1948), Kohler et al. (1955), Bruin & Keijman (1979), Morton (1983), and Linacre (1993) methods.

MATERIAL AND METHODS

This study considered the reservoirs of two important hydroelectric power plants in Brazil, Tucuruí and Lajeado, which are located in regions with different climatic conditions. The Tucuruí HPP is located in the Tocantins-Araguaia hydrographic region in the state of Pará (Figure 1). Its reservoir has an area of 2,875 km^2 and a cumulative total volume of 50.27 billion m^3 (Ferreira, 2012). The Lajeado HPP is also in the Tocantins-Araguaia hydrographic region but in the state of Tocantins (Figure 1). Its reservoir has an area of 630 km^2 and a total volume of 5.20 billion m^3 (INVESTCO, 2015).

According to Köppen-Geiger, the region where the Tucuruí HPP reservoir is located has a humid tropical climate (Am), with two well-defined seasons, the rainy season from December to May and the dry season from June to November. According to the Köppen-Geiger classification, the region where the Lajeado HPP reservoir is located has a tropical climate with a dry season (Aw); the rainy season is from November to April, and the dry season is from May to October (Peel et al., 2007).

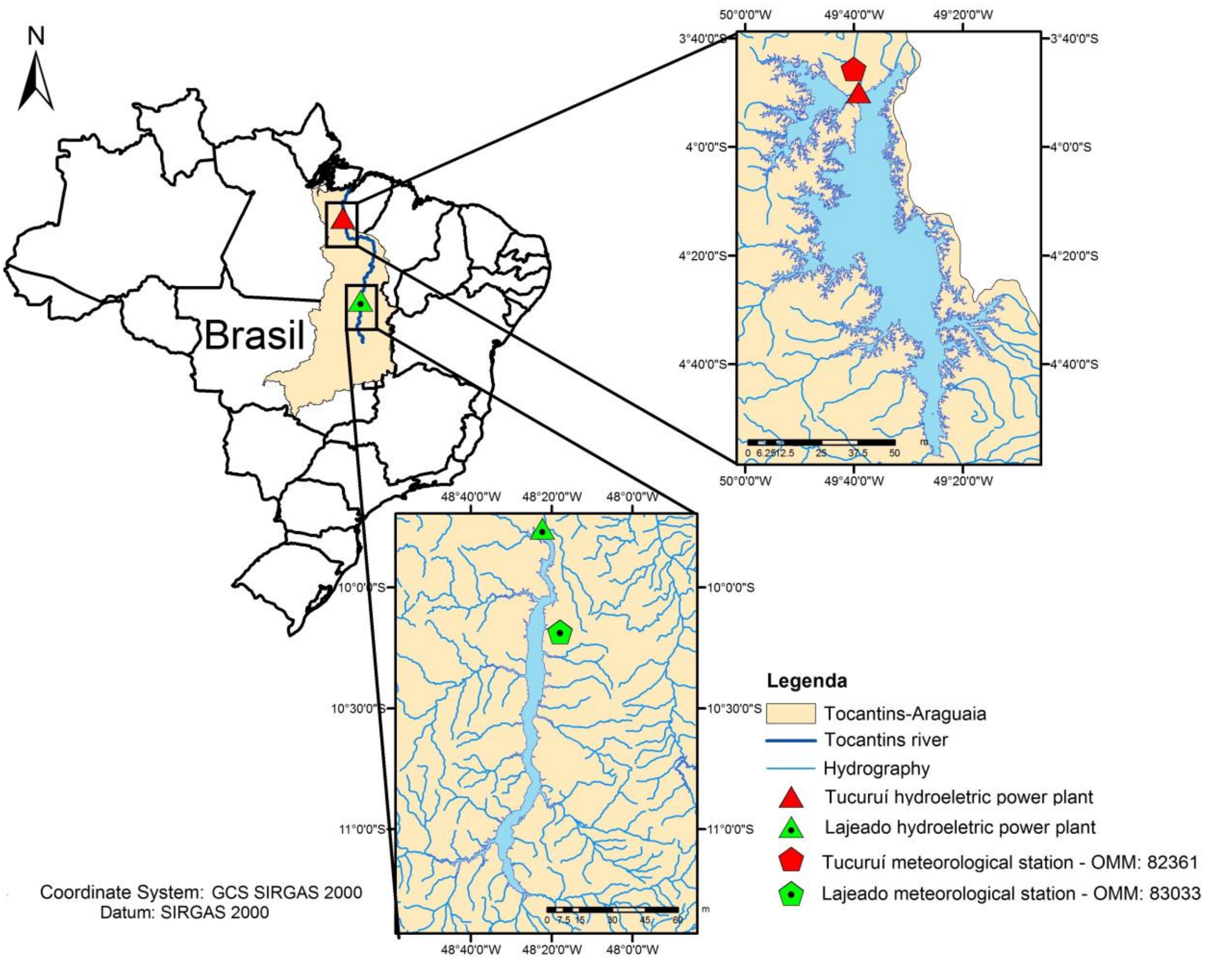

FIGURE 1. Locations of the Tucuruí and Lajeado hydroelectric power plant reservoirs.

Meteorological data from the meteorological stations of Tucuruí (WMO: 82361) and Palmas (OMM: 83033) (Figure 1), provided by the Brazilian National Institute of Meteorology (INMET), were used to calculate the evaporation rates of the reservoirs. The data baseline for the calculation of the evaporation was selected from the operation start date of the hydroelectric power plants, eliminating the years with missing data, resulting in a monthly data historical series of 19 years (1986 to 1990 and 2001 to 2014) for the Tucuruí station and of 13 years (2002 to 2014) for the Palmas station.

The estimation of the evaporation rates in the reservoirs was carried out based on the following methodologies: Penman (1948), Kohler et al. (1955), Bruin & Keijman (1979), Morton (1983) and Linacre (1993).

Penman (1948) (Equation 1) proposed an analytical solution for the energy balance and mass transfer equations, generating a unique equation for the estimation of evaporation expressed by:

$$E_R = \frac{1}{\rho}\left[86{,}4 \times \frac{\Delta}{\Delta+\gamma} \times \frac{R_n}{\lambda_p} + \frac{\gamma}{\Delta+\gamma} \times 0{,}26\left(0{,}5+0{,}54u_2\right)\left(e_s-e_a\right)\right] \quad (1)$$

where,

E_R - reservoir evaporation (mm day^{-1});

Δ - the slope of the saturated vapor pressure–temperature curve at mean air temperature (kPa °C^{-1});

R_n - daily radiation balance measured on the open water surface (W m^{-2});

γ - psychometric constant (kPa °C^{-1});

e_s - water vapor saturation pressure at the air temperature (mbar);

e_a - water vapor partial pressure the air temperature (mbar);

λ - evaporation latent heat (MJ kg^{-1}), and

ρ - water density (kg m^{-3}).

The Linacre (1993) method (Equation 2) is a parameterization of the Penman method, which requires only precipitation, wind speed, mean air temperature and radiation balance data, and is expressed by the following equation:

$$E_R = \left(0.015 + 0.00042T + 10^{-6}h\right) \times [0{,}8R_s - 40 + 2{,}5Fu(T - T_d)] \quad (2)$$

where,

E_R - reservoir evaporation (mm $month^{-1}$);

T - mean daily air temperature (°C);

R_s - incident solar radiation on the reservoir water surface (W m^{-2});

F - correction factor due to local altitude (dimensionless);

u - windspeed at 2 m above surface (m s^{-1});

h - local altitude (m), and

T_d - mean monthly dew point temperature (°C).

The Kohler et al. (1955) method (Equation 3) also consists of a modification of the Penman equation, obtained from several tank and pond evaporation observations, and the estimated evaporation is given by the following equation:

$$E_R = 0{,}7\left(\frac{\Delta R_n}{\Delta+\gamma_l} + \frac{\gamma_l E_a}{\Delta+\gamma_l}\right) \quad (3)$$

where,

E_R - reservoir evaporation (mm day^{-1});

E_a - evaporation given by the aerodynamic equation (mm day^{-1});

R_n - daily radiation balance measured on the open water surface, in equivalent evaporated water depth (mm day^{-1}), and

γ_l - corrected psychrometric constant (kPa °C^{-1}).

Morton (1983) proposed the complementary relationship lake evaporation method (CRLE) based on the concept of a complementary relationship between potential and real evapotranspiration, and it is expressed by the following equation:

$$E_R = 13 + 1{,}12\left(1 + \frac{0.66\dfrac{P}{P_s}}{\Delta_{pl}}\right)^{-1} R_{TP} \quad (4)$$

where,

E_R - reservoir evaporation (mm $month^{-1}$);

P - atmospheric pressure at the locality (mbar);

P_S - atmospheric pressure at sea level (mbar);

Δ_{pl} - slope of the saturated vapor pressure–temperature curve at the potential evapotranspiration equilibrium temperature (mbar °C^{-1}), and

R_{TP} - net radiation at the potential evapotranspiration equilibrium temperature (W m^{-2}).

The method of Bruin & Keijman (1979) consists of a semi-empirical equation (Equation 5) that determines the evaporation rates due to the air humidity above the water body, the stored heat in the reservoir and the psychrometric constant.

$$E_R = \left(\frac{\Delta}{0{,}85\Delta + 0{,}63\gamma}\right)\frac{R_n}{\lambda\rho} \times 86{,}4 \quad (5)$$

where,

E_R - reservoir evaporation (mm day^{-1}) and

ρ - water density (kg m^{-3}).

For the purposes of comparison between the different methods, the Penman method was adopted as the standard since it is based on the physical processes that govern the evaporation phenomenon through energy balance and mass transfer theory (Pereira et al., 2013); it is also the most used method worldwide to estimate the evaporation in lakes and reservoirs.

In the case of the annual evaporation estimate, the comparison between the methods was performed through analysis of variance, in a completely randomized design, and through multiple comparison procedures by Dunnett's test. For the monthly estimation of evaporation, the comparison between the methods was done through analysis of variance in subdivided plots, with the methods in the main plots and the months in the subplots, and Dunnett's and Tukey's tests were also used. For all analyses, a significance level (α) of 0.05 was considered.

From the estimated values of annual evaporation rates in the reservoirs, it was possible to obtain the average volume of evaporated water per unit time of the hydroelectric power plant reservoirs with the methods that did not differ statistically from the Penman method on an annual basis based on [eq. (6)]:

$$Q_{EV} = \frac{EV \times A}{86.400} \tag{6}$$

where,

Q_{EV} - mean evaporated water volume from the hydroelectric power plant reservoir per time unit ($m^3\ s^{-1}$);

EV - reservoir evaporation rate ($m\ day^{-1}$), and

A - reservoir area (m^2).

In addition to the mean evaporated water volume from the hydroelectric power plant reservoir, the mean net evaporated water volume from the hydroelectric power plant reservoir per unit time (Equation 7) was calculated, discounting what would already be lost by actual evapotranspiration of the area corresponding to the reservoir surface.

$$Q_{EVL} = \frac{(EV - ET) \times A}{86.400} \tag{7}$$

where,

Q_{EVL} - mean net evaporated water volume from the hydroelectric power plant reservoir per unit time ($m^3\ s^{-1}$) and

ET - evapotranspiration rate considering the vegetation that existed in the area before the construction of the reservoir ($m\ day^{-1}$).

The actual evapotranspiration rate relative to the period prior to the construction of the reservoirs was determined using the climatological water balance method proposed by Thornthwaite & Mather (1955) and using the historical dataset from 1976 to 1984 for the Tucuruí station and from 1994 to 2001 for the Palmas station, corresponding to the periods prior to the construction of the reservoirs.

The mean volumes of evaporated water per unit time of the Tucuruí and Lajeado hydroelectric reservoirs were compared with the natural discharge data of the Tocantins river, provided by the ONS (2014), with withdrawal discharge data in the Tocantins-Araguaia hydrographic region provided by ANA (2013).

RESULTS AND DISCUSSION

Tucuruí reservoir evaporation

The mean annual total evaporation values for the Tucuruí reservoir are shown in Table 1, and the results of the analysis of variance for the evaporation estimation methods are shown in Table 2.

TABLE 1. Total mean evaporation in the Tucuruí reservoir.

Method	Mean annual evaporation (mm/year)
Penman	1.784
Linacre	1.449*
Kohler	1.285*
Morton	1.267*
Bruin-Keijman	2.001*

* Means with an asterisk in the line differ from the standard method (Penman) at the 5% level of probability by Dunnett's test.

TABLE 2. Variance analysis of the annual evaporation estimation methods in the Tucuruí reservoir.

Source of variation	d.f. (1)	MS (2)	
Method	4	2.091.889**	
Residual	95	18.427	
CV (%) (3)			8,72

**** F is significant at the 1% level of probability. (1) Degrees of freedom, (2) mean square, and (3) coefficient of variation.

As can be seen in Table 2, the F-test was significant at the 1% probability level for the annual mean evaporation data, indicating that the reservoir evaporation estimation methods have a different effect at the level of significance at which the test was performed.

Based on the data in Table 1, it was found that on an annual basis, all the methods studied differed statistically from the Penman method, defined as the standard, by Dunnett's test. The methods of Linacre, Kohler et al. and Morton underestimated evaporation values in relation to Penman by approximately 19%, 28% and 29%, respectively, while the Bruin-Keijman method overestimated it by 12%.

The underestimation of the annual evaporation by the Kohler et al. method in relation to the Penman method could be derived from the consideration that the evaporation in the reservoir in this method is 70% of the evaporation that would occur in a Class A tank; however, for areas when the water temperature of the tank is higher than that of the air, this value can reach 80% (Gangopadhyana et al., 1996).

Of the evaluated methods, the Linacre method is the only one that estimates the balance of radiation from data on average precipitation, making it more sensitive to this variable. Thus, its underestimation in relation to the annual estimate using the Penman method is explained by the high rainfall rates during most of the year in the region of Tucuruí, and therefore, the method tends to underestimate the incident radiation and consequently evaporation.

The Morton method presented the greatest underestimation of evaporation in relation to Penman, with the greatest discrepancy of all the methods probably due to the lack of sensitivity of the method to wind speed. On the other hand, the Bruin-Keijman method overestimated annual evaporation relative to the Penman method. Such behavior was possibly due to the use of an empirical relationship to estimate the Bowen constant, which was overestimated over that used in the Penman method.

According to Dunnett's test, all the analyzed methods differ statistically from the standard method, indicating that none of the methods could be used in place of the Penman method to calculate the average annual evaporation in the Tucuruí reservoir.

Figure 2 shows the time distribution of the monthly average evaporation in the Tucuruí reservoir estimated by all methods analyzed.

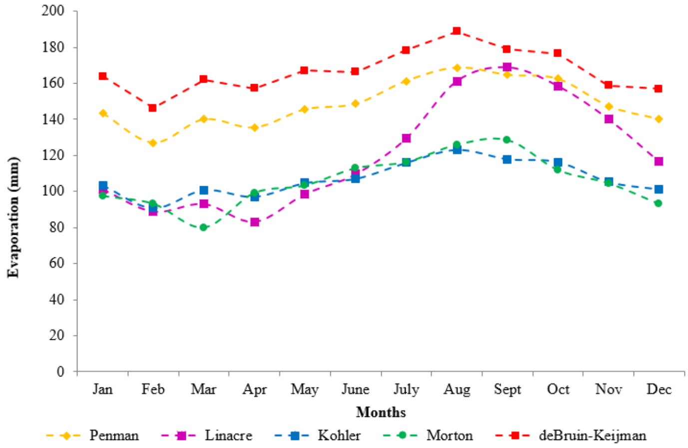

FIGURE 2. Mean monthly evaporation distribution in the Tucuruí reservoir.

From the analysis of Figure 2, it is observed that the Kohler et al., Morton and Bruin-Keijman methods presented seasonal behavior similar to the Penman method but that the Kohler et al. and Morton methods showed lower mean monthly evaporation values than the Penman method in all months of the year, while the Bruin-Keijman method overestimated the results in all months of the year.

The analysis also verified that the Linacre method demonstrated a completely different behavior from the Penman method, underestimating evaporation in the rainy season, from December to July, and obtaining values very close to the standard method in the dry period, from August to November. Such behavior is similar to that observed in the estimation of annual evaporation. This underestimation causes problems for water resource management since underestimates of evaporation can cause erroneous estimation of the water availability downstream of the reservoir, compromising multiple water uses.

The results of the analysis of variance for the methods of estimation of evaporation are presented in Table 3, and the average monthly evaporation values in the Tucuruí reservoir are shown in Table 4.

TABLE 3. Variance analysis of monthly evaporation estimation methods in the Tucuruí reservoir.

Source of variation	d.f. (1)	MS (2)
Block	19	3.695,58**
Method	4	174.322,28**
Month	11	22.161,75**
Method X Month	44	2.048,59**
Residual	1121	203,97
CV (%) (3)		12,80

** F is significant at the 1% level of probability. (1) Degrees of freedom, (2) mean square, and (3) coefficient of variation.

TABLE 4. Mean monthly evaporation in the Tucuruí reservoir.

Month	Penman	Linacre	Kohler	Morton	Bruin-Keijman
Jan	143,33 d	101,15 ef*	103,55 bcde*	97,55 ef*	163,76 cde*
Feb	127,10 e	88,84 fg*	90,91 e*	93,26 fg*	146,13 f*
Mar	139,97 de	93,06 fg*	100,89 de*	80,09 g*	162,10 de*
Apr	135,43 de	83,16 g*	97,18 de*	99,25 def*	157,09 ef*
May	145,54 d	98,55 ef*	104,78 bcde*	103,40 cdef*	166,97 bcde*
June	148,59 bcd	109,55 de*	107,13 bcd*	112,97 bcd*	166,26 bcde*
July	161,28 abc	129,47 bc*	115,98 abc*	116,40 abc*	178,41 abc*
Aug	168,70 a	161,31 a	123,15 a*	125,96 ab*	188,78 a*
Sept	164,67 a	168,96 a	118,02 ab*	128,58 a*	178,93 ab
Oct	162,44 ab	158,56 a	116,41 ab*	111,94 bcde*	176,48 abcd
Nov	147,28 cd	140,08 b	105,39 bcde*	104,59 cdef*	158,90 ef
Dec	140,07 dc	116,46 c*	101,28 cde*	93,13 fg*	156,86 ef*

The means followed by at least one letter in the column do not differ on a 5% significance level of probability by Tukey's test.
* Means with an asterisk in the line differs from the standard method (Penman) at 5% of probability by Dunnett's test.

As can be observed in Table 3, the interaction between the evaporation estimation methods and the months of the year was significant, indicating that the effects of the factors act in a dependent way. Thus, the methods and the months could not be analyzed separately, and the interaction was performed through Tukey's and Dunnett's tests.

In Tucuruí, the dry period and the peaks of insolation and wind speed occur in the months of June to November, thus explaining the observation that all methods have their peaks of evaporation in the interval from July to October. The rainy season and the lowest values of insolation and wind speed occur from December to May, thus explaining why all the methods present minimum values of evaporation in the interval from November to May.

In Table 4, the results of the methods of Kohler et al. and Morton for the estimation of evaporation were not statistically equal to those provided by the Penman method, and all values for both methods were underestimated in relation to the standard. The explanation for the underestimation of monthly evaporation by these two methods is the same as previously provided for annual evaporation.

The Bruin-Keijman method did not differ statistically from the Penman method for the months of September, October and November, and the other months had values overestimated in relation to the standard. This overestimation occurred because during this period, there was an increase in the wind speed values in Tucuruí, and since the Bruin-Keijman method has no sensitivity to wind speed, this factor compensates for the overestimation of its empirical formulation, as mentioned above, resulting in values very close to those obtained by the Penman method.

Similarly, the estimates using the Linacre method did not differ statistically from the estimates using the Penman method in the months of August, September, October and November. As the climate of the region presents two well-defined seasons and as the method is sensitive to precipitation, there was a tendency towards underestimating evaporation in the months with high rainfall indexes, and results were closer to the standard in the dry months.

Based on the results obtained, all the methods analyzed differ statistically from the Penman method in most of the months of the year, except for the Linacre and Bruin-Keijman methods, which show similar behavior to the Penman method in the driest period of the year. Given that these two methods are simpler and require less climate data compared to the Penman method, the possibility of using them in the calculation of monthly evaporation in the Tucuruí reservoir in the dry season could be considered.

Lajeado reservoir evaporation

The mean annual total evaporation values for the Lajeado reservoir are shown in Table 5, and the results of the analysis of variance for the evaporation estimation methods are shown in Table 6.

TABLE 5. Total mean evaporation in the Lajeado reservoir.

Method	Mean annual evaporation (mm/year)
Penman	1.882
Linacre	1.685*
Kohler	1.389*
Morton	1.671*
Bruin-Keijman	1.976*

** Means with an asterisk in the line differ from the standard method (Penman) at the 5% level of probability by Dunnett's test.

TABLE 6. Variance analysis of the annual evaporation estimation methods in the Lajeado reservoir.

Source of variation	d.f. (1)	MS (2)	
Method	4	665.343**	
Residual	60	7.664	
CV (%) (3)			5,09

**** F is significant at the 1% level of probability. (1) Degrees of freedom, (2) mean square, and (3) coefficient of variation.

As can be seen in Table 6, the F test was significant at the 1% probability level for the annual mean evaporation data, indicating that just as in Tucuruí, the evaporation estimation methods of the reservoir have a differentiated effect at the level of significance of the test in Lajeado.

Based on the data in Table 5, it can be seen that similar to the behavior in Tucuruí, the Linacre, Kohler et al. and Morton methods applied to Lajeado underestimated the mean annual evaporation values in relation to the Penman method by approximately 10%, 26% and 11%, respectively, while the Bruin-Keijman method overestimated the annual evaporation average obtained by the standard method by 5%. The explanation for the behavior of the results of the various methods in relation to the Penman method for Lajeado is the same as described for Tucuruí.

According to Dunnett's test, all the methods analyzed differ statistically from the standard method, and it is not possible to use any of them as substitutes for the Penman method to calculate the mean annual evaporation in the Lajeado reservoir.

Analyzing Tables 1 and 5, the mean annual evaporation in Lajeado was higher than that in Tucuruí for all the analyzed methods, except for the Bruin-Keijman method. This is due to Lajeado's climate, because it has a dry season with low rainfall and high insolation and wind speed, which promotes higher evaporation values during this period. The Bruin-Keijman method, however, presented a lower value in Lajeado than in Tucuruí probably due to the greater latitude of the locality, a factor that affects the balance of radiation, a variable of greater relevance in the calculation of evaporation by this method.

Figure 3 shows the time distribution of the mean monthly evaporation in the Lajeado reservoir estimated by all methods analyzed.

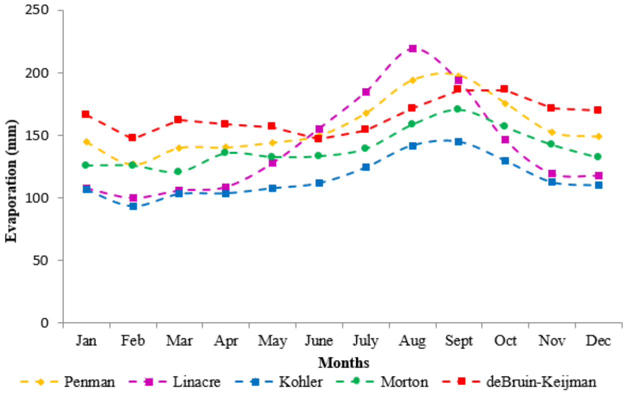

FIGURE 3. Mean monthly evaporation distribution in the Lajeado reservoir.

From the analysis of Figure 3, only the Kohler et al. and Morton methods presented the same trend as the Penman method in most months, although they underestimated the values in relation to the standard. The Linacre method presented values higher than those obtained by the Penman method in the dry season and lower values in the rainy season. It is also observed that the Bruin-Keijman method values were higher than the Penman method values in the months of October to May and lower in the period from June to September.

The results of the analysis of variance for the methods of estimation of evaporation are presented in Table 7, and the average monthly evaporation values in the Lajeado reservoir are shown in Table 8.

TABLE 7. Variance analysis of monthly evaporation estimation methods in Lajeado reservoir.

Source of variation	d.f. (1)	MS (2)	
Blocks	12	1.453,22**	
Method	4	55.444,14**	
Month	11	24.619,10**	
Method X Month	44	2.665,64**	
Residual	708	172,68	
CV (%) (3)			9,16

** F is significant at the 1% level of probability. (1) Degrees of freedom, (2) mean square, and (3) coefficient of variation.

TABLE 8. Mean monthly evaporation in the Lajeado reservoir.

Month	**Penman**	**Linacre**	**Kohler**	**Morton**	**Bruin-Keijman**
Jan	144,79 ef	107,73 ef*	106,46 def*	125,59 de*	166,24 b*
Feb	127,00 f	99,88 f*	93,49 f*	125,49 de	147,00 c*
Mar	140,10 ef	105,82 ef*	103,14 ef*	120,38 e*	161,95 bc*
Apr	140,39 ef	108,58 ef*	103,70 ef*	135,38 de	158,79 bc*
May	144,30 ef	127,62 d*	107,75 def*	132,50 de	156,52 bc
June	149,76 de	155,26 c	111,73 cdef*	133,05 de*	146,58 c
July	167,38 cd	184,38 b*	124,15 bcd*	138,93 cd*	153,95 bc*
Aug	193,63 ab	219,11 a*	141,79 a*	158,34 ab*	171,29 ab*
Sept	197,70 a	193,67 b	144,81 ab*	170,44 a*	186,14 a
Oct	175,72 bc	146,36 c*	129,69 abc*	156,51 abc*	186,13 a
Nov	152,59 de	119,38 de*	112,60 cde*	142,31 bcd	171,39 ab*
Dec	149,08 de	117,61 def*	109,95 def*	131,95 de*	169,64 ab*

The means followed by at least one letter in the column do not differ on a 5% significance level of probability by Tukey's test.
* Means with an asterisk in the line differs from the standard method (Penman) at 5% of probability by Dunnett's test.

As can be observed in Table 7, the interaction between evaporation estimation methods and the months of the year was significant for the Lajeado method, indicating that the effects of the factors act in a dependent way. Thus, as in Tucuruí, it was necessary to perform the unfolding of the interaction through Tukey's and Dunnett's tests.

In Lajeado, the dry period and the peaks of insolation and wind speed occur in the months of May to September, thus explaining the fact that most methods have their peaks of evaporation within this interval. The rainy season occurs from October to April, and the lowest values of insolation and wind speed occur, respectively, in the months of December to March and November to May, thus explaining why most of the methods have a minimum evaporation value within this range. The Bruin-Keijman method had maximum and minimum values displaced in relation to the other methods due to its sensitivity to the solar radiation incident on the surface of the reservoir, which is highest from August to December and lowest from February to July.

Table 8 shows that the Linacre method obtained results that did not differ statistically from those of the Penman method, except in the months of June and September. In the months of July and August, the Linacre method overestimated evaporation in relation to the Penman method, whereas in the months of October to May, it underestimated evaporation. For Tucuruí, this underestimation can be explained by the fact that the Linacre method is the only method that directly considers precipitation in its equation.

The Kohler et al. method statistically differed from Penman in all months of the year, and all values were underestimated in relation to the standard. This behavior was identical to that found for Tucuruí, and it can be explained in the same way.

The Morton method had results that did not differ statistically from those of the Penman method except for the months of February, April, May and November, and the other values were underestimated in relation to the standard. This underestimation is due to the lack of sensitivity of the method to wind speed. This behavior was different from that found for Tucuruí, where evaporation was underestimated in all months of the year. The underestimation occurs because the wind speed in Tucuruí is practically constant throughout the year and has values higher than Palmas in most months, causing the evaporation to be underestimated in relation to the Penman method estimation.

The Bruin-Keijman method had results that did not differ statistically from the standard, except for the months of May, June, September and October, and this method overestimated evaporation in relation to the Penman method estimation in all other months. This behavior was similar to that found for Tucuruí, where the results obtained by the Bruin-Keijman method did not differ statistically from the Penman method results, except for the months where higher wind speed values occurred.

Based on the results of this study, all the analyzed methods differ statistically from the Penman method in most of the months of the year and therefore cannot be substituted in the calculation of the monthly evaporation in the Lajeado reservoir.

Mean evaporated water volumes per unit time in the Tucuruí and Lajeado reservoirs

The mean evaporated water volumes per unit time at the Tucuruí and Lajeado hydroelectric reservoirs were calculated from the evaporation results obtained by the Penman method since none of the other alternative methods evaluated showed behavior similar to that of the standard.

The mean evaporated water volume per unit time at the Tucuruí HPP reservoir was estimated at 163 m^3/s, while the mean net evaporated water volume per unit time was estimated at 69 m^3/s. According to data provided by ONS (2014), the mean annual natural discharge of the Tocantins river in Tucuruí is 10,970 m^3/s, and thus, the mean evaporated water volume per unit time and mean net evaporated water volumes per unit time in the reservoir correspond, respectively, to 1.5% and 0.6% of the mean natural discharge of the Tocantins river in the studied locality.

Although the Tucuruí reservoir represents a small part of the natural discharge of the Tocantins river, mean evaporated water volume per unit time in this reservoir is approximately 20% greater than the total withdrawal discharge for the multiple uses in the of Tocantins-Araguaia hydrographic region, which is 135.6 m^3/s according to ANA (2013). The mean net evaporated water volume per unit time in the reservoir corresponds to approximately 51% of the total water demand of the basin.

In Lajeado, the mean evaporated water volume per unit time in the reservoir was estimated at 38 m^3/s, and the mean net evaporated water volume per unit time was 16 m^3/s. According to the data provided by ONS (2014), the mean annual natural discharge of the Tocantins river in Lajeado is 2,430 m^3/s, and therefore, the mean evaporated water volume per unit time and the mean net evaporated water volume per unit time in the reservoir correspond, respectively, to 1.6% and 0.7% of the mean natural discharge of the Tocantins river in the studied locality.

Although the Lajeado reservoir is also a small part of the natural discharge of the Tocantins river, the mean evaporated water volume per unit time and the mean net evaporated water volume per unit time in this reservoir corresponds to 28% and 12% of the entire withdrawal discharge for the various multiple uses in the Tocantins-Araguaia hydrographic region according to ANA (2013) data.

In Brazil, the use of hydroelectric energy has been considered a non-consumptive use of water resources because all the water used in the process returns to the water sources. However, the volumes of water evaporated in the reservoirs do not necessarily return to the original catchment basin in the form of precipitation, which may compromise water availability, the rate of discharge variation in the watercourses and the ability for multiple use of water.

This work provides a scientific basis that demonstrates that the production of hydroelectric energy, in most cases, significantly consumes water and that it should not be considered a non-consumptive use of water resources. In the specific case of the Tucuruí and Lajeado HPPs, which were the object of study in the present work, it was proven that the evaporation losses in the reservoirs were high when compared to the water demands associated with all other uses in the Tocantins-Araguaia hydrographic region and, consequently, that the production of hydroelectric power should be considered a consumptive use of water resources in the region.

CONCLUSIONS

1. The mean annual evaporation rates in the Tucuruí and Lajeado reservoirs, estimated by the Penman method, were similar, with values of 1,784 mm and 1,882 mm, respectively.
2. The mean annual evaporation rates in the Tucuruí and Lajeado reservoirs, estimated by the Penman method, were similar, with values of 1,784 mm and 1,882 mm, respectively.
3. The Linacre and Bruin-Keijman methods behave similarly to the Penman method for the driest period of the year in Tucuruí and can be used as an alternative to estimate the monthly evaporation rates of the reservoir in this period.
4. The Linacre, Kohler et al., Morton, and Bruin-Keijman methods cannot be used as substitutes for the Penman method to estimate the mean annual evaporation rates in the Tucuruí and Lajeado reservoirs.
5. The mean evaporated water volume per unit time and the mean net evaporated water volume per unit time in the Tucuruí reservoir, corresponding to 163 m^3/s and 69 m^3/s, respectively, do not represent an exact value in relation to the mean natural discharge of the Tocantins river. On the other hand, these parameters account for approximately 120% and 51% of total water demand relative to consumptive uses in the Tocantins-Araguaia hydrographic region.
6. The mean evaporated water volume per unit time and the mean net evaporated water volume per unit time in the Lajeado reservoir, corresponding to 38 m^3/s and 16 m^3/s, respectively, also do not represent an expressive value in relation to the mean natural discharge of the Tocantins river; however, they represent approximately 28% and 12% of the total water demand relative to the consumptive uses in the hydrographic region of Tocantins-Araguaia.
7. The generation of energy in hydroelectric power plants should be considered a consumptive use of water resources due to evaporation losses resulting from the formation of the water reservoirs.

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