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A CURVA DE PERMANÊNCIA DE VAZÕES E A DISPONIBILIDADE HÍDRICA PARA OUTORGA NO ESTADO DO PARANÁ

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1 RESUMO

O conhecimento da disponibilidade hídrica dos corpos d'água é imprescindível para a implementação do instrumento de outorga de uso de recursos hídricos. No estado do Paraná, a disponibilidade hídrica é estimada a partir da curva de permanência. No entanto, a curva de permanência é tradicionalmente obtida a partir de toda a série histórica de vazões, ordenada de forma decrescente, calculando-se então as vazões associadas às probabilidades de excedência. Esta curva é, portanto, sujeita aos eventos extremos de anos secos ou muito chuvosos. As curvas de permanência anuais representam o comportamento médio ou mediano da bacia hidrográfica, e podem ser utilizadas como alternativa para a estimativa da disponibilidade hídrica. Além disso, auxiliar a análise de risco inerente ao processo de outorga. O objetivo deste trabalho foi investigar a construção de curvas de permanência e intervalos de confiança aplicando técnicas estatísticas de estimação de quantis e reamostragem. Os resultados indicam que a curva de permanência anual tem grande potencial para flexibilizar a outorga no estado.

Palavras-chave: gestão da água, recursos hídricos, vazões mínimas.

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FLOW DURATION CURVES AND WATER AVAILABILITY FOR GRANTING IN THE STATE OF PARANÁ

2 ABSTRACT

In Paraná, water availability for granting is estimated from the permanence curve, traditionally obtained from the entire historical flow rate series, ordered in a decreasing manner, and subsequently calculating the flow rates associated with the exceedance probabilities. It is therefore subjected to the extreme events of dry or very rainy years. The solution to this can be the use of annual permanence curves, which represent the average behavior of the river basin. In addition to that, obtaining confidence intervals associated with the permanence curves can assist the risk analysis inherent to the granting process. The

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objective of this paper was to investigate the elaboration of permanence curves and confidence intervals by applying quantile estimation and resampling statistical techniques. The results indicate that the annual permanence curve presents significant potential to increase granting flexibility in the state.

Keywords: water management, water resources, minimum flows.

3 INTRODUCTION

Law 9,433/97 (BRAZIL, 1997) provides for the implementation of granting the right to use water resources as an important management tool. Knowledge of water availability and the estimation of reference flows are fundamental steps in this process (CRUZ; SILVEIRA, 2007).

When managing a watershed, it is important to meet the demands of water resource users while ensuring the minimum flows necessary for the conservation of natural resources. Therefore, more conservative, or more restrictive, reference flows tend to prioritize water resource conservation. Conversely, less restrictive reference flows prioritize meeting demand over conservation (CRUZ; SILVEIRA, 2007).

The reference flows used in Brazil are seven-day flows with a ten-year return period ($Q_{7.10}$) and flows with 90% (Q_{90}) and 95% (Q_{95}) permanence (ANA, 2021). The $Q_{7.10 \text{ flow rate}}$ is obtained by fitting probability distributions to the annual series of minimum flows with a seven-day duration, which is the most restrictive reference flow of the three. The Q_{90} and $Q_{95 \text{ flows}}$ are obtained from the long-period permanence curves.

Long-term permanence curves for any historical series are constructed on the basis of the complete observation period, and the analysis of flow exceedances is performed via a probabilistic approach (PUMO et al., 2014). However, they are often quite sensitive to extreme hydrological events, and consequently, the reference flows (Q_{90} and Q_{95}) are often quite restrictive, as they are affected by the occurrence of dry years in the series. Another important aspect of long-term permanence curves is that they cannot assess the uncertainty associated with reference flow estimates (WMO, 2008).

An alternative that can be applied to make the granting more flexible without losing sight of the necessary conservation of water and the environment is the use of reference flows that take into account the interannual variation in flows (ALMEIDA; CURI, 2016).

Vogel and Fennessey (1994) suggested a nonparametric method for constructing individual permanence curves for each year, allowing the calculation of the median flow associated with each exceedance probability. The median flows form the annual permanence curve, which represents the probability of the flow being exceeded in a typical year (neither rainy nor dry). The annual permanence curve is, therefore, less sensitive to dry periods and the length of the historical series (SMAKHTIN, 2001).

Furthermore, this approach allows the construction of confidence intervals to assess the uncertainty associated with the curves. These intervals represent the variability of the permanence flow rates for each year—that is, the probability that, in any given year, the permanence flow rate will be within this interval (VOGEL; FENNESSEY, 1994). This allows water resource managers to estimate the risk that water availability will differ from the allocated flow rate (CRUZ; SILVEIRA, 2007).

More recently, Pumo et al. (2014) presented a hydrological model for constructing annual permanence curves for river basins without historical flow records. The model, although complex, requires only a few parameters and climate data as inputs. The model was tested in a small river basin in Italy and appears to have potential for application within a flow regionalization scheme. The main drawback presented by the authors is the tendency to underestimate flows in cases where groundwater flow is the main contributor to the flow in the stream. In much of Brazil, this occurs during dry periods or prolonged droughts. For cases where historical flow records exist, there is no advantage in applying this model.

In Brazil, Cruz and Tucci (2008) compared long-term permanence curves with annual permanence curves obtained according to the suggestion of Vogel and Fennessey (1994). They reported that flows with permanence greater than 40%, obtained from the annual curves, were almost always higher than the flows obtained from the long-term curves. The authors state that the method of calculating annual reference flows is promising for the water resource management process and for establishing concession criteria, as it does not restrict water use for different socioeconomic activities.

The method proposed by Vogel and Fennessey (1994) and applied in Brazil by Cruz and Tucci (2008) produces satisfactory annual permanence curves and, consequently, good estimates of reference flows for typical years. However, the confidence intervals associated with these curves are often very wide because the upper and lower limits are defined by the position of the ordered flow values (at each exceedance probability). Currently, computational resources are accessible; therefore, the adoption of more sophisticated statistical techniques for constructing confidence intervals is justified.

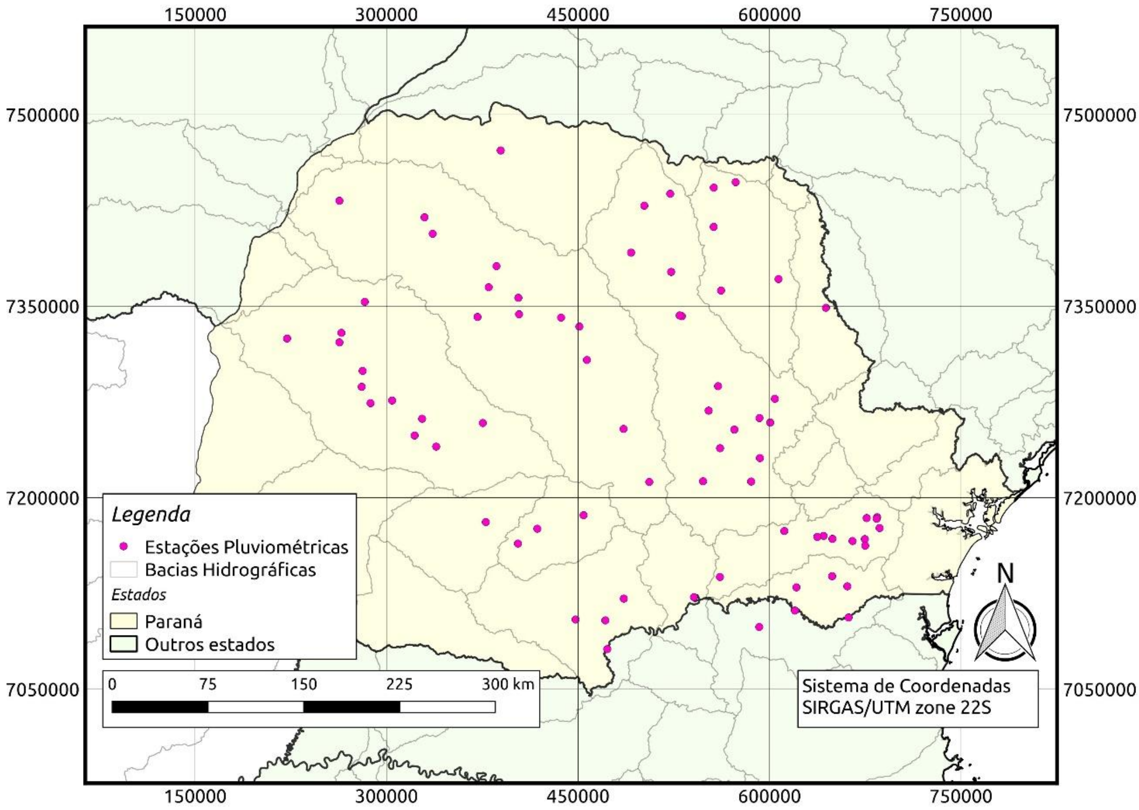
In view of this, the objective of this study was to evaluate the interannual variation in water availability for concession in hydrographic basins in the state of Paraná by comparing the current reference flow (Q_{95}), obtained from the long-term permanence curve, and the reference flow on an annual basis, associated with confidence intervals.

4 MATERIALS AND METHODS

4.1. Study area and hydrological series

For this study, historical series from 75 fluviometric stations distributed across seven river basins in the state of Paraná were analyzed (Figure 1). The series were obtained through the Hidroweb portal, which is maintained by the National Water Agency (ANA, 2021). The average length of the series is 42 years, ranging from 23--78 years, and they present no gaps within the period of record. All calculations and statistical analyses were performed with R (R CORE TEAM, 2018) and RStudio (RSTUDIO TEAM, 2016) software.

Figure 1. Distribution of the fluviometric stations used in the study.



4.2 Long-term residence curve

The long-term permanence curve was constructed by relating the frequency and magnitude of daily flows from historical series. To construct the curves, the flows were divided into 50 classes, whose intervals were calculated via Equation (1):

$$Q_{j+1} = \exp\left(\ln Q_j + \frac{\ln Q_{max} - \ln Q_{min}}{50}\right) (1)$$

where Q_{j+1} is the upper limit of each class interval (for j=1, $Q_j = Q_{min}$); Q_{max} is the maximum flow rate of the series; and Q_{min} is the minimum flow rate of the series.

After the intervals were defined, the frequency associated with each class was calculated via Equation 2:

$$f_k = 100 \frac{N_{qk}}{N} (2)$$

where f_k is the frequency associated with each class interval k; N_{qk} is the number of average daily flows observed within class interval k; and N is the total number of average daily flows in the series.

The curves were constructed by plotting the accumulated frequency on the abscissa axis and the lower limits of each class on the ordinate axis.

4.3. Annual permanence curve

To develop the annual permanence curves, the flow values from each time series were grouped according to the year of occurrence. Consequently, each year in the series presented 365 flow values, which were then sorted in descending order (for leap years, the highest flow was discarded). Table 1 provides an example of how the data were organized.

Table 1. Example of the grouping and decreasing ordering of flows for each year of the hydrological series (Tamanduá Station/Code 64242000/Itararé Hydrographic Basin)

Position	1976	1977	1978	1979	1980	...	2000	2001	2002	2003
1	93.0	105.4	141.5	140.8	133.4	...	231.3	132.7	198.3	279.6
2	88.2	82.8	95.5	139.5	109.8	...	172.5	118.2	187.8	168.2
3	87.0	78.8	81.7	129.4	95.5	...	142.9	106.7	178.3	149.8
...	...	...	...	...	...	...	...	...	...	...
361	12.2	8.9	10.9	12.9	9.5	...	10.8	20.9	14.6	9.1
362	12.2	8.9	10.5	12.9	9.5	...	10.8	20.9	14.3	9.1
363	12.2	8.9	10.5	12.9	9.5	...	10.8	20.9	13.9	8.8
364	12.2	8.3	9.9	12.6	9.5	...	10.8	20.9	13.9	8.3
365	10.6	6.8	9.9	12.2	9.2	...	10.5	20.9	11.1	8.0

According to this flow organization method, as illustrated in Table 1, it is possible to develop an individual permanence curve for each year of the series, and these curves should differ from one another owing to the natural variation in flows from one year to the next. To summarize this natural variability, it is possible to calculate a measure of central tendency, such as the mean or median (VOGEL; FENNESSEY, 1994). In other words, it is possible to calculate a mean or median permanence curve that represents the average behavior of the station, called *the annual permanence curve*, and, in addition, obtain its confidence interval.

The median was calculated via the nonparametric estimator proposed by Harrell and Davis (1982). For this purpose, the flows (at each position) were treated as a random variable of size n, originating from a continuous probability distribution with function F(.). If $X_1 \leq, \ldots, X_n$ represents the sample order statistic, the expected value of the k-th order statistic is given by:

$$E\left[X_{(k)}\right] = \frac{1}{\beta[k,n-k+1]}\int_{-\infty}^{\infty} xF(x)^{k-1}[1-F(x)]^{n-k}\,dF(x) \quad (3)$$

$$E\left[X_{(k)}\right] = \frac{1}{\beta[k,n-k+1]}\int_{0}^{1} F^{-1}(y)y^{k-1}(1-y)^{n-k}\,dy \quad (4)$$

where β[a,b] represents the beta function. Taking k = (n+ 1)p (independent of whether k is or is not an integer) so that $E[X_{(n+1)p}]$ converges to the population quantile estimator $F^{-1}(p)$, for $p \in (0,1)$, as $n \to \infty$, we arrive at the Harrell and Davis estimator:

$$Q_p = \sum_{i=1}^{n} \lambda_i X_{(i)} \quad (5)$$

where:

$$\lambda_i = \frac{1}{\beta[(n+1)p,(n+1)(1-p)]}\int_{\frac{(i-1)}{n}}^{\frac{i}{n}} y^{(n+1)p-1}(1-y)^{(n+1)(1-p)-1}\,dy \quad (6)$$

$$\lambda_i = I_{\frac{i}{n}}[(n+1)p,(n+1)(1-p)] - I_{\frac{(i-1)}{n}}[(n+1)p,(n+1)(1-p)] \quad (7)$$

$EI_x [a,b]$ represents the incomplete beta function. For more details, discussion and comparison of quantile estimators, especially the median, we recommend reading the texts by Harrel and Davis (1982), Parzen (1979), Sheather and Marron (1990) and Vogel and Fennessey (1994).

The confidence interval for the median was calculated via the *bootstrap procedure* proposed by Efron (1979), which is a resampling method with replacement. *Bootstrapping* generally consists of the following procedure: 1) obtain a population sample of size n; 2) extract a sample, with replacement, from the original sample, with the same size n; this step is repeated B times; 3) calculate the median for each sample, thus creating B estimates of the median; and 4) construct the sampling distribution and, from it, calculate the standard error of the estimate and the confidence interval.

4.4. Comparison between long-term and annual dwell curves

First, a visual comparison was made between the curves for each fluviometric station analyzed. The discharge at 95% permanence was subsequently calculated for both the long-term permanence curve ($Q_{95\,lp}$) and the annual permanence curve (Q_{95a}). The difference between Q_{95a} and Q_{95lp} is called ΔQ_{95}, which can also be presented in absolute terms (Equation 8) or in percentage terms (Equation 9):

$$\Delta Q_{95} = Q_{95a} - Q_{95lp} \quad (8)$$

$$\Delta Q_{95} = 100 \left(\frac{Q_{95a}}{Q_{95lp}} - 1 \right) \quad (9)$$

5 RESULTS AND DISCUSSION

Tables 2 and 3 present the reference flows calculated from the long-period permanence curve (Q_{95lp}) and the annual permanence curve (Q_{95a}) for all the fluviometric stations used in the study, as well as the percentage difference between them (ΔQ_{95}) and the confidence interval of Q_{95a} (CI). For all the stations studied, the value of Q_{95a} was greater than the value of Q_{95lp}; that is, the Q_{95} estimated from the annual permanence curve was always greater than the estimate from the long-period curve.

Table 2. Flow with 95% permanence obtained from the long-term (Q $_{95lp}$) and annual (Q $_{95a)}$ permanence curves for the Cinzas, Iguaçu, Itararé, and Pirarapó basins

Code	Bowl	Area (km2)	Q95lp (m3/s)	Q95a (m3/s)	IC (m3/s)		DQ95 (%)
64360000	Ashes	2020	6.6	9.4	8.3	10.9	41.7
64370000	Ashes	5637	11.5	16.1	14.8	18.1	39.9
64380000	Ashes	1070	2.9	4.3	3.6	5.1	44.6
64382000	Ashes	2610	7.5	9.6	8.3	11.0	28.7
64390000	Ashes	3490	5.6	8.1	7.4	8.9	44.1
65006055	Iguaçu	89	0.3	0.6	0.4	0.8	88.7
65006075	Iguaçu	385	0.8	2.2	1.8	2.6	163.1
65010000	Iguaçu	106	0.8	0.9	0.8	1.1	20.7
65011400	Iguaçu	43	0.6	0.9	0.8	1.1	41.6
65017006	Iguaçu	1160	6.2	7.6	6.8	8.7	22.3
65017035	Iguaçu	68	0.3	0.4	0.3	0.5	46.1
65019700	Iguaçu	262	0.4	1.5	0.8	2.6	265.3
65025000	Iguaçu	2330	13.1	16.2	13.8	19.2	23.4
65027000	Iguaçu	231	1.0	1.4	1,2	1.6	40.4
65028000	Iguaçu	2740	17.7	20.6	18.1	23.6	16.4
65035000	Iguaçu	3620	14.8	19.5	18.0	21.6	31.6
65060000	Iguaçu	6050	24.1	32.5	30.4	34.5	34.9
65090000	Iguaçu	803	6.8	8.0	7.2	8.7	17.2
65100000	Iguaçu	3450	0.8	0.9	0.8	1.1	20.7
65135000	Iguaçu	605	3.6	4.3	4.0	4.7	20.6
65136550	Iguaçu	939	6.3	8.0	7.0	9.5	26.6
65155000	Iguaçu	939	10.5	13.3	12.0	14.9	27.0
65220000	Iguaçu	18600	84.5	106.8	99.9	116.7	26.4
65310000	Iguaçu	24200	104.7	129.0	121.5	137.5	23.2
65365000	Iguaçu	65	1.1	1.3	1.1	1.4	17.4
65370000	Iguaçu	1010	4.1	5.3	4.6	6.0	28.8
65385000	Iguaçu	1380	5.5	6.0	5.1	6.7	9.8
65415000	Iguaçu	327	1.7	2.1	1.8	2.4	21.8
65810000	Iguaçu	726	2.9	3.6	3.2	4.1	25.1
65815050	Iguaçu	2220	12.5	16.6	13.6	21.6	32.8
65825000	Iguaçu	3930	20.6	28.0	25.9	30.9	35.9
65855000	Iguaçu	1490	5.5	8.3	6.8	9.9	51.6
64242000	Itarare	1690	11.6	13.6	11.9	15.3	17.2
64550000	Pirapo	4490	29.8	35.1	32.7	37.6	17.8

CI is the confidence interval of Q $_{95a}$; ΔQ $_{95}$ is the increment in the estimate of Q $_{95}$ made with the annual curve in relation to the long-period curve.

Table 3. Flow with 95% permanence obtained from the long-term ($Q_{95\,lp}$) and annual (Q_{95a}) permanence curves for the Ivaí, Piquiri, and Tibagi Basins

Code	Bowl	Area (km2)	Q95lp (m3/s)	Q95a (m3/s)	IC (m3/s)		DQ95 (%)
64620000	Ivaí	1090	3.4	4.6	4.1	5.2	34.1
64625000	Ivaí	3560	9.0	10.9	10.0	12.7	21.1
64645000	Ivaí	8540	34.9	40.8	37.4	45.6	16.9
64652000	Ivaí	2610	5.3	6.4	5.5	7.6	21.5
64655000	Ivaí	12700	33.6	49.8	43.0	57.3	48.2
64659000	Ivaí	3290	5.7	7.6	6.2	9.1	33.0
64660500	Ivaí	19400	65.5	83.4	68.7	104.0	27.3
64671000	Ivaí	853	5.7	7.0	5.7	8.7	23.5
64673000	Ivaí	1530	11.3	14.8	12.5	16.9	31.0
64675002	Ivaí	23100	93.1	114.0	96.4	134.0	22.4
64682000	Ivaí	818	9.5	10.8	10.1	11.5	13.7
64685000	Ivaí	28400	137.3	166.0	147.6	189.5	20.9
64693000	Ivaí	34400	218.6	241.0	219.3	273.5	10.2
64767000	Piquiri	3540	13.5	18.5	16.2	20.3	37.0
64771500	Piquiri	4160	13.0	18.7	15.9	21.2	43.8
64773000	Piquiri	757	1.4	2.0	1.6	2.3	40.7
64775000	Piquiri	2520	9.1	11.7	9.9	13.3	28.6
64785000	Piquiri	1340	8.7	12.0	10.6	13.8	37.9
64790000	Piquiri	598	4.7	6.2	5.2	7.5	31.9
64795000	Piquiri	11200	47.3	60.9	51.7	71.3	28.8
64799500	Piquiri	12100	64.6	82.3	68.5	99.5	27.4
64810000	Piquiri	2040	20.4	24.9	23.0	27.2	22.1
64815000	Piquiri	2960	27.7	31.5	29.4	33.9	13.7
64820000	Piquiri	17400	111.1	133.0	116.8	155.0	19.7
64830000	Piquiri	20900	142.5	167.0	146.0	198.2	17.2
64440000	Tibagi	1340	5.1	6.1	5.2	7.2	19.2
64442800	Tibagi	1340	4.9	6.3	5.4	7.4	28.6
64447000	Tibagi	5710	21.2	28.7	23.6	32.6	35.4
64450002	Tibagi	433	1.8	2.6	2.3	3.4	46.7
64453000	Tibagi	1040	6.7	8.4	7.6	9.4	25.2
64460000	Tibagi	744	2.4	3.4	2.8	3.9	40.4
64465000	Tibagi	8840	34.6	48.1	43.1	52.7	39.0
64475000	Tibagi	1190	3.6	4.6	3.7	5.7	26.4
64477020	Tibagi	208	0.8	1,2	1.0	1.5	48.8
64477600	Tibagi	1590	7.8	9.6	8.4	10.9	22.4
64491000	Tibagi	16100	60.5	68.0	61.9	83.7	12.4
64491260	Tibagi	203	0.5	0.7	0.5	0.8	33.2
64500000	Tibagi	59	0.6	0.8	0.7	0.9	25.7
64502000	Tibagi	820	6.4	7.3	6.0	10.5	14.1
64507000	Tibagi	21900	76.3	116.0	103.3	127.8	52.0
64508500	Tibagi	1050	3.9	5.5	4.8	6.3	40.5

CI is the confidence interval of Q_{95a}; ΔQ_{95} is the increment in the estimate of Q_{95} made with the annual curve in relation to the long-period curve.

To better interpret the results, some descriptive statistics related to ΔQ_{95} are presented in Table 4, which are grouped according to the main river basins covered by the study. On average, the $\Delta Q_{95\ value}$ was 34.6%, ranging from 24.9% in the Ivaí Basin to 43.7% in the Iguaçu Basin.

In the overall analysis, the median was 27.4%; that is, at 50% of the stations used in this study, the $\Delta Q_{95\ value}$ was greater than 27.4%. In this case, the Cinzas Basin stands out, where the median was equal to 41.7%, and the Tibagi Basin, with a median equal to 30.9%.

The $\Delta Q_{95\ values}$ presented in Tables 2 and 3 show that the Q_{95} estimate based on the annual permanence curve can be a way to make the concession more flexible because it is based on the average hydrological behavior of the river basins and not on the atypical behavior that occurs in dry or very rainy years. For the vast majority of the stations analyzed, the flow estimated from the long-term permanence curve (Q_{95lp}) was lower than the lower limit of the $Q_{95a\ confidence\ interval}$, with the exception of only two stations: 65385000 in the Iguaçu Basin (Table 2) and 64502000 in the Tibagi Basin (Table 3).

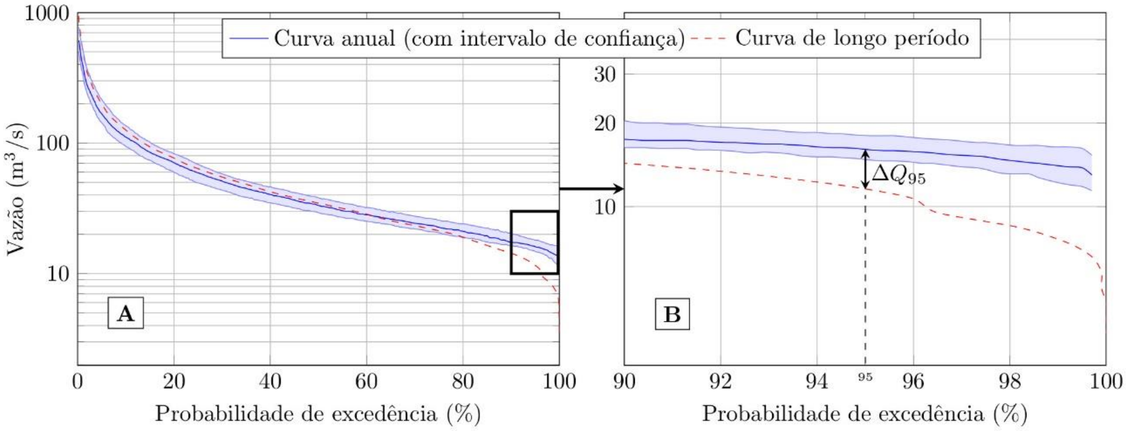
Table 4. Descriptive statistics of ΔQ_{95} grouped according to the main river basins used in the study

Hydrographic Basin	Average	Median	1st Quartile	3rd Quartile	Maximum	Minimum
Ivaí	24.9	22.7	20.9	31.0	48.2	10.2
Ashes	39.8	41.7	39.9	44.1	44.6	28.7
Piquiri	29.1	28.7	21.5	37.3	43.8	13.7
Tibagi	31.9	30.9	24.5	40.4	52.0	12.4
Iguaçu	43.7	26.6	21.2	38.2	265.3	9.8
Global	34.6	27.4	21.0	39.5	265.3	9.8

The difference between the long-term permanence curve and the annual permanence curve can be easily observed in Figure 2. The long-term curve is higher than the annual curve up to an exceedance probability of approximately 60%, and from this point on, it becomes lower than the annual curve. Up to an exceedance probability of 80%, it remains within the confidence interval of the annual curve, after which it decreases significantly (Figure 2A). This behavior was similar for the other stations studied.

Figure 2B shows the visual magnification applied to the permanence curves to detail the range of greatest interest for water availability and grant studies and the $\Delta Q_{95\ value}$. In the example in question, ΔQ_{95} is equal to 4.6 m^3/s, or 39.9%.

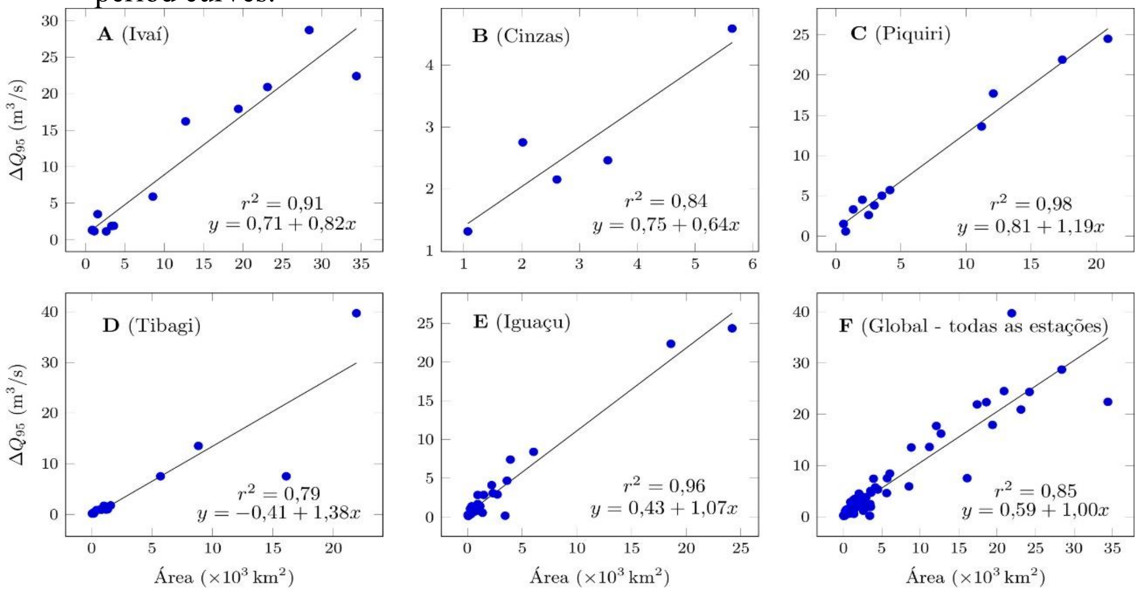
Figure 2. Annual and long-term residence curve for station 64370000 (gray).



Importantly, the confidence interval is close to the annual permanence curve. This is due to the application of the resampling technique. *bootstrap*. In the example shown in Figure 2, the Q_{95} value estimated from the annual permanence curve was 16.1 m^3/s, within the confidence interval $14.8 \leq Q_{95a} \leq 18.1$ m^3/s. The value estimated from the long-term permanence curve ($Q_{95\,lp}$) was 11.5 m^3/s. In this case, even if we adopted the annual permanence curve cautiously, assuming the lower limit of the confidence interval as an indicator of water availability, we would still have a 28.7% increase in water availability compared with the long-term permanence curve. A similar conclusion was presented by Cruz and Silveira in 2007.

Linear regression analysis revealed an increasing trend in ΔQ_{95} as the drainage area increased (Figure 3). The regression presented in Figure 3F (Global - all stations) presented an R^2 value of 0.85 and a linear coefficient close to zero. When the stations were separated into groups according to the river basins covered by the study (Figure 3AE), the R 2 values remained high, ranging from 0.79--0.98, and the linear coefficient values remained close to zero. These The results of indicate that the regression equations effectively represent the variation in ΔQ_{95} as a function of the drainage area.

Figure 3. Linear regression between the area of the hydrographic basins and the increase in the value of ΔQ $_{95}$ when estimated by the annual curves in relation to the long-period curves.



Therefore, the larger the drainage area is, the greater the advantage of adopting the annual permanence curve, which can considerably simplify the concession process. On the other hand, for very small drainage areas, the ΔQ $_{95}$ value will also be reduced; that is, the Q $_{95}$ estimate from the annual permanence curve will not differ significantly from that obtained via the long-term permanence curve. This can have significant consequences for watercourses located at the headwaters of large river basins, which are highly susceptible to human influences. In these cases, the concession process should be more restrictive and judicious.

$_{95}$ values and the length of the historical series (in years). This is seen as positive and, at the same time, expected since the annual permanence curve represents the median behavior of the river basin and is therefore more robust (it is independent of the length of the series and is not excessively influenced by the occurrence of atypical years).

6 CONCLUSIONS

Water availability estimates made with the annual permanence curve, as well as the confidence intervals obtained with the resampling technique *bootstrap*, are robust, as they are not excessively susceptible to the presence of dry or very rainy years in the historical series.

Water availability estimates made via the annual permanence curve are always higher than those made via the long-term permanence curve, which allows for flexibility in granting the right to use water resources.

The adoption of the annual permanence curve is more advantageous when the drainage area of the river basin is larger.

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