



## Hydrological regionalization of streamflows for the Tocantins River Basin in Brazilian Cerrado biome

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### ABSTRACT

The Brazilian Cerrado biome is the largest and richest tropical savanna in the world and is among the 25 biodiversity hotspots identified worldwide. However, the lack of adequate hydrological monitoring in this region has led to problems in the management of water resources. In order to provide tools for the adequate management of water resources in the Brazilian Cerrado biome region, this paper develops the regionalization of maximum, mean and minimum streamflows in the Tocantins River Basin (287,405.5 km<sup>2</sup>), fully located in the Brazilian Cerrado biome. The streamflow records of 32 gauging stations in the Tocantins River Basin are examined using the Mann-Kendall test and the hydrological homogeneity non-parametric index-flood method. One homogeneous region was identified for the estimate of the streamflows  $Q_{tm}$  (long-term mean streamflow),  $Q_{90\%}$  (streamflow with 90% of exceeding time),  $Q_{95\%}$  (streamflow with 95% of exceeding time) and  $Q_{7,10}$  (minimum annual streamflow over 7 days and return period of 10 years). Two homogeneous regions were identified for maximum annual streamflow estimation and the Generalized Extreme Value distribution is found to describe the distribution of maximum events appropriately within the both regions. Regional models were developed for each streamflow of each region and evaluated by cross-validation. These models can be used for the estimation of maximum, mean and minimum streamflows in ungauged basins within the Tocantins River Basin within the area boundaries identified. Therefore, the results provided in this paper are valuable tools for practicing water-resource managers in the Brazilian Cerrado biome.

**Keywords:** l-moments, statistical hydrology, water use rights concessions.

### Regionalização hidrológica de vazões para a bacia do rio Tocantins no bioma Cerrado brasileiro

#### RESUMO

O bioma Cerrado brasileiro é a maior e mais rica savana tropical do mundo e está entre os 25 hotspots de biodiversidade identificados em todo o mundo. No entanto, o escasso monitoramento hidrológico, recorrente nesta região, tem gerado problemas na gestão dos recursos hídricos. A fim de fornecer ferramentas para a gestão adequada dos recursos hídricos



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na região do bioma Cerrado brasileiro, este trabalho desenvolve a regionalização das vazões máximas, médias e mínimas na bacia do rio Tocantins (287.405,5 km<sup>2</sup>), totalmente localizada no bioma Cerrado brasileiro. Os registros de vazão de 32 estações fluviométricas na bacia do rio Tocantins foram examinados usando o teste de Mann-Kendall e o método não paramétrico de homogeneidade hidrológica index-flood. Uma região homogênea foi identificada para a estimativa das vazões  $Q_{ltm}$  (vazão média de longo termo),  $Q_{90\%}$  (vazão igualada ou excedida em 90% do tempo),  $Q_{95\%}$  (vazão igualada ou excedida em 95% do tempo) e  $Q_{7,10}$  (vazão mínima anual das médias de 7 dias e tempo de retorno de 10 anos). Duas regiões homogêneas foram identificadas para a estimativa da vazão máxima anual e a distribuição de valor extremo generalizado foi encontrada para descrever a distribuição de eventos máximos apropriadamente dentro de ambas as regiões. Modelos regionais foram desenvolvidos para cada vazão de cada região e avaliados pela validação cruzada. Esses modelos podem ser usados para a estimativa de vazões máximas, médias e mínimas em bacias não medidas dentro da bacia do rio Tocantins, dentro dos limites de área identificados. Portanto, os resultados fornecidos neste artigo são ferramentas valiosas para a prática de gestores de recursos hídricos no bioma Cerrado brasileiro.

**Palavras-chave:** concessões de direitos de uso de água, hidrologia estatística, momentos I.

## 1. INTRODUCTION

The volume of fresh water in Brazil accounts for about 12% of the planet's total, and is one of the largest reserves in the world. However, the natural distribution of fresh water shows great spatial disparity across the territory. Along with this factor, the different types of water use in the basins lead to conflicts for the right to use and uncertainties regarding the risks of flooding. Therefore, for the maintenance of life and environmental preservation, more effective actions are needed in the management of water resources (ANA, 2019a; Charles, 2020).

The Brazilian Cerrado biome is the largest and richest tropical savanna in the world and is among the 25 biodiversity hotspots identified worldwide (Myers *et al.*, 2000; Silva and Bates, 2002). In addition, this region encompasses the recharge area of several aquifers and important rivers in Brazil, being recognized as the "cradle of Brazil's water" (Lima, 2011). However, the lack of adequate hydrological monitoring in this region has led to problems in the management of water resources, which may further compromise the sustainability of this important biome. Thus, improving the knowledge base on streamflow in the Cerrado biome is essential for water management in Brazil and for ensuring water security and economic development (Rodrigues *et al.*, 2021).

The Tocantins River Basin (287,405.5 km<sup>2</sup>) is a large area of the Cerrado biome, which has been confronting water resource management problems around the expansion of water-using sectors, such as irrigated agriculture and hydro-energy. Irrigated agriculture is the primary consumer of water in this basin (ANA, 2019b), it presents a demand for the use of water of 44.3%. In addition, this basin is the third-ranked Brazilian basin in hydroelectric potential (ELETROBRAS, 2016). The TRB covers three Brazilian states: Goiás, Tocantins and Maranhão, which use streamflows that are exceeded 90 and 95% of the time ( $Q_{90\%}$  and  $Q_{95\%}$ , respectively) as references for granting water use rights.

Hydrological monitoring is the ideal way to determine streamflows in watercourses of interest. However, in countries such as Brazil, whose dimensions are continental, the density of streamflow gauging stations is unsatisfactory, which compromises the estimation of streamflows for water resource management (Melati and Marcuzzo, 2016). According to Pugliesi *et al.* (2016) the need to understand streamflow behavior is one of the biggest problems that occur in ungauged basins. Another obstacle that occurs mainly in medium- and small-gauged basins is the unavailability of longer time series, which limits the estimation of reliable quantiles (Beskow *et al.*, 2016).

Rainfall-runoff models are widely used to estimate the streamflow, but calibrating these models in ungauged catchments is a challenge (Pool *et al.*, 2017). Thus, to mitigate the effect of this lack of data, the streamflow regionalization method is an alternative to obtain hydrological information in locations with little or even without datasets. Streamflow regionalization can be applied within a region with similar hydrological behaviour using statistical procedures (Naghetini and Pinto, 2007; Wolff *et al.*, 2014). In this approach, the streamflow statistics at ungauged sites are conditioned by the streamflow statistics at a gauged site, using catchment descriptors as similarity measure (Cupak, 2020). Furthermore, the regionalization models fitted for a given basin should not be applied using inputs out of the boundaries (Silveira and Tucci, 1998). In the TRB, there are no established regionalized models. Therefore, there is a need to develop models which can be applied in the conditions of the Tocantins River Basin.

Maximum, mean and minimum streamflows estimates are essential for water-resource management. Maximum streamflows are essential for hydraulic structure designs, such as dams, bridges, culverts, and urban drainage systems, and for flood risk assessments. Mean streamflow is fundamental for hydropower planning. Minimum streamflows are important as reference for water-use rights concessions, water supply and habitat protection (Beskow *et al.*, 2016).

In order to provide tools for the adequate management of water resources in the Brazilian Cerrado biome region, the objectives of the study were: i) to evaluate the suitability of 10 probability distributions functions using L-moments method and goodness-of-fit test; and, ii) to develop the regionalization of the maximum, mean and minimum streamflows ( $Q_{\max}$ ,  $Q_{\text{tm}}$ ,  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{7,10}$ ) for the Tocantins River Basin (287,405.5 km<sup>2</sup>), fully located in the Brazilian Cerrado biome. The novelty of this study lies in estimation of reliable and robust flows in data scarce regions by using a combination of statistical techniques.

## 2. MATERIAL AND METHODS

### 2.1. Study area and streamflow data

The Tocantins River Basin (TRB) (Figure 1) comprises a drainage area of 287,405.5 km<sup>2</sup>, is located in the states of Goiás, Tocantins and Maranhão, in the northern region of Brazil, and includes 213 municipalities. This basin is fully inserted in the Cerrado biome and is part of the Tocantins-Araguaia Basin (TARB). The TRB was delimited in the Itaguatins streamflow station (National Water Agency code 23710000).

According to Köppen's climate classification system, the climate of the studied basin is Aw (tropical savanna), with a rainy season in the summer (from November to April) and a dry season in the winter (from May to October) (Kottek *et al.*, 2006; EMBRAPA, 2018).

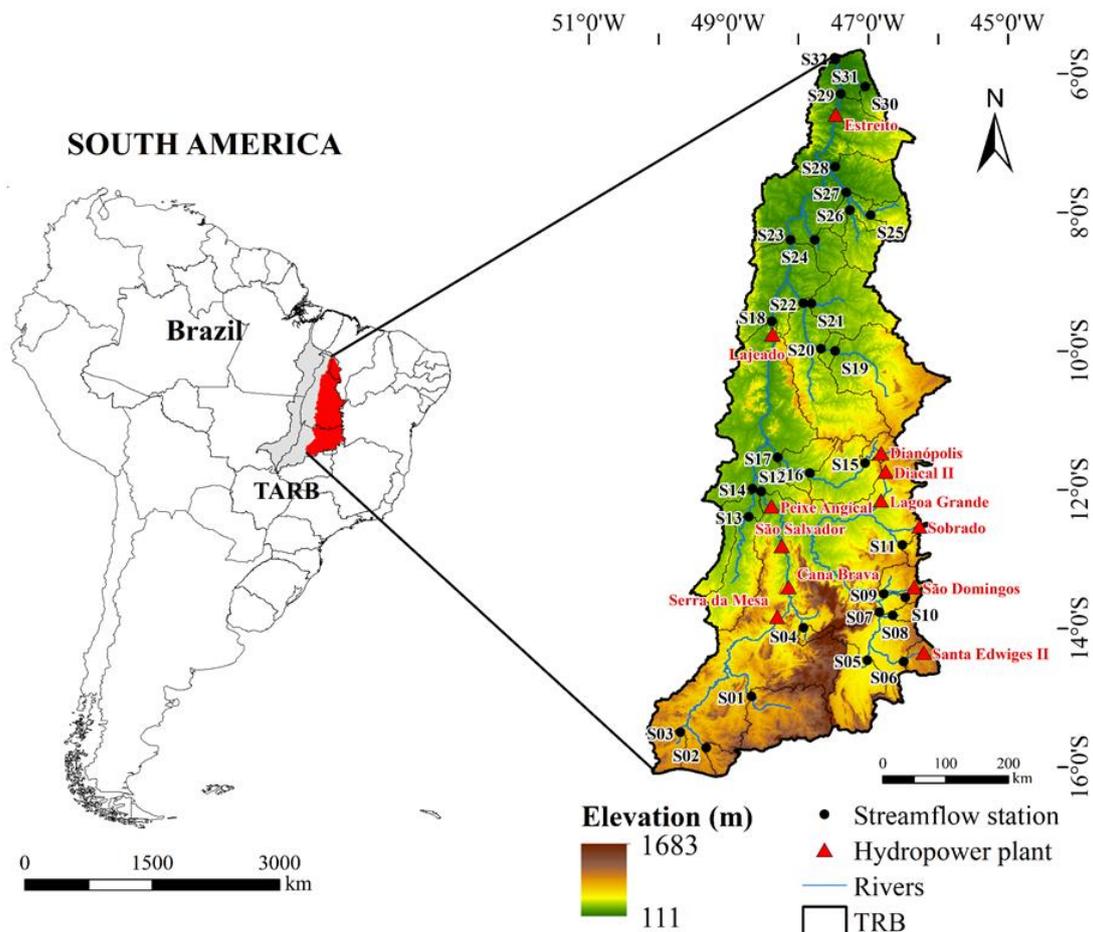
Twelve hydroelectric plants (Figure 1) are located in TRB and are responsible for a hydropower potential of 4475 MW (ELETROBRAS, 2016). The hydroelectric plants with their respective hydropower potentials and year of start of operation are: Serra da Mesa (1275 MW, 1998); Estreito (1087 MW, 2011); Lajeado (903 MW, 2001); Peixe Angical (452 MW, 2006); Cana Brava (450 MW, 2002); São Salvador (241 MW, 2009); Lagoa Grande (26 MW, 2008); Santa Edwiges II (13 MW, 2006); São Domingos (12 MW, 1991); Dianópolis (6 MW, 1994); Diacal II (5 MW, 1999); and Sobrado (5 MW, 1994). Among these hydroelectric plants, the Serra da Mesa HPP, located at the upper reaches of the Tocantins River, stands out for having the greatest hydropower potential, reservoir and flow regulation capacity (ANEEL, 2018).

Daily streamflow data were obtained from the National Water Agency (ANA) for 32 streamflow gauging stations (Figure 1) with at least 10 years of continuous record (Cassalho *et al.*, 2017). Precautions were taken to ensure the natural representation of the streamflows in the study area. Thus, to avoid the regulation effect of dams on the streamflow behavior, only data prior to the start of reservoir operations were used for their downstream stations. In this way,

13 streamflow gauging stations had their series shortened, while the other 19 streamflow gauging stations had all available data kept. Table 1 shows the characteristics of the streamflow gauging stations and their record lengths used in this study, which ranged from 1955-2017. Figure 1 shows the location of the Tocantins River Basin (TRB) with the thirty-two streamflow gauging stations, and the twelve hydropower plants.

**Table 1.** The characteristics of streamflow gauging stations in Tocantins River Basin.

Station n°	Station ID	DA (km <sup>2</sup> )	Affected by reservoir	Most influential HPP installation year	Record length
S01	20050000	11008	No	-	1966 - 2012
S02	20100000	1585.2	No	-	1965 - 2017
S03	20200000	2772.3	No	-	1965 - 2017
S04	20950000	884	No	-	1980 - 2006
S05	21220000	7277	No	-	1976 - 2017
S06	21300000	2260	Yes	2006	1975 - 2005
S07	21500000	20212.7	Yes	2006	1971 - 2005
S08	21510000	795	No	-	1975 - 2005
S09	21560000	2733.5	Yes	1991	1977 - 1990
S10	21580000	281.4	No	-	1975 - 2014
S11	21750000	1224	No	-	1975 - 2014
S12	22050001	122319.8	Yes	1998	1971 - 1997
S13	22100000	8682.9	No	-	1975 - 2014
S14	22150000	13582.9	No	-	1972 - 2005
S15	22190000	1767	Yes	1994	1976 - 1993
S16	22220000	10077.3	Yes	1994	1975 - 1993
S17	22250000	14424.7	Yes	1994	1970 - 1993
S18	22500000	178453.3	Yes	1998	1970 - 1997
S19	22680000	16862	No	-	1974 - 2017
S20	22700000	17535.1	No	-	1972 - 2014
S21	22850000	9396.6	No	-	1974 - 2009
S22	22900000	43376.7	No	-	1970 - 2017
S23	23100000	235213.9	Yes	1998	1970 - 1997
S24	23150000	2854.8	No	-	1974 - 2017
S25	23220000	2938.4	No	-	1985 - 2014
S26	23230000	4031.1	No	-	1984 - 2014
S27	23250000	9809.8	No	-	1972 - 2017
S28	23300000	267392.3	Yes	1998	1962 - 1997
S29	23600000	281136.9	Yes	1998	1955 - 1997
S30	23650000	1566.9	No	-	2000 - 2014
S31	23700000	287336.3	Yes	1998	1974 - 1997
S32	23710000	287405.5	Yes	1998	1970 - 1997



**Figure 1.** Geographical location of the Tocantins River Basin (TRB) with the thirty-two streamflow stations and the twelve hydropower plants.

Based on the daily streamflow historical series of the 32 streamflow gauging stations, three new series were generated for each station, referring to: the maximum annual streamflow ( $Q_{\max}$ ), mean annual streamflow ( $Q_{\text{mean}}$ ) and mean minimum streamflow over seven consecutive days ( $Q_7$ ).

The first analysis in this study was to determine which series were stationary and therefore could be used as a basis for regionalization. To determine whether a given historical series is stationary, it is necessary to apply a trend test (Naghetini and Pinto, 2007). The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is the most recommended to evaluate trends in hydrological time series (Hamed, 2008; Zhang *et al.*, 2015; Wang *et al.*, 2015). Thus, this test was applied to the 32 historical series of  $Q_{\max}$ ,  $Q_{\text{mean}}$  and  $Q_7$  to select those data to be used in the streamflow regionalization. This is one of the most important steps in the flow regionalization process, as it prevents the spread of local trends to the rest of the basin, which justified the exclusion of periods subsequent to the installation of the reservoirs. This test was performed using the Kendall package from RStudio.

Daily series from stations whose  $Q_{\text{mean}}$  series are stationary were used to obtain  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{\text{lim}}$  (Beskow *et al.*, 2016). For the stations whose  $Q_7$  series are stationary, PDFs (probability distribution functions) were fitted to obtain the quantile associated with the return period (RP) of 10 years ( $Q_{7,10}$ ). For the stations with  $Q_{\max}$  stationary series, PDFs were fitted to regionalize the maximum annual streamflows as a function of RP.

## 2.2. Probability distribution functions (PDF)

To regionalize streamflows associated with RPs, it is necessary to model the frequency of

occurrence by a PDF.  $Q_{\max}$  and  $Q_7$  were modeled by different PDFs, selecting the most adequate for each situation.

The following PDFs were fitted to the maximum annual streamflow series: two-parameter log-normal (LN2); Gumbel (or Extreme Values - EV1); Generalized Pareto (GPA); Gamma (GAM); three-parameter log-normal (LN3); Generalized extreme values (GEV); Pearson type III (PE3); Generalized logistic (GLO); Kappa (KAP); and Wakeby (WAK). These distributions were also fitted by Cassalho *et al.* (2018; 2019) to historical streamflow series from watersheds in Rio Grande do Sul. The same distributions were fitted to  $Q_7$  series, except GPA distribution, however, Weibull distribution was also fitted to these series. Detailed descriptions of these PDFs are further presented in Naghettini and Pinto (2007) and Cassalho *et al.* (2018).

The L-moments method was used to estimate the parameters of the PDFs (Hosking and Wallis, 1997; Cassalho *et al.*, 2017). The best PDF for each  $Q_7$  historical series was selected based on the Anderson-Darling (AD) goodness of fit test (Anderson and Darling, 1954), with a significance level of 5%, being the one with the lowest Anderson-Darling value among the PDFs. The adequate PDF to regionalize  $Q_{\max}$  streamflow was also selected based on the Anderson-Darling goodness of fit test, with a significance level of 5%. However, it was the one that fitted all  $Q_{\max}$  series and presented lower AD value among the PDFs that fitted all  $Q_{\max}$  series. The Anderson-Darling test places more weight on observations in the tails of the PDFs, which is a desirable feature when modeling extreme events (Naghettini and Pinto, 2007).

### 2.3. Streamflow regionalization

Streamflow regionalization allows transferring information from a basin where data are available to another where little or no data are available through a mathematical model that is valid for a hydrologically homogeneous region (Naghettini and Pinto, 2007). Thus, to evaluate the homogeneity of the TRB, the non-parametric index-flood method was applied to the  $Q_{\max}$ ,  $Q_{\text{mean}}$  and  $Q_7$  historical series that showed stationarity. This method was originally introduced by Dalrymple (1960) and exhibits good results.

Typically, index-flood method is based on the analyses of a graphically frequency distribution of the dimensionless streamflows from each station. This analysis is the preliminary step of the dimensionless curve regionalization method (Euclides *et al.*, 2001). To apply this method, the streamflows were initially dimensionless as follows (Equation 1):

$$Q_{id} = \frac{Q_i}{Q_{\text{mean}}} \quad (1)$$

Where  $Q_{id}$  is the dimensionless streamflow,  $Q_i$  is the observed streamflow in ascending order at position  $i$ , and  $Q_{\text{mean}}$  is the average observed streamflows of the series.

The frequency of occurrence of the events was calculated by applying the Weibull procedure (Equation 2):

$$P(Q_{id}) = \frac{i}{N+1} \quad (2)$$

Where  $P(Q_{id})$  is the non-exceedance frequency of the streamflow of order  $i$  and  $N$  is the number of events.

After obtaining the dimensionless streamflows and their respective frequencies of occurrence, these data were plotted. To evaluate the homogeneity of the  $Q_{\max}$ ,  $Q_{\text{mean}}$  and  $Q_7$  series, three graphics were plotted (one for each set). This method considers that the dimensionless streamflow versus frequency of occurrence curves for stations within the same hydrologically homogeneous region are similar, thus configuring the criterion for the identification of homogeneous regions.

The homogeneous regions identified by the index-flood method for  $Q_{\max}$  were used in the regionalization of the maximum annual streamflows as function of RP. The regions identified for  $Q_{\text{mean}}$  were used in the regionalization of  $Q_{\text{lim}}$ ,  $Q_{90\%}$  and  $Q_{95\%}$ , and those identified for  $Q_7$  were used in the regionalization of  $Q_{7,10}$ .

To develop the regionalization models, it is essential to know the independent variables that better explain streamflow behaviors. The independent variables to describe this relationship could be the drainage area, drainage density, length and steepness of the main river, average annual rainfall, land cover, among others (de Souza *et al.*, 2021). Cassalho *et al.* (2017; 2019) highlight that to reduce uncertainties related to the regionalization process, the parsimony principle should be considered, which means that a phenomenon should be explained with the lowest number of explanatory variables. In this way, this study used the drainage area as an explanatory variable. Drainage area is the variable most used in different regionalization studies (Naghetini and Pinto, 2007; Beskow *et al.*, 2016; Melati and Marcuzzo, 2016; Bazzo *et al.*, 2017), mainly because it is easily obtained, enabling the use of the generated models in ungauged basins. Thus, the drainage area of each sub-basin was obtained using the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) digital elevation model (DEM) combined with calculations made using the Raster Calculator Tool in ArcGIS 10.1 (ESRI, 2013).

According to Naghetini and Pinto (2007), the main methods applied to streamflow regionalization in a hydrologically homogeneous region are (i) the method that regionalizes the quantiles associated with a previously specified risk and (ii) the method that regionalizes a dimensionless probability curve, which is called the index-flood method. Method (i) was applied to regionalize  $Q_{\text{lim}}$ ,  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{7,10}$ . Method (ii) was used to regionalize the maximum annual streamflows as a function of RP (PDF regionalization). These regionalizations allow the estimation of varied quantiles to the most diverse demands in the homogeneous region, thus, are tools of extreme importance for water resources management.

The streamflows associated with specific risks were regionalized by fitting a regression model, which considers streamflow to be regionalized as the dependent variable and, in the case of this study, the drainage area as the independent variable.

The regionalization of the maximum annual streamflows as a function of RP ( $Q_{\max}(\text{RP})$ ) using the index-flood method was performed based on the following Equation 3:

$$Q_{\max}(\text{RP}) = X^{\text{RP}} \cdot Q_{\text{mean\_max}} \quad (3)$$

Where  $Q_{\max}(\text{RP})$  is the estimated maximum annual streamflow for a given return period and  $X^{\text{RP}}$  is the dimensionless regional quantile function obtained parametrically by fitting a PDF to the dimensionless regional data. This PDF must fit all  $Q_{\max}$  series within the homogeneous region.  $Q_{\text{mean\_max}}$  is the scaling factor known as “index flood,” which consists of the regional function of the mean maximum annual streamflow (mean of the  $Q_{\max}$  series) as a function of the drainage area, which is obtained using method (i).

Regionalization models were fitted according to the power mathematical model, as suggested by Lisboa *et al.* (2008), Beskow *et al.* (2016) and Cassalho *et al.* (2017). To evaluate the capability of the regional models, the cross-validation method was applied using the root mean square error (RMSE) and the coefficient of determination ( $R^2$ ) as objective functions (Veza *et al.*, 2010). In addition, to quantify the performance of the regional models and compare the observed quantiles to the estimated ones, the confidence index (c) proposed by Camargo and Sentelhas (1997) was used according to the following classification:  $c > 0.85$  (excellent),  $0.76 \leq c \leq 0.85$  (very good),  $0.66 \leq c \leq 0.75$  (good),  $0.61 \leq c \leq 0.65$  (moderate),  $0.51 \leq c \leq 0.60$  (fair),  $0.41 \leq c \leq 0.50$  (poor), and  $c \leq 0.40$  (very poor).

### 3. RESULTS AND DISCUSSION

#### 3.1. Preliminary analysis and delimitation of the homogeneous regions

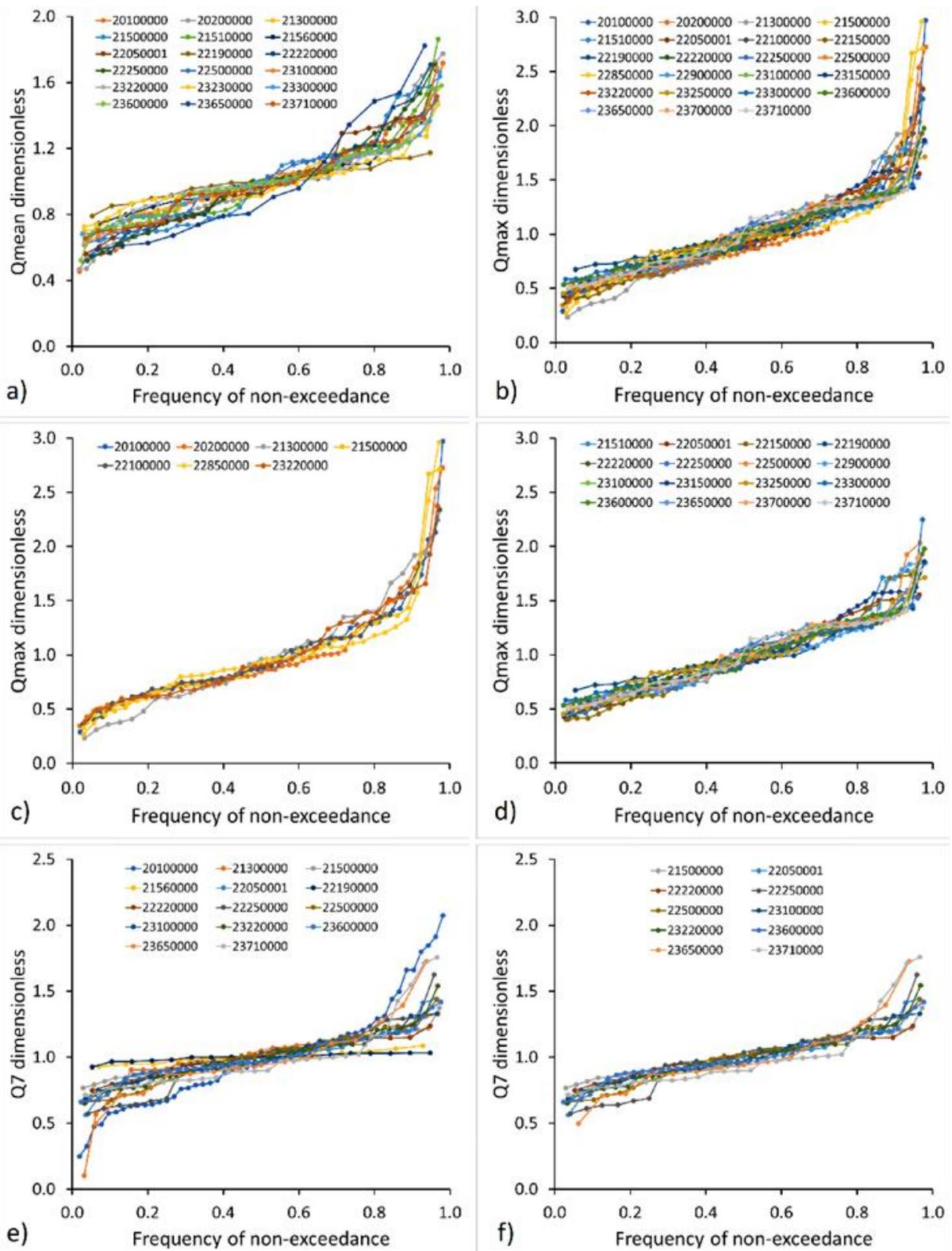
Based on the Mann-Kendall test, out of 32 streamflow-gauging stations with at least 10 years of data, 23 stations for the  $Q_{\max}$  series, 18 for the  $Q_{\text{mean}}$ , and 14 stations for  $Q_7$  series could be considered stationary and adequate for regionalization.

Figures 2a, 2b and 2e depict the empirical dimensionless streamflow versus frequency curves for the  $Q_{\text{mean}}$ ,  $Q_{\max}$  and  $Q_7$  series, respectively. Figure 2a shows that the 18 streamflow gauging stations had similar behavior, thus forming a single homogeneous region regarding  $Q_{\text{mean}}$ . However, Figure 2b shows that the 23  $Q_{\max}$  series did not have the same behavior and therefore should not comprise a single homogeneous region. Therefore, for  $Q_{\max}$ , the existence of two homogeneous regions was observed, namely, one region consisting of 7 streamflow stations, Region 1 (Figure 2c), and the other region consisting of 16 streamflow stations, Region 2 (Figure 2d). Figure 2e shows that the 14 historical  $Q_7$  series did not indicate homogeneous behavior. Graphical analysis indicates that a homogeneous region with 10 streamflow stations can be defined (Figure 2f). However, the other series did not conform to each other, and to define a second homogeneous region for this variable was not possible. A similar process was applied by Noto and La Loggia (2009), who removed approximately 8% of the data because they did not show behavior consistent with the defined hydrological region. Table 2 presents the systematization of the homogeneous regions for the  $Q_{\max}$ ,  $Q_{\text{mean}}$ , and  $Q_7$  series. In addition, it can be seen in Table 2 that the stations did not present common periods, since according to Hosking and Wallis (1997) the series can be considered homogenous and representative of the variable under analysis, so that the use of the same period is unnecessary.

**Table 2.** Homogeneous regions for the  $Q_{\max}$ ,  $Q_7$  and  $Q_{\text{mean}}$  series.

Station	Years	$Q_{\max}$	$Q_7$	$Q_{\text{mean}}$	Station	Years	$Q_{\max}$	$Q_7$	$Q_{\text{mean}}$
20050000	45	ET	ET	ET	22250000	24	2	1	1
20100000	52	1	ER	1	22500000	28	2	1	1
20200000	53	1	ET	1	22680000	44	ET	ET	ET
20950000	27	ET	ET	ET	22700000	43	ET	ET	ET
21220000	41	ET	ET	ET	22850000	34	1	ET	ET
21300000	31	1	ER	1	22900000	48	2	ET	ET
21500000	35	1	1	1	23100000	28	2	1	1
21510000	29	2	ET	1	23150000	44	2	ET	ET
21560000	13	ET	ER	1	23220000	30	1	1	1
21580000	35	ET	ET	ET	23230000	31	ET	ET	1
21750000	40	ET	ET	ET	23250000	46	2	ET	ET
22050001	27	2	1	1	23300000	36	2	ET	1
22100000	37	1	ET	ET	23600000	43	2	1	1
22150000	34	2	ET	ET	23650000	14	2	1	1
22190000	18	2	ER	1	23700000	24	2	ET	ET
22220000	19	2	1	1	23710000	28	2	1	1

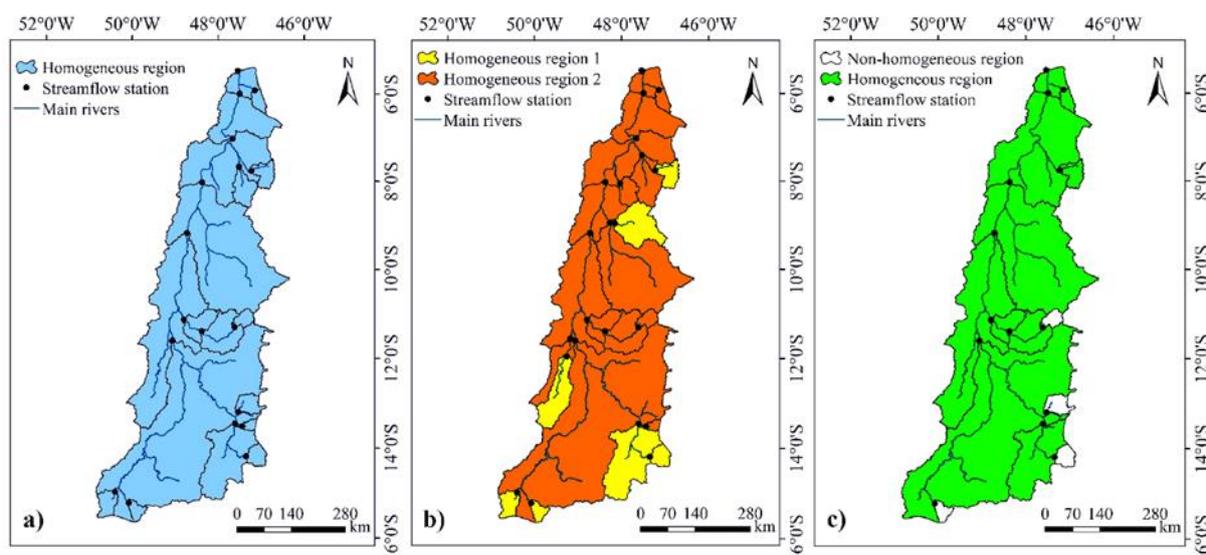
Note: ET – Excluded from the Mann-Kendall test. ER – Excluded from the delineation of homogeneous regions. Regions 1 and 2 are homogeneous.



**Figure 2.** Index-flood method applied to the mean annual streamflow (a) and maximum annual streamflow (b) series; subdivision of the maximum annual streamflows into two homogeneous regions, Region 1 (c) and Region 2 (d); minimum streamflow over seven consecutive days (e); and definition of a homogeneous region for  $Q_7$  (f).

The geographic location of the homogeneous regions determined for the  $Q_{mean}$ ,  $Q_{max}$  and  $Q_7$  is shown in Figures 3 a, b and c. Possible characteristics that led to the differentiation between homogeneous regions and the removal of some series were identified based on the

evaluation of the physiographic characteristics of the TRB. Such characteristics were obtained from land use (IBGE, 2000), soils (EMBRAPA, 2011), hydrogeological (Diniz *et al.*, 2014) and slope (ASTER DEM) maps. For the  $Q_{\max}$  homogeneous regions, Figures 2c and 2d show that Region 1 has a wider range of variation than Region 2. Thus, Region 1 was found to have characteristics that favor surface runoff, such as a high percentage of anthropogenic land cover and Petric Plinthosol, which has a low infiltrability. Regarding the removal of some  $Q_7$  series, Figures 2e and 2f show that the excluded series have more complex characteristics than the rest of the basin, such as amplitude of variation. Thus, based on the physiographic evaluation of these areas, it was observed that the basins having the smallest amplitude of variation in  $Q_7$  are small drainage areas with a low slope and high hydrogeological favorability, as demonstrated by the Urucuia aquifer.



**Figure 3.** Geographic location of the homogeneous regions of the TRB determined by the index-flood method for  $Q_{\text{mean}}$  (a),  $Q_{\text{max}}$  (b) and  $Q_7$  (c).

### 3.2. Regionalization of $Q_{90\%}$ , $Q_{95\%}$ and $Q_{\text{ltm}}$

Table 3 shows the minimum with 90% and 95% permanence ( $Q_{90\%}$  and  $Q_{95\%}$ ) and long-term mean ( $Q_{\text{ltm}}$ ) streamflows obtained by means of the permanence curves of the observed data at each of the 18 streamflow-gauging stations. Table 4 shows the regionalization models of  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{\text{ltm}}$  streamflows fitted for the Tocantins River Basin. It can be seen in Table 4 that the three models fitted are classified as “excellent” based on a confidence index value ( $c$ )  $> 0.85$  (Camargo and Sentelhas, 1997). Besides that, the  $R^2$  values showed that the models explain at least 98% of the variation in  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{\text{ltm}}$ . When regionalizing  $Q_{90\%}$  for river basins fully inserted in the state of Rio Grande do Sul, Brazil, Beskow *et al.* (2016) obtained models with confidence indices ( $c$ ) ranging from 0.71 to 0.99, considering the drainage area as the only explanatory variable. When regionalizing  $Q_{95\%}$  for the Taquari-Antas River Basin, located in the state of Rio Grande do Sul, Brazil, Bazzo *et al.* (2017) obtained models with  $R^2$  coefficients ranging from 0.77 to 0.99, also considering the drainage area as the only explanatory variable. Thus, the models provided in this study can be used for the estimation of  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{\text{ltm}}$  in ungauged basins in the Tocantins River Basin, within the homogeneous region for mean annual streamflow and within the drainage area boundary from 795 to 287,405.5 km<sup>2</sup>. Therefore, they are important tools in the context of the quantitative management of water resources and for Cerrado biome conservation, since the  $Q_{90\%}$  and  $Q_{95\%}$  are the reference streamflows for granting water use rights in the states of Goiás, Tocantins and Maranhão, located in the studied basin.

**Table 3.** Data of streamflow-gauging stations used to regionalize  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{l\text{tm}}$  and their respective values estimated by historical series.

Station	Drainage Area (km <sup>2</sup> )	$Q_{l\text{tm}}$ (m <sup>3</sup> s <sup>-1</sup> )	$Q_{90\%}$ (m <sup>3</sup> s <sup>-1</sup> )	$Q_{95\%}$ (m <sup>3</sup> s <sup>-1</sup> )
20100000	1585.2	33.22	8.53	6.91
20200000	2772.3	60.24	13.39	10.10
21300000	2260.0	54.87	30.65	28.23
21500000	20212.7	208.46	61.65	56.39
21510000	795.0	14.70	7.01	6.66
21560000	2733.5	48.95	23.85	22.90
22050001	122319.8	1848.67	612.30	552.93
22190000	1767.0	45.54	27.20	26.84
22220000	10077.3	151.50	30.19	27.90
22250000	14424.7	211.93	37.11	31.49
22500000	178453.3	2539.28	641.81	548.30
23100000	235213.9	3584.10	1014.64	906.73
23220000	2938.4	32.58	12.74	11.35
23230000	4031.1	77.73	33.85	31.89
23300000	267392.3	4033.50	1188.63	1059.14
23600000	281136.9	4509.36	1321.20	1185.28
23650000	1566.9	26.37	3.35	2.92
23710000	287405.5	4810.91	1428.29	1286.68

**Table 4.** Regionalization models for  $Q_{90\%}$ ,  $Q_{95\%}$  and  $Q_{l\text{tm}}$  (m<sup>3</sup> s<sup>-1</sup>) as a function of the drainage area (DA) (km<sup>2</sup>) for the  $Q_{\text{mean}}$  streamflow hydrologically homogeneous region of the Tocantins River Basin, and their results of the performance evaluation indexes.

Regionalization model	Fitting			Cross-validation		
	R <sup>2</sup>	RMSE	c	R <sup>2</sup>	RMSE	c
$Q_{90\%} = 4.2306 \times 10^{-4} \text{ DA}^{1.1912}$	0.991	52.49	0.993	0.975	86.15	0.981
$Q_{95\%} = 2.6040 \times 10^{-4} \text{ DA}^{1.2211}$	0.988	52.88	0.991	0.968	86.94	0.975
$Q_{l\text{tm}} = 2.4323 \times 10^{-3} \text{ DA}^{1.1498}$	0.998	91.74	0.998	0.995	132.24	0.996

### 3.3. Regionalization of $Q_{7,10}$

Table 5 shows the best PDF used to adjust the  $Q_7$  series at each of the 10 streamflow-gauging stations and their respective estimated values of  $Q_7$  streamflow for a return period of 10 years ( $Q_{7,10}$ ). The best PDF was the one with the lowest Anderson-Darling (AD) test value among the adequate PDFs, considering a significance level of 5%. The Wakeby PDF showed the best performance among the PDFs for 5 historical series, the Weibull PDF showed the best performance for 2 series, and the Pearson, GLO and GEV PDFs showed the best performance for 1 historical series each. Leme and Chaudhry (2005), comparing the Weibull and Gumbel PDFs in the determination of  $Q_{7,10}$  streamflow in the Jaguari Mirim River Basin, Brazil, pointed to the Weibull distribution as the one that provides the best fit. Chen *et al.* (2006), comparing five PDFs in the determination of  $Q_{7,10}$  streamflow in the Dongjiang basin, South China, pointed to the three-parameter lognormal (LN3) distribution as the one that provides the best fit, outperforming generalized logistic (GLO), generalized extreme value (GEV), Pearson type III

(PIII) and generalized Pareto (GPD) distributions. Amorim *et al.* (2020), characterizing the  $Q_{7,10}$  streamflow in the Mortes River Basin, southeastern Brazil, tested ten PDFs, the same ones studied in this work. The distributions that stood out most were those of Wakeby, Kappa, GEV, GLO, GPA, Weibull and PE3, which showed the best performance for 8, 3, 2, 1, 1, 1 and 1 series, respectively. Thus, it can be seen that there is not a better PDF for all regions, thereby, to reduce errors in the  $Q_{7,10}$  estimate, one can highlight the importance of this PDFs analysis.

**Table 5.** The best PDF used to adjust the  $Q_7$  series at each of the 10 streamflow gauging stations, along with its Anderson-Darling (AD) test value and estimated value of  $Q_{7,10}$ .

Station	Drainage Area (km <sup>2</sup> )	Best PDF	AD of the Best PDF	$Q_{7,10}$ (m <sup>3</sup> s <sup>-1</sup> )
21500000	20212.7	Pearson	0.499	48.33
22050001	122319.8	GLO	0.171	453.99
22220000	10077.3	Wakeby	0.141	21.51
22250000	14424.7	Weibull	0.513	20.92
22500000	178453.3	Weibull	0.229	404.55
23100000	235213.9	Wakeby	0.175	720.99
23220000	2938.4	Wakeby	0.191	8.99
23600000	281136.9	Wakeby	0.307	985.46
23650000	1566.9	Wakeby	0.206	2.49
23710000	287405.5	GEV	0.262	1066.01

Table 6 shows the regionalization model of  $Q_{7,10}$  streamflow fitted for the  $Q_7$  streamflow hydrologically homogeneous region of the Tocantins River Basin, along with the accuracy statistics associated with fitting and cross-validation. It can be seen in Table 6 that the fitted model can explain 97.5% of the variation in  $Q_{7,10}$  based on only the drainage area. Furthermore, the confidence index value ( $c$ ) > 0.85 showed that the model is classified as “excellent” (Camargo and Sentelhas, 1997), which demonstrates the quality of the regionalization model. When regionalizing  $Q_{7,10}$  for the São Paulo State, Brazil, Wolff *et al.* (2014) obtained a model with confidence index ( $c$ ) of 0.94 and  $R^2$  coefficient of 0.92, considering the drainage area as the only explanatory variable. When regionalizing  $Q_{7,10}$  for the Mortes River Basin, southeastern Brazil, Amorim *et al.* (2020) obtained model with  $R^2$  coefficient of 0.99, also considering the drainage area as the only explanatory variable. Thus, the  $Q_{7,10}$  model provided in this study can be used in ungauged basins in the Tocantins River Basin, within the  $Q_7$  streamflow hydrologically homogeneous region and within the drainage area boundary from 1566.9 to 287,405.5 km<sup>2</sup>. The previous finding is important, since  $Q_{7,10}$  is used as reference streamflow for the water use right concession in Minas Gerais, São Paulo and Espírito Santo states (ANA, 2007), close to the studied basin, thus, the  $Q_{7,10}$  model developed in the present study is an alternative for the management of water resources.

**Table 6.** Regionalization model for  $Q_{7,10}$  (m<sup>3</sup> s<sup>-1</sup>) as a function of the drainage area (DA) (km<sup>2</sup>) for the  $Q_7$  streamflow hydrologically homogeneous region of the Tocantins River Basin, and its result of the performance evaluation indexes.

Regionalization model	Fitting			Cross-validation		
	R <sup>2</sup>	RMSE	c	R <sup>2</sup>	RMSE	c
$Q_{7,10} = 4.0506 \times 10^{-5} \text{ DA}^{1.3552}$	0.975	71.08	0.981	0.928	120.26	0.945

### 3.4. Regionalization of $Q_{\max}$

Table 7 shows the results of the Anderson-Darling (AD) test for the best PDF, the one with the lowest AD value, and for GEV PDF, which was the only one accepted for all  $Q_{\max}$  series, considering a significance level of 5%. The Wakeby PDF showed the best performance among the PDFs for 10 historical series of  $Q_{\max}$ , the Kappa and GEV PDFs showed the best performance for 4 historical series each, the Pearson PDF was the best for 3 series, and the LN2 and GLO PDFs showed the best performance for 1 historical series each. However, considering that the goal is to define a regional function that is capable of estimating the  $Q_{\max}$  streamflow for different RPs, and that the GEV PDF was the only one that had a good fit for all  $Q_{\max}$  series within the homogeneous regions 1 and 2, the GEV PDF was adopted here. Morais *et al.* (2020), in a regionalization study for the Araguaia River Basin, Brazil, also identified the GEV PDF as the only one that had a good fit for all  $Q_{\max}$  series. Kumar *et al.* (2003), when evaluating 12 PDFs in a regionalization study of  $Q_{\max}$  for Middle Ganga Plains Subzone 1 (f) of India, identified the GEV PDF as the most robust. Noto and La Loggia (2009), comparing 4 PDFs in the determination of  $Q_{\max}$  streamflow in a case study on the island of Sicily, Italy, pointed to the GEV PDF as the one that provides the best fit. The robustness of the GEV for modeling  $Q_{\max}$  was also identified by Seckin *et al.* (2011), when evaluating 6 PDFs in Turkey; by Cassalho *et al.* (2017), when evaluating 6 PDFs in the Mirim-São Gonçalo Basin, Brazil; and by Cassalho *et al.* (2018), when evaluating 4 PDFs in Rio Grande do Sul state, Brazil. Therefore, the results of these studies corroborate the findings of the present study.

Table 7 also shows the fitted parameters of the GEV distribution and the length of each series. From these data, it was possible to estimate the regional parameters of the GEV distribution by means of the mean weighted by the length of the series, as recommended by Naghettini and Pinto (2007). The regional parameters of the GEV PDF obtained for Region 1 were  $\xi = 0.766$ ,  $\alpha = 0.328$  and  $\kappa = -0.125$ , and for Region 2 were  $\xi = 0.849$ ,  $\alpha = 0.315$  and  $\kappa = 0.112$ . Therefore, the term  $X^{RP}$  of Equation 3 was defined for both regions.

Table 7 also shows the mean maximum annual streamflow ( $Q_{\text{mean\_max}}$ ) observed at each of the 23 streamflow-gauging stations. Table 8 shows the regionalization models of  $Q_{\text{mean\_max}}$  streamflow fitted as a function of the drainage area for the homogeneous regions 1 and 2 of the TRB. It can be seen in Table 8 that the fitted models are classified as "excellent" based on the confidence index value ( $c$ ) > 0.85 (Camargo and Sentelhas, 1997). In addition, the  $R^2$  values showed that the models explain at least 86% of the variation in  $Q_{\text{mean\_max}}$  streamflow, and the cross-validation results demonstrated the predictive ability of the models. When regionalizing  $Q_{\text{mean\_max}}$  in a case study on the island of Sicily, Italy, Noto and La Loggia (2009) obtained a model with  $R^2$  coefficient of 0.77, considering the drainage area as the only explanatory variable. When regionalizing  $Q_{\text{mean\_max}}$  for the Araguaia River Basin, Brazil, Morais *et al.* (2020) obtained power mathematical models with  $R^2$  coefficients ranging from 0.87 to 0.9 and confidence index values ( $c$ ) > 0.85, considering the drainage area as the only explanatory variable. When regionalizing  $Q_{\text{mean\_max}}$  for the state of Rio Grande do Sul, Brazil, Cassalho *et al.* (2018) obtained models with  $R^2$  coefficients ranging from 0.57 to 0.96, also considering the drainage area as the only explanatory variable. Thus, the  $Q_{\text{mean\_max}}$  models provided in this study can be used in ungauged basins in the Tocantins River Basin, within their respective  $Q_{\max}$  streamflow homogeneous regions, and within the drainage area boundary from 795 to 287,405.5 km<sup>2</sup> (Region 1) and from 1585.2 to 20,212.7 km<sup>2</sup> (Region 2). Therefore, the term "index flood" of Equation 3 was defined for both regions.

**Table 7.** Results of the Anderson-Darling (AD) goodness of fit test and the parameters of position ( $\xi$ ), scale ( $\alpha$ ) and shape ( $\kappa$ ) fitted for the GEV PDF, along with the observed  $Q_{\text{mean\_max}}$  streamflow and the length of the data series in years (N) at each of the 23 streamflow-gauging stations.

Station	Drainage Area (km <sup>2</sup> )	$Q_{\text{mean\_max}}$ (m <sup>3</sup> s <sup>-1</sup> )	Best PDF	AD of the Best PDF	AD of the GEV PDF	$\xi$	$\alpha$	$\kappa$	N
20100000	1585.2	168.25	Kappa	0.115	0.119	0.769	0.318	-0.132	52
20200000	2772.3	368.14	GEV	0.25	0.25	0.752	0.285	-0.231	53
21300000	2260.0	401.78	Kappa	0.113	0.157	0.757	0.447	0.034	31
21500000	20212.7	1271.00	GLO	0.165	0.224	0.746	0.328	-0.169	35
21510000	795.0	100.23	Pearson	0.296	0.319	0.812	0.352	0.046	29
22050001	122319.8	9580.38	Wakeby	0.212	0.343	0.866	0.366	0.264	27
22100000	8682.9	593.14	Wakeby	0.142	0.162	0.788	0.324	-0.072	37
22150000	13582.9	793.96	Wakeby	0.193	0.326	0.815	0.391	0.117	34
22190000	1767.0	207.60	Wakeby	0.232	0.272	0.883	0.203	0.002	18
22220000	10077.3	1110.98	Wakeby	0.088	0.128	0.901	0.325	0.360	19
22250000	14424.7	1551.00	Wakeby	0.318	0.398	0.891	0.360	0.363	24
22500000	178453.3	11492.77	Kappa	0.346	0.366	0.824	0.312	0.012	28
22850000	9396.6	1032.89	Wakeby	0.149	0.565	0.773	0.299	-0.157	34
22900000	43376.7	2697.00	Wakeby	0.332	0.417	0.822	0.276	-0.065	48
23100000	235213.9	15098.70	GEV	0.397	0.397	0.863	0.336	0.204	28
23150000	2854.8	312.89	Pearson	0.339	0.453	0.826	0.320	0.034	44
23220000	2938.4	144.18	Pearson	0.256	0.308	0.783	0.332	-0.070	30
23250000	9809.8	612.73	Wakeby	0.303	0.32	0.864	0.298	0.139	46
23300000	267392.3	14681.06	Kappa	0.474	0.554	0.848	0.257	-0.014	36
23600000	281136.9	17016.38	LN2	0.567	0.585	0.848	0.284	0.044	43
23650000	1566.9	331.02	Wakeby	0.347	0.445	0.869	0.338	0.229	14
23700000	287336.3	19975.07	GEV	0.526	0.526	0.859	0.327	0.169	24
23710000	287405.5	19339.39	GEV	0.739	0.739	0.880	0.332	0.268	28

**Table 8.** Regionalization models for  $Q_{\text{mean\_max}}$  ( $\text{m}^3 \text{s}^{-1}$ ) as a function of the drainage area (DA) ( $\text{km}^2$ ) for the  $Q_{\text{max}}$  streamflow hydrologically homogeneous regions of Tocantins River Basin, and their results of the performance evaluation indexes.

Region	Regionalization model	Fitting			Cross-validation		
		R <sup>2</sup>	RMSE	c	R <sup>2</sup>	RMSE	c
1	$Q_{\text{mean\_max}} = 1.3233 \text{ DA}^{0.6964}$	0.869	171.25	0.898	0.768	227.90	0.811
2	$Q_{\text{mean\_max}} = 0.2004 \text{ DA}^{0.9084}$	0.986	963.21	0.989	0.977	1228.28	0.983

Based on the coupling of the  $Q_{\text{mean\_max}}$  models and regional parameters of the GEV distribution to Equation 3, the regional functions Equation 4 and Equation 5 were obtained for  $Q_{\text{max}}$  homogeneous regions 1 and 2, respectively, to estimate the maximum annual streamflow in  $\text{m}^3 \text{s}^{-1}$  as a function of the RP (years) and of the drainage area DA ( $\text{km}^2$ ). These models allow the direct estimation of the  $Q_{\text{max}}$  associated with different return periods for ungauged basins located within the respective homogeneous regions, within the drainage area boundary from 795 to 287,405.5  $\text{km}^2$  (Region 1) and from 1585.2 to 20,212.7  $\text{km}^2$  (Region 2). Therefore, these regional functions are extremely important tools for the management of water resources in the Tocantins River Basin, especially for planning hydraulic structures. In addition, it can be highlighted that despite the good results obtained in all regionalization models, the use of field monitored data is the best option, since the regionalization process presents uncertainties, as well as any other data simulation process.

$$Q_{\text{max\_R1}}(RP, DA) = 0.766 + \frac{0.328}{-0.125} \cdot \left[ 1 - \left( -\text{Ln} \left( 1 - \frac{1}{RP} \right) \right)^{-0.125} \right] \cdot 1.3233 \cdot \text{DA}^{0.6964} \quad (4)$$

$$Q_{\text{max\_R2}}(RP, DA) = 0.849 + \frac{0.315}{0.112} \cdot \left[ 1 - \left( -\text{Ln} \left( 1 - \frac{1}{RP} \right) \right)^{0.112} \right] \cdot 0.2004 \cdot \text{DA}^{0.9084} \quad (5)$$

At the end, it is highlighted that the estimates of the regionalization models represent the flow in natural-flow conditions in the basins. This means that the approach will most probably not work or will be misleading if flow regimes analysed are continually changing under man-induced impacts.

## 4. CONCLUSIONS

In the present study,  $Q_{90\%}$ ,  $Q_{95\%}$ ,  $Q_{\text{ltm}}$ ,  $Q_{7,10}$ , and  $Q_{\text{max}}$  as a function of return period were regionalized. Considering the results, the following conclusions were drawn: i) The non-parametric index-flood method for identification of hydrologically homogeneous regions was adequate for the Tocantins River Basin, presenting results that are consistent with the physiographic reality of the basin; ii) The Wakeby distribution was the one that adjusted to the highest number of  $Q_7$  and  $Q_{\text{max}}$  series among the analyzed PDFs, and the GEV distribution was the most robust in relation to  $Q_{\text{max}}$ , being the only one that adjusted all the series; iii) All fitted models were adequate according to the statistics used; iv) The drainage area as the only explanatory variable was robust for all fittings, which confirms the benefits of its use, especially in terms of ease of use of the generated models; v) The fitted regional models are an alternative for generating data for the poor hydrological monitoring of this important basin of the Brazilian Cerrado; and, vi) The streamflows regionalized in this study are important for water resource management in the Tocantins River Basin because they contribute to several initiatives ranging from the planning of hydraulic structures to the quantitative management of reference streamflows for water-use concessions.

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