Streamflow regionalization for the Mortes River Basin upstream from the Funil Hydropower Plant, MG

Jhones da Silva Amorim[1]*[iD]**; Rubens Junqueira[1]**[iD]**; Vanessa Alves Mantovani[1]**[iD]**;
Marcelo Ribeiro Viola[1]**[iD]**; Carlos Rogério de Mello[2]**[iD]**; Nicole Lopes Bento[2]**[iD]**;**

[1]Departamento de Recursos Hídricos e Saneamento. Laboratório de Hidráulica. Universidade Federal de Lavras (UFLA), Caixa Postal 3037, CEP: 37200-900, Lavras, MG, Brazil. E-mail: rubensjunqueira@live.com, vanismantovani@hotmail.com, marcelo.viola@ufla.br
[2]Departamento de Engenharia. Universidade Federal de Lavras (UFLA), Caixa Postal 3037, CEP: 37200-900, Lavras, MG, Brazil. E-mail: crmello@deg.ufla.br, nicolelbento@gmail.com
*Corresponding author. E-mail: jhonesamorim@gmail.com

ABSTRACT

Maximum and minimum streamflow are fundamental for water resource management, especially for water rights. However, lack of monitoring and scarce streamflow data limit such studies. Streamflow regionalization is a useful tool to overcome these limitations. The study developed models for regionalization of the maximum and minimum reference streamflows for the Mortes River Basin (MRB) (Water Resources Planning and Management Unit - GD2), Southern Minas Gerais State. The study used long-term streamflow historical series provided by the Brazilian National Water Agency (ANA). Previous exploratory analysis was performed, and it was observed that the streamflow series are stationary according to the Mann-Kendall test. The estimation of the streamflow for different return periods (RP) was performed by fitting Probability Density Functions (PDFs) that were tested by the Anderson-Darling (AD) test. The Generalized Extreme Values (GEV) and Wakeby were the most appropriate PDFs for maximum and minimum streamflows, respectively. The streamflow models were fitted using a power regression procedure, considering the drainage area of the watersheds as inputs. The fittings reached the coefficient of determination (R^2) greater than 0.90. Thus, the streamflow regionalization models demonstrated good performance and are a potential tool to be used for water resource management in the studied basin.

Keywords: probability density functions, statistical hydrology, water resource management.

Regionalização de vazões para a bacia hidrográfica do Rio das Mortes a montante da Usina Hidrelétrica do Funil, MG

RESUMO

Vazões máximas e mínimas são fundamentais para a gestão dos recursos hídricos, especialmente para outorga de uso da água. Entretanto, a falta de monitoramento e a escassez de dados de vazão são fatores limitantes para tais estudos. Para contornar tal dificuldade, uma das ferramentas mais utilizadas é a regionalização de vazões. O objetivo neste estudo foi desenvolver modelos de regionalização para vazões máximas e mínimas de referênciapara a bacia hidrográfica do Rio das Mortes (MRB) (Unidade de Planejamento e Gestão dos Recursos

Hídricos - GD2), sul do estado de Minas Gerais. As séries históricas de vazão de longo termo utilizadas foram disponibilizada pela Agência Nacional das Águas (ANA). Uma análise exploratório preliminar foi realizada, bem como a análise da estacionariedade das séries por meio do teste de tendências de Mann-Kendall. As Funções Densidade de Probabilidade (PDFs) com diferentes números de parâmetros foram utilizadas para estimar as vazões mínimas e máximas associadas a diferentes tempos de retorno e a performance foi avaliada por meio do teste de Anderson-Darling. A Generalized Extreme Values e Wakeby foram as distribuições mais apropriadas para vazões máximas e mínimas, respectivamente. O modelo de regressão para vazões foi ajustado utilizando como variável independente a área de drenagem das estações fluviométricas, sendo que os coeficientes de determinação obtidos foram superiores a 0,90. Desta forma, os modelos de regionalização demonstraram uma boa performance e são uma ferramenta potencial para ser utilizada na gestão dos recursos hídricos.

Palavras-chave: funções densidade de probabilidade, gestão dos recursos hídricos, hidrologia estatística.

1. INTRODUCTION

To perform studies regarding floods and droughts, analyses of different scenarios of water uses, and the streamflow prediction, among other possible applications, it is important to understand the behavior of streamflow in basins as accurately as possible (Fan *et al.*, 2014). This understanding may be performed by analyzing the minimum reference streamflows and the frequency (or return period) of the historical floods, using historical series.

Despite the importance of these studies for water resource management, streamflow data have often been a limiting factor for most of the region of interest (Zaman *et al.*, 2012). Concerning the number of fluviometric gauge stations, Brazil has only a few stations, and some of them present short or even insufficient streamflow data, especially in small-medium basins (Beskow *et al.*, 2014).

A common practice adopted to overcome this problem is streamflow regionalization (Agarwal *et al.*, 2016), which is still considered a challenging issue for hydrological science (Samuel *et al.*, 2011; Agarwal *et al.*, 2016). In general, regionalization is a technique that transfers hydrologic information from a monitored drainage basin to sub-basins with scarce data (Mwale *et al.*, 2011). The quality of the regionalization depends on the hydrological homogeneity between the sites of interest and the monitored site (Razavi and Coulibali, 2013). Beskow *et al.* (2014) emphasized that clustering into homogeneous regions increases the success potential of the regionalization study.

In the quantile regionalization method, streamflows are calculated for different return periods (RP) based on the frequency distribution for J stations (QTJ) within the region. From these results, the parameters of the model are estimated by multiple regression procedures taking QTJ values and exploratory variables, such as drainage area, length of the main watercourse, slope of the basin, and rainfall of the respective stations (Naghettini and Pinto, 2007). Multiple regression is one of the most used methods to obtain a model for the regionalization of the streamflows (Pruski *et al.*, 2012).

The regionalization method based on the probability density functions (PDF) parameters requires the same frequency distribution for all fluviometric stations. Further, the parameters are related to the physiographic and/or climatic characteristics of the respective basin. The PDF parameters can be derived based on statistical criteria for their fitting, and then, they can be obtained with a single function for the entire region (Cassalho *et al.*, 2018).

Other approaches to regionalization have been used. McIntyre *et al.* (2005) presented a method based on ensemble modeling in which the relationship between the model parameters

and the basin characteristics (e.g., area, perimeter) should be dealt with as a response surface of likelihood. This surface must be integrated into a representative range of the basin characteristics to generate a continuous joint distribution function. Therefore, the model parameters are kept as an ensemble and its interdependencies are not neglected. Despite some advantages, McIntyre *et al.* (2005) pointed to an underestimation of peak flows in a study carried out in the United Kingdom.

A "similarity" approach is when the parameters from a gauged basin are calibrated and transferred to the ungauged basin. In this procedure, an appropriate calibrated basin is selected through physical similarities between it and the ungauged basin. According to Choubin *et al.* (2019), accessing some geo-environmental information may be the main limitation of the similarity approach, mainly if rainfall-runoff models are used to estimate the streamflow in ungauged basins. Gibbs *et al.* (2012) point out that for regions where the number of appropriated calibrated basins is low, the similarity approach is less attractive.

Given that the regionalization of quantiles obtained from regression using as independent variables the physiographic characteristics has presented satisfactory results in Brazil (Maciel *et al.*, 2019; Silva *et al.*, 2006), this method has been applied frequently in studies in several places in this country. In addition, in cases that basin characteristics are available in GIS databases, the regression approach may be more appropriate (Gibbs *et al.*, 2012).

Grande River Basin (GRB) is located in southeastern Brazil. This basin corresponds to approximately 12% of the hydropower produced in Brazil (Nobrega *et al.*, 2011). Mortes River Basin (MRB) is one of the sub-basins of the GRB, and plays an important hydrological function for the water resources management, especially feeding the Funil Hydropower Plant (Oliveira, 2013). In addition, MRB develops several mining activities, focused on metallurgy and limestone, and agriculture, mainly coffee production (Minas Gerais, 2013). Despite the importance of MRB and a lot of water rights being discussed in the basin, there are few studies in this sense in the region.

Silva *et al.* (2006) performed hydrological regionalization in the GRB. However, PDFs more appropriate to simulate the frequency distribution, with 4 and 5 parameters, were not tested, which limited their study. A more appropriate study is then necessary. Moreover, PDFs with a greater number of parameters can be considered as a fundamental flood distribution and have been used successfully in hydrological modeling (Busaba Bodin *et al.*, 2016).

Therefore, a robust statistical study was proposed for the streamflows and, thus, for the regionalization process. The objectives of the study were: i) to compare the performance of PDFs with 2 to 5 parameters using the L-moments method (LMM); and, ii) to develop the streamflow regionalization of the maximum and minimum streamflows ($Q_{7,10}$ and Q_{90}) for the Mortes River Basin, southeast Brazil.

2. MATERIALS AND METHODS

2.1. Study Area

The study was carried out in the Mortes River Basin (MRB), affluent of the Grande River Basin, in southeastern Brazil. Regarding the Minas Gerais Water Resources Planning, this basin is known as UPGRH-GD2 (Figure 1). MRB is located in southern Minas Gerais State, with an area of approximately 10,540 km². This basin includes the Jacaré, Cervo, and Mortes Rivers, which are the main tributaries to the Funil hydropower plant reservoir (Eduardo *et al.*, 2016), whose installed power is 180 MW.

The predominant climates are the Cwa and Cwb, according to the Köppen classification, with a mean annual precipitation of 1500 mm and an average annual temperature of 18°C (Eduardo *et al.*, 2016). For both climate types, summer is characterized by moderate

temperatures and approximately 80% of the total precipitation falls in this season, while the winter is cold and dry.
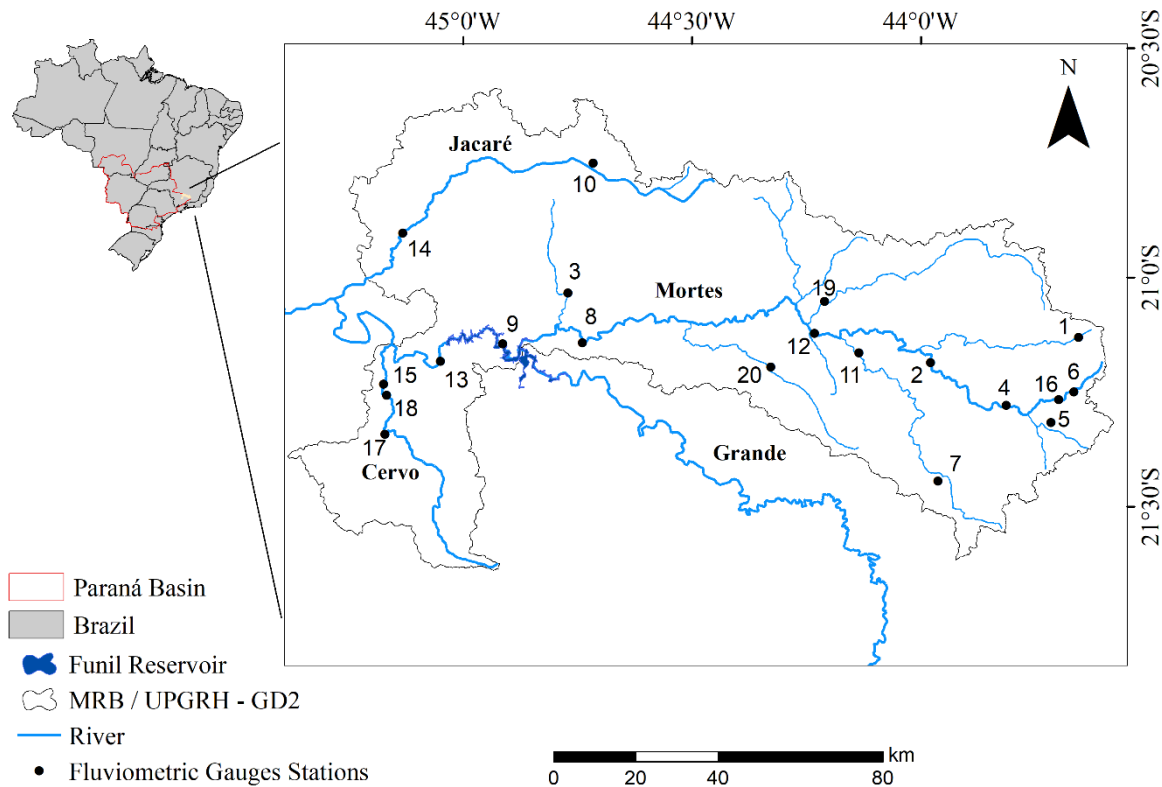
Figure 1. Study area location and fluviometric gauges stations.

The terrain is gently undulating to undulating relief, with a predominance of Cambisols in the headwaters and Latosols and Argisols in regions where the terrain is smooth. The altitude ranges from 770 to 1498 m. The predominant vegetation comprises high-altitude fields in the upstream regions with the occurrence of the seasonal semideciduous forest (IMGA, 2013, Scolforo and Carvalho, 2006).

2.2. Streamflow Database

The fluviometric gauge stations available in the Brazilian National Water Agency (ANA) Hidroweb platform in MRB are shown in Figure 1. Because of the availability of monitored data, the streamflow stations were selected based on a minimum of 10 years of daily observations (Beskow *et al.* 2014; Caldeira *et al.* 2015; Cassalho *et al.*, 2018). The maximum and minimum annual streamflow historical series were defined taking the maximum and minimum streamflow rates observed in each hydrological year (October to September) of the fluviometric gauge stations.

The historical series must be independent, randomness, homogeneity, and stationarity to fit the PDFs (Cassalho *et al.*, 2018). Trend analysis was performed using the Mann-Kendall test (Mann, 1945; Kendall, 1975). The primary advantages of this test are that it does not require a Gauss distribution and is less influenced by abrupt changes (Salviano *et al.*, 2016).

The test is based on accepting (or not accepting) the null hypothesis H_0 with a probability significant level α. H_0 hypothesis assumes that the data (x_1, ..., x_n) of the series do not exhibit any trends or significant temporal variations.

The Mann-Kendall's Z_{MK} index follows a normal distribution and can be obtained from Equations 1, 2 and 3. A decreasing trend is observed when Z_{MK} is negative and positive values

result in an increasing trend (Salviano *et al.*, 2016). In the cited equations, *X* is the streamflow value in the series, and the variable *S* can be compared to a normal distribution when $n \geq 8$. The indices *i* and *J* represent the position of *x* in the series.

$$z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}; \ \mathrm{para}\ S\ >\ 0 \\ \quad 0; \ \mathrm{para}\ S\ =\ 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}; \mathrm{para}\ S\ <\ 0 \end{cases} \tag{1}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2}$$

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} +1; \ \mathrm{se}\ x_j > x_i \\ \quad 0; \mathrm{se}\ x_j = x_i \\ -1; \mathrm{se}\ x_j < x_i \end{cases} \tag{3}$$

A significance level of 5% was adopted. Thus, the series shows no trend if the absolute value of Z_{MK} is less than or equal to 1.96. This level of significance was chosen because it is the most commonly used to avoid Type I and Type II errors.

2.3. Probability Distribution Functions and Regionalization

Before fitting the PDFs, an exploratory analysis of the data from each station was performed to identify possible outliers, which were identified using a box plot. The parameters of the PDFs were estimated using the Moments-L (LMM). According to Cassalho *et al.* (2018), this method is less sensitive to the presence of outliers and less susceptible to bias.

The PDF has an impact on the estimates of quantiles, which may lead to an overestimation or underestimation (Rahman *et al.*, 2015). The PDFs used in this study were the ones available in the studies by Cassalho *et al.* (2018), Naghettini and Pinto (2007) and Mello and Silva (2013), i.e., the 3-parameter log-normal (LN3), 3-parameter Pearson (PE3), the Gumbel extreme value, the Generalized Extreme Values (GEV), Gamma, Weibull, the 4-parameter Kappa, the 5-parameter Wakeby, the generalized logistic (GLO) and the generalized Pareto (GPA).

The goodness-of-fit values of the PDFs were evaluated using the Anderson-Darling (AD) test. This test performs well when used to evaluate asymmetric distributions and is one of the most commonly used in hydrology (Baldassarre *et al.*, 2009; Rahman *et al.*, 2015). Another advantage of this test is the ability to compare two or more PDFs (Naghettini and Pinto, 2007).

The homogeneous regions were identified based on statistical criteria, comparing the observed frequencies made dimensionless by dividing the long-term mean streamflows of the respective series (Naghettini and Pinto, 2007). This criterion is necessary to identify stations with the same hydrological behavior so that the data can be extrapolated to other regions without monitoring.

Morphometric data used as inputs for the regression models was the drainage area of each station as it can be easily obtained from topographic maps or remote sensing. The return periods of 2, 5, 10, 20, 50, 100, 500, and 1000 years for maximum streamflow and $Q_{7,10}$ and Q_{90} for the minimum streamflow are used to perform the regionalization models.

3. RESULTS AND DISCUSSION

Based on the Mann-Kendall test, at the significance level of 5%, 14 series of maximum streamflow and 17 series of Q7 could be considered as stationary and adequate for fitting the PDFs and, subsequently, for regionalization (Table 1). As discussed by Ishak *et al.* (2013), this step is essential to avoid mistakes that result from the changes caused by non-stationarity of the

series in the estimation of streamflow for different return periods, which may compromise the application of the regionalization technique.

Table 1. Mann-Kendall test results, best PDF fitted and Q_{90} for fluviometric gauge stations in MRB.

Number	Drainage Area (km²)	Maximum streamflow		Minimum streamflow		Q_{90} (m³.s⁻¹)
		$|Z_{Mk}|$	Best PDF fitted	$|Z_{Mk}|$	Best PDF fitted	
1	20.21	1.94	Kappa	0.82	GPA	1.51
2	1024.00	1.57	Weibull	0.01	Wakeby	8.92
3	351.55	0.17	Wakeby	0.38	Wakeby	1.92
4	563.85	2.09	-	4.25	-	5.28
5	58.68	1.14	LN3	0.11	Wakeby	1.59
6	122.18	1.30	Wakeby	0.53	Weibull	1.35
7	184.67	3.53	-	1.37	GLO	1.52
8	6043.49	0.20	Kappa	1.44	Wakeby	41.71
9	14046.03	2.48	-	2.21	-	146.50
10	382.81	0.27	Wakeby	1.07	Kappa	2.35
11	827.51	0.51	Kappa	0.04	Wakeby	6.54
12	2707.50	1.08	Wakeby	0.92	PE3	20.72
13	14406.42	0.11	Wakeby	0.54	GEV	127.00
14	1617.95	0.91	Weibull	1.03	PE3	10.20
15	1053.93	0.16	GLO	0.11	Kappa	5.26
16	182.71	2.30	-	0.33	Wakeby	6.41
17	390.22	0.12	GLO	0.89	PE3	2.64
18	1022.24	0.27	GEV	2.69	-	6.76
19	642.55	2.18	-	0.77	Wakeby	3.70
20	272.62	2.21	-	1.93	Wakeby	1.77

The data demonstrate that GLO, GEV, Gamma, and LN3 PDFs had good performances for most of the maximum and minimum series (Table 2). Furthermore, Weibull distribution also showed a good performance for several Q7 series that it is in accordance with the studies of Lopes *et al.* (2017) and Barbosa *et al.* (2005). This demonstrates that such PDFs are the most recommended for MRB, being able to estimate the studied streamflow in this basin.

Table 2. Numbers of historical series fitted and the best fit for each PDFs according to the AD results.

Maximum streamflow			Minimum streamflow		
PDF	AD (5%)	Best fitted to	PDF	AD (5%)	Best fitted to
Gumbel	11	-	Gumbel	8	-
Gamma	11	-	Gamma	14	-
GEV	14	1	GEV	15	2
Kappa	8	3	Kappa	13	3
GLO	14	2	GLO	15	1
GPA	3	-	GPA	5	1
Weibull	9	2	Weibull	14	1
Wakeby	9	5	Wakeby	15	8
PE3	12	-	PE3	15	1
LN3	14	1	LN3	9	-

GEV PDF had a good fit for almost all the series, except for two minimum series (Table 2). Cassalho *et al.* (2018), in a regionalization study for the São Gonçalo Mirim Basin, also identified GEV as the best PDF to estimate maximum streamflow, demonstrating a good performance of this distribution.

For maximum streamflow estimates, some studies indicate that the best fits were obtained with the 3-parameter Pearson PDF. However, the LN3P (AD = 0.406) showed slightly inferior performance than GEV (AD = 0.405) (Table 1), and both showed better performance than Pearson PDF. A similar result was found by Lopes *et al.* (2017) in a regionalization study conducted in the Teles Pires River Basin, in which LN3P PDF showed better adjustment for maximum flows.

Regarding PDFs with more parameters, the 4-parameter Kappa presented adequate results for most of the historical series (57% for the maximum and 76% for minimum streamflows). In addition, Kappa PDF produced the best fit for three series of both maximum and minimum streamflows. This higher performance was also observed by Beskow *et al.* (2014) in a study of rainfall series in the state of Rio Grande do Sul, Brazil, applying Kappa PDF. Despite the good performance, Kappa is still little-used in Brazil. The Cassalho *et al.* (2018) study was one of the first studies that applied Kappa PDF in a maximum streamflow frequency analysis in Brazil.

The best performing PDF was the 5-parameter Wakeby, which had a good fit for 64% of the maximum series and 88% of the Q7 series. This PDF had the least overall values for the AD test, indicating better estimations of the streamflow in MRB. The results obtained by Yerdelen *et al.* (2010) on streamflow regionalization in the Çoruh Basin, Turkey, showed that Wakeby PDF appeared to be a robust distribution in two of the five regions where the Çoruh Basin was subdivided, which were more heterogeneous. This flexibility of the Wakeby PDF application was also highlighted by Rahman *et al.* (2015).

The historical series were grouped based on an analysis of the empirical frequencies made dimensionless dividing them by their respective mean streamflow. Using these frequencies as criteria and observing their behavior, homogeneous regions were obtained for the series of maximum streamflow and Q7 (Figure 2). The other historical series were not used since they did not present similar hydrological behavior. It has been demonstrated that the method based on the empirical frequencies was able to identify the homogeneous region within MRB.

In a regionalization study conducted in the Doce River Basin, Ribeiro *et al.* (2005) established the minimum threshold of six stations per region. This criterion has also been adopted in other studies in Brazil (Cassalho *et al.*, 2018; Lopes *et al.*, 2017). Therefore, the number of stations selected for the homogeneous region (eight series for maximum streamflow and seven series for Q7) is following the abovementioned criteria.
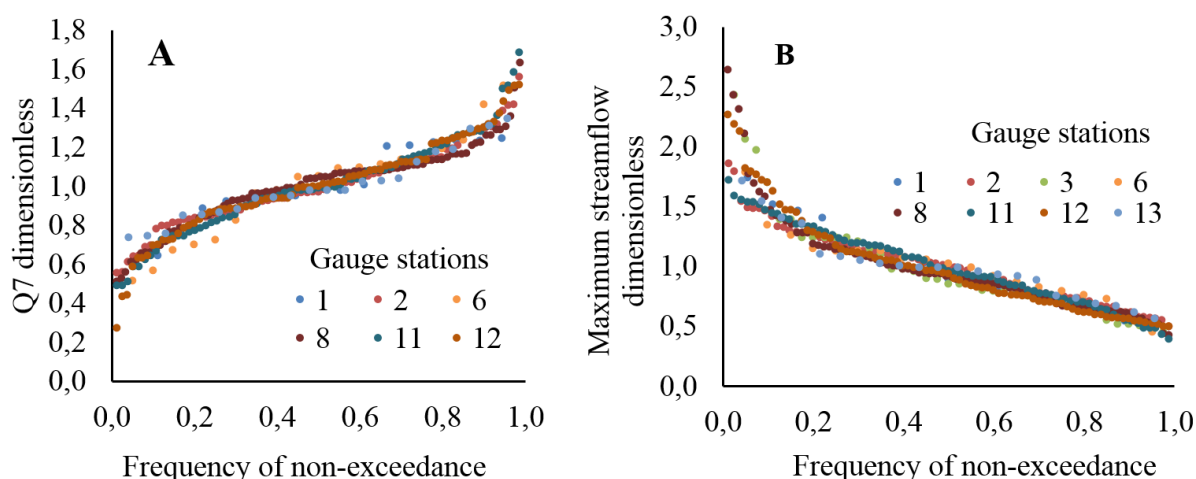
Figure 2. A) homogeneous regions for the series of Q7 and B) homogeneous regions for the series of maximum streamflow.

Since the Weibull PDF was the only one that had a good fit for all Q7 series within the homogeneous region, this PDF was used to calculate $Q_{7,10}$, which consists of calculating the minimum streamflow of 7-day consecutive duration (Q7) series with a return period of 10 years.

$Q_{7,10}$ is extremely important for water resources rights in MRB, which is entirely within Minas Gerais State. The minimum streamflow in 90% of the time ($Q_{90\%}$) was obtained from the historical series positioned in descending order, calculating the excess frequency of 90%.

The models fitted for the maximum streamflow associated with the return periods analyzed in this study and the minimum reference flows in the homogeneous region are shown in Table 3. The contribution areas for each station ranged from slightly larger than 20 km² to larger than 14,000 km² (Table 1). This range is relevant for the application of the regionalization models because, according to Pruski *et al.* (2012), the estimates of streamflow should not be performed for areas outside the intervals used to fit the regression model.

For the maximum streamflow, the PDF parameters could not be regionalized with the best PDF (GEV) due to the coefficient of determination (R^2) for the shape parameter (κ) was not satisfactory. Therefore, the quantiles were calculated based on the distribution that best fitted to the series in each station (Table 1). In this case, the regionalization was conducted based on the return periods along with the drainage area of the sub-basins.

The only physiographic variable used as input in the models was the drainage area (Table 3). The R^2 values indicate the suitability of the models to estimate the maximum streamflow, considering the return periods, and minimum reference streamflow using only the drainage area.

Table 3. Regionalization models and their respective coefficient of determination.

Maximum Streamflow	R^2	Minimum Streamflow	R^2
RP (2) = 0.17*(Area$^{0.92}$)	0.9995	$Q_{90} = 1.76 \times 10^{-03}$*(Area$^{1.17}$)	0.9974
RP (5) = 0.51*(Area$^{0.83}$)	0.9995	$Q_{7,10} = 2.33 \times 10^{-4}$*(Area$^{1.343}$)	0.9957
RP (10) = 0.76*(Area$^{0.80}$)	0.9983		
RP (20) = 0.98*(Area$^{0.79}$)	0.9963		
RP (50) = 1.22*(Area$^{0.79}$)	0.9925		
RP (100) = 1.38*(Area$^{0.79}$)	0.9887		
RP (500) = 1.71*(Area$^{0.80}$)	0.9762		
RP (1000) = 1.86*(Area$^{0.80}$)	0.9693		

The result presented in Table 3 is similar to what was observed in the study of Lopes *et al.* (2017) and Pruski *et al.* (2012) in Brazilian basins, where the regressions that considered the drainage area provided better performance than another criterion. However, Silva *et al.* (2006) observed that, although the drainage area of the sub-basins has been the only significant morphometric variable for prediction of $Q_{7,10}$, the inclusion of the annual precipitation improved the models for streamflow estimates in the upper Grande River Basin.

It was observed that as the return period increases, there is a reduction in the goodness-of-fit of the models, as indicated by the R^2 values (Table 3). This feature is associated with the length of the series, which were mostly short; It is therefore associated with uncertainty regarding the PDF fitting. Nevertheless, the use of equations may assist in the design of hydraulic structures that use the return periods considered here as safety margins.

The models fitted for Q_{90} and $Q_{7,10}$ had very high R^2 values, which indicates reliability for their use for minimum reference streamflow estimates in MRB, mainly for studies involving water rights use concessions in regions with no fluviometric gauge stations.

Despite the good results obtained in the streamflow estimates through the regionalization process, the monitoring of this variable in the field and the quality of the measurements remains a challenge for the hydrological studies in this region. In addition, the regionalization process presents some uncertainties, as does any other technique used for data simulation.

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4. CONCLUSIONS

The analysis of the empirical dimensionless frequencies was able to identify homogeneous regions for maximum and minimum streamflows in MRB. Thus, a hydrological behavior was observed mainly in the main channel of the Mortes River.

Although the distributions with fewer parameters were fitted in most of the maximum streamflows series, the PDF with four and five parameters showed greater plausibility in estimating the quantiles according to AD, except GPA PDF. Regarding minimum streamflows, Wakeby PDF was the one that adjusted to the highest number of series and best performance among the analyzed PDFs.

The area demonstrates a satisfactory input for streamflow regionalization, with coefficients of determination R^2 greater than 0.9 for all the studied streamflow. Hydrological homogeneity may be the factor that favored this result.

5. ACKNOWLEDGEMENTS

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