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# Estimative of reference flows for water resources planning and control: hydrologic regional indicators application

## Estimativa de vazões de referência para planejamento e controle de recursos hídricos: aplicação de indicadores hidrológicos regionais

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## ABSTRACT

Due to limitations of hydrometeorological monitoring network related to spatial station distribution and extension of historical series, tools that aim to improve consistency and optimize available data analysis have become essential. In this context, regionalization techniques stand out, once the main focus is the delimitation of hydrologically homogeneous regions with the subsequent spatial transposition of hydrological variables of interest. Regional indicators, defined as the mean values of hydrological variables and characteristics of a homogeneous region, constitute an expeditious approach to hydrological regionalization. The main perspective of the study was to evaluate the use of regional indicators when quantifying reference flows associated with average flow, drought, or flood conditions. The study area selected was the Manhuaçu River basin, a major Doce River tributary, located in the state of Minas Gerais, Brazil. The results showed that the regional indicators allow estimates of diverse reference flows with mean errors lower than 30%, considered satisfactory for the study area. However, the conventional method of flow regionalization presented more consistent results, with mean errors usually lower than 20%, regardless of the reference flow analyzed. It was also observed that adopting historical flow series with varied extensions did not produce relevant differences when appropriating the diverse reference flows for the Manhuaçu River basin, with none exceeding 3%.

**Keywords:** regionalization; indicators; droughts; floods; Manhuaçu River.

## RESUMO

Em função das limitações da rede de monitoramento hidrometeorológico, tanto do ponto de vista da distribuição espacial quanto da extensão das séries históricas, ferramentas que busquem dar consistência e otimizar a análises dos dados disponíveis vêm ganhando espaço. Neste contexto, destacam-se as técnicas de regionalização, cujo principal foco é a delimitação de regiões hidrologicamente homogêneas com a subsequente transposição espacial de variáveis hidrológicas de interesse. Os indicadores regionais, definidos como valores médios de uma variável hidrológica e característicos de uma região homogênea, constituem abordagem expedita de regionalização hidrológica. O presente estudo teve como principal perspectiva avaliar o emprego de indicadores regionais quando da quantificação de vazões de referência associadas às condições médias de escoamento, estiagens ou cheias. A área de estudo selecionada para a condução do estudo foi a bacia hidrográfica do rio Manhuaçu, importante afluente do rio Doce, Minas Gerais, Brasil. Os resultados demonstraram que os indicadores regionais permitem estimativas de diferentes vazões de referências com erros médios inferiores a 30%, considerados satisfatórios para a área de estudo. No entanto, o método convencional de regionalização de vazões apresentou resultados mais consistentes, com erros médios usualmente inferiores a 20%, independentemente da vazão de referência analisada. Observou-se, adicionalmente, que a adoção de séries históricas de vazões com diferentes extensões não produziu diferenças relevantes quando da apropriação das diferentes vazões de referência para a bacia hidrográfica do rio Manhuaçu, com diferenças que não superaram 3%.

**Palavras-chave:** regionalização; indicadores; secas; cheias; rio Manhuaçu.

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## Introduction

The availability of water, which exhibits significant temporal and spatial variability (Lira and Cardoso, 2018), is a permanent social concern, particularly when considering the world's population growth in a context of uncertainties associated with variations in precipitation due to climate changes (O'Gorman, 2015; Tabari, 2020), land use changes (Gomes et al., 2022; Silva et al., 2022). and increasing water pollution (Dutra et al., 2022). Moreover, the large volumes of water discharged during flood periods can lead to significant social, economic, and environmental problems in addition to the potential loss of human lives. Therefore, flow quantification becomes one of the most relevant stages for adequate decision-making associated with water resources planning and control (Mendonça, 2003).

The appropriation of reference flows that allows the characterization of different flow conditions (droughts, floods, or average long-term flows) usually requires historical flow series established through systematic monitoring of watercourses that involves daily water levels measurements, the establishment of key curves, and with the aid of this hydrological function, the conversion of levels into flows. It is important to note that the monitoring work that allows the establishment of historical series of flows is not always simple due to adverse weather conditions, location of stations in difficult access places, occasional river intermittencies, and in some cases, large widths of Brazilian water bodies (Tucci et al., 1995).

The Brazilian hydrological monitoring network is limited, with heterogeneous station distribution. In different parts of the national territory, it presents low density with short historical series and/or excess of failures. However, the knowledge of flows at different points of a hydrographic basin constitutes essential information for decision-making associated with the adequate management of water resources (Piol et al., 2019).

In this context, the creation of alternatives to optimize the available hydrological information becomes a necessity. Among the available methods, hydrological regionalization has been widely used by water resources management and control agencies and is recurrently the central tool for regulating water use grants and charges (Bazzo et al., 2017; Maciel et al., 2019; Piol et al., 2019).

Hydrological regionalization is a set of statistical procedures that allow the maximum use of information existing in a site to estimate hydrological variables or parameters in places without or with insufficient data, thus allowing knowledge about spatial distributions of hydrological variables or parameters and improvement of temporal estimation (Tucci, 2002).

A relevant set of regionalization methods has been established, involving different hydrological variables and different methodological approaches, as illustrated by Razavi and Coulibaly (2013), Boscarello et al. (2016), Swain and Patra (2017), Qamar et al. (2018), Silva et al. (2019), Althoff et al. (2021), Golian et al. (2021), and Singh and Devi (2022).

Among the most recurrently applied methods in Brazil are the Characteristic Values Method (Baena et al., 2004; Pessoa et al., 2011; Moreira and Silva, 2014; Bazzo et al., 2017; Amorim et al., 2020), the Dimensional Curve Method (Tucci et al., 1995; Pinto, 2006; Piol, 2017), the Parameter Method (Wolff, 2014; Piol, 2017), and the Exponential Curve Method (Calmon et al. 2016; Piol et al., 2019; Rodrigues et al., 2022).

Regional indicators, defined as the mean values of hydrological variables and characteristics of a homogeneous region, are considered alternatives to the methods usually applied for hydrological variables regionalization (Piol et al., 2019). It is an expeditious approach, substantially simpler than conventional hydrological regionalization methods. Reis et al. (2008) established regional indicators for the appropriation of mean, minimum, and maximum flows for the Itabapoana River basin, a region that covers municipalities in the states of Espírito Santo, Rio de Janeiro, and Minas Gerais. On the other hand, Piol et al. (2019) established regional indicators associated with the flow duration curve for the Itapemirim River basin and for the Capixaba portion of the Itabapoana River basin, regions in the southern Espírito Santo. The mentioned authors observed that regional indicators allowed consistent appropriation of the evaluated flows.

The Manhaçu River basin, a major Doce River tributary, has a drainage area of 9,189 km² and encompasses (partially or entirely) 32 municipalities in Minas Gerais state, Brazil. The watershed is located within the Atlantic Forest biome, with agriculture occupying 65% of its territory. The most significant water demands in the watershed are for irrigation and human supply, accounting for approximately 87% of the water extracted. Insufficient sewage treatment services in the municipalities, combined with erosion and siltation processes, press the water resources of the region. In this context, appropriate assessment of the watercourse regime becomes relevant (ANA, 2021).

This work aimed at evaluating the use of regional indicators for reference flow appropriation as an alternative to the approach usually applied for watercourse flow regionalization. The objects of analysis were flows associated with average conditions, droughts, and floods. The study was conducted based on the analysis of the historical watercourse flow series for the Manhuaçu River basin.

## Methodology

### Study area

The Manhuaçu River basin is an important sub-basin of the Doce River watershed. According to information from the review and update of the Integrated Water Resources Plan for the Rio Doce Basin (ANA, 2021), the basin presents a 9,189 km² drainage area distributed in Minas Gerais, corresponding to approximately 10.48% of the Doce basin area. Manhuaçu basin covers, totally or partially, 32 municipalities (Aimorés, Alto Caparaó, Alto Jequitibá, Alvarenga, Caratinga, Chalet, Conceição de Ipanema, Conselheiro Pena, Durandé, Ibatiba, Imbé de Minas, Inhapim, Ipanema, Itueta, Iúna, Lajinha, Luisburgo, Manhuaçu, Manhumirim, Martins Soares, Mutum, Piedade de Caratinga, Pocrane, Reduto, Resplendor, Santa Bárbara do Leste, Santa Rita do Itueto, Santana do Manhuaçu, São João do Manhuaçu, São José do Mantimento, Simonésia, and Taparuba). According to the latest estimates from the Brazilian Institute of Geography and Statistics (IBGE, 2021), the resident population in the Manhuaçu River basin was 569,088 inhabitants.

The main basin watercourse and springs of Manhuaçu River, are located in the Serra da Seritinga, on the border between the municipalities of Divino and São João do Manhuaçu, traveling a distance of approximately 347 kilometers until it drains into the Doce River, near Aimorés (ANA, 2021).

The basin is located in the Atlantic Forest biome, one of the biomes with the greatest biodiversity in Brazil. Currently, it is estimated that approximately 65% of the soil of the basin is destined for agriculture. Irrigation accounts for 59% of water consumption in the basin, followed by human supply, responsible for about 28%. Water use for animal watering and industrial purposes is less relevant in the basin (ANA, 2021).

### Fluviometric data

The historical series of flows and the fluviometric station drainage areas of the Manhuaçu river basin were obtained from the National Agency for Water and Basic Sanitation (ANA) Hidroweb site. Figure 1 shows the location of the fluviometric stations selected for the regional flow analysis.

Table 1 presents the selected fluviometric stations with each corresponding drainage area, Hidroweb site identification codes, and historic series extensions.

The reference flows and flow indicators were initially appropriated assuming 30 years of long historical series, from 1984 to 2014, with data available for all stations. In a subsequent work stage, seeking to evaluate the influence of historical series extensions, reference flows, and flow indicators were estimated considering the complete fluviometric station flow series as indicated in Table 1. This was reproduced based on the approach employed by Piol (2017) when conducting studies on the regionalization of long-term average flows, characteristic flows of the flow permanence curve, and minimum flows associated with different return periods.

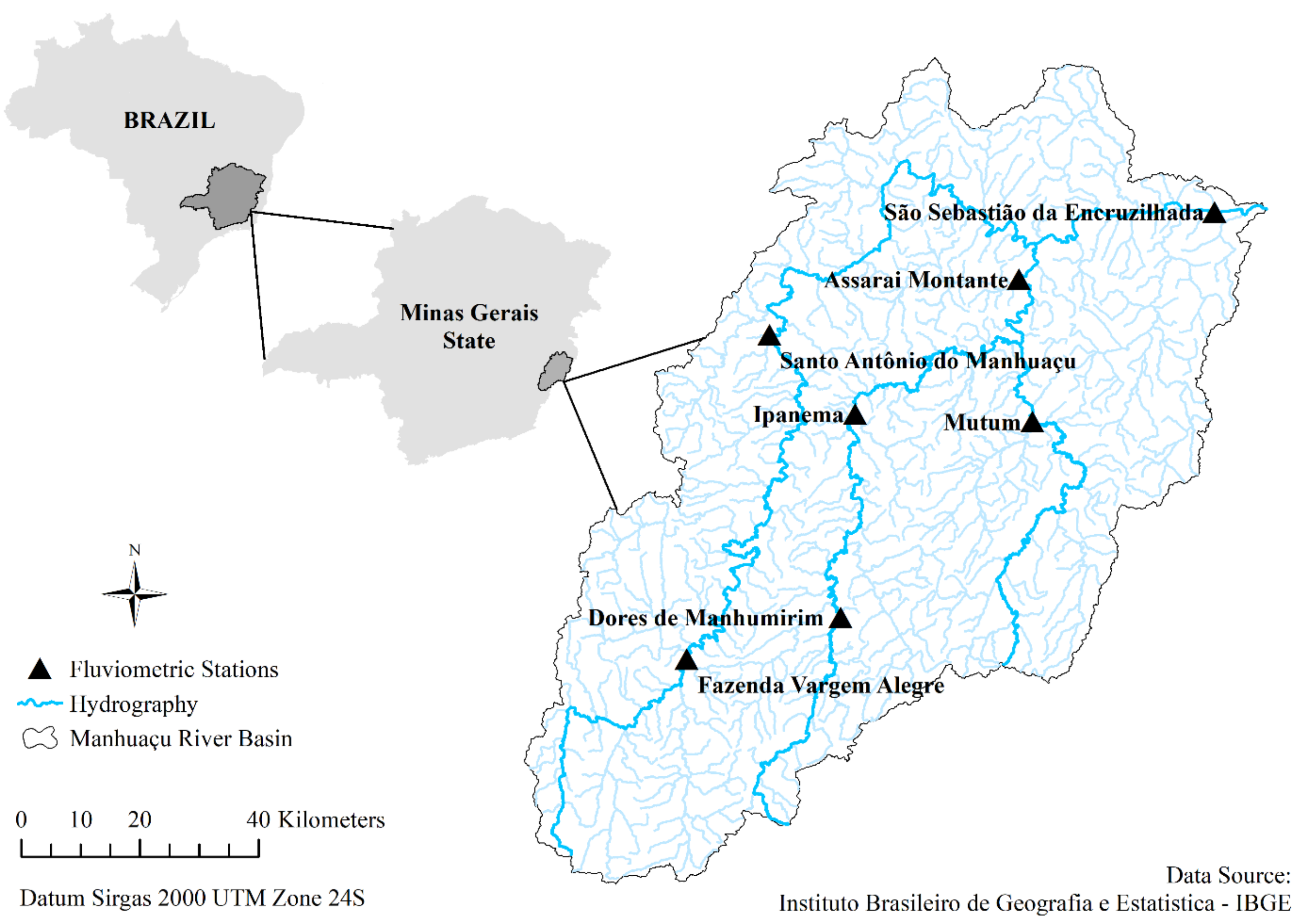


**Figure 1 – Fluviometric stations located in the Manhuaçu River basin.**

**Table 1 – Fluviometric stations installed and in operation in the Manhuaçu River basin.**

| Station | River | Code | Drainage Area (km²) | Series Extension (Years) |
|---|---|---|---|---|
| Fazenda Vargem Alegre | Manhuaçu | 56960005 | 1,070 | 30 |
| São Sebastião da Encruzilhada | Manhuaçu | 56990000 | 8,720 | 75 |
| Assarai Montante | Pocrane | 56989400 | 3,190 | 37 |
| Mutum | São Manoel | 56989001 | 1,180 | 40 |
| Ipanema | José Pedro | 56988500 | 1,410 | 75 |
| Dores de Manhumirim | José Pedro | 56983000 | 384 | 75 |
| Santo Antônio do Manhuaçu | Manhuaçu | 56978000 | 2,350 | 48 |

## Reference flows and regional indicators evaluation

According to ordinance no. 48 of the Minas Gerais State Water Management Institute (Igam), issued on October 4, 2019 (Igam, 2019), the reference flow for the calculation of maximum grants of water withdrawal from rivers in the state is the minimum streamflow of seven consecutive days and ten years of return period ($Q_{7.10}$). Due to this condition, $Q_{7.10}$ was the first minimum reference flow rate considered in the present study. The minimum flows with permanence of 90% ($Q_{90}$) and 95% ($Q_{95}$) were also considered for the appropriation of the regional indicators $r_{7.10}$, $Rcp_{90}$, and $Rcp_{95}$ because they constitute the flows that regulate water use grants in most Brazilian states. The granting of water use, an instrument established by the National Water Resources Policy (Law No. 9.433, January 8, 1997), has as its main objectives the control of water uses and the effective exercise of rights to access water. In Brazil, water supply for human or industrial purposes, irrigation, aquaculture, hydroelectric power generation, final disposal of effluents, and other uses that may alter the regime, quantity, or quality of water resources, require granting.

For the appropriation of regional flow indicators associated with the average flow conditions (q and $Rcp_{50}$), the average long-period flow ($Q_m$) and the flow rate with permanence of 50% ($Q_{50}$) were selected. The assessment of average flow conditions is a central aspect for water resources planning and management, as it establishes the limit for watercourses regulation in a basin.

The description of maximum streamflow behavior is relevant for the development of risk management policies and urban planning. Information on maximum flows associated with different return periods allows for the identification of high-risk areas, land use and land occupation planning, and implementation of flood mitigation measures such as the creation of buffer zones and the development of alert systems. For the appropriation of regional flow indicators associated with the maximum flows $r_{2\text{ and}}$ $r_{100}$, the maximum daily flows with return periods of two and one hundred years, respectively, were selected. According to Tucci et al. (2003) and Reis et al. (2008), the flow associated with a two-year return period indicates the average flooding flow, a value which corresponds approximately to the limit of the lower bed of alluvial rivers; the flow associated with the return period of one hundred years usually represents the upper limit of the riverside flood range.

Table 2 presents the regional indicators evaluated in this work.

**Table 2 – Regional flow indicators evaluated.**

| Indicator type | Indicator | | Unit |
|---|---|---|---|
| Average flow | $q = \frac{Qm}{A}$ | (1) | L/s.km² |
| | $Rcp_{50} = \frac{Q50}{Qm}$ | (2) | Dimensionless |
| Minimum flow | $Rcp_{95} = \frac{Q95}{Qm}$ | (3) | Dimensionless |
| | $Rcp_{90} = \frac{Q90}{Qm}$ | (4) | Dimensionless |
| | $r_{7,10} = \frac{Q_{7,10}}{Qm}$ | (5) | Dimensionless |
| | $r_m = \frac{Q95}{Q_{7,10}}$ | (6) | Dimensionless |
| Maximum flow | $r_2 = \frac{Q2years}{Qm}$ | (7) | Dimensionless |
| | $r_{100} = \frac{Q100years}{Qm}$ | (8) | Dimensionless |

For the appropriation of the $Q_{50}$, $Q_{90,}$ and $Q_{95}$ flows, the permanence curves of the fluviometric stations' flow were constructed considering the division of the historical series into 50 class intervals. The definition of class intervals was based on a logarithmic scale because of the large variations of flow magnitudes.

To evaluate the $Q_{7.10}$ flow and the maximum daily flows with return periods of two and one hundred years, Gumbel, Weibull, Log-Normal type II, Log-Normal type III, Pearson type III, and Log-Pearson type III distributions were chosen. All probability distributions used for evaluations of maximum and minimum reference flows were presented in detail by Kite (1988). All the flow values used for the appropriation of regional flow indicators were estimated through SisCAH software, a publicly available program, produced and released by the Water Resources Research Group at the Universidade Federal de Viçosa.

The selection of the probability distribution used for the evaluation of the maximum and minimum flows occurred as a function of the analysis of the standard error of estimation, assuming the distribution that was not rejected in any of the fluviometric stations and that presented the lowest standard error of estimation in most of the stations analyzed.

To evaluate the regional flow indicators responses, we considered the percentage errors between flows appropriated from the fluviometric records and flows estimated through regional flow indicators and coefficients of variation, according to Equations 1 and 2, respectively.

$$\text{error}(\%) = \frac{(\text{Qestimated} - \text{Qreal})}{\text{Qreal}}.100 \quad (1)$$

$$\text{CV} = \frac{S}{r_i} \quad (2)$$

In Equations 1 and 2:

$Q_{estimated}$: the value of the reference flow rate obtained from the regional flow indicators;

$Q_{real}$: flow rate estimated from the fluviometric stations flow records;

CV: coefficient of variation expressed in percentage;

S: standard deviation of the indicators;

$r_i$: average value of each indicator obtained for the Manhuaçu River basin.

### Conventional regionalization of reference flows

Regional functions were established by regression analysis to appropriate the different reference flows. The functions produced were potential and the area was the independent variable used for the conformation of all regional functions. Although other physiographic and climatological variables can be regarded as independent variables for the definition of regional functions, only the area was considered because it is the only physiographic variable used to define regional flow indicators, as stated by Silva Junior (2003) and Novaes et al. (2007). Additionally, it is important to note that the drainage area is one of the physical variables with significant relevance for conducting hydrological regionalization studies, as suggested by Lall and Olds (1987), Mwakalila (2003), Baena et al. (2004), and Bárdossy (2007).

All regression analyses necessary to define the regional functions were conducted using a Microsoft Excel spreadsheet. The correlation coefficients associated with regression analyses, the percentage errors between flows appropriated from the fluviometric records, and flows estimated through regional functions constituted parameters to evaluate the responses of the regional functions produced.

## Results and Discussion

Table 3 summarizes the average long-term flows associated with different permanencies (50, 90, and 95%), maximum flows for return periods of two and one hundred years, and $Q_{7.10}$ flows, estimated with SisCAH software for the Manhuaçu River basin fluviometric station series, considering the period from 1984 to 2014.

As for the appropriation of the minimum flows Q7.10, the Log-Pearson type III probability distribution was applied, while for the maximum flows associated with return periods of two and one hundred years, the Log-Normal type II distribution was considered.

The values of the indicators estimated for the diverse fluviometric stations, as well as their estimated means and coefficients of variation for the study area are shown in Table 4. It is worth noting that the mean values of the indicators define the regional indicator for the study area.

The coefficients of variation appropriated for the Manhuaçu River basin ranged between 4% ($Rpc_{50}$) and 22% ($r_{7.10}$ and r100). This variation range is considerably smaller than that reported by Reis et al. (2008), who presented coefficients of variation between 6 and 52% when appropriating the same set of indicators. As for the aforementioned authors, the lowest coefficients of variation were associated with the $rcp_{50}$ and $r_m$ indicators. Additionally, it is relevant to cite that the appropriated coefficient of variation for the specific flow (20%) was similar to that obtained by these authors (22%).

Through a Microsoft Excel spreadsheet, potential equations were generated that correlate the values of drainage areas with the different reference flow rates evaluated. Figure 2 presents the scatter plots generated between drainage areas of the streamflow stations and the reference flows under analysis, as well as the produced regional functions and their corresponding correlation coefficients.

**Table 3 – Reference flows for Manhuaçu River basin fluviometric stations.**

| Station | Reference flows ($m^3.s^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $Q_m$ | $Q_{50}$ | $Q_{90}$ | $Q_{95}$ | $Q_{7,10}$ | $Q_{2years}$ | $Q_{100years}$ |
| Fazenda Vargem Alegre | 17.26 | 11.08 | 4.25 | 2.93 | 1.70 | 118.29 | 327.91 |
| São Sebastião da Encruzilhada | 99.52 | 67.00 | 33.81 | 28.94 | 19.98 | 585.92 | 1,390.04 |
| Assaraí Montante | 36.68 | 23.87 | 12.01 | 10.35 | 7.55 | 297.25 | 986.05 |
| Mutum | 13.37 | 8.06 | 4.09 | 3.44 | 2.40 | 127.47 | 453.37 |
| Ipanema | 20.57 | 13.84 | 6.88 | 5.97 | 4.41 | 173.19 | 461.43 |
| Dores de Manhumirim | 6.80 | 4.44 | 2.16 | 1.86 | 1.30 | 45.62 | 80.42 |
| Santo Antônio do Manhuaçu | 40.96 | 27.76 | 14.16 | 12.21 | 8.64 | 248.16 | 628.10 |

$Q_m$: average long-period flow; $Q_{50}$: flow rate with permanence of 50%; $Q_{90}$: flow rate with permanence of 90%; $Q_{95}$: flow rate with permanence of 95%; $Q_{7,10}$: minimum streamflow of seven consecutive days and ten-year return period; $Q_{2years}$: maximum daily flows with return periods of two years; $Q_{100year}$: maximum daily flows with return period of one hundred years.

**Table 4 – Regional flow indicators for the Manhuaçu River basin.**

| Stations | Indicators | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | q (L/s.Km²) | $Rcp_{95}$ | $Rcp_{90}$ | $Rcp_{50}$ | $r_{7,10}$ | $r_m$ | $r_2$ | $r_{100}$ |
| Fazenda Vargem Alegre | 16.13 | 0.17 | 0.25 | 0.64 | 0.10 | 1.72 | 6.85 | 2.77 |
| São Sebastião da Encruzilhada | 11.41 | 0.29 | 0.34 | 0.67 | 0.20 | 1.45 | 5.89 | 2.37 |
| Assaraí Montante | 11.50 | 0.28 | 0.33 | 0.65 | 0.21 | 1.37 | 8.10 | 3.32 |
| Mutum | 11.33 | 0.26 | 0.31 | 0.60 | 0.18 | 1.39 | 9.53 | 3.56 |
| Ipanema | 14.59 | 0.29 | 0.33 | 0.66 | 0.12 | 1.35 | 8.42 | 2.66 |
| Dores do Manhumirim | 17.71 | 0.27 | 0.32 | 0.65 | 0.19 | 1.43 | 6.71 | 1.76 |
| Santo Antônio do Manhuaçu | 17.43 | 0.30 | 0.35 | 0.68 | 0.21 | 1.41 | 6.06 | 2.53 |
| **Average** | **14.30** | **0.27** | **0.32** | **0.65** | **0.19** | **1.45** | **7.37** | **2.71** |
| **Variation coefficient (%)** | **20** | **17** | **11** | **4** | **22** | **9** | **18** | **22** |

q and $rpc_{50}$: average flow indicators; $rcp_{90}$, $rcp_{95}$, $r_{7,10}$, and $r_m$: minimum flow indicators; $r_2$ and $r_{100}$: maximum flow indicators.

In the equations presented in Figure 2, for drainage area A, the unit is km² and the reference flows are calculated in $m^3.s^{-1}$. The regional functions, fitted by regression analyses presented correlation coefficients ($R^2$) ranging from 0.91 to 0.98. These can be considered very good values when conducting regional flow analysis, as suggested by Eletrobras (1985) when regionalizing flows for the Upper Paraguay River basin (distributed among the states of Amazonas, Mato Grosso, and Mato Grosso do Sul), and also by Piol et al. (2019) when conducting the regionalization of flow duration curves and defining regional flow indicators for the Itapemirim River basins (watercourse within Espírito Santo state).

In order to verify the relevance of the appropriation of regional flow indicators from historical series presenting the same extension (homogeneous series), indicators appropriation was repeated assuming the complete available historical series (heterogeneous series), a perspective that allows maximum use of the available data for each station even though presenting beginning and ending in different years.

Considering heterogeneous series, regional indicators q, $Rcp_{50}$, $r_2$, and $r_{100}$ presented coefficients of variation equal to or lower than those estimated from homogeneous historical series; inverse condition was observed for indicators $Rcp_{95}$, $Rcp_{90}$, $r_{7,10}$, and $r_m$. It is important to note that the coefficient of variation differences, in both situations, were small, not exceeding 3%.

Table 6 summarizes the varied reference flows appropriated for the Manhuaçu River basin by different approaches in the present study. Table 7, in turn, presents the percentage errors for the estimated flows for the different approaches (regional functions, indicators obtained from homogeneous, and heterogeneous series) in relation to the flows appropriated from the fluviometric station flow records (gathered in Table 2).

From a simple inspection of regional indicators, flows (actual and estimated), and estimated percentage errors gathered in Tables 3 to 7, the following observations were considered relevant:

- For the Manhuaçu River basin, the average errors between flows estimated from historical series and appropriated by regional analysis, regardless of the approach, did not exceed 30% — a condition considered satisfactory by Piol (2017) when conducting studies on flow regionalization;
- The regional functions established for flow appropriation, assuming exclusively the drainage area as an explanatory variable, produced, for all the reference flows analyzed, mean errors lower than those associated with the use of regional flow indicators;
- The lower errors in flow estimates were associated with $Q_m$ and $Q_{50}$ flows, which usually present a strong correlation with drainage areas, as noted by Eletrobras (1985) and Piol (2017), and for the maximum flows for a two-year return period. Regardless of the regionalization approach employed, the average errors associated with these flows did not exceed 20% for the Manhuaçu River basin data. It is relevant to note that Reis et al. (2008) and Piol et al. (2019) reported that the indicators associated with the mean flow conditions (q and $rcp_{50}$) are generally consistent, usually producing satisfactory responses. For the Itabapoana River basin, $Q_m$ and $Q_{50}$ were estimated by Reis et al. (2008) with mean errors of 19 and 5%, respectively. Piol et al. (2019), in turn, appropriated the $Q_{50}$ flow for the Itapemirim River with an error of 17%;
- The consideration of estimated regional flow indicators and the adoption of historical series with the same or different extensions did not produce relevant differences when appropriating the diverse reference flows. This fact may be due to the maintenance of the average and extreme flows (maximum and minimum) behaviors in the

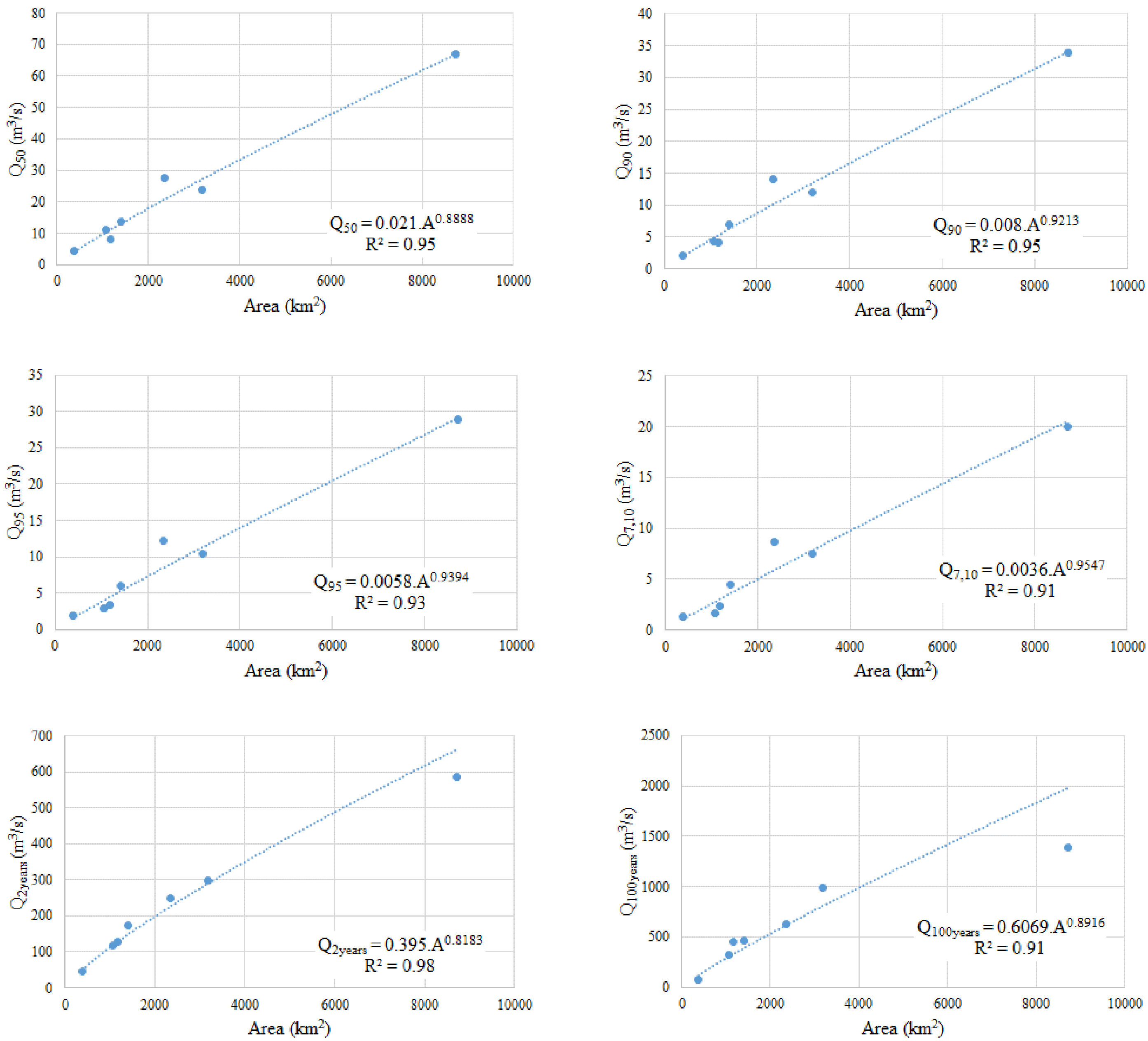


**Figure 2 – Scatter plots associated with different reference flows and produced regional functions.**

complementary parts of the historical series, for the common period between 1984 and 2014. Piol (2017), using a series of different lengths to evaluate reference flows, obtained variations below 10% for long-term mean flows and maximum variations of 30% for flows with different durations ($Q_{50}$, $Q_{90}$, and $Q_{95}$), and minimum flows associated with return periods of ten and one hundred years;

- Although the mean errors associated with the different reference flows were considered satisfactory for the Manhuaçu River basin, the responses for the diverse fluviometric station series showed pronounced variations. For the Mutum station series, significant errors in the appropriation of minimum and average flows were noted. For the Santo Antônio do Manhuaçu station series, relevant errors in the appropriation of only the minimum reference flows were observed. On the other hand, for the São Sebastião da Encruzilhada and Dores do Manhumirim series, larger errors derived from maximum flow estimation.

**Table 5 – Regional flow indicators for the Manhuaçu River basin considering historical series and presenting different extensions (heterogeneous series).**

| Stations | Indicators | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | q (L/s.Km$^2$) | Rcp$_{95}$ | Rcp$_{90}$ | Rcp$_{50}$ | r$_{7,10}$ | r$_m$ | r$_2$ | r$_{100}$ |
| Fazenda Vargem Alegre | 16.13 | 0.17 | 0.25 | 0.64 | 0.10 | 1.72 | 6.85 | 2.77 |
| São Sebastião da Encruzilhada | 11.51 | 0.28 | 0.35 | 0.71 | 0.19 | 1.51 | 5.32 | 2.47 |
| Assaraí Montante | 12.11 | 0.28 | 0.33 | 0.65 | 0.20 | 1.40 | 7.64 | 3.19 |
| Mutum | 11.56 | 0.26 | 0.31 | 0.63 | 0.18 | 1.38 | 8.89 | 3.49 |
| Ipanema | 14.75 | 0.31 | 0.35 | 0.69 | 0.23 | 1.34 | 6.95 | 2.88 |
| Dores do Manhumirim | 17.73 | 0.26 | 0.31 | 0.67 | 0.19 | 1.39 | 6.19 | 1.86 |
| Santo Antônio do Manhuaçu | 17.16 | 0.31 | 0.35 | 0.69 | 0.23 | 1.34 | 5.64 | 2.53 |
| **Média** | **14.42** | **0.27** | **0.32** | **0.67** | **0.19** | **1.44** | **6.78** | **2.74** |
| **Variation coefficient (%)** | **19** | **18** | **12** | **4** | **23** | **10** | **18** | **19** |

q and rpc$_{50}$: average flow indicators; rcp$_{90}$, rcp$_{95}$, r$_{7,10}$, and r$_m$: minimum flow indicators; r$_2$ and r$_{100}$: maximum flow indicators.

**Table 6 – Reference flows (m$^3$.s$^{-1}$) appropriated for the Manhuaçu River basin by different methodological approaches.**

| Reference flows | | Fluviometric stations | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Fazenda Vargem Alegre | São Sebastião da Encruzilhada | Assaraí Montante | Mutum | Ipanema | Dores do Manhumirim | Santo Antônio do Manhuaçu |
| Q$_m$ | Regional function | 15.97 | 99.72 | 41.45 | 17.40 | 20.32 | 6.53 | 31.74 |
| | Indicator–Homogeneous series | 15.30 | 124.70 | 45.62 | 16.87 | 20.16 | 5.49 | 33.60 |
| | Indicator–Heterogeneous series | 15.43 | 125.75 | 46.00 | 17.02 | 20.33 | 5.54 | 33.89 |
| Q$_{50}$ | Regional function | 10.31 | 66.67 | 27.25 | 11.25 | 13.18 | 4.14 | 20.76 |
| | Indicator–Homogeneous series | 9.96 | 81.14 | 29.68 | 10.98 | 13.12 | 3.57 | 21.87 |
| | Indicator–Heterogeneous series | 10.34 | 84.25 | 30.82 | 11.40 | 13.62 | 3.71 | 22.71 |
| Q$_{90}$ | Regional function | 4.94 | 34.16 | 13.52 | 5.41 | 6.37 | 1.92 | 10.21 |
| | Indicator–Homogeneous series | 4.85 | 39.49 | 14.45 | 5.34 | 6.39 | 1.74 | 10.64 |
| | Indicator–Heterogeneous series | 4.95 | 40.37 | 14.77 | 5.46 | 6.53 | 1.78 | 10.88 |
| Q$_{95}$ | Regional function | 4.07 | 29.18 | 11.35 | 4.46 | 5.27 | 1.55 | 8.52 |
| | Indicator–Homogeneous series | 4.07 | 33.17 | 12.13 | 4.49 | 5.36 | 1.46 | 8.94 |
| | Indicator–Heterogeneous series | 4.10 | 33.44 | 12.23 | 4.53 | 5.41 | 1.47 | 9.01 |
| Q$_{7.10}$ | Regional function | 2.77 | 20.46 | 7.85 | 3.04 | 3.60 | 1.04 | 5.86 |
| | Indicator–Homogeneous series | 2.86 | 23.27 | 8.51 | 3.15 | 3.76 | 1.02 | 6.27 |
| | Indicator–Heterogeneous series | 2.90 | 23.64 | 8.65 | 3.20 | 3.82 | 1.04 | 6.37 |
| Q$_{2years}$ | Regional function | 119.00 | 662.40 | 290.90 | 128.92 | 149.14 | 51.45 | 226.54 |
| | Indicator–Homogeneous series | 112.71 | 918.57 | 336.04 | 124.30 | 148.53 | 40.45 | 247.55 |
| | Indicator–Heterogeneous series | 104.69 | 853.18 | 312.11 | 115.45 | 137.96 | 37.57 | 229.93 |
| Q$_{100years}$ | Regional function | 304.87 | 1,979.16 | 807.42 | 332.67 | 389.91 | 122.27 | 614.84 |
| | Indicator–Homogeneous series | 305.56 | 2,490.19 | 910.98 | 336.98 | 402.66 | 109.66 | 671.10 |
| | Indicator–Heterogeneous series | 294.60 | 2,400.86 | 878.30 | 324.89 | 388.21 | 105.73 | 647.02 |

Q$_m$: average long-period flow; Q$_{50}$: flow rate with permanence of 50%; Q$_{90}$: flow rate with permanence of 90%; Q$_{95}$: flow rate with permanence of 95%; Q$_{7,10}$: minimum streamflow of seven consecutive days and ten-year return period; Q$_{2years}$: maximum daily flows with return period of two years; Q$_{100years}$: maximum daily flows with return period of one hundred years.

**Table 7 – Estimated errors (%) obtained from the reference flows appropriated for the Manhuaçu River basin.**

| Reference flows | | Fazenda Vargem Alegre | São Sebastião da Encruzilhada | Assaraí Montante | Mutum | Ipanema | Dores do Manhumirim | Santo Antônio do Manhuaçu | Average Error (%) |
|---|---|---|---|---|---|---|---|---|---|
| $Q_m$ | Regional function | 7.46 | 0.65 | 7.30 | 27.59 | 2.30 | 4.08 | 21.29 | **10.10** |
| | Indicator–Homogeneous series | 11.35 | 24.24 | 18.09 | 23.75 | 3.06 | 19.32 | 16.68 | **16.64** |
| | Indicator–Heterogeneous series | 10.60 | 25.28 | 19.09 | 24.80 | 2.24 | 18.64 | 15.97 | **16.66** |
| $Q_{50}$ | Regional function | 6.94 | 6.38 | 6.14 | 31.74 | 8.62 | 8.64 | 25.16 | **13.37** |
| | Indicator–Homogeneous series | 10.14 | 13.94 | 15.62 | 28.60 | 9.04 | 21.21 | 21.18 | **17.10** |
| | Indicator–Heterogeneous series | 6.69 | 18.31 | 20.05 | 33.52 | 5.55 | 18.19 | 18.16 | **17.21** |
| $Q_{90}$ | Regional function | 16.41 | 1.82 | 6.65 | 29.48 | 13.41 | 9.40 | 28.52 | **15.10** |
| | Indicator–Homogeneous series | 14.11 | 13.51 | 13.93 | 27.90 | 13.26 | 18.07 | 25.46 | **18.03** |
| | Indicator–Heterogeneous series | 16.64 | 16.03 | 16.46 | 30.74 | 11.33 | 16.25 | 23.81 | **18.75** |
| $Q_{95}$ | Regional function | 38.75 | 2.70 | 5.47 | 27.88 | 17.21 | 13.16 | 30.96 | **19.45** |
| | Indicator–Homogeneous series | 38.87 | 16.73 | 12.79 | 28.76 | 15.75 | 18.32 | 27.53 | **22.68** |
| | Indicator–Heterogeneous series | 40.02 | 17.69 | 13.72 | 29.82 | 15.05 | 17.65 | 26.93 | **22.98** |
| $Q_{7.10}$ | Regional function | 63.02 | 8.95 | 1.97 | 20.66 | 24.24 | 19.09 | 36.16 | **24.87** |
| | Indicator–Homogeneous series | 67.95 | 23.93 | 10.61 | 24.88 | 20.93 | 20.58 | 31.74 | **28.66** |
| | Indicator–Heterogeneous series | 70.62 | 25.89 | 12.36 | 26.86 | 19.68 | 19.32 | 30.66 | **29.34** |
| $Q_{2years}$ | Regional function | 0.60 | 23.97 | 1.47 | 6.35 | 3.12 | 22.02 | 0.32 | **8.26** |
| | Indicator–Homogeneous series | 4.71 | 71.91 | 13.82 | 2.54 | 2.69 | 4.06 | 8.93 | **15.52** |
| | Indicator–Heterogeneous series | 11.50 | 59.67 | 5.72 | 4.76 | 4.62 | 10.89 | 1.17 | **14.05** |
| $Q_{100years}$ | Regional function | 7.03 | 44.64 | 16.51 | 22.21 | 7.46 | 45.63 | 1.80 | **20.76** |
| | Indicator–Homogeneous series | 6.82 | 81.99 | 5.81 | 21.20 | 4.44 | 30.62 | 11.12 | **23.14** |
| | Indicator–Heterogeneous series | 12.46 | 70.97 | 11.51 | 25.97 | 10.22 | 22.71 | 4.39 | **22.60** |

(Columns Fazenda Vargem Alegre through Santo Antônio do Manhuaçu: Fluviometric stations)

$Q_m$: average long-period flow; $Q_{50}$: flow rate with permanence of 50%; $Q_{90}$: flow rate with permanence of 90%; $Q_{95}$: flow rate with permanence of 95%; $Q_{7,10}$: minimum streamflow of seven consecutive days and ten-year return period; $Q_{2years}$: maximum daily flows with return period of two years; $Q_{100years}$: maximum daily flows with return period of one hundred years.

## Conclusions

The regional flow indicators established for the evaluation of different reference flows were consistent, producing average estimation errors for the Manhuaçu River basin that varied between 14 and 30%, not exceeding the limit considered adequate for estimating flows based on hydrological regionalization studies.

The regional functions established for flow appropriation, assuming exclusively the drainage area as an explanatory variable, were more consistent than the flow indicators, producing average errors ranging between 8 and 20%, invariably lower than those associated with the use of regional flow indicators.

For the Manhuaçu River basin, the regional flow indicators estimated from historical series with similar or different extensions did not produce relevant differences in the appropriation of the diverse reference flows, with the highest variations not exceeding 3%.

### Contribution of authors:

PIOL, M. S.: Data curation; Investigation; Methodology; Software; Validation; Visualization; Writing — original draft; Writing — review & editing. REIS, J. A. T.: Conceptualization; Data curation; Investigation; Methodology; Supervision; Validation; Visualization; Writing — original draft; Writing — review & editing. RODRIGUES, M. B.: Data curation; Validation; Visualization; Writing — original draft; Writing — review & editing. MENDONÇA, A. S. F.: Validation; Visualization; Writing — original draft; Writing — review & editing. SILVA, F. G. B.: Validation; Visualization; Writing — original draft; Writing — review & editing. SILVA, A. T. Y. L.: Validation; Visualization; Writing — original draft; Writing — review & editing.

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