

# Regionalization of mean and minimum reference flows in ungauged basins with hydropower development in southern Santa Catarina, Brazil

Regionalização de vazões de referência médias e mínimas em bacias não monitoradas com aproveitamento hidrelétrico no sul de Santa Catarina, Brasil

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**ABSTRACT:** Accurate streamflow estimation in ungauged basins is essential for sustainable water resource management and the optimal design of hydropower projects. This study develops and validates regression-based regionalization models to estimate reference flows ( $Q_{MLT}$ ,  $Q_{7,10}$ ,  $Q_{98D}$ , and  $Q_{98M}$ ) in the Tubarão River Basin (BHRT), located in Santa Catarina, southern Brazil. The basin hosts 30 small hydropower plants (CGHs and PCHs) with a combined installed capacity of approximately 73.5 MW. Ten streamflow stations and fourteen rainfall stations were analyzed using data from 1986 to 2021. Physical and climatic attributes of the basins were extracted. Based on Pearson correlation, two Hydrologically Homogeneous Regions (HHRs) were identified, for which linear, logarithmic, power-law and exponential regionalization equations were fitted. The equations showed  $R^2 > 0.90$ , relative error  $< 30\%$ , and satisfactory performance (MAE, RMSE, logNSE). Drainage area was the most important variable correlated with streamflow. The results indicate that the proposed equations are effective tools for estimating reference flows in ungauged regions, supporting energy planning and water resources management in the BHRT.

**Keywords:** Flow Regionalization; Ungauged Basins; Regression Models; Homogeneous Region.

**RESUMO:** Estimar precisamente as vazões em bacias não monitoradas é essencial para o gerenciamento sustentável dos recursos hídricos e para o dimensionamento de projetos hidrelétricos. Este estudo desenvolve e valida modelos de regionalização baseados em regressão para estimar vazões de referência ( $Q_{MLT}$ ,  $Q_{7,10}$ ,  $Q_{98D}$  e  $Q_{98M}$ ) na Bacia Hidrográfica do Rio Tubarão (BHRT), localizada em Santa Catarina, sul do Brasil. A bacia abriga 30 pequenas centrais hidrelétricas (CGHs e PCHs), com capacidade instalada de aproximadamente 73,5 MW. Foram analisadas dez estações fluviométricas e quatorze estações pluviométricas, utilizando dados do período de 1986 a 2021. Foram extraídos atributos físicos e climáticos das sub-bacias. Com base na correlação de Pearson, foram identificadas duas Regiões Hidrológicamente Homogêneas (RHHs), para as quais foram ajustadas equações de regionalização lineares, logarítmicas, potenciais e exponenciais. As equações apresentaram  $R^2 > 0,90$ , erro relativo  $< 30\%$  e desempenho satisfatório (MAE, RMSE, logNSE). A área de drenagem foi a variável mais importante correlacionada com a vazão. Os resultados indicam que as equações propostas são ferramentas eficazes para estimar vazões de referência em regiões não monitoradas, apoiando o planejamento energético e o gerenciamento de recursos hídricos na BHRT.

**Palavras-chave:** Regionalização de Vazões; Bacias sem dados; Modelos de Regressão; Região Homogênea.

## 1. Introduction

One of the foremost global challenges in the 21st century is reconciling economic and social development with the urgent need to mitigate climate change through the adoption of renewable energy sources and sustainable consumption practices (Abid et al. 2023). Within this context, Brazil presents a unique advantage, owing to its predominantly renewable electricity matrix—hydropower alone accounts for 60.15% of total electricity generation, as reported in the 2024 National Energy Balance (Empresa de Pesquisa Energética, 2025).

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Despite this significant hydroelectric capacity, substantial challenges persist in the management and monitoring of water resources, which are critical to ensuring water security and the operational efficiency of hydroelectric systems. Hydropower potential in Brazil is geographically widespread, with the highest use observed in the Northeast (94%), Southeast (89%), and South (88%) regions, while the North (9%) and Center-West (31%) remain largely underutilized. Notably, these latter regions encompass approximately 70% of Brazil's untapped hydroelectric potential, underscoring the strategic importance of effective water resources management for national energy security.

The evaluation of hydroelectric potential is intrinsically linked to the hydrological characteristics of river basins. Flow availability is commonly assessed through statistical analyses of streamflow series, using probability distribution functions or Flow Duration Curves (FDC) (Back et al., 2019). However, accurately estimating river discharge for hydrological design remains a complex task due to the inherent stochasticity of climate and the resulting temporal variability in river flows as well as the spatial heterogeneity of basin characteristics such as soil type, geology and topography (Collischonn, 2023).

To address temporal variability and support water allocation and infrastructure planning, reference flows are widely used. These flows are statistical representations of long-term streamflow behavior and are essential for evaluating water availability under average and extreme conditions, including droughts and floods (Sorribas et al., 2021). In Brazil, commonly adopted reference flows include the long-term mean flow ( $Q_{MLT}$ ), flow duration metrics (e.g.,  $Q_{95}$ ,  $Q_{98}$ ), and the minimum 7-day average flow with a 10-year return period ( $Q_{7,10}$ ), as defined by the National Water and Sanitation Agency (Agência Nacional de Águas, 2019).  $Q_{MLT}$  represents the cumulative runoff volume at a given location and serves as an indicator of maximum water availability and climate variability (Collischonn, 2023; Tucci, 2017). In contrast, minimum flow statistics such as  $Q_{7,10}$  are used in water scarcity scenarios, derived from high percentiles of flow frequency distributions or based on statistical return periods (Tucci, 2017; Agência Nacional de Águas, 2019; Collischonn, 2023). The FDC method, which relates flow magnitude to exceedance probability, remains a fundamental tool for characterizing hydrological regimes, especially when based on daily data, which provide more realistic estimates than monthly or annual aggregations (Tucci, 2009; Back et al., 2019). According to Brazil's regulations, hydroelectric potential assessments typically utilize  $Q_{MLT}$  in combination with minimum flow indicators such as  $Q_{95}$ ,  $Q_{98}$ , or  $Q_{7,10}$  (Agência Nacional de Águas, 2019; Brasil, 2020). These minimum flow statistics are also used to establish ecological flow requirements, ensuring the preservation of aquatic ecosystems. They serve as regulatory benchmarks for determining the maximum permissible withdrawal for water use permits (Agência Nacional de Águas, 2019).

In hydrological regionalization, there is no single method that performs best across all regions or flow metrics, as model performance depends on hydroclimatic conditions, basin characteristics, and the intended application. Consequently, the literature consistently recommends testing multiple regionalization approaches to assess performance and uncertainty. Most studies converge on three main methods: spatial proximity, physical or physiographic similarity, and regression-based models, which represent the conceptual approaches used in practice and differ in their assumptions and strengths, particularly when estimating distinct reference flows such as long-term mean and low flows (Yang et al., 2020; Guo et al., 2021; Baez-Villanueva et al., 2021; Vaca et al., 2025).

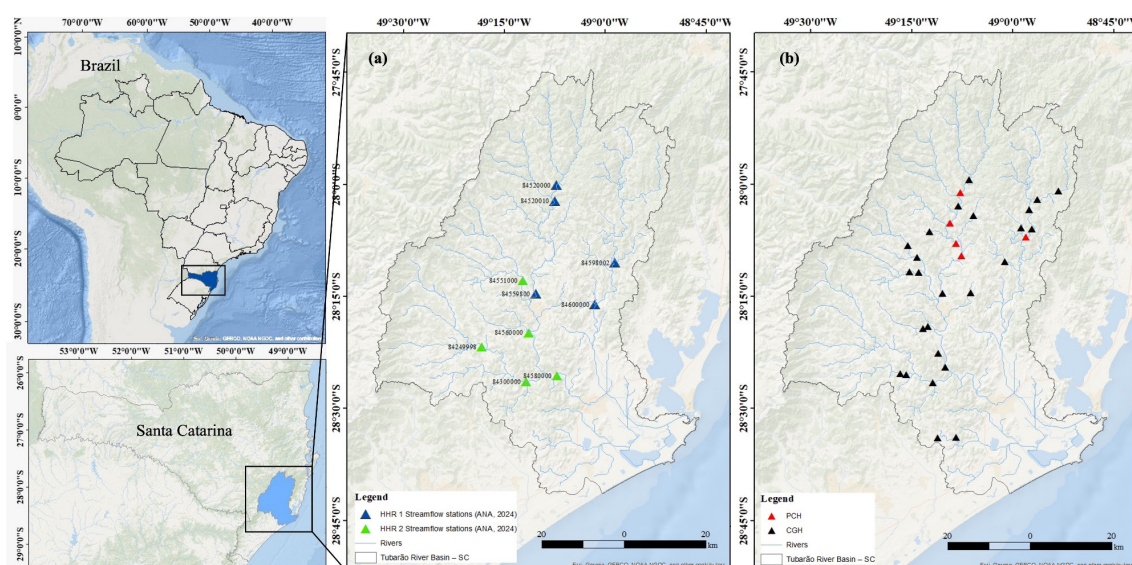
Reliable estimation of reference flows, however, requires long and consistent streamflow records, yet many Brazilian river basins lack adequate hydrological monitoring. In such data-scarce contexts, simplified approaches such as flow regionalization become essential (Tucci, 2017). Among the available techniques, regression-based regionalization methods have been widely applied in Brazil, as they establish empirical relationships between reference flows and basin attributes within hydrologically homogeneous regions (Centrais Elétricas Brasileiras, 1985; Tucci, 2017). Several studies have demonstrated the effectiveness of this approach for estimating both mean and minimum flows (e.g., Bazzo et al., 2017; Maciel et al., 2019; Matos et al., 2020; Rocha et al., 2024; Zagonel, 2021). Despite their widespread application, there is still limited evidence on the performance of these approaches in basins with hydropower development and sparse hydrological monitoring, particularly in southern Brazil.

Recently, Brazil has witnessed a shift toward decentralized power generation, which offers benefits such as reduced transmission losses and lower environmental impacts. Consequently, there has been an increased focus on the development of small hydroelectric plants (PCHs) and hydroelectric generating stations (CGHs) (Agência Nacional de Energia Elétrica, 2024). These facilities are frequently located in mountainous terrain and on small-to-medium rivers, where hydrological data scarcity is more pronounced, further emphasizing the need for flow regionalization studies. The Tubarão River Basin in southern Santa Catarina exemplifies this situation, hosting several small and medium hydroelectric facilities that collectively generate approximately 73.5 MW of electricity (Agência Nacional de Energia Elétrica, 2024). This substantial hydroelectric potential highlights the strategic importance of accurate flow estimation for plant design and operational management. These hydroelectric projects also support regional energy independence and play a key role in the local energy transition by reducing dependence on coal-fired power generation.

In this context, the present study aims to evaluate regression-based regionalization models for estimating reference flows, specifically  $Q_{MLT}$ ,  $Q_{7,10}$  and  $Q_{98}$  (monthly and daily), at ungauged sites within the Tubarão River Basin, Santa Catarina, Brazil, contributing to hydropower planning and water resources management in data scarce regions.

## 2. Material and Methods

The Tubarão River Basin (4,735.00 km<sup>2</sup>) is located in the southern region of Santa Catarina State, Brazil (Figure 1). The main watercourse, the Tubarão River, extends for 120.0 km, originating in the coastal mountain ranges and discharging into the Santo Antônio Lagoon, approximately 3.0 km from the Atlantic Ocean. Among its main tributaries are the Braço do Norte and Capivari Rivers, which exhibit favorable conditions for hydroelectric generation due to their hydrological and topographic features. The terrain is composed of 27% flat areas, 33% undulating slopes, and 40% mountainous regions. Currently, these tributaries host 25 Hydroelectric Generating Plants (CGHs) and 5 Small Hydroelectric Plants (PCHs), as indicated in Figure 1b (Agência Nacional de Energia Elétrica, 2024).



**Figure 1.** Location of the Tubarão River Basin: (a) streamflow gauging stations used in the study; (b) hydroelectric plants in operation.

**Source:** Authors, 2025.

The basin is characterized by two Köppen climate subtypes: Cfa (humid mesothermal with hot summers) prevailing in the lowlands, and Cfb (humid mesothermal with mild summers) dominating elevations above 900 meters. The Cfa subtype presents average monthly temperatures exceeding 10°C during the coldest month and over 22°C during the warmest month, while Cfb maintains maximum monthly averages below 22°C. The mean annual relative humidity is 81.5% (Pandolfo et al., 2002; Alvares et al., 2013), and annual precipitation ranges from 1,378 mm to 2,072 mm, with spatial and temporal variability.

To ensure hydrological consistency, streamflow and precipitation data were analyzed over a simultaneous observation period from 1986 to 2021. This approach, involving simultaneous streamflow and precipitation data, is consistent and was employed by Euclides et al. (2001) in regional flow studies in Minas Gerais, Brazil. Time series quality control followed rigorous standards, allowing a maximum of 10% missing data, in accordance with recommendations by Cupak (2017) and Molina et al. (2014). A total of 14 rainfall stations and 10 streamflow gauging stations, maintained by the National Water and Sanitation Agency (ANA), were used (Figure 1a; Table 1). The region also contains monitoring stations operated by the electrical sector; however, these could not be used in the current analysis due to insufficient data availability or quality.

The reference flows  $Q_{MLT}$ ,  $Q_{7,10}$  and  $Q_{98}$  are essential for assessing water availability and evaluating hydroelectric potential.  $Q_{MLT}$  represents the long-term mean discharge, preferably over periods exceeding 20 years (Tucci, 2017).  $Q_{7,10}$  and  $Q_{98}$  serve as critical thresholds for water rights allocation, ensuring downstream flow maintenance to support ecological integrity and water use (Agência Nacional de Águas, 2019).

Daily and monthly flow data were analyzed using the SisCAH 1.0 software (Sousa, 2009).  $Q_{7,10}$  was estimated using the two-parameter Weibull and Log-Pearson Type III distributions, which exhibited the best fit, corroborating results found by Galatto & Back (2023) for the adjacent Araranguá River Basin. For the monthly  $Q_{98}$  ( $Q_{98M}$ ), calculations were performed in Excel using the PERCENTILE.INC function, applying the percentile 2 to derive flows equaled or exceeded 98% of the time (Microsoft Corporation, 2018).

Reference flows were regionalized through linear, logarithmic, potential, and exponential regression models. These models establish statistical relationships between flow rates and basin attributes, following methods proposed by Naghettini & Pinto (2007), Tucci (2017), and Maciel et al. (2019). The explanatory variables used included: drainage area (A), mean slope of the main river (MSS), drainage density (Dd), and mean annual rainfall (MAR). The methodology comprised: (a) obtaining A values from ANA station data (Table 1); (b) calculating MSS as the elevation difference between river source and mouth divided by river length; (c) computing Dd as the ratio of total river length to basin area; and (d) estimating mean annual precipitation using the Isohyetal method, derived from data from the 14 rainfall stations. Physical and climatic parameters were extracted using ArcGIS 10.8 (Environmental Systems Research Institute, 2020) and a 30-meter resolution Digital Elevation Model (Instituto Nacional de Pesquisas Espaciais, 2024). The isohyet map was generated using the Inverse Distance Weighted (IDW) interpolation method, with 10 mm contour intervals and power parameter of 2.

Pearson correlation analysis was used to identify Hydrologically Homogeneous Regions (HHRs), based on the relationship between flows and basin characteristics. Regression models for  $Q_{MLT}$ ,  $Q_{7,10}$ , and  $Q_{98}$  were developed using variables with the strongest correlations and implemented using Stata 14.2 (StataCorp, 2016). The equations considered included the following forms:

$$Q = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (1)$$

$$Q = \beta_0 \cdot e^{\beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n} \quad (2)$$

$$Q = \beta_0 \cdot X_1^{\beta_1} \cdot X_2^{\beta_2} \cdot \dots \cdot X_n^{\beta_n} \quad (3)$$

$$\ln Q = \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \dots + \beta_n \ln X_n \quad (4)$$

where  $Q$  represents the estimated flow,  $X_1$  to  $X_n$  are the independent variables, and  $\beta_0$  to  $\beta_n$  are regression coefficients.

Hydrological homogeneity was evaluated using the coefficient of determination ( $R^2$ ), adjusted  $R^2$  ( $R^2a$ ), factor standard error ( $\sigma F$ ), and relative error (RE%). Based on standards from Tucci (2017), Bazzo et al. (2017), and Centrais Elétricas Brasileiras (1985), regions were considered homogeneous if  $R^2$  and  $R^2a$  were  $\geq 0.90$ ,  $\sigma F < 1.5$ , and  $RE\% < 30\%$ .

Model validation was essential to assess under- or overestimation tendencies, as emphasized by Maciel et al. (2019). Therefore, estimated flows were compared with observed values at streamflow stations using the following performance metrics:

$$RE\% = \left( \frac{Q_{obs} - Q_{est}}{Q_{obs}} \right) \times 100 \quad (5)$$

$$MAE = \frac{\sum_{i=1}^n |(Q_{est} - Q_{obs})|}{n} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Q_{est} - Q_{obs})^2}{n}} \quad (7)$$

$$\log NSE = 1 - \frac{\sum_{i=1}^n (\log(Q_{obs}) - \log(Q_{est}))^2}{\sum_{i=1}^n (\log(Q_{obs}) - \overline{\log(Q_{obs})})^2} \quad (8)$$

$$R^2 = 1 - \frac{Res^2}{Tot^2} \quad (9)$$

$$R^2_a = 1 - \frac{(1 - R^2) * (n - 1)}{n - k - 1} \quad (10)$$

where  $Q_{obs}$  is the observed flow,  $Q_{est}$  is the estimated flow,  $n$  is the number of data points,  $Res$  is the residual sum of squares and  $Tot$  is the total sum of squares.

MAE and RMSE provide insight into the average magnitude of estimation errors. The logNSE is particularly effective for evaluating model performance during low-flow conditions. Values of  $\logNSE > 0.7$  are considered satisfactory for regionalized minimum flow modeling (Moriassi et al., 2007; Oudin et al., 2008; Pushpalatha et al., 2012; Souza & Santos, 2013). The coefficient of determination ( $R^2$ ) is used to quantify how much of the variability observed in the measured data is captured by the model, with values closer to 1 indicating a stronger agreement between simulated and observed values (Moriassi et al., 2007). In addition to  $R^2$ , the adjusted coefficient of determination ( $R^2_a$ ) was used to account for model complexity. Unlike  $R^2$ , which may increase with the inclusion of additional predictors regardless of their contribution,  $R^2_a$  penalizes the number of explanatory variables relative to sample size, providing a more reliable measure of model performance and enabling fair comparisons among models with different complexities (Montgomery et al., 2012).

### 3. Results and Discussion

Table 1 presents the values of the reference flows  $Q_{98}$ , both daily ( $Q_{98D}$ ) and monthly ( $Q_{98M}$ ), along with the relative error (RE%) between these two observed flows. Additionally, it includes the flow rates  $Q_{7,10}$  and  $Q_{MLT}$ , calculated for the ten streamflow gauging stations located within the Tubarão River Basin (BHRT).

**Table 1.** Physical and climatic characteristics and reference flows of the river gauging stations in the BHRT.

Code	MAR	A	Dd	MSS	$Q_{98D}$	$Q_{98M}$	RE	$Q_{7,10}$	$Q_{MLT}$
84580000	1619.57	2740.00	2.98	8.15	17.94	24.80	27.66%	10.00	77.58
84560000	1647.40	1690.00	3.32	9.45	10.49	14.06	25.39%	9.31	47.60
84559800	1771.96	1515.00	3.40	10.09	8.02	10.17	21.14%	7.51	33.64
84300000	1594.73	822.00	2.40	6.10	4.08	6.09	33.00%	3.20	26.78
84600000	1656.15	770.00	2.32	12.27	7.13	8.48	15.92%	6.43	23.10
84520010	1834.46	676.00	3.50	21.02	6.02	7.61	20.89%	5.18	20.79
84598002	1701.76	620.00	2.32	11.86	5.55	6.49	14.48%	5.20	17.43
84249998	1606.44	599.00	2.39	23.53	2.79	3.84	27.34%	2.21	18.49
84520000	1820.53	380.00	2.72	17.62	3.71	4.62	19.70%	3.44	11.29
84551000	1419.76	379.00	3.00	19.58	1.90	2.90	34.48%	1.51	13.14

Code refers to the official station identification number assigned by ANA.

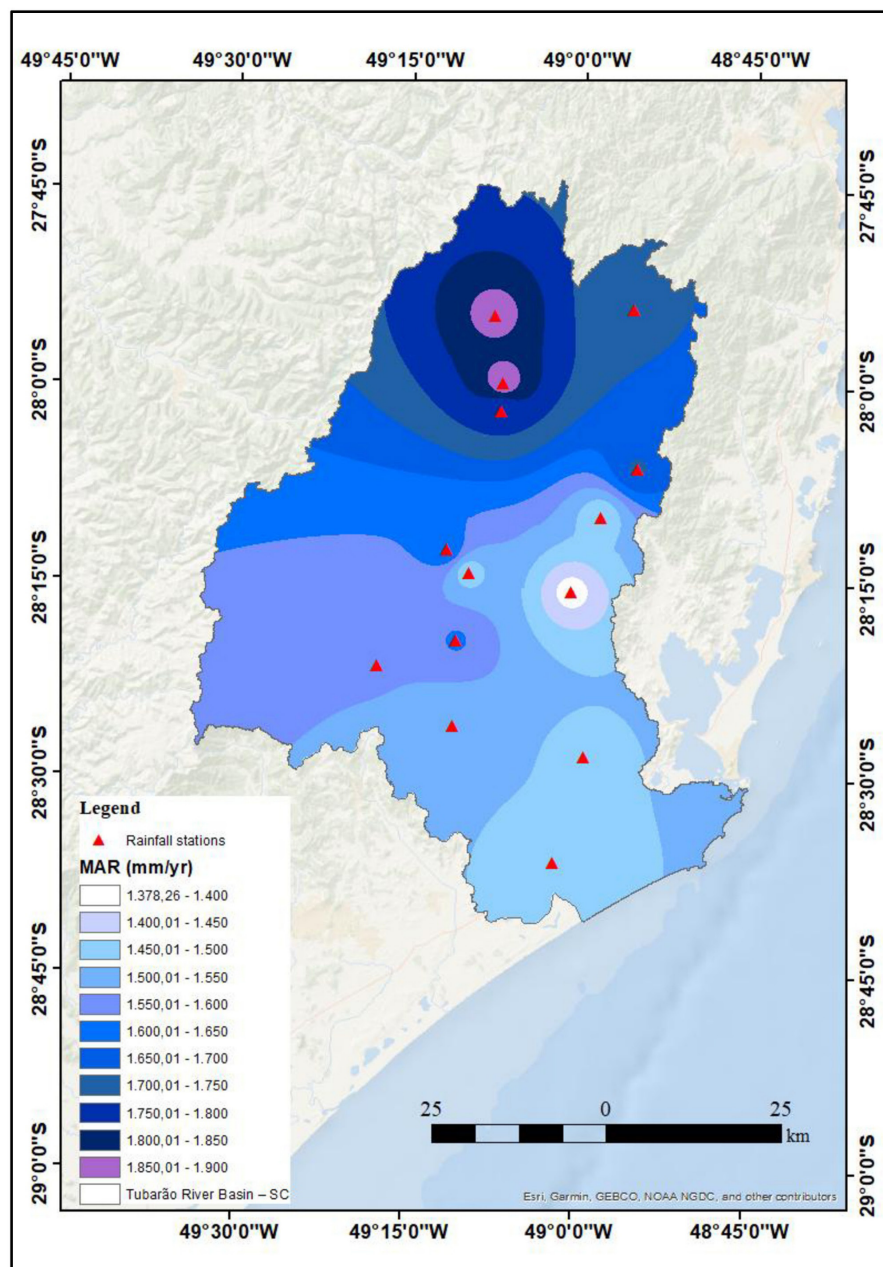
The Pouso River Basin (station 84580000) had the largest drainage area (2,740.00 km<sup>2</sup>), whereas the smallest was the Pequeno River Basin (station 84551000, 379.00 km<sup>2</sup>). Drainage densities ranged from 2.32 to 3.50 km.km<sup>-2</sup>, suggesting favorable drainage conditions in the BHRT. The steepest slopes were observed in the upstream basins of the Orleans Montante (84249998) and Santa Rosa de Lima (84520010) stations, with gradients of 23.53 and 21.02 m.km<sup>-1</sup>, respectively, both located in headwater regions.

The results indicate that the relative error between daily  $Q_{98}$  ( $Q_{98D}$ ) and monthly  $Q_{98}$  ( $Q_{98M}$ ) exceeded at least 14% across all stations, with RE% ranging from 14.48% (0.94 m<sup>3</sup>.s<sup>-1</sup>) at station 84598002 (822.00 km<sup>2</sup>) to 34.48% (1.0 m<sup>3</sup>.s<sup>-1</sup>) at station 84551000 (379.00 km<sup>2</sup>). This pattern aligns with findings in the literature, where the use of monthly flow data to construct flow duration curves is reported to systematically overestimate minimum reference flows. Back et al. (2019), for example, in their study in the Timbó River, northern Santa Catarina, demonstrated that average minimum flows may be overestimated by more than 25% when based on monthly series, emphasizing that daily series yield more realistic values.

From an economic standpoint, Costa & Santos (2018) demonstrated that reliance on monthly flow data can result in an overestimation of the installed capacity in hydropower plants by up to 25%, as observed in the Itajaí-Açu River Basin. This issue has important implications for the BHRT, which hosts 25 CGHs and 5 PCHs installed along the Braço do Norte and Capivari Rivers, with a combined installed capacity of approximately 73.5 MW (Agência Nacional de Energia Elétrica, 2024).

It is likely that overestimated flows influenced the sizing of these facilities. Furthermore, such discrepancies may affect the technical and economic viability of future hydropower developments and the allocation of water use rights.

Figure 2 presents the isohyet map based on 14 rainfall stations covering the 1986–2021 period. The spatial distribution of annual rainfall is heterogeneous, ranging from 1,378.3 mm to 1,886.6 mm, with a standard deviation of 160.9 mm. Precipitation is higher in the headwaters, particularly in the Serra Geral region, and decreases toward the Atlantic coast. This spatial pattern is consistent with Back & Poletto (2018), who identified similar rainfall ranges for southern Santa Catarina. Orographic effects, intensified by the South Atlantic high-pressure system and the regional relief, are key drivers of this rainfall gradient (Gotado et al., 2018; Reboita et al., 2012).



**Figure 2.** Average annual rainfall of the Tubarão River Basin (SC).

**Source:** Authors, 2025.

As shown in Table 2, Pearson correlation analysis indicated the highest coefficients when dividing the BHRT into two hydrologically homogeneous regions: HHR 1 (stations 84559800, 84520010, 84520000, 84600000, 84598002) and HHR 2 (stations 84249998, 84560000, 84551000, 84580000, 84300000). These groups are spatially coherent, with HHR 1 in the northern part and HHR 2 in the southern part of the basin.

**Table 2.** Pearson correlation of HHR 1 and HHR 2.

HHR1								
	MAR	A	Dd	MSS	Q <sub>98D</sub>	Q <sub>98M</sub>	Q <sub>7,10</sub>	Q <sub>MLT</sub>
MAR	1	-0.096	0.760	0.719	-0.403	-0.278	-0.433	-0.182
A		1	0.489	-0.603	0.872	0.910	0.905	0.972
Dd			1	0.382	0.283	0.405	0.238	0.471
MSS				1	-0.576	-0.512	-0.669	-0.550
HHR2								
	MAR	A	Dd	MSS	Q <sub>98D</sub>	Q <sub>98M</sub>	Q <sub>7,10</sub>	Q <sub>MLT</sub>
MAR	1	0.582	-0.043	-0.469	0.546	0.535	0.645	0.578
A		1	0.479	-0.615	0.999	0.998	0.945	0.999
Dd			1	-0.238	0.507	0.493	0.642	0.458
MSS				1	-0.595	-0.605	-0.636	-0.635

Among the tested variables, drainage area (A) showed the strongest correlation with reference flows in both HHRs, indicating its suitability as the primary regionalization parameter. HHR 2 exhibited generally higher correlation coefficients, reflecting greater hydrological similarity among its contributing basins. According to Asuero et al. (2006), *r* values above 0.70 are considered high, and values above 0.90 are considered very high—supporting the robustness of the hydrological groupings. The literature considers regionalization equations statistically satisfactory when *R*<sup>2</sup> and adjusted *R*<sup>2</sup> exceed 0.75 and the standard error of estimate ( $\sigma F$ ) is below 1.5 (Maciel et al., 2019; Bazzo et al., 2017; Centrais Elétricas Brasileiras, 1985). The results in this study satisfy these thresholds, confirming their applicability for estimating reference flows at ungauged sites.

Table 3 summarizes the regression models developed for each HHR. In both regions, the best-performing models used only the drainage area (A) as the explanatory variable, outperforming models that included other basin descriptors such as drainage density (Dd), main river slope (MSS), and mean annual rainfall (MAR).

**Table 3.** Regression models for HHR 1 and HHR 2.

HHR	Flow	Model	Equation	R <sup>2</sup>	R <sup>2a</sup>	$\sigma F$
1	Q <sub>98D</sub>	Logarithmic	$Q_{98D} = 3.135575 * LnA - 14.51827$	0.906	0.875	1.1
	Q <sub>98M</sub>	Logarithmic	$Q_{98M} = 4.066744 * LnA - 19.2491$	0.943	0.923	1.5
	Q <sub>7,10</sub>	Logarithmic	$Q_{7,10} = 2.964037 * LnA - 13.92507$	0.935	0.913	1.1
	Q <sub>MLT</sub>	Logarithmic	$Q_{MLT} = 16.43248 * LnA - 86.72994$	0.989	0.985	1.5
2	Q <sub>98D</sub>	Linear	$Q_{98D} = 0.0069531 * A - 1.223594$	0.998	0.997	1.1
	Q <sub>98M</sub>	Linear	$Q_{98M} = 0.0094497 * A - 1.436379$	0.997	0.996	1.4
	Q <sub>7,10</sub>	Potential	$Q_{7,10} = 0.0029 * A^{1.05121}$	0.963	0.950	1.2
	Q <sub>MLT</sub>	Linear	$Q_{MLT} = 0.0270765 * A + 2.980669$	0.998	0.998	1.3

All equations demonstrated high predictive capacity, with *R*<sup>2</sup> and adjusted *R*<sup>2</sup> values exceeding 0.875. This finding corroborates several prior studies across different hydrographic contexts (e.g., Zagonel, 2021; Maciel et al., 2019; Bazzo et al., 2017), where drainage area was the dominant factor in explaining variations in Q<sub>95</sub>, Q<sub>7,10</sub>, and Q<sub>MLT</sub>. The predominance of this variable is especially relevant in the BHRT due to the limited availability of monitoring data, highlighting the practicality of using drainage area-based models for hydroelectric planning and water resource management.

The regionalization models produced relative errors (RE%) below 30% for all gauging stations (Table 4). The lowest errors were found for  $Q_{MLT}$  in both HHRs (3.42% in HHR 1; 2.66% in HHR 2), while the highest occurred for  $Q_{7,10}$  in HHR 2 (11.52%). These results are in line with prior studies (e.g., Cadorin, 2021; Aguiar, 2020), and reflect the increased variability associated with low flows, as also noted by Novaes et al. (2007) and Cecílio et al. (2018).

**Table 4.** Observed and Estimated Reference Flows ( $Q_{98D}$ ,  $Q_{98M}$ ,  $Q_{7,10}$ ,  $Q_{MLT}$ ) for HHR 1 and 2 and Relative Errors

HHR 1												
Code	$Q_{98D}$ ( $m^3.s^{-1}$ )			$Q_{98M}$ ( $m^3.s^{-1}$ )			$Q_{7,10}$ ( $m^3.s^{-1}$ )			$Q_{MLT}$ ( $m^3.s^{-1}$ )		
	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%
84559800	8.02	8.44	-5.29	10.17	10.53	-3.56	7.51	7.78	-3.61	33.64	33.61	0.10
84520010	6.02	5.91	1.77	7.61	7.25	4.72	5.18	5.39	-4.04	20.79	20.35	2.13
84520000	3.71	4.11	-10.72	4.62	4.91	-6.23	3.44	3.68	-7.03	11.29	10.88	3.62
84600000	7.13	6.32	11.33	8.48	7.78	8.25	6.43	5.78	10.19	23.1	22.49	2.65
84598002	5.55	5.64	-1.67	6.49	6.90	-6.30	5.2	5.13	1.29	17.43	18.93	-8.58
<i>Mean RE</i>			<b>6.15</b>			<b>5.82</b>			<b>5.23</b>			<b>3.42</b>
HHR 2												
Code	$Q_{98D}$ ( $m^3.s^{-1}$ )			$Q_{98M}$ ( $m^3.s^{-1}$ )			$Q_{7,10}$ ( $m^3.s^{-1}$ )			$Q_{MLT}$ ( $m^3.s^{-1}$ )		
	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%	$Q_{obs}$	$Q_{est}$	RE%
84249998	2.79	2.94	-5.42%	3.84	4.22	-10.00%	2.21	2.41	-9.06%	18.49	19.20	-3.84%
84560000	10.49	10.53	-0.35%	14.06	14.53	-3.37%	9.31	7.17	22.97%	47.6	48.74	-2.39%
84551000	1.9	1.41	25.70%	2.9	2.15	26.03%	1.51	1.49	1.35%	13.14	13.24	-0.78%
84580000	17.94	17.83	0.62%	24.8	24.46	1.39%	10	11.92	-19.18%	77.58	77.17	0.53%
84300000	4.08	4.49	-10.09%	6.09	6.33	-3.96%	3.2	3.36	-5.05%	26.78	25.24	5.76%
<i>Mean RE</i>			<b>8.44</b>			<b>8.95</b>			<b>11.52</b>			<b>2.66</b>

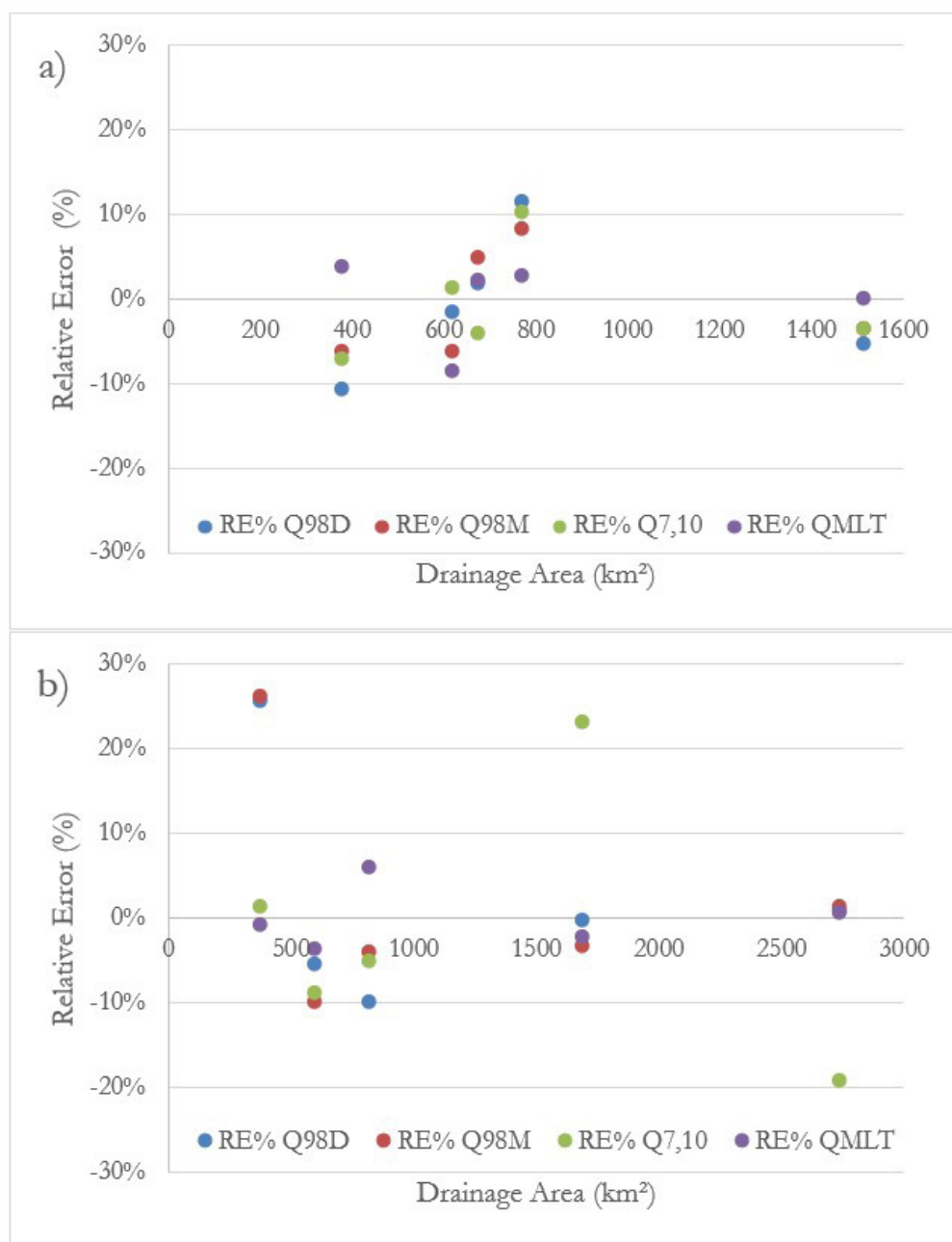
Although Cadorin (2021) reported errors exceeding 30% for  $Q_{7,10}$  in some BHRT stations, this discrepancy may be attributed to differences in the simultaneity criteria used for rainfall and streamflow series, as well as differences in the study period. Positive RE% values indicate underestimation, while negative values indicate overestimation. Both conditions can affect hydropower sizing and operational efficiency. Smaller basins exhibited larger relative errors (Figure 3), confirming that flow regionalization in such areas involves greater uncertainty, especially for minimum flows such as  $Q_{98}$  and  $Q_{7,10}$  (Corseuil et al., 2024).

Table 5 reports the performance metrics: mean absolute error (MAE), root mean square error (RMSE), and the Nash-Sutcliffe Efficiency in logarithmic form (LogNash). MAE ranged from 0.289 to 0.599  $m^3.s^{-1}$  in HHR 1 and from 0.240 to 0.888  $m^3.s^{-1}$  in HHR 2. These values are lower than those reported in similar studies for the BHRT and other basins (e.g., Aguiar, 2020; Matos et al., 2020; Araújo et al., 2018).

In general, the regression equations adjusted for each HHR performed well, as indicated by the MAE values, which ranged from 0.289 to 0.599  $m^3.s^{-1}$  for HHR 1 and 0.240 to 0.888  $m^3.s^{-1}$  for HHR 2. In previous studies in the Tubarão River Basin, Aguiar (2020) found MAE < 2.0  $m^3.s^{-1}$  in the regionalization of  $Q_{98}$ , considering these results to be satisfactory. Also, Matos et al. (2020) and Araújo et al. (2018) reported a good fit of the models, even with higher MAE values of 14.1  $m^3.s^{-1}$  for  $Q_{95}$  and 36.1  $m^3.s^{-1}$  for  $Q_{MLT}$ , respectively.

The RMSE values were also low, ranging from 0.349 to 0.772  $m^3.s^{-1}$  in HHR 1 and from 0.298 to 1.290  $m^3.s^{-1}$  in HHR 2. In the study of reference flow regionalization, Araújo et al. (2018) considered satisfactory values for the RMSE of up to 8.94  $m^3.s^{-1}$  for  $Q_{7,10}$  and 91.15  $m^3.s^{-1}$  for  $Q_{MLT}$ . The proximity between the MAE and RMSE values shows low error dispersion and reinforces the quality of the equations' fit.

In turn, the Nash-Sutcliffe Log (LogNash) was between 0.920 and 0.997, indicating optimum model performance, as classified by Moriasi et al. (2007), i.e. the closer to 1, the greater the agreement between estimated and observed flows.



**Figure 3.** Relation between drainage area and relative error for (a) HHR 1 and (b) HHR 2.

**Table 5.** Performance Parameters of the Reference Flows for HHR 1 and HHR 2.

HHR	Flow	MAE (m <sup>3</sup> .s <sup>-1</sup> )	RMSE (m <sup>3</sup> .s <sup>-1</sup> )	LogNash (dimensionless)
01	Q <sub>98D</sub>	0.366	0.450	0.920
	Q <sub>98M</sub>	0.424	0.447	0.948
	Q <sub>7,10</sub>	0.289	0.349	0.945
	Q <sub>MLT</sub>	0.599	0.772	0.985
02	Q <sub>98D</sub>	0.240	0.298	0.971
	Q <sub>98M</sub>	0.440	0.473	0.968
	Q <sub>7,10</sub>	0.888	1.290	0.962
	Q <sub>MLT</sub>	0.781	0.934	0.997

## 4. Conclusions

This study demonstrated the effectiveness and robustness of regionalization equations for estimating reference flows ( $Q_{98D}$ ,  $Q_{98M}$ ,  $Q_{7,10}$  and  $Q_{MLT}$ ) in the Tubarão River Basin (BHRT), a basin with high hydropower generation potential. The results highlight the relevance of the proposed approach for supporting renewable energy expansion and water resources management in southern Santa Catarina. By identifying two hydrologically homogeneous regions and using drainage area as the sole explanatory variable, the models achieved high predictive performance while preserving methodological simplicity and practical applicability.

All regionalization models presented relative errors within acceptable limits (<30%), with the lowest errors observed in HHR 2, indicating a higher degree of internal hydrological consistency in the sub-region. The use of single, physically measurable parameter (A) enhances the applicability of the proposed equations in ungauged basin within the BHRT, where hydrological data availability is limited and decision-making often relies on simplified, yet reliable, estimation tools.

Model reliability was further supported by performance metrics (MAE, RMSE, and LogNash) which indicated low dispersion and minimal bias between observed and estimated flows. When compared to previous studies conducted in the BHRT, the results represent an improvement in predictive accuracy, reinforcing the role of flow regionalization as a key instrument for sustainable water resource management, hydropower project planning, and regulatory decision-making.

Future research should apply the regionalized reference flows to access hydropower generation potential, enabling the evaluation of whether existing and planned hydropower facilities are adequately sized in relation to stream flow availability and expected energy production. Additionally, the integration of hydrometeorological data from stations operated by the electric sector could expand spatial coverage and improve model's robustness. Further investigations may also explore alternative regionalization approach and incorporate geological, soil, and land-use variables, which have been shown to contribute to explain the spatial variability of mean and minimum flows in hydrological studies.

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