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Minimum flow and water availability in the Baixo Paraíba do Sul watershed, Brazil: impacts of climate change and demand trends

Vazão mínima e disponibilidade de água na bacia do Baixo Paraíba do Sul, Brasil: impactos das mudanças climáticas e tendências de demanda

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ABSTRACT

The Paraíba do Sul River watershed in Rio de Janeiro, Brazil, has experienced significant changes in precipitation patterns and flow regimes due to climate change and anthropogenic pressures, such as water transpositions and hydropower reservoirs. This study aimed to assess water availability trends, focusing on minimum flows in the Baixo Paraíba do Sul region and its key tributaries: Pomba, Muriaé, and Dois Rios. Using a statistical approach, historical flow data from 2012 to 2022 were analyzed, including the severe 2014-2015 drought. The methodology involved exceedance probabilities (Q95) and frequency analysis to evaluate monthly flow variability. Results showed considerable reductions in Q95 flows: 30.9% in the main Paraíba do Sul channel, 35.9% in Dois Rios, 42.4% in Muriaé, and 46.3% in Pomba. Additionally, monthly flows fell below residual levels in 22%, 19.7%, 18.9%, and 11.4% of cases for these regions, respectively. These findings highlight the urgent need to revise the watershed management plan to address current water demands and adapt to climatic changes effectively.

Keywords: Statistical Hydrology. Watershed Plan. Water Security. Frequency Analysis. Q95.

RESUMO

A bacia hidrográfica do Rio Paraíba do Sul no Rio de Janeiro, Brasil, tem experimentado mudanças significativas nos padrões de precipitação e regimes de fluxo devido às mudanças climáticas e pressões antrópicas, como transposições de água e reservatórios hidrelétricos. Este estudo teve como objetivo avaliar as tendências de disponibilidade hídrica, com foco nas vazões mínimas na região do Baixo Paraíba do Sul e seus principais tributários: Pomba, Muriaé e Dois Rios. Usando uma abordagem estatística, dados históricos de vazão de 2012 a 2022 foram analisados, incluindo a seca severa de 2014-2015. A metodologia envolveu probabilidades de excedência (Q95) e análise de frequência para avaliar a variabilidade mensal da vazão. Os resultados mostraram reduções consideráveis nas vazões Q95: 30,9% no canal principal do Paraíba do Sul, 35,9% em Dois Rios, 42,4% em Muriaé e 46,3% em Pomba. Além disso, os fluxos mensais caíram abaixo dos níveis residuais em 22%, 19,7%, 18,9% e 11,4% dos casos para essas regiões, respectivamente. Essas descobertas destacam a necessidade urgente de revisar o plano de gestão da bacia hidrográfica para abordar as demandas atuais de água e se adaptar às mudanças climáticas de forma eficaz.

Palavras-chave: Hidrologia Estatística. Plano de Bacia Hidrográfica. Segurança Hídrica. Análise de Frequência. Q95.

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1. INTRODUCTION

Climate change has intensified the frequency and severity of extreme precipitation events, challenging water sustainability and aligning with the objectives of UN Sustainable Development Goal (SDG) 6, which advocates for improved water security management (PONTES et al., 2022; TABARI, 2020). These extremes, including floods and droughts, are influenced by climatic and surface conditions and exhibit spatial heterogeneity, posing significant risks to hydrological systems (EDAMO et al., 2023). In regions like the Paraíba do Sul River Watershed (PSRW), such variability necessitates precise assessments of water availability, particularly for minimum flows, which are critical for water resource management, ecosystem health, and socio-economic activities (GRANEMANN et al., 2018).

The PSRW, covering 62,074 km² across one of Brazil's most economically vital regions, alternates between severe floods and prolonged droughts (SALES et al, 2020). Notable events include the 2011 Nova Friburgo flood, with 209.6 mm of rainfall in four days, and the extreme 2014-2015 drought, the most severe in 85 years, which disrupted water supplies, energy generation, and agricultural productivity (SANTANA et al., 2021). These events highlight the region's vulnerability and emphasize the need for enhanced management strategies tailored to evolving climatic and hydrological conditions.

Traditional statistical approaches for evaluating minimum flows, such as Q95, are widely used in Brazil, including by the State Institute for the Environment (INEA) in Rio de Janeiro and the National Water and Sanitation Agency (ANA) (GASQUES et al., 2018; RIO DE JANEIRO, 2019; IKEMOTO & NAPOLEÃO, 2023). While effective for long-term planning, reliance on historical series can obscure recent climatic trends, smoothing short-term variability and potentially misrepresenting current water availability (PONTES et al., 2022). Given the intensifying impacts of climate change, a more localized and temporally sensitive approach is essential to accurately reflect changing hydrological conditions.

This study addresses these gaps by reassessing water availability in the Baixo Paraíba do Sul Watershed (BPSW) and its key tributaries – Pomba, Muriaé, and Dois Rios – using updated statistical methods. Unlike earlier assessments, it incorporates frequency analysis of monthly average flows alongside recalculated Q95 values for the 2012-2022 period, capturing the severe 2014-2015 drought and other critical events. By comparing Q95, the study provides a nuanced understanding of hydrological variability and offers a refined framework for adaptive water management under changing climatic conditions.

2. MATERIALS AND METHODS

2.1 Study Area and Monitoring Stations

The BPSW, located within the RH-IX Hydrographic Region of Rio de Janeiro, is influenced by the entire upstream Paraíba do Sul catchment and discharges into the Atlantic Ocean at Atafona, in São João da Barra city. This study focuses on the Pomba, Muriaé, and Dois Rios watersheds, the principal tributaries of the PSRW in its northern section, which are critical to regional hydrological dynamics and directly contribute to the river's flow at its estuary.

Fluviometric stations operated by the ANA were strategically chosen near the confluence of each tributary with the BPSW to accurately capture upstream hydrological conditions. Additionally, the Ilha dos Pombos Hydroelectric Plant station was included to monitor the downstream section of the Paraíba do Sul River, capturing cumulative contributions from the entire upstream watershed. Table 1 summarizes the selected monitoring stations, and Figure 1 depicts the sub-basins and their respective locations.

Table 1. ANA fluviometric stations designated as control points for each watershed.

ANA Code	Station	Watershed	City	Latitude	Longitude	Drainage Area (km^2)
58792100	Aperibé	Pomba	Aperibé	-21.621	-42.100	8530
58874000	Dois Rios	Dois Rios	São Fidélis	-21.644	-41.859	3120
58653500	UHE Ilha dos Pombos Jusante	Paraíba do Sul Main course	Carmo	-21.835	-42.582	34400
58974000	Campos - Ponte Municipal		Campos dos Goytacazes	-21.751	-41.324	55700
58960000	Cardoso Moreira	Muriaé	Cardoso Moreira	-21.492	-41.614	7210

2.2 Residual flows in the BPSW

Residual or ecological flow represents the minimum flow necessary to maintain the integrity of aquatic ecosystems. According to Longhi & Formiga (2011), over 200 methodologies are available for determining these flow values. In 2014, COHIDRO, commissioned by the Integration Committee of the Paraíba do Sul Watershed (CEIVAP), established residual flow rates for various points within the PSRW). This study adopts the FDC methodology (Q95), which is based on long-term historical data from specific control points. The Q95 values derived from this methodology were then applied to other locations within the watershed using modeling techniques, incorporating quantitative water balance calculations as part of the watershed management plan. The residual flow values employed in this study for the selected fluviometric stations are listed in Table 2.

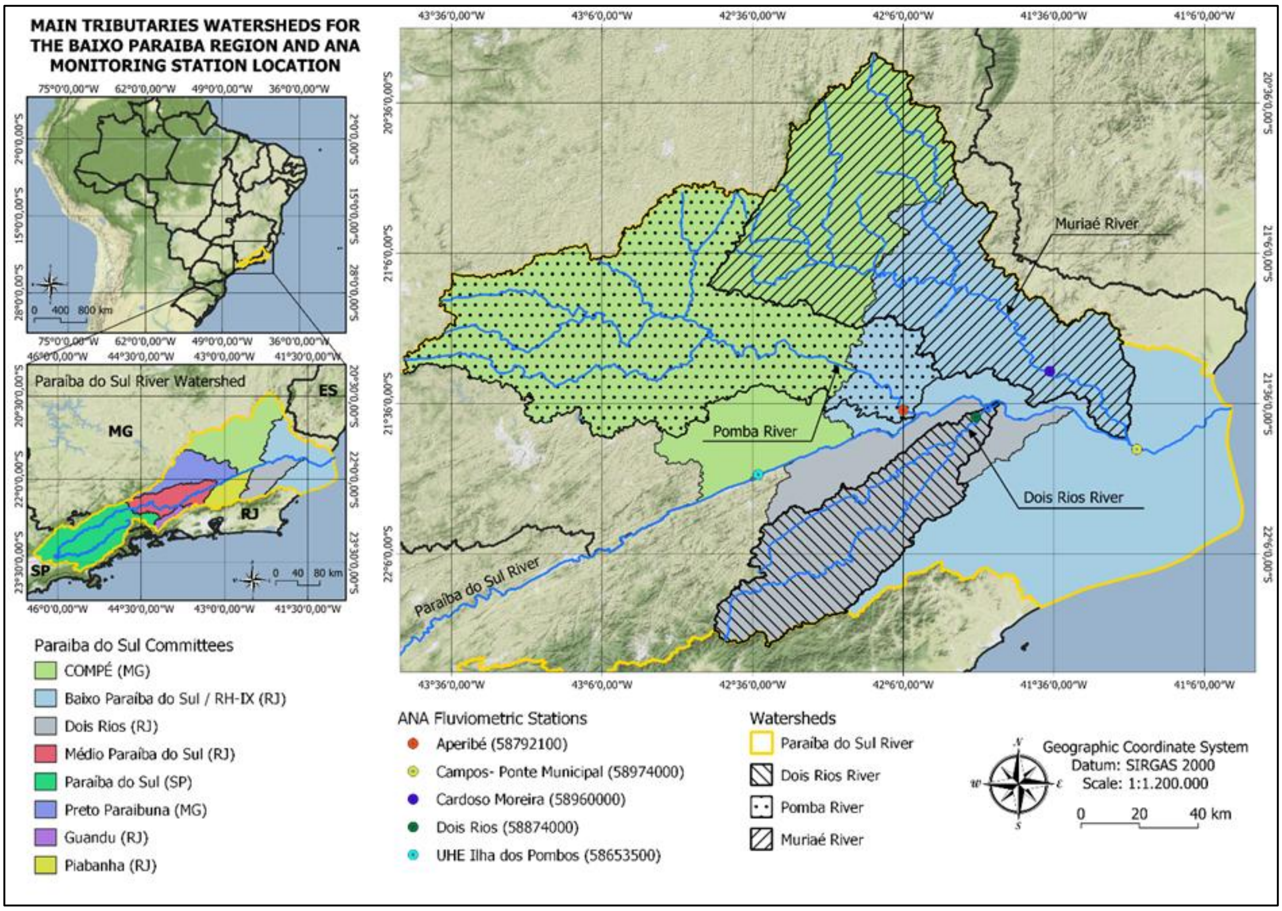

Figure 1. Location of the Paraíba do Sul River Watershed Committees, Pomba, Muriaé, and Dois Rios Watersheds, and ANA Fluviometric Stations Used as Control Points.

Table 2. Residual flow values calculated by COHIDRO (2014) for selected ANA stations.

River	Control point (ANA Station)	Historical series size	Residual flow (m³/s)
Paraíba do Sul	Campos – Ponte Municipal	1934 – 2011	252.02
Muriaé	Cardoso Moreira	1934 – 2012	21.20
Pomba	Aperibé	Modeladed	42.43
Dois Rios	Dois Rios	Modeladed	15.14

2.3. Water availability statistics

2.3.1 Frequency analysis of average monthly flows

To assess the monthly average flow behavior in the BPSW, a frequency analysis was performed, categorizing flows into three classes: critical, alert, and normal. The critical flow threshold was defined using the residual flow values established by COHIDRO (Table 2), with flows below this threshold classified as critical. These residual flow values are crucial for local water management, as they inform water allocation and resource protection efforts. The alert flow range, defined by the Baixo Paraíba do Sul and Itabapoana Watershed Committee (CBH-BPSI), spans from the residual flow value up to 20% above it. Flows exceeding this upper limit (residual flow plus 20%) were categorized as normal. These thresholds, established by both the CBH-BPSI and Civil Defense for local water resource management, are fundamental for evaluating water availability and guiding responses to water scarcity. The specific thresholds for each classification are shown in Table 3.

The analysis of average monthly flow data at the Aperibé and Dois Rios stations revealed gaps in the time series, necessitating the estimation of the missing values. These estimates were generated using linear regression models, based on data from hydrologically similar reference stations. This method utilized the correlation between the incomplete flow records and those from nearby stations to produce reliable average flow estimates. While linear regression is generally not suitable for daily flow predictions due to the inherent variability, its application to average flow data is well-established and commonly employed, as highlighted by Collischonn & Dornelles (2013).

Table 3. Classification criteria for monthly average flows into criticality classes.

Campos (Paraíba do Sul River)	Cardoso (Muriaé River)	Aperibé (Pomba River)	Dois Rios (Dois Rios River)	Criticality Classes
≥ 315.03	≥ 26.50	≥ 53.04	≥ 18.92	Normal (N)
315.03 < x < 252.02	26.50 < x < 21.20	53.04 < x < 42.43	18.92 < x < 15.14	Alert (A)
≤ 252.02	≤ 21.20	≤ 42.43	≤ 15.14	Crític (C)

To select the most appropriate reference station for each case, a two-step methodology was employed. Initially, visual inspection of the flow curves for the study period identified homogeneous hydrological behavior across the stations. This was further validated by a collinearity matrix, following the guidelines of Naghettini & Pinto (2007), which confirmed strong correlations among the stations. These findings supported the selection of reference data for interpolation.

The identified gaps in the time series occurred from January 2012 to February 2016 for the Aperibé station and between October and December 2022 for the Dois Rios station. Therefore, only the complete time series data from March 2016 to September 2022 were used in the regression methodology, ensuring consistency and reliability in the analysis.

2.3.2. Determination of Q95 Flows Using Flow Duration Curves

The flow duration curve (FDC) is a statistical tool that relates river discharge to its exceedance probability over a defined period (NAGHETTINI & PINTO, 2007). The curve is constructed by organizing historical flow data in descending order, allowing for the calculation of exceedance probabilities for each flow value. The probability of exceedance is determined using Equation 1.

$$P = \frac{m}{N+1} \times 100 \qquad (1)$$

Where P represents the exceedance probability, mmm is the rank of the flow in the ordered list (with m=1 for the highest flow), and N is the total number of observations. The FDC is then created by plotting the exceedance probability on the x-axis and the corresponding flow values on the y-axis, illustrating the relationship between flow magnitude and its likelihood of occurrence. The Q95 flow, defined as the discharge equaled or exceeded 95% of the time, is identified by locating the corresponding point on the curve.

To assess variations in residual flows, a comparative analysis was conducted between the Q95 values from COHIDRO (2014) and the observed flows from 2012 to 2022. FDCs were generated for the Cardoso Moreira, Campos – Ponte Municipal, Ilha dos Pombos, and Dois Rios stations using their respective daily flow series. This analysis aimed to identify trends in minimum flow thresholds over time, providing insights into recent hydrological changes. The gap in flow series for the Aperibé station prevented the construction of FDC, so its Q95 value was estimated through regionalization using data from nearby stations.

2.3.3 Regionalization Method

Regionalization of flow is a fundamental technique in hydrology, especially valuable in regions with sparse gauging stations or limited reliable historical flow data. Tucci's method is a prominent approach in this field, offering a systematic framework for estimating streamflow characteristics at ungauged sites based on the attributes of nearby gauged locations. This methodology plays a critical role in water resource management, hydrological modeling, and flood risk assessment.

As outlined by Tucci (2001), the transposition of flow (Q) involves a regression equation that incorporates both physical and climatic characteristics of the watershed. Key factors influencing this estimation include the drainage area (A), average annual precipitation (P), river slope (D), drainage density (DD), and river length (L). These variables are integrated into a power-law equation, expressed as:

$$Q = a \,.\, A^{b} . P^{c} . D^{d} . DD^{e} . L^{f} \quad (2)$$

Where a, b, c, d, e and f are coefficients determined through regression analysis. This equation facilitates the extrapolation of flow values to ungauged sites by leveraging measurable watershed attributes, ensuring a robust and scalable estimation approach. The application of Tucci's method enhances the accuracy of hydrological analyses, even in data-scarce environments.

3. RESULTS

3.1 Frequence analysis of average monthly flows

The collinearity matrix (Table 4) demonstrated strong correlations among the analyzed stations, with correlation coefficients consistently exceeding 0.85. This high degree of correlation indicates a homogeneous hydrological behavior across the study area. Specifically, the Campos - Ponte Municipal station exhibited the strongest correlation, making it the optimal reference for interpolating missing flow data at the Aperibé and Dois Rios stations.

For the Aperibé station, missing data from January 2012 to February 2016 were estimated using the regression equation y=0.2321x−18.934, which produced a high coefficient of determination (r^2 = 0.9366). This strong r^2 value suggests that the model provides a reliable approximation for the missing data. Similarly, for the Dois Rios station, missing flow data from October 2022 to December 2022 were estimated using the equation y=0.0609x+0.6994, with an r^2 of 0.9083. The solid correlation between these stations provided the foundation for accurate and reliable filling of the missing time series data.

Table 4. Correlation matrix for control stations (Mar/2016 - Dec/2022).

	CARDOSO MOREIRA	CAMPOS	ILHA DOS POMBOS	DOIS RIOS	APERIBÉ
CARDOSO MOREIRA	1.000	0.950	0.866	0.903	0.966
CAMPOS		1.000	0.966	0.953	0.968
ILHA POMBOS			1.000	0.912	0.898
DOIS RIOS				1.000	0.911
APERIBÉ					1.000

The regression-based estimations provided a complete time series of monthly average flows for the Aperibé and Dois Rios stations, covering the period from 2012 to 2022. These updated datasets, along with the original time series from the Campos – Ponte Municipal and Ilha dos Pombos stations, are depicted in Figure 2. The reconstructed series highlights a coherent hydrological pattern across the North and Northwest Fluminense regions, particularly in the Baixo Paraíba do Sul area.

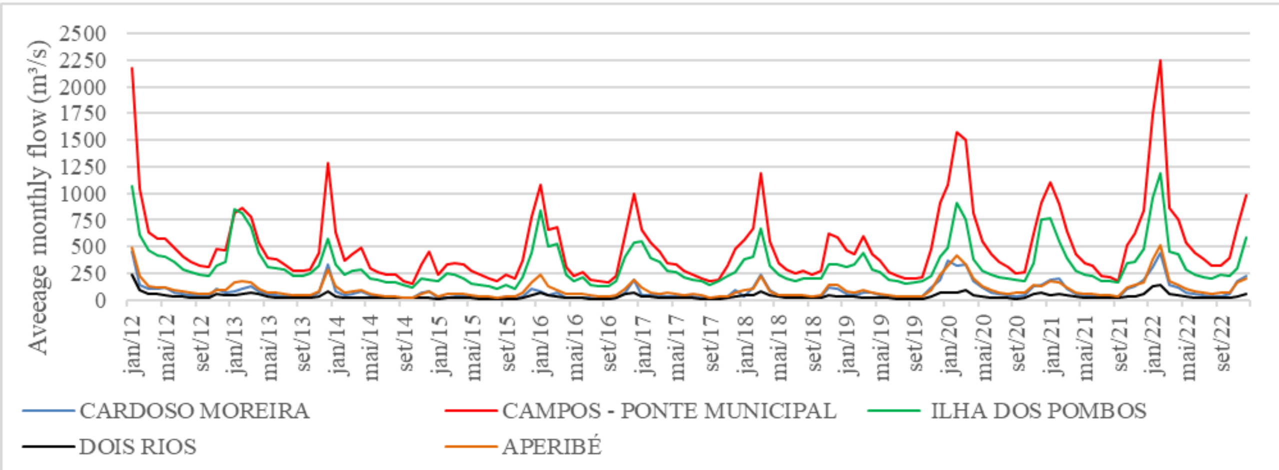

Figure 2. Time series of monthly average flows (2012-2022) for all ANA stations, including interpolated data for Aperibé and Dois Rios.

The analysis of the time series data reveals a strong hydrological connection between the tributary stations (Pomba, Muriaé, and Dois Rios) and the main channel stations (Ilha dos Pombos and Campos - Ponte Municipal). Notably, flow patterns at the Campos – Ponte Municipal station exert a significant influence on the Ilha dos Pombos station. Additionally, the high correlation between tributary and main channel flows indicates that the operation of upstream dam gates is well-aligned with the natural hydrological behavior of these tributaries.

The analysis of flow conditions at various monitoring stations from 2012 to 2022 revealed notable variations in the frequency of occurrences where flows fell below critical and alert thresholds. The frequency distribution, shown in Table 5, illustrates how flows are distributed across different frequency classes annually. It is important to note that this classification reflects average monthly flow conditions, not the total number of days within each class, providing a broader perspective on the hydrological regime over the study period.

Table 5. Frequency distribution of monthly channel flows (2012-2022) by criticality.

Year	CAMPOS			CARDOSO MOREIRA			DOIS RIOS			APERIBÉ		
	N	A	C	N	A	C	N	A	C	N	A	C
2012	11	1	0	12	0	0	11	1	0	11	1	0
2013	9	3	0	11	1	0	12	0	0	9	3	0
2014	6	2	4	9	1	2	4	5	3	6	1	5
2015	5	1	6	7	0	5	3	3	6	5	1	6
2016	5	2	5	5	3	4	7	2	3	6	4	2
2017	7	1	4	9	1	2	7	2	3	7	1	4
2018	7	3	2	11	1	0	9	3	0	6	3	3
2019	7	1	4	8	3	1	7	1	4	7	0	5
2020	9	2	1	12	0	0	8	2	2	12	0	0
2021	9	0	3	9	2	1	8	2	2	9	2	1
2022	12	0	0	12	0	0	8	2	2	12	0	0
Total	87 65.9%	16 12.1%	29 22.0%	105 79.5%	12 9.1%	15 11.4%	84 63.6%	23 17.4%	25 18.9%	90 68.2%	16 12.1%	26 19.7%

At the Campos – Ponte Municipal station, located along the main channel of the Paraíba do Sul River, flows fell below the residual flow threshold of 252.02 m³/s for 22% of the study period, or 29 months. Analysis by year revealed that critical flow conditions were most frequent between 2014 and 2017, with 2015 being the most severe year, recording seven months of critical flows. Conversely, 2022 marked a year of recovery, with all 12 months classified as normal flow conditions, indicating significant improvement in water availability.

Similarly, at the Aperibé station, within the Pomba River watershed, flows fell below the ecological flow threshold of 42.43 m³/s for 19.7% of the time, or 26 months. The most critical years for this station were between 2014 and 2019, with 2015 again being the worst year, recording six months of flows below the threshold. In comparison to Campos, Aperibé experienced a more prolonged drought. However, 2020 and 2022 saw all 12 months classified as normal, signaling a return to favorable flow conditions.

At the Dois Rios station, representing the Dois Rios River watershed, flows fell below the residual flow threshold of 15.14 m³/s for 18.9% of the study period, or 25 months. Critical flow conditions were most prevalent between 2014 and 2017, with 2015 again being the most severe year, recording the highest frequency of critical flow months. In contrast, the station showed greater stability during periods of normal flow, with only 2014 and 2015 experiencing less than six months of normal flow. From 2016 to 2022, a trend toward stabilization emerged, with at least eight months each year consistently recording normal flow, indicating a gradual recovery and reduction in flow variability over the analyzed period.

In the Muriaé River watershed, represented by the Cardoso Moreira station, flow conditions were less severe, with flows falling below the residual flow threshold of 21.20 m³/s for only 11.4% of the study period, or 15 months. Although 2015 had a relatively higher frequency of critical flow months, the overall incidence was lower compared to the other stations. In contrast, 2020 and 2022 saw the most favorable conditions, with a significant portion of the year (12 months) maintaining normal flow levels. These findings indicate that the Muriaé watershed experienced the least reduction in flow during the study period, reflecting greater hydrological stability.

Overall, the analysis highlights that critical flow conditions were the most severe between 2014 and 2017, with 2015 consistently being the most challenging year across all stations, reflecting widespread hydrological stress. In contrast, 2022 marked a period of recovery, with improved flow conditions observed at several stations. This temporal variability emphasizes the fluctuating nature of water availability in the study region and underscores the importance of adaptive water management strategies that account for both climatic and anthropogenic influences on flow regimes.

3.2 Q95 flow assessment

The Campos station recorded the highest Q95 value of 174.22 m³/s, reflecting its large catchment area and significant contribution to regional flow. Similarly, the Ilha dos Pombos station recorded a Q95 of 120.23 m³/s, indicating substantial flow, though slightly lower than that of Campos. In contrast, the tributary watersheds exhibited notably lower Q95 values. The Cardoso Moreira station recorded a Q95 of 12.22 m³/s, while the Dois Rios station had the lowest Q95 value of 9.70 m³/s.

To estimate the Q95 for the Aperibé station, regionalization was conducted using the Q95 values from these stations, incorporating their respective drainage areas (Table 2). The regionalization model, expressed as $Q95 = 0.0011 * A^{1.098}$, demonstrated a high coefficient of determination ($r^2 = 0.985$), indicating strong predictive ability. Applying this model, the estimated Q95 flow for the Aperibé station was 22.78 m³/s.

Table 6 presents the percentage and volumetric (m³/s) reductions in Q95 flows for each monitoring station, highlighting the severity of the water crisis impacting the watershed over the past decade. These reductions align with trends observed in the average monthly frequency analysis discussed in Section 3.1.

Table 6. Comparison of Q95 Values: Watershed Plan vs. Observed Flows (2012–2022).

Watershed	Control point ANA station	Q95 (m³/s) COHIDRO	Q95 (m³/s) 2012 a 2022	Q95 variation	
				m³/s	%
Paraíba do Sul (main)	Campos – Ponte Municipal	252.02	174.22	-77.80	-30.9
Muriaé	Cardoso Moreira	21.20	12.22	-8.98	-42.4
Dois Rios	Dois Rios	15.14	9.70	-5.43	-35.9
Pomba	Aperibé	42.43	22.78	-19.65	-46.3

The Pomba River watershed, a major tributary supplying the largest volume of water to the North and Northwest Fluminense regions, saw a significant decline in Q95 flows. The Q95 flow dropped by 19.65 m³/s, representing a 46.3% reduction. This substantial decrease underscores the severe hydrological stress on the watershed and highlights the need for effective, long-term water resource management strategies to address these challenges.

The Muriaé watershed experienced a Q95 reduction of 8.98 m³/s, reflecting a 42.4% decrease. Despite this, it was the least impacted by monthly average flows falling below the residual flow threshold set by COHIDRO.

The Dois Rios watershed saw a Q95 decline of 5.43 m³/s, or 35.9%. Although it has a smaller drainage area, the Dois Rios watershed contributes flows like the Muriaé, highlighting its importance within the overall hydrological system.

In the main channel of the Paraíba do Sul River, at the Campos - Ponte Municipal station, a Q95 reduction of 77.80 m³/s was observed, representing a 30.9% deficit. Although the percentage reduction was lower than in some tributaries, the absolute reduction is particularly significant – approximately twice the combined deficit of the three primary tributaries. This substantial decrease underscores the severity of the overall water deficit in the watershed during the evaluation period.

4. DISCUSSION

The results of this study indicate a significant and consistent reduction in minimum flow values across the northern and northeastern regions of the Paraíba do Sul River Basin, particularly in the lower flow rates subbasins. This trend highlights the cumulative effects of both climate change and anthropogenic pressures, with decreasing flow rates evident in all subbasins towards the river's final segment. Such widespread reductions underscore the necessity for basin-wide management strategies that account for the ongoing and future challenges in water resource management.

The recalculated Q95 values further reveal an alarming trend of increasing low-flow periods, reinforcing the concerns of worsening water scarcity in the region. This aligns with projections by Paiva et al. (2024), who forecast a near 25% reduction in both high and low river flows by 2055. Moreover, the increased frequency of extreme weather events, including droughts and floods, as highlighted by Oliveira et al. (2023), further underscores the urgency of adaptive water management strategies. Hence, this study reinforces the need for recalibrating hydrological models to reflect these changes and better assess the region’s vulnerability to future flow fluctuations.

Additionally, the findings corroborate the predictions of Paiva et al. (2024), emphasizing the challenges posed by climate change to water availability and hydropower generation in the Paraíba do Sul Basin. The devastating impact of the 2014-2016 drought, the worst in the region since 1931, highlighted the critical need for robust drought management strategies (VASCONCELOS et al., 2019; FORMIGA-JOHNSSO & BRITTO, 2020). By refining low-flow metrics, this study offers a more accurate tool to assess the region’s preparedness for similar events in the future.

This study also highlights the increasing pressure on water resources, with projections suggesting a 123% rise in demand by 2040 (SILVA & FISH, 2019). Given the limited potential for inter-basin water transfers, which are predicted to be feasible in only 40% of the years (SILVA & FISH, 2019), these growing demands will exacerbate water stress in the region. This reinforces the need for improved water governance strategies that prioritize efficiency, reuse, and sustainable resource allocation. As Paiva et al. (2024) suggest, water governance is increasingly contentious, and innovative solutions are essential to balance competing demands. Our findings support this, emphasizing that water management must evolve to address both climatic and anthropogenic pressures.

Considering these challenges, integrated water management strategies, as proposed by Hussain & Mumtaz (2014), are crucial to mitigating the risks posed by climate change. Developing new water sources, such as desalination or advanced wastewater reuse, combined with improved conservation practices, could alleviate pressure on regional water supplies. Furthermore, incorporating adaptive management approaches into governance frameworks will be essential to accommodate unforeseen hydrological changes and ensure the long-term sustainability of water resources.

While this study provides valuable insights, it does have some limitations. The methods used to estimate missing data assume stable upstream-downstream relationships over time. However, factors such as land use changes, dam construction, and environmental degradation could alter these relationships, potentially affecting flow predictions. Future research should explore dynamic modeling approaches, such as machine learning algorithms, to better capture the non-linear relationships governing river flow dynamics, in conjunction with physical modeling technique

Additionally, the relatively short study period (2012-2022) limits the ability to fully capture long-term hydrological trends, especially in the context of ongoing climate change. While short-term studies are valuable for immediate decision-making, they may not fully represent the broader impacts of climate change and anthropogenic pressures on the basin's hydrology. Expanding the dataset to include earlier years and integrating climate projections over a longer horizon would provide a more comprehensive understanding of long-term trends, thus refining water management strategies for the future.

Given the observed reductions in flow across multiple subbasins, the region is likely to face progressive water scarcity in the long term. Even without accounting for future climatic extremes, the continued decline in minimum flows signals severe constraints on water availability, necessitating urgent and sustained management interventions

5. CONCLUSIONS

This study provided critical insights into the evolving water scarcity challenges faced by the Baixo Paraíba do Sul region, highlighting a significant and persistent reduction in water availability across multiple watersheds. The findings, particularly the analysis of the frequency of critical low-flow events and the comparison of Q95 values from 2012 to 2022 with those of the watershed plan, reveal a substantial decline in flow rates – exceeding 30% in most control stations. This trend not only underscores the severity of the region's water scarcity but also points to a broader, basin-wide issue rather than isolated anomalies.

The methodology employed, combining frequency analysis with the comparison of Q95 values, has proven effective in assessing and illustrating the pressing water management challenges in the region. It offers a solid framework for future evaluations and contributes valuable data for policy discussions and management strategies. However, the study also acknowledges limitations such as the reliance on short-term data and interpolation methods, which may introduce uncertainty, especially when extrapolating beyond the observed periods and locations.

Given the substantial decrease in water availability observed, it is imperative that water management strategies are urgently revised and updated to reflect the new realities of the watershed. This study calls for the immediate implementation of continuous monitoring and further research to assess the long-term trajectory of water resources in the region, ensuring that adaptive management strategies are in place to address the worsening water scarcity crisis. The need for a comprehensive update to the watershed plan is clear, as it is crucial to ensure the sustainability of water resources and protect the region's hydrological resilience against ongoing climate and anthropogenic pressures.

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