

Article

Impacts of Climate Change on the Hydrology of a Highly Disturbed Tropical River Basin

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Abstract

Climate change significantly affects hydrological responses, yet studies addressing future water availability in the Paraopeba River Basin (PRB), an important tributary of the São Francisco River Basin in Brazil, remain limited, particularly under CMIP6 scenarios and using distributed hydrological modeling approaches. In this context, this study evaluated the hydrological responses of the PRB, under climate change using the MHD-INPE. Future projections were based on an ensemble of seven climate models from the NEX-GDDP-CMIP6 collection, considering a baseline period (1992–2014), three future periods 17(2040–2060, 2061–2080 and 2081–2100) and two socioeconomic scenarios (SSP245 and SSP585). The model satisfactorily reproduced observed streamflow during the baseline period. Under the SSP585 scenario, the projections indicate stronger alterations in water availability, with a potential intensification of flood and drought events, as reflected by reductions in minimum streamflows (Q_{90}) and increases in maximum streamflows (Q_{10}), particularly in sub-basins 4 and 5, where Q_{90} reductions approach 30% and Q_{10} increases reach 11.7%. Additionally, a decrease in $Q_{7,10}$ values was observed, which enabled the analysis of the Conflict Index (I_{cg}), indicating that water withdrawals currently granted may exceed the limits established by existing legislation in future scenarios ($I_{cg} > 1$).

Keywords: hydrological modeling; MHD-INPE; water availability; climate change; Paraopeba River Basin; CMIP6



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1. Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that global surface temperature is approaching and in some recent records exceeding the 1.5 °C threshold, highlighting the acceleration of climate change and its intensification in recent decades [1–3]. These climatic changes disrupt the hydrological cycle, increasing the frequency and intensity of extreme events such as droughts, heat waves, and extreme precipitation [4–6]. Such changes directly affect water availability, posing risks to ecosystems, infrastructure, and water-dependent economic sectors.

Hydrological imbalances intensify competition among multiple water uses, amplifying social, environmental, and economic vulnerabilities [7–9]. In this context, the Paraopeba River Basin (PRB), an important tributary of the São Francisco River, plays a strategic role in regional water security. The basin supplies approximately 53% of the population of the Metropolitan Region of Belo Horizonte and supports industrial, mining, hydroelectric, and urban demands [10–14]. The severe water scarcity observed between 2013 and 2015 exposed the basin's vulnerability to hydroclimatic extremes and reinforced the need for robust long-term projections of water availability. Beyond climate stress, the PRB is also a highly disturbed basin, where intensive land use, mining activity, and multiple abstractions can modify runoff generation and baseflow maintenance, increasing sensitivity to both drought and flood hazards [10–14].

To evaluate hydrological responses under future climate conditions, Global Climate Models (GCMs), combined with hydrological models, have become essential tools for the mathematical representation of atmospheric processes across different time scales under future climate conditions [6,15,16]. Among the various existing GCMs, the models of the sixth phase of the Coupled Model Intercomparison Project (CMIP6) are particularly noteworthy. Compared to previous generations of CMIPs, CMIP6 demonstrates improvements in the simulation of temperature extremes at the global scale, in addition to a better representation of precipitation declines. In contrast to CMIP5, which only provides scenarios based on radiative forcings, the sixth phase incorporates the Shared Socioeconomic Pathways (SSPs), consisting of five narratives that link socioeconomic, demographic, technological, political, and institutional trends [17,18]. These narratives include the SSP245 and SSP585 scenarios, which represent intermediate and pessimistic pathways, respectively.

Among the various modeling tools in hydrology for assessing climate change, the Distributed Hydrological Model of the National Institute for Space Research (MHD-INPE) demonstrated ability to represent rainfall–runoff processes and enables the integration of atmospheric model outputs in studies of global environmental change [17]. The MHD-INPE has been used satisfactorily in studies on the impacts of climate change [13,16,17]. Ref. [16] evaluated the effects of climate change with MHD-INPE in the Ribeirão Jaguarua Watershed using three global climate models (HadGEM2-ES, Eta-MIROC5, and Eta-CanESM2) and two scenarios, RCP4.5 and RCP8.5. Similarly, ref. [17] analyzed the uncertainties in long-term runoff estimates, considering future RCP 4.5 and 8.5 scenarios, using MIROC5, HadGEM2-ES, CANESM2, and BESM climate models in Budyko and the MHD-INPE model.

Previous studies provide important foundations but also reveal methodological gaps that motivate the present work. Ref. [18] showed that changes in vegetation cover and land-use configuration can substantially alter components of the water balance, supporting the use of distributed modeling for identifying spatially heterogeneous vulnerabilities within the PRB. However, that approach was primarily designed for land-use scenarios and historical-period behavior and did not quantify climate change-driven shifts in legally relevant low-flow metrics or future multi-model uncertainty. Similarly, at the São Francisco Basin scale, ref. [19] integrated CMIP6 projections with consumptive demand trajectories and reservoir system modeling. Although these results highlight basin-wide vulnerability and the value of integrating climate with management variables, such analyses are typically conducted at macro-basin resolution, limiting their ability to identify sub-basin hotspots and to evaluate allocation metrics used in local permitting practice.

Studies in Brazilian basins have commonly linked GCM projections and hydrological models to evaluate future water availability and demand. These studies provide important demonstrations of hydrological models applicability, but they also reflect common limitations, including the predominance of RCPs forcing. Thus, the novelty of this study

lies in the systematic integration of high-resolution NEX-GDDP-CMIP6 projections with a distributed hydrological model (MHD-INPE) to evaluate climate change impacts on water availability in a highly disturbed tropical basin at sub-basin scale. In addition, this study adopts a sub-basin approach, enabling a more detailed identification of critical areas while explicitly accounting for the uneven spatial distribution of the population across the basin. In this context, assessing changes in mean streamflow alone is insufficient, as water management systems are primarily stressed during extreme conditions. The advancement of this research lies in assessing hydrological indicators directly related to water management and legislation ($Q_{7,10}$, Q_{90} , and Q_{10}), thereby translating climate projections into operational implications for water security.

Therefore, this research advances the state of knowledge by employing a larger ensemble of CMIP6 models from the NEX-GDDP collection and by incorporating the SSP245 and SSP585 scenarios. It is guided by the following research question: How will projected climate changes under SSP245 and SSP585 scenarios affect water availability in the Paraopeba River Basin across different future time slices?

In this context, the purpose of this study was to evaluate the impact of climate change on water availability in the Paraopeba River Basin using the MHD-INPE model. For this purpose, seven climate models from the NEX-GDDP-CMIP6 collection and two SSP scenarios (SSP245 and SSP585) were selected. The climate models were evaluated for three time-slices: near future, mid-future, and end of the century. The results contribute not only to advancing hydrological modeling applications under CMIP6 but also to supporting adaptive planning strategies aimed at preventing future water supply crises in one of Brazil's most socioeconomically relevant basins. Beyond its regional relevance, the integrated CMIP6–MHD-INPE framework proposed here is transferable to other basins, contributing to global efforts aligned with Sustainable Development Goals 6 (Clean Water and Sanitation) and 13 (Climate Action) by supporting sustainable water allocation and climate adaptation planning.

2. Materials and Methods

2.1. Study Area Description

The Paraopeba River basin (Figure 1), one of the main tributaries of the São Francisco River, rises in the municipality of Cristiano Ottoni and runs approximately 510 km to its mouth at the Três Marias reservoir in Felixlândia. The basin covers 48 municipalities across an area of 12,500 km².

One of the most important sources of water supply is the Paraopeba system, composed of three reservoirs: Rio Manso, Serra Azul, and Vargem das Flores, which is responsible for supplying the Belo Horizonte metropolitan region, which corresponds to approximately 3.5 million people [6,13,14,20,21]. The basin has a variety of economic activities, such as industrial centers (steel, textile, food, automotive, petrochemical, etc.), mining, hydroelectric plants, and large urban centers of economic and cultural relevance [10–12] and is divided into three sub-basins: Upper Paraopeba, Middle Paraopeba, and Lower Paraopeba. Mining activities, which are extensive in the basin, can change natural drainage patterns, affecting both water quality and flow regimes. Agricultural expansion intensifies water withdrawals for irrigation and, due to land use changes, contributes to reduced baseflow during dry periods. Hydropower generation depends directly on streamflow regulation, influencing reservoir operations and downstream discharge patterns. The combined pressures of these users amplify the basin's vulnerability to climate changes, reinforcing the need for integrated hydrological assessments that explicitly account for the cumulative impacts of economic activities on water availability and security on a sub basin level.

Agricultural activities predominate in the Upper and Middle Paraopeba, with production mainly supplying the metropolitan region of Belo Horizonte [21,22]. Mining activities are more concentrated in the Middle Paraopeba, followed by the Lower and Upper Paraopeba, with emphasis on the production of fine aggregates for civil construction, ornamental stones, and iron ore [10,22].

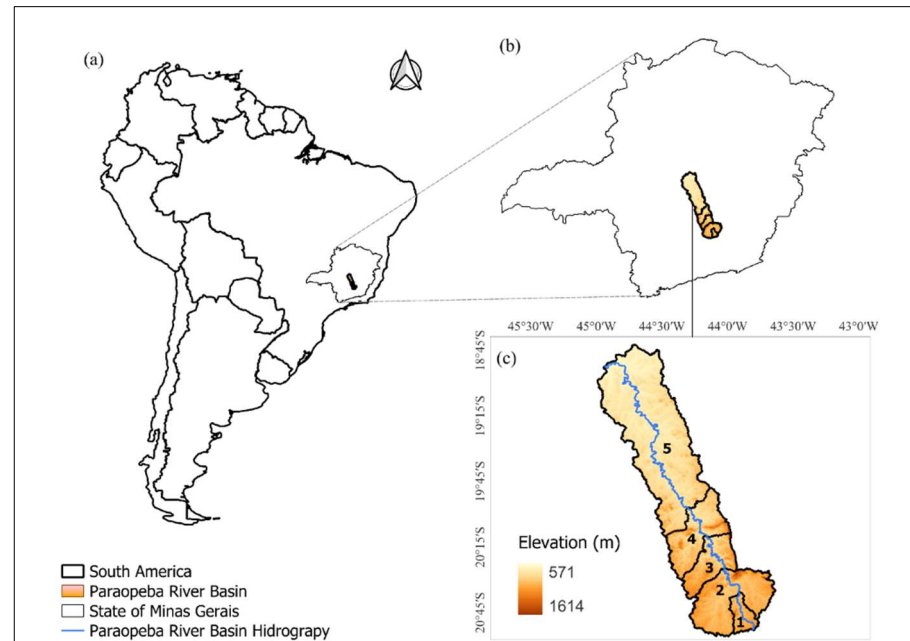


Figure 1. Location of the Paraopeba River Basin. (a) Location in South America; (b) Location in the state of Minas Gerais; (c) Detail of the Paraopeba River Basin, with the location of hydrometric stations and respective sub-basins.

Electricity production in the PRB occurs through the Retiro Baixo hydroelectric plants, with a production capacity of 82.00 MW. There is also a thermoelectric plant in Igarapé [23].

The average annual rainfall in the PRB is 1700 mm in the headwaters and 1150 mm in the region near the mouth. According to the Köppen climate classification, the basin has three climate types: Cwb, Cwa, and Aw [11,24]. The Cwb type is predominant, covering about 62.50% of the municipalities, followed by Cwa and Aw with 35.42% and 2.08%, respectively.

2.2. Distributed Hydrological Model of the National Institute for Space Research (MHD-INPE)

The hydrological simulations for future scenarios were performed using the Distributed Hydrological Model of the National Institute for Space Research (MHD-INPE). This model is a regular grid distributed model [25], which seamlessly integrates land use and land cover changes and climate scenarios, making it suitable for the application of this study.

The runoff generation and flow separation processes in the MHD-INPE are modeled by integrating concepts of probabilistic distribution of storage capacity, as used in the Xinanjiang model [26], along with the principles adopted in TopModel [26]. The methodologies establish a correlation between the hydrological response of the basin and the self-organization patterns observed on a large scale.

The input data required for the calibration and validation stages of the hydrological model include spatial topographic information, rainfall and river flow data, soil class, land use and cover, and meteorological data [13,25].

For the Paraopeba River Basin, the cells were discretized at approximately 5 km. The warm-up period covered 1986 to 1987, and calibration and validation were conducted for

the periods 1996 to 2018 and from 1988 to 1995, respectively, using daily discharges. For the Retiro Baixo Montante, the warm-up, calibration, and validation periods correspond to 2011 to 2012, 2015 to 2018, and 2013 to 2014, respectively. Considering the statistics indices average values for the five sub-basins, calibration results showed NSE (Nash–Sutcliffe Efficiency), LNSE (Logarithmic Nash–Sutcliffe Efficiency), KGE (Kling–Gupta Efficiency), R^2 (Coefficient of Determination), and PBIAS (Percent Bias) of 0.81, 0.85, 0.84, 0.82, and -6.50% , respectively. During validation, the corresponding values were 0.76, 0.75, 0.72, 0.82, and 9.35% . These results indicate satisfactory overall model performance. The calibration was performed based on the parameters suggested by [13] with daily data. Additional details are provided in the referenced study.

To simulate future scenarios, it is necessary to have precipitation and meteorological data, which consists of five variables: air temperature, dew point temperature, wind speed, solar radiation, and atmospheric pressure [26].

Climate change projections and future scenarios were obtained from the NEX-GDDP-CMIP6 (NASA Earth Exchange Global Daily Downscaled Projections) dataset, released in 2022, which provides outputs from 35 global models from CMIP6 [27]. This database already presents bias correction, based on the Bias-Correction Spatial Disaggregation (BCSD) method, and allows for higher-resolution analyses that account for the effects of local topography on climate processes [28]. The NEX-GDDP-CMIP6 database provides historical daily data for the period 1950–2014, as well as future projections based on the Shared Socioeconomic Pathways (SSPs) for the period 2015–2100, with a spatial resolution of $0.25^\circ \times 0.25^\circ$ and referenced to the WGS 84 datum [28,29]. It is important to highlight that this grid was subsequently interpolated to the basin grid.

In this study, seven of the 35 available climate models from the NEX-GDDP-CMIP6 collection were selected based on the evaluation performed by [6], which assessed the performance of CMIP6 climate models in the Paraopeba River Basin. The assessment conducted by [6] consisted of an analysis of the performance of 17 models derived from the NEX-GDDP-CMIP6 collection, focusing on simulated precipitation due to the additional uncertainty associated with precipitation projections in Global Circulation Models. The seven best-performing climate models were then selected. Model performance was evaluated against observed precipitation data from the BR-DWGD grid using statistical metrics, which enabled the calculation of the Pielke index. The baseline climate was characterized using data from 1992 to 2014. Future projections were evaluated for the periods 2040–2060 (near future), 2061–2080 (mid-future), and 2081–2100 (end of the century). For analysis, the scenarios selected were SSP245 (trend scenario) and SSP585 (pessimistic scenario).

The SSP245 and SSP585 scenarios were selected due to their contrasting trajectories, which allow changes to be assessed considering different levels of radiative forces and socioeconomic development patterns. The SSP245 scenario corresponds to average emissions (intermediate scenario), representing the “middle of the road, in which no significant improvements are observed in relation to historical patterns [6,28,30]. In comparison, the SSP585 scenario represents a society that is highly driven and impacted using fossil fuels, which have a greater impact on climate change [31,32]. The schematic representation of the data and projections used in this study is shown in Figure 2.

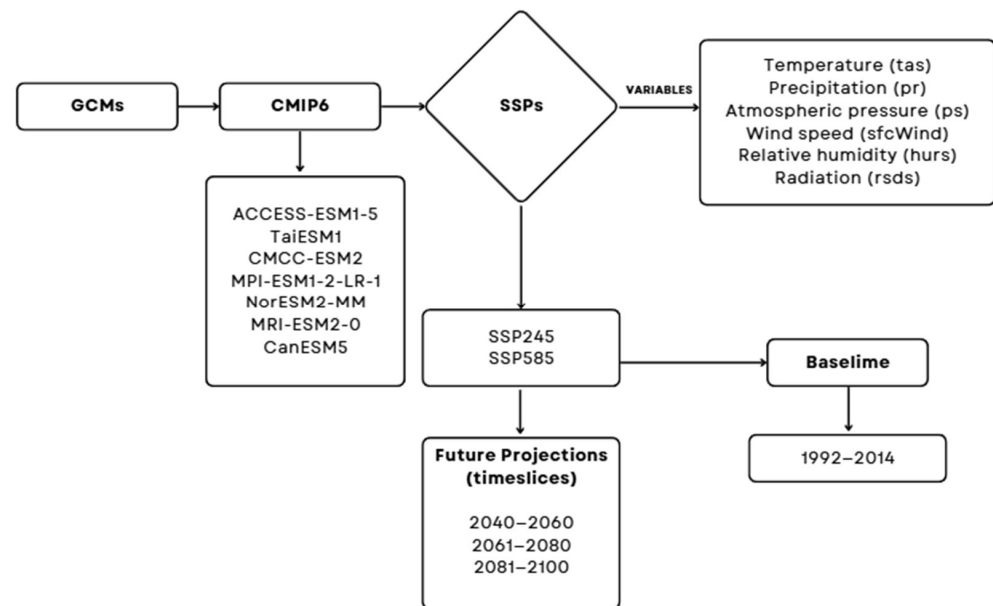


Figure 2. Schematic representation of the data input and meteorological variables used in the MHD-INPE.

2.3. Assessment of the Impacts of Climate Changes

Under baseline scenario, the Q_{10} and Q_{90} streamflow percentiles, which is the streamflow exceeded by 10% and 90% of the time, respectively, were evaluated during the validation of simulated streamflow. Q_{10} reflects high streamflow conditions and may be related to flood potential, while Q_{90} represents streamflow conditions and is associated with drought risk and directly related to ecological flows, consumptive water uses, and hydropower. Changes in these indicators provide information on the intensification of hydrological extremes and the vulnerability of the basin in future climate scenarios.

In addition, for the future projections, $Q_{7,10}$ was also evaluated for the PRB, which, according to IGAM Ordinance No. 48, dated 4 October 2019, Minas Gerais, constitutes the reference low-flow metric adopted in the state of Minas Gerais and represents a highly restrictive hydrological condition.

According to data provided by IGAM for the Paraopeba River Basin, in 2023 there were currently 555 surface water abstraction permits, of which 82% correspond to consumptive uses and 18% to non-consumptive uses. The main authorized water uses include irrigation, human consumption, public water supply, livestock watering, industrial use, mining, and other minor uses.

To calculate $Q_{7,10}$ values for observed and simulated streamflow data, a probabilistic fit to the Gumbel distribution was carried out, considering annual mean minimum streamflow over seven consecutive days and accounting for three time-slices (2040–2060, 2061–2080, and 2081–2100), which represent the near future, mid-future and end-of-century periods, respectively. The goodness-of-fit of the series was assessed using the Kolmogorov–Smirnov test, adopting a significance level of 0.05.

The conflict index I_{cg} (Equation (1), proposed by [33] was also evaluated). This index evaluated whether the streamflows water permits upstream of the control section exceed the limits set by the legislation If the ($I_{cg} > 1$) or are within legal limits ($0 \leq I_{cg} \leq 1$). The I_{cg} is calculated based on two variables: authorized water uses and $Q_{7,10}$ streamflows. For this calculation, the currently authorized water uses in the five sub-basins, as presented by [13], and $Q_{7,10}$ in future scenarios were considered.

$$I_{cg} = \frac{Q_{out}}{0.30 \times Q_{7,10}} \quad (1)$$

where:

Q_{out} granted water withdrawals, (m³/s),

$Q_{7,10}$, streamflow rate (m³/s) established by IGAM Ordinance No. 48, of 4 October 2019 [32].

It is important to highlight that the use of 30% of the reference streamflow ($Q_{7,10}$) is justified since, in the state of Minas Gerais, where the study basin is located, the authorized water concession for use corresponds to 30% of $Q_{7,10}$.

For the streamflows simulated by the MHD-INPE under future projections, statistical descriptors were also applied, including MWH (hydrological response to high-flow conditions, considering streamflows with a probability of exceedance lower than 5%), MWL (hydrological response to low-flow conditions, considering flows with a probability of exceedance greater than 95%), QSM (which represents the average variability of flow coefficients), and SEASON (which describes flow seasonality). These descriptors are presented in Equations (2)–(4).

$$MWH = \frac{\sum_{h=1}^H Q_h}{H} \quad (2)$$

$$MWL = \frac{\sum_{l=1}^L Q_l}{L} \quad (3)$$

$$QSM = \frac{Q_{0.8} - Q_{0.2}}{\underline{Q}} \quad (4)$$

$$SEASON = \frac{Q_{rainy} - Q_{dry}}{\underline{Q}} \quad (5)$$

where:

Q_h , flow rate (m³/s) with a probability of exceedance <5%;

Q_l , flow rate (m³/s) with a probability of exceedance >95%;

H and L , data in the respective interval;

$Q_{0.8}$, flow rate (m³/s) for the 0.8 quantile;

$Q_{0.2}$, flow rate (m³/s) for the 0.2 quantile;

$\underline{Q}$, average flow rate for the entire period;

Q_{rainy} , average between the flow rate for the rainy periods;

Q_{dry} , average between the flow rate for the dry periods.

3. Results

Simulated Streamflow in the Baseline Scenario

The observed and simulated streamflows from the ensemble of models (ACCESS-ESM1-5, TaiESM1, CMCC-ESM2, MPI-ESM1-2-LR-1, NorESM2-MM, MRI-ESM2-0, and CanESM5) are presented in the streamflow duration curve (Figure 3), for the baseline scenario (1992–2014).

In general, the results show a good fit between the observed and simulated daily streamflows, indicating that the ensemble of climate models satisfactorily represents the hydrological behavior of each sub-basin. However, as expected, the greatest difficulties in the simulations are for minimum and maximum streamflows. It is observed that the greatest tendency to overestimate Q_{10} and Q_{90} is evident in sub-basins 1 and 2 (Table 1). This overestimation can be attributed to the cascade of uncertainties associated with hydrological processes. It is important to highlight that sub-basins 1 and 2 have small drainage areas and are in headwater regions, which increases their sensitivity to spatial and temporal

variability in precipitation. Therefore, in addition to the uncertainties inherent to the atmospheric processes represented by climate models on a coarser spatial scale, there are also limitations related to the physical representation of these sub-basins, which may not adequately capture climate variability at the local scale.

Table 1. Q_{10} , Q_{50} and Q_{90} and relative differences in simulated and observed streamflows in sub-basins 1 to 5. Overestimates and underestimates of simulated streamflow in %.

Sub-Basin	Q_{10} (m ³ /s)			Q_{50}			Q_{90}		
	Sim.	Obs.	Dif. %	Sim.	Obs.	Dif. %	Sim.	Obs.	Dif. %
1	15.74	13.42	17%	6.02	4.85	24%	3.08	2.25	37%
2	111.20	91.34	22%	37.97	29.19	30%	15.38	13.42	15%
3	118.05	117.11	1%	44.28	39.24	13%	20.20	19.26	5%
4	165.50	165.46	0%	54.22	51.94	4%	23.23	24.65	−6%
5	212.26	217.40	−2%	79.20	69.36	14%	34.14	29.47	16%

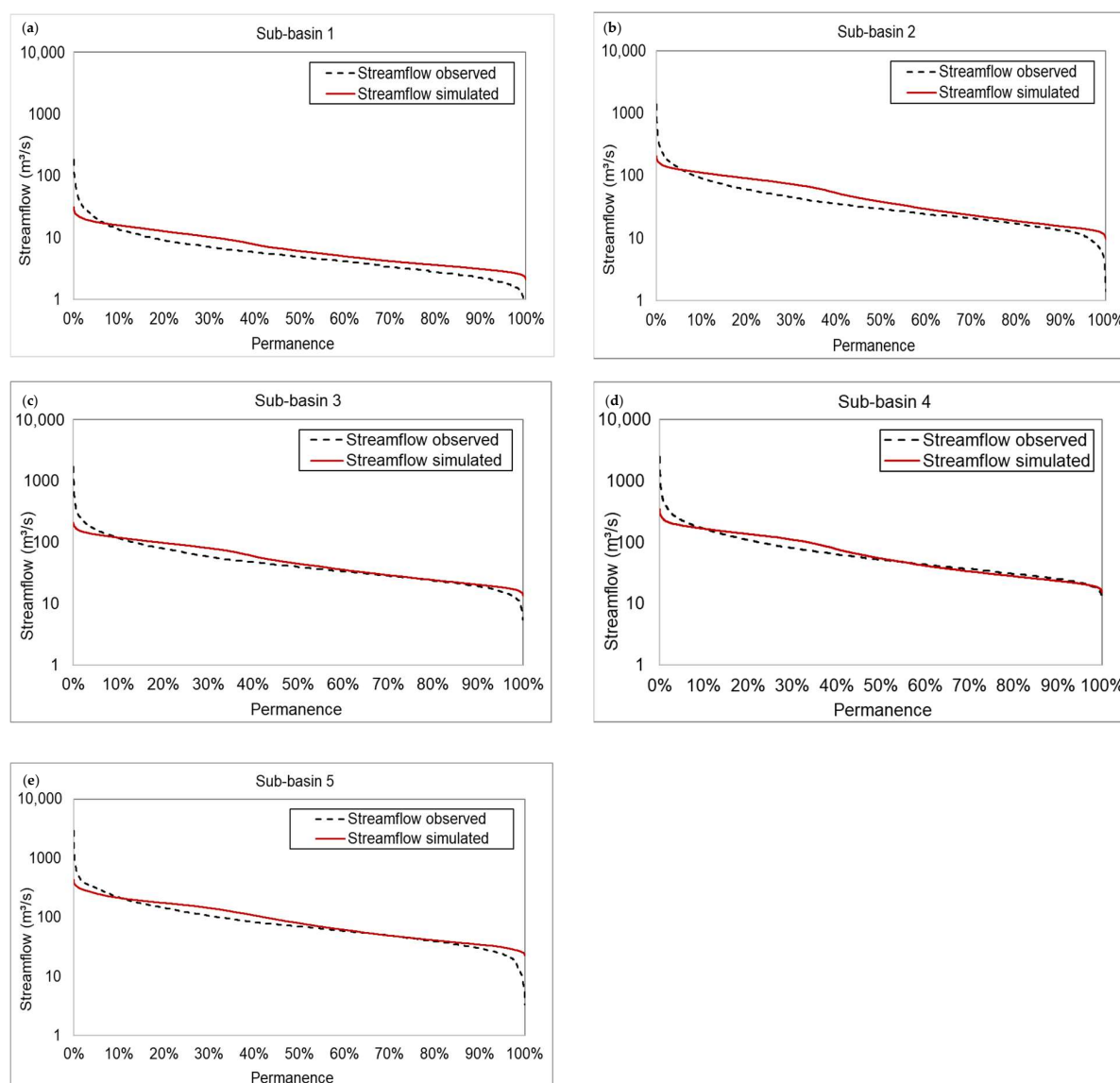


Figure 3. Streamflow duration curve of simulated flows considering the streamflow observed and simulated in each sub-basin. (a) Sub-basin 1. (b) Sub-basin 2. (c) Sub-basin 3. (d) Sub-basin 4. (e) Sub-basin 5.

It is important to highlight that, according to [17], discharge extremes must be evaluated with caution when assessing future scenarios. Climate models still exhibit uncertainties inherent to climate processes, due to the dynamic nature of the atmosphere [17,34]. Additionally, ref. [35] emphasizes that uncertainties in the coupling of climate projections and hydrological models may be associated with the complexity of natural systems, the simplification of hydrological processes, and model parameterization, among other factors. Ref. [13] also reports difficulties in accurately adjusting extreme streamflows, which may be related to the extrapolations required in MHD-INPE simulations. These difficulties occur due to precipitation network data, which is generally sparse at headwaters where altitude ranges are higher, affecting the spatial distribution of rainfall mainly from extreme events; and extrapolation of the rating curve especially for high flows.

Given that the ensemble of models demonstrated a good fit between the permanence curve of observed daily streamflows and simulated streamflows (Table 1 and Figure 3), the behavior of streamflows in future scenarios in each sub-basin was subsequently evaluated. Overall, the flow permanence curves reveal significant changes, mainly at the extremes, in the SSP245 and SSP585 scenarios in the sub-basins considered in this study (Figure 4).

When analyzing the three time slices, the results indicate that the most pronounced changes in water availability are associated with the SSP585 scenario, particularly toward the end of the century (2081–2100). The most significant hydrological variability was observed in sub-basins 4 and 5 (Figure 4g–j). In sub-basin 4 an increase in maximum streamflows (Q_{10}) is projected, particularly under the SSP585 scenario, with increases of 10.3% and 11.7%, relative to the near-future period and the end of the century, respectively. Reductions in Q_{90} were also identified, becoming more pronounced toward the end of the century, with declines exceeding 20% in both scenarios. In sub-basin 5, Q_{90} reductions reach nearly 30% by the end of the century under the SSP585 scenario.

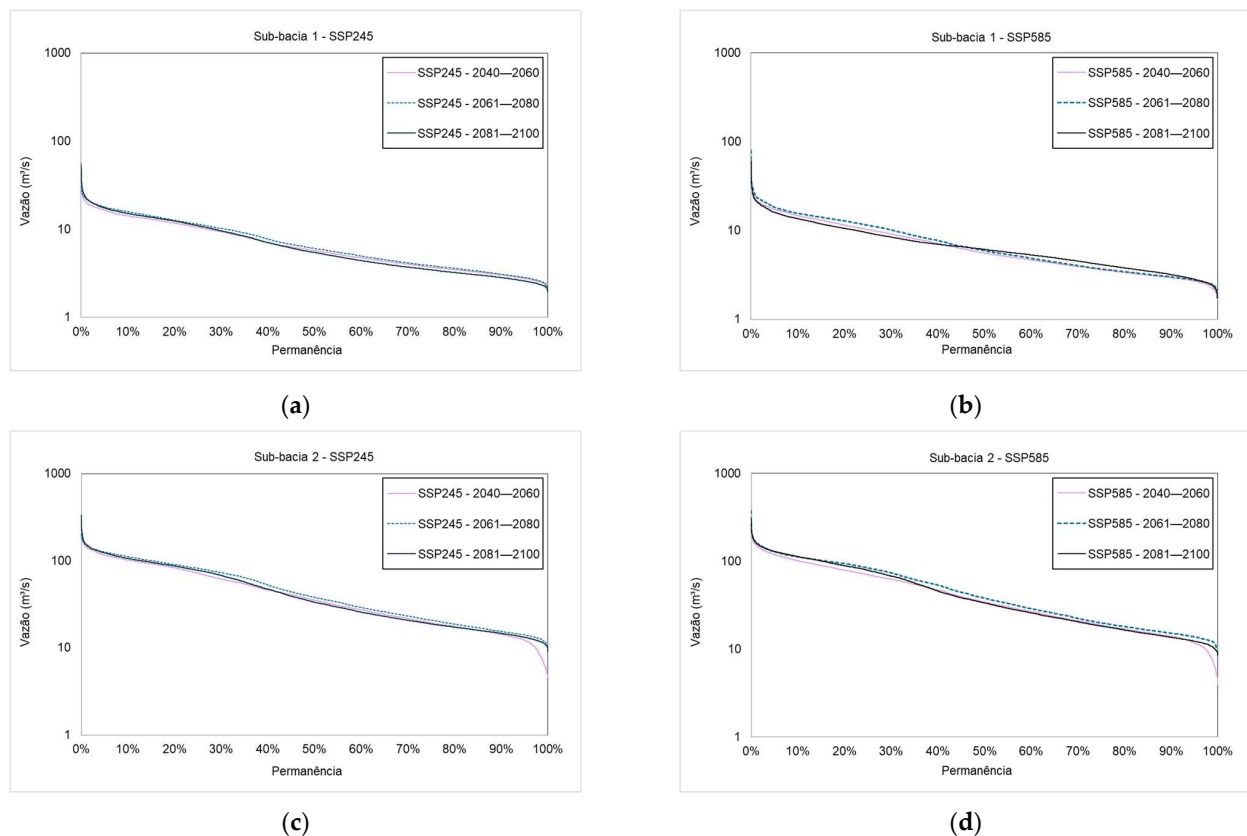


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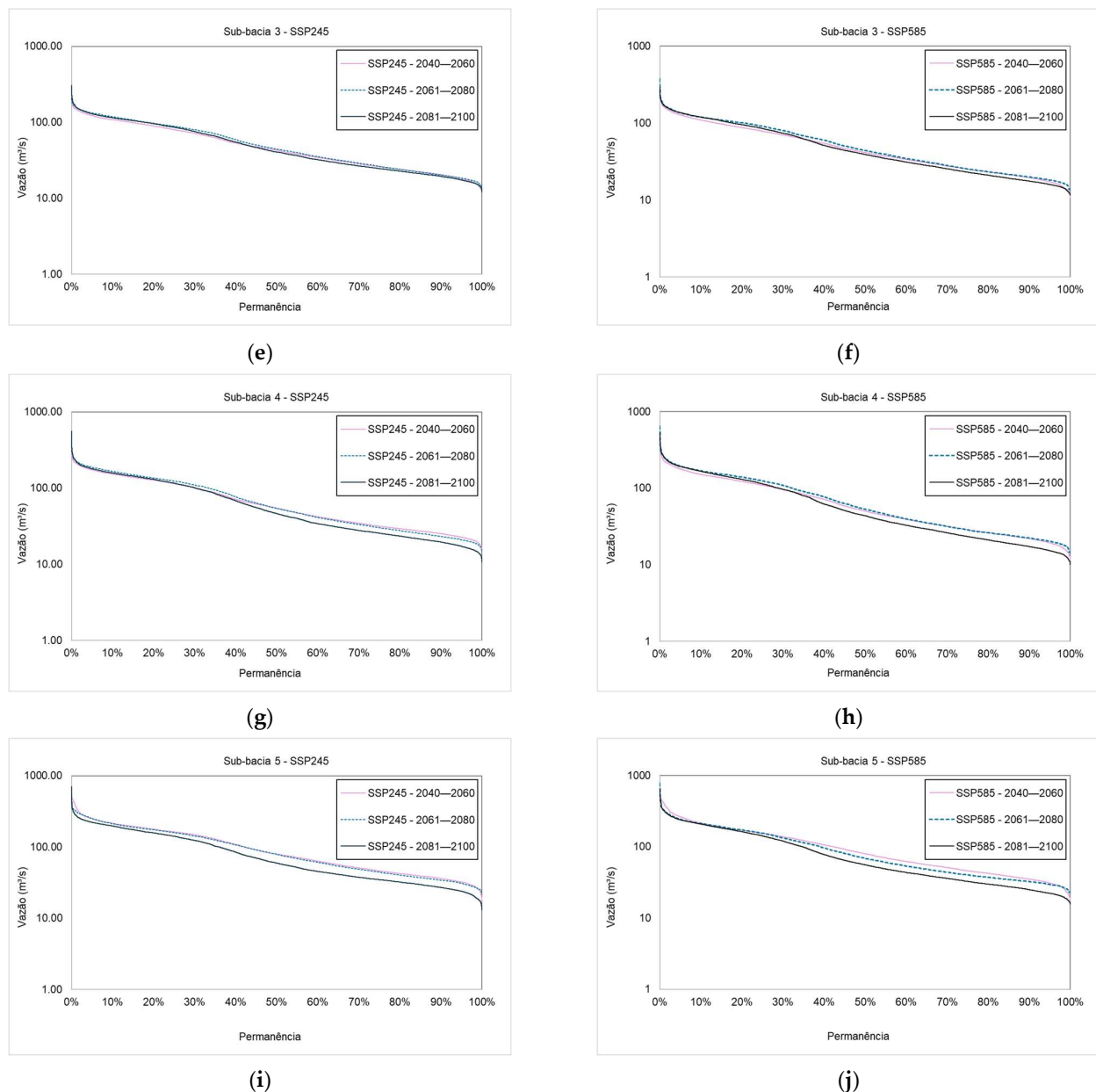


Figure 4. Streamflow duration curve of simulated flows considering the SSP245 and SSP585 scenarios. (a) Sub-basin 1 under SSP245 scenario. (b) Sub-basin 1 under SSP585 scenario. (c) Sub-basin 2 under SSP245 scenario. (d) Sub-basin 2 under SSP585 scenario. (e) Sub-basin 3 under SSP245 scenario. (f) Sub-basin 3 under SSP585 scenario. (g) Sub-basin 4 under SSP245 scenario. (h) Sub-basin 4 under SSP585 scenario. (i) Sub-basin 5 under SSP245 scenario. (j) Sub-basin 5 under SSP585 scenario.

In addition to the analysis, Table 2 shows the results of $Q_{7,10}$ for the future scenarios in each sub-basin. Except for sub-basin 1 (during the mid-future and end of the century) and sub-basin 5 (during the mid-future), reductions in $Q_{7,10}$ were observed in the remaining sub-basins under the SSP585 scenario when compared to SSP245.

The Conflict Index (I_{cg}) is presented in Figure 5. As shown in this figure, except for sub-basin 1, the results for future scenarios indicate that the granted water withdrawals tend to exceed the maximum limits of $Q_{7,10}$. It is worth noting that the risk of water-use conflicts becomes more pronounced in sub-basins 4 and 5, with the most critical impacts projected for the end of the century. Under current basin conditions, difficulties in maintaining the granted streamflows have already been identified, as reported by [13]. Therefore, under

future climate scenarios, an intensification of water-use conflicts is expected, potentially compromising basin water security and the sustainability of existing water uses.

Table 2. $Q_{7,10}$ for the future scenarios in each sub-basin.

Sub-Basin	$Q_{7,10}$ (m ³ /s)	
	SSP245	SSP585
2040–2060		
1	2.28	2.09
2	8.90	8.46
3	14.23	12.73
4	17.86	13.74
5	20.85	19.00
2061–2080		
1	2.35	2.35
2	11.42	11.46
3	15.21	15.13
4	16.99	16.45
5	21.16	24.48
2081–2100		
1	2.18	2.21
2	10.72	9.70
3	14.24	12.66
4	13.37	11.56
5	18.07	17.02

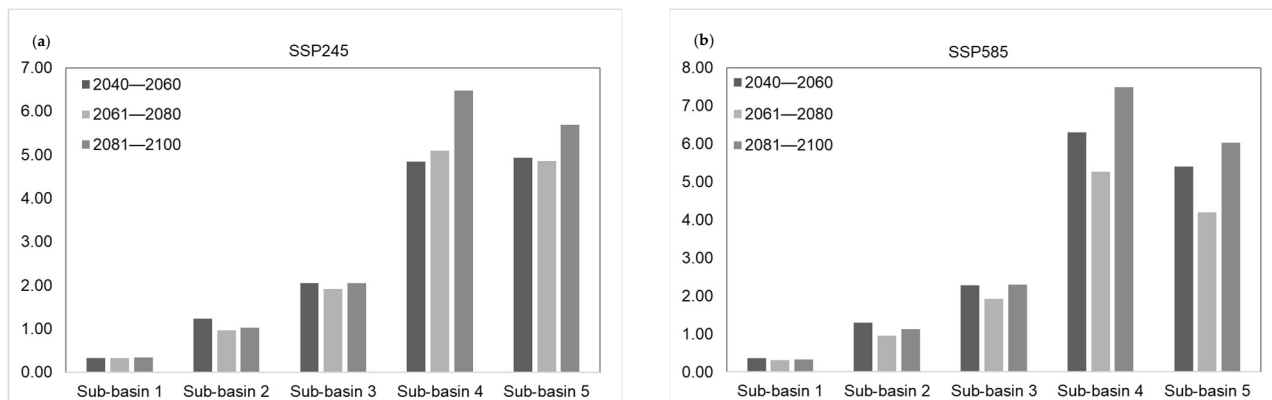


Figure 5. The conflict Index (Icg) for future scenarios in each sub-basin. (a) Icg under SSP245 scenario. (b) Icg under SSP585 scenario.

Figure 6 presents the statistical descriptors (QSM, SEASON, MWH and MWL) of the streamflow duration curve in each sub-basin. Regarding seasonality (SEASON), which shows the effects of differences in streamflow in the dry and rainy seasons, there is a reduction in all scenarios evaluated, especially in the mid-future. This decrease indicates an intensification of streamflow seasonality, characterized by a stronger temporal concentration of flows within specific periods of the year.

The QSM represents the average segment of the streamflow duration curve [36] and reflects intraseasonal variability. The projected variation of the QSM initially shows a slight increase in the first time windows, possibly associated with the intensification of significant rainfall events or the increase in seasonal recharge; however, at the end of the century, especially under the SSP585 scenario, a significant reduction is observed in

sub-basins 1 and 2, suggesting that the increase in temperature and the consequent increase in evapotranspiration outweigh any gains in precipitation.

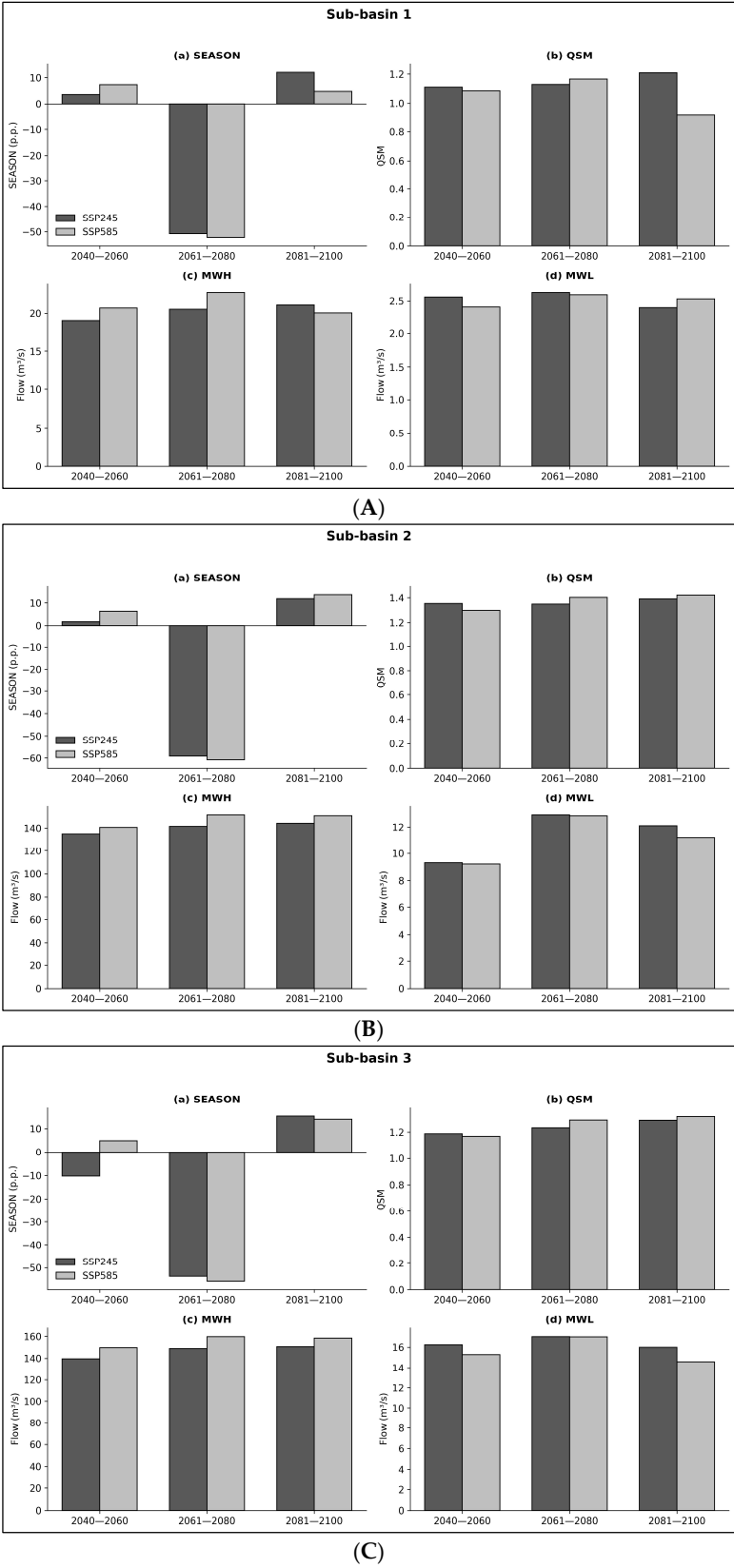


Figure 6. Cont.

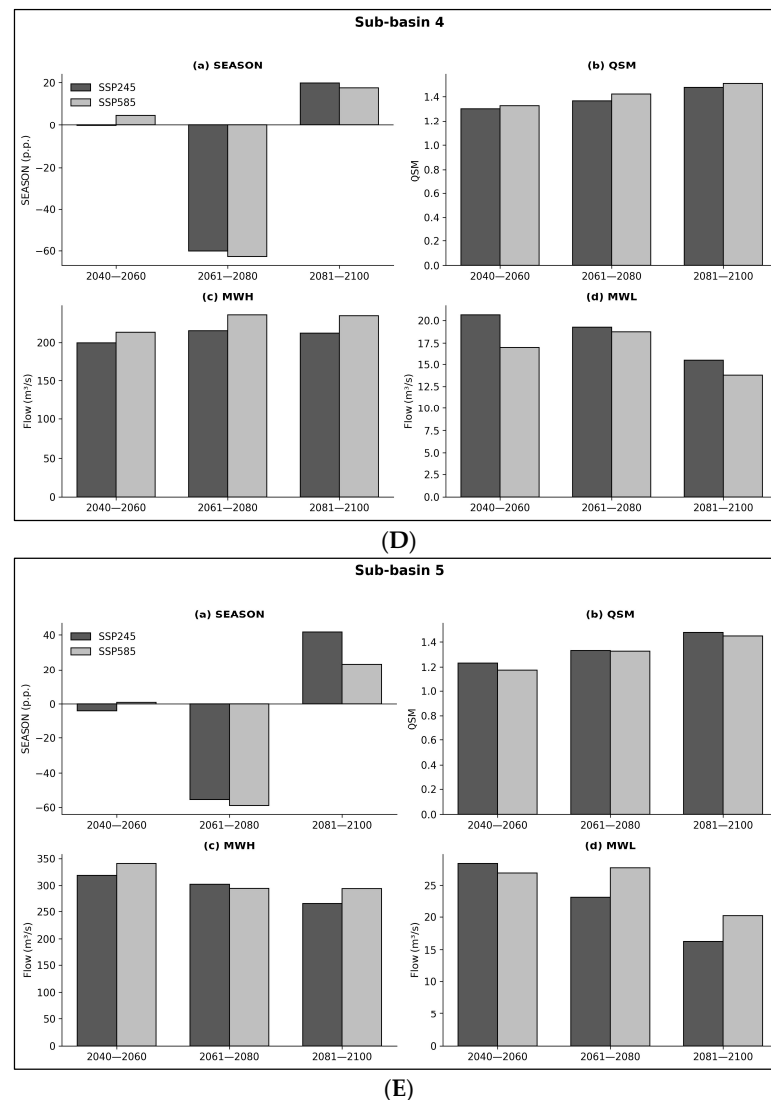


Figure 6. Statistical descriptors (SEASON, SQM, MWH and MWL) of the streamflow duration curve in each sub-basin. (A) SEASON, SQM, MWH and MWL—Sub-basin 1. (B) SEASON, SQM, MWH and MWL—Sub-basin 2. (C) SEASON, SQM, MWH and MWL—Sub-basin 3. (D) SEASON, SQM, MWH and MWL—Sub-basin 4. (E) SEASON, SQM, MWH and MWL—Sub-basin 5.

The MWH (Figure 6C) and MWL (Figure 6D) indicators represent, respectively, the average flood and drought streamflows. In most sub-basins, there is an increase in the average maximum streamflows, which may indicate an increase in the occurrence of large flood events. On the other hand, the MWL indicates a decrease in the average minimum streamflows, which may compromise the maintenance of base runoff, affecting the recharge of aquifers, especially towards the end of the century.

Given that the ensemble of models demonstrated an adequate agreement between the flow duration curve of observed daily streamflows and simulated streamflows (Table 1 and Figure 3), the behavior of streamflows in future scenarios in each sub-basin was subsequently evaluated. Overall, streamflow duration curves reveal significant changes, mainly at the extremes, in the SSP245 and SSP585 scenarios in the sub-basins considered in this study (Figure 4).

4. Discussion

The projected increase in Q_{10} combined with the reduction in Q_{90} and $Q_{7,10}$ indicates a trend toward amplification of hydrological extremes. This pattern suggests an increase in

maximum streamflow and a reduction in minimum streamflow. This behavior suggests changes in the seasonal distribution of precipitation, leading to more intense flooding events and more severe droughts. This interpretation is consistent with the findings of [17], who assessed the impacts of climate change on mining regions in the state of Minas Gerais. According to their study, climate extremes are expected to intensify, particularly under the high-emission scenario [1,6].

The reduction in SEASON and MWL, together with the increase in MWH, reflects a redistribution of streamflow associated with changes in precipitation patterns and atmospheric demand. Under projected climate conditions, rainfall tends to occur in fewer but more intense events, increasing surface runoff as precipitation intensity more frequently exceeds soil infiltration capacity, thereby amplifying peak flows (MWH and Q_{10}). Simultaneously, longer dry periods combined with higher temperatures enhance evapotranspiration and reduce groundwater recharge, leading to diminished baseflow contributions and lower MWL and Q_{90} values. Similar mechanisms have been discussed by [4,12], who emphasize that increased atmospheric demand and rainfall variability play a central role in altering runoff regimes under climate change.

The stronger responses observed in sub-basins 4 and 5 may be associated with their hydrological and geomorphological characteristics, as well as higher water demand pressures. Land uses in these sub-basins tend to reduce infiltration capacity and increase surface runoff, amplifying peak flows during intense rainfall events while simultaneously reducing groundwater recharge and baseflow contributions during dry periods [10,12].

Estimation of $Q_{7,10}$ was based on a stationary Gumbel distribution fitted to annual minimum streamflow. The results are interpreted within the framework of conditional stationarity for each time-slice. In other words, although long-term climate change may induce nonstationary behavior over the entire projection horizon [17,35], the changes within each selected period are considered sufficiently gradual that the statistical properties of annual minimum flows can be approximated as stationary. This approach is commonly applied in multi-decadal periods and assumes a condition of pseudo-stationarity within each slice in climate conditions.

It should also be recognized that the assessment of future water use conflicts was conducted, assuming unchanged overtime water permits, based on current conditions. This assumption represents a limitation of the study. Additionally, the climate projections were derived from the NEX-GDDP-CMIP6 dataset using the Bias-Correction Spatial Disaggregation (BCSD) method. Although BCSD improves the statistical agreement between modeled and observed historical climate, it assumes that bias structures remain constant over time and may not fully capture changes in the frequency and intensity of extreme events [27,29]. Moreover, the interpolation of the $0.25^\circ \times 0.25^\circ$ climate grids to the basin discretization can introduce spatial smoothing effects, particularly in regions with complex topography, potentially affecting the simulated hydrological response.

5. Conclusions

The results demonstrate that projected climate changes under the SSP scenarios are likely to substantially modify the hydrological regime of the Paraopeba River Basin. The ensemble of CMIP6 models coupled with the MHD-INPE model consistently indicates reductions in minimum streamflow and increases in maximum streamflow, particularly under the high-emission SSP585 scenario toward the end of the century. The most pronounced impacts were identified in sub-basins 4 and 5, where Q_{90} reductions approach 30% and Q_{10} increases reach up to 11.7%, evidencing a clear intensification of hydrological extremes.

This shift in the flow regime suggests a growing frequency of intense flood events combined with increased susceptibility to prolonged drought periods. The projected reductions

in $Q_{7,10}$ (the reference low streamflow metric adopted for water allocation in Minas Gerais), reinforce concerns regarding the sustainability of currently granted water withdrawals. The elevated values of the Conflict Index (Icg), especially in sub-basins 4 and 5, indicate that water use conflicts may intensify under future climate conditions potentially compromising regional water security.

Beyond extreme flows, the study reveals structural changes in the basin's hydrological dynamics. Reductions in seasonality (SEASON), decreases in low-flow indicators (MWL), and increases in high-flow indicators (MWH) collectively point to a more irregular and temporally concentrated flow regime. These alterations are likely associated with more concentrated precipitation events and increased evapotranspiration rates under warmer conditions. Such modifications affect not only the magnitude of water availability but also the reliability and predictability of the hydrological system, which are critical for the planning and operation of water supply systems, irrigation schemes, industrial uses, and hydropower generation, posing additional challenges to water managers.

From a water management perspective, the findings underscore the urgent need to incorporate climate change projections into water resources planning and regulatory frameworks in the Paraopeba River Basin. The projected changes call for adaptive and risk-informed management strategies, including periodic reassessment of water allocation criteria, revision of water use permits based on hydrological risk indicators, strengthening of hydrometeorological monitoring networks, integration between water resources management and land-use planning, and the promotion of ecosystem restoration and conservation measures to enhance basin resilience.

Considering the limitations of this study, it can be concluded that the projections are subject to uncertainties related to climate model structure, scenario spread among SSPs, and assumptions within the hydrological modeling framework. Although these factors influence the magnitude of projected impacts, the overall trend toward intensified hydrological extremes and increased allocation stress remains consistent across models and scenarios.

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Abbreviations

The following abbreviations are used in this manuscript:

CMIP6	Coupled Model Intercomparison Project Phase 6
GCM	Global Climate Models
SSPs	Shared Socioeconomic Pathways

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