Uncertainties in Water Scarcity Index due to water use and climate changes: Case of two Legal Amazon watersheds

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Abstract: Water scarcity is a major global problem with the potential to impact socioeconomic development and the environment. Currently, mitigating issues related to the lack of water has become an aim for the public and private sectors. Water scarcity can be estimated by the ratio between water use (withdrawal or consumption) and water availability (a minimum discharge), named Water Stress Index (WSI). But some uncertainties can influence the perception of water scarcity, such as population growth, land cover, climate changes, uncontrolled water use, and the scale at which the WSI is evaluated. To improve the knowledge about water management in two basins in eastern Legal Amazon, We estimated WSI at unit-catchments scale from MGB hydrologic model, water use data, and climate change projections. Our results showed a safe water situation in most parts of the basins, but first-order unit-catchments need more attention due to high WSI values being able to compromise downstream water use.

Key-words: Water scarcity, water stress index, climate change, water availability, Legal Amazon

1. Introduction

Water scarcity is a general term for the lack of water availability. The term is often used to evaluate availability in a long-term situation where water restrictions are imposed for its multiple uses (Smakhtin et al., 2004). To better understand the water balance and availability in each use scenario under scrutiny, it is usual to compute a water scarcity index. Water Scarcity Indexes vary and are defined with an emphasis on a specific subject, such as water quantity, water quality, water withdrawal, water shortage, and droughts (Liu et al., 2016). Using an index for defining the availability (or the lack of) is common and aids the decision-making process to better prioritize water planning.

Currently, the Water Scarcity Index is available on a broader scale. However, the decision-making process in water planning needs information on local or regional scales (Castro et al., 2018). For instance, global scale studies indicate a low degree of water scarcity in Brazil (ANA, 2019), which is contradictory when analyzing data, especially in the northeast region, where aridity and desertification due to droughts are also an issue (Brêda et al., 2020; Sathler, 2021). Using a global scale index tends to generalize hypotheses and results, giving a false sentiment of comfort due to the Brazilian global water availability. Nonetheless, the reality of specific sites in Brazil is different. There are situations of a permanent water shortage (Teixeira et al., 2021) or an intermittent water scarcity issue in major cities (Millington, 2018).

From a strictly quantitative point-of-view local or regional studies face the complex problem of correcting accounts for water availability. Changes in land cover, population growth, regional or even national economic drivers, and climate change are only a few features that can change water availability long-term (Dehghani et al., 2022). On top of that, the uncontrolled change in water use is much more prominent and difficult to estimate than the change in the natural availability in a river basin. Additionally, the correct estimation of WSI depends upon the water availability projection, which can differ regarding water withdrawal or water consumption. Using one of the two water depletion rates changes the WSI and can lead to different conclusions while planning the water use for river basins in the future (Huang et al., 2021).

To account for all the features that can impact water availability and, thus, the WSI on a long-term basis, there are mathematical tools that can be modified to account for and display water balance results in future projections. Spatial distributed hydrological models can give relevant insights regarding the water availability in river basins (Brêda et al., 2020; Quedi and Fan, 2020). The fact that hydrological models account for many natural hydrological processes such as precipitation, evapotranspiration, infiltration, routing, and storage, combined with the flexibility to account for water consumption and withdrawal, turn these tools as turning points to account for water availability in long-term projections (Gaelen et al., 2017; Guug et al., 2020; Jiang et al., 2022). Despite the modeling robustness and capability, only a few studies regarding water scarcity use hydrologic models. Nevertheless, these studies focus on large-scale river basins neglecting local changes in first-order catchments, which are important to correctly account for water availability in river basins (Degefu et al., 2019; Liu et al., 2021; Munia et al., 2020).

Water availability is complex to describe considering the many features involved in its accountability. The complexity has a larger scale when it is analyzed in environments (or basins) with many uses, which is the case of the Legal Amazon. Created in 1953, the legal amazon is a geopolitical instrument to include the northern Brazilian territory in the country's socioeconomic structure. The Legal Amazon has a heterogeneity of economic activities, which all rely upon water availability. The main economic sectors observed in its composition are agricultural, forestry, mineral, industrial, and urban activities (Tanure et al., 2020). In the eastern portion of the Legal Amazon, there is a deforestation territory known as the arc of deforestation. Its importance to the biome is unaccountable and has been the subject of many studies emphasizing climate change and water regulation (Cavalcante et al., 2022, 2019; Pìnheiro et al., 2022). In addition, the eastern legal amazon is accountable for Brazil's most important mining site (Pontes et al., 2022). It is also a key logistic pathway for Brazil since it contains the Carajás Railway and the Ponta da Madeira maritime terminal (Xavier et al., 2021).

Evaluating the water scarcity index in a heterogeneous region such as the eastern legal amazon is challenging since there are still multiple research initiatives to understand the water dynamics and the role of climate change over the region. An even more complex analysis is performed to evaluate those indexes for local management scales. The aim of this article is to evaluate water scarcity indexes in two local river basins of the Eastern Legal Amazon using a spatial distributed hydrological model. The WSI is computed considering even low-order river catchment inside larger river basins. Also, the results considering future projections of water availability are analyzed by verifying the use of projected water consumption vs. withdrawal.

2. Study area

2.1. Itacaiúnas watershed

The IRB is located in the Araguaia-Tocantins hydrographic region (Brasil, 2003), and it has a total drainage area of approximately 42,000 km² (Pontes et al., 2019) (Figure 1). The basin's elevation is characterized by a plateau called "Serra de Carajás," with altitudes ranging between 300 and 900 meters above sea level. Adjacent to the Serra dos Carajás, the elevation varies between 80 and 300 meters. The basin is located in the eastern Amazon biome, but about 50% of its native rainforest has been replaced by pasture in the last fifty years (Souza-Filho et al., 2018). The land use is dominated by extensive pasturelands surrounding a mosaic of forest remnants composed of indigenous lands and conservation units (commonly named Mosaic of Carajás - MoC), which occupy 11,700 km2, or approximately a quarter of the watershed area.

The predominant climate class is tropical monsoon (Alvares et al., 2003). The mean air temperature is 27.2◦C, and the highest rainfall rates are concentrated between December and April, during the wet season. And the lowest amounts of rain are observed between May and November in the dry season. The seasonality of the IRB water regime is explained by the meteorological systems that act on the basin, mainly during the rainy season, such as the Intertropical Convergence Zone (ITCZ), South Atlantic Convergence Zone (SACZ), in addition to local mesoscale systems due to diurnal convection. Also, the intense deforestation in the last five decades caused an increase in the mean, maximum, and minimum streamflow values (Pontes et al., 2019; Cavalcante et al., 2019).

2.2. Pindaré, Mearim, Itacapecurú, and Munim watersheds

With a drainage area of 165,199 km2, the Pindaré, Mearim, Itapicuru, and Munim basin (PMIMB) is located in the central portion of the state of Maranhão, in northeastern Brazil (Figure 1). The PMIMB region is composed of four large basins, Pindaré (40,663 km2), Mearim (55,788 km2), Itapicuru (52,951 km2), Munim (15,838 km2), and its drainage flows (south-north direction) into the São Marcos and São José Bays, in the Atlantic Ocean. The basin's topography is not very pronounced, ranging from 255 (upstream) to 0 meters (downstream). The PMIMB is inserted in the transition zone between the two largest biomes in Brazil: the Amazon and the Cerrado. It is pressured by the advance of deforestation in the region called the new agricultural frontier of Brazil, the MATOPIBA, an acronym of the states (Maranhão, Tocantins, Piauí, and Bahia) (Silva-Junior et al., 2020; Xavier et al., 2021). About this, we highlight in table x the decadal changes in the main land uses in PMIMB for the last thirty years.

The predominant climate class is a tropical zone with dry winter (Alvares et al., 2013). The average air temperature is 26◦C, and the highest rainfall is concentrated between December and May, during the rainy season. And the lowest volumes of rain are observed between June and November in the dry season. The seasonality of the water regime of the PMIMB is explained by the meteorological systems that act over the basin, especially during the wet season, such as the Intertropical Convergence Zone (ITCZ), the Upper Tropospheric Cyclonic Vortex (UTCV), and the Mesoscale Convective Systems (MCS) (Lyra et al., 2022).

Figure. 1. Location and Land Use for the A) PMIMB and B) IRB basins for the year 2020 according to the data in table 1.

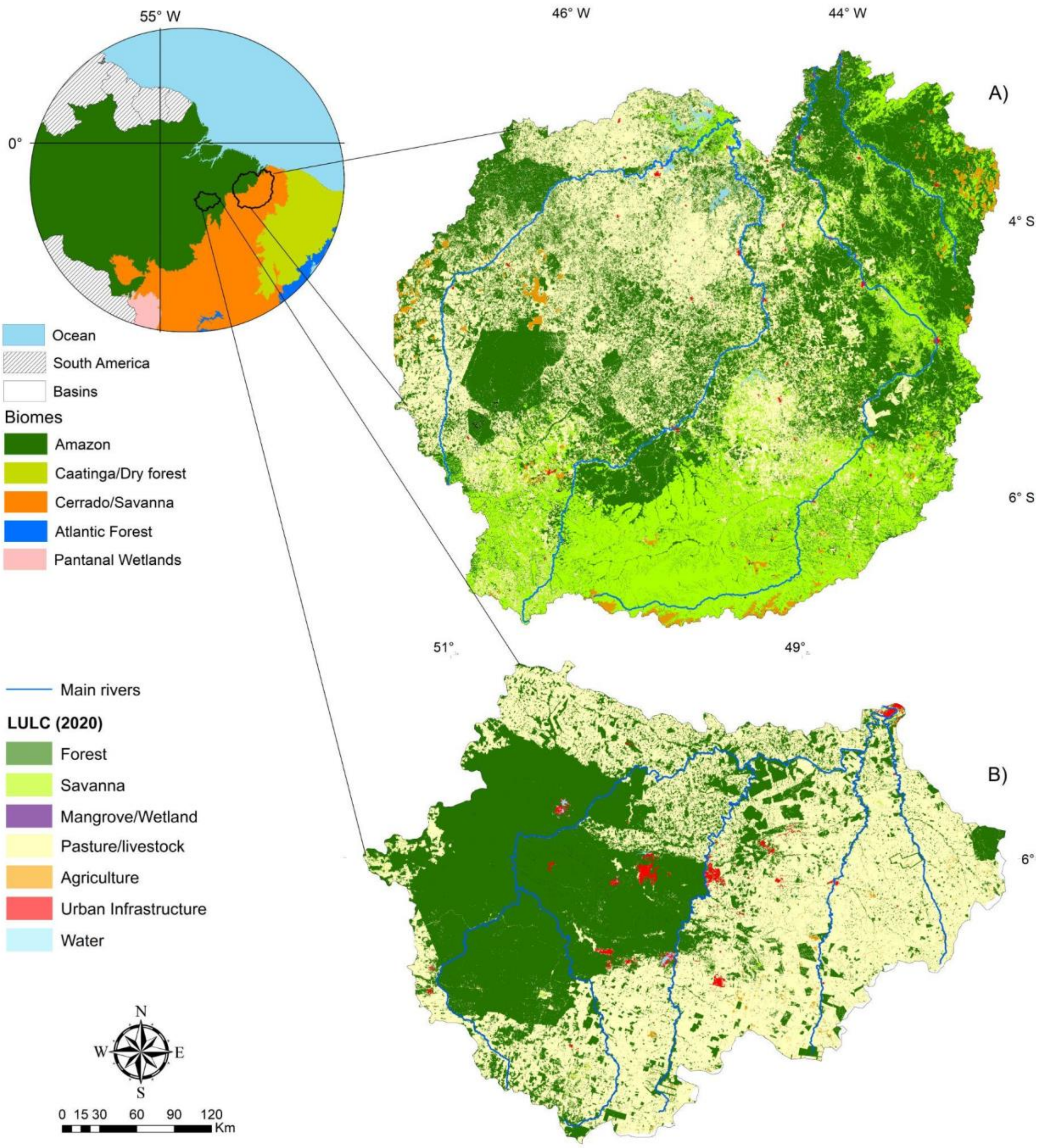


Table 1 presents the location, population, area, elevation, climate, hydrological features, land use, and land cover changes in the IRB and PMIMB.

Table 1. Location, population, area, elevation, climate, hydrological features, and land use and land cover (2020 year) for the IRB and PMIMB.

Characteristic		**IRB**	**PMIMB**
Location		Pará state, the northern region of Brazil	Maranhão state, the northeastern region of Brazil
Population		700,000 hab	4,340.803 hab
Area		42,000 km²	165,200 km²
Elevation		80 to 900 m	0 to 255 m
Biome		Amazon	Amazon and Cerrado
Köppen's climate type[1]		Tropical monsoon	Tropical with dry winter
Precipitation	Mean annual	1900 mm	1543 mm
	Wet season	1600 mm	1360 mm
	Dry season	100 mm	183 mm
Streamflow	Mean annual	900 m³/s	1,255 m³/s
Land use, land cover class in 2020	Forest	45.1 %	43.5 %
	Agriculture	0.41 %	4.7 %
	Pasture/livestock	53.1 %	30.3 %
	Mining/industry	0.46 %	0.01 %
	Urban	0.29 %	0.23 %

According to Alvares et al. (2003); Souza et al. (2020).

3. Methods

3.1. Water scarcity index and use scenarios

The water scarcity index (WSI) is calculated by the accumulated water use and availability ratio at the point assessed. The degrees of water scarcity criticality used in this study are based on earlier studies (Smakhtin et al., 2004): WSI=<0.2 (very low water stress); 0.2<WSI=<0.4 (low water stress); 0.4=<WSI<0.6 (moderate water stress); 0.6=<WSI<0.8 (high water stress); 0.8=<WSI=<1 (very high water stress).

The surface water availability is a minimum reference flow for management purposes and represents the water supply to be considered in the water balance. In Brazil, each state has adopted criteria for establishing the reference flow used to define the maximum flow subject to the right of water use. In this study, water availability is considered as the discharge exceeded or equaled 90% of the time (Q90).

Despite the simple definition of WSI, these estimates have some uncertainty, such as the water quantity used by users and the limitation of water availability imposed by the law. This study proposes two scenarios for water scarcity assessment to represent these uncertainties. The first scenario (Restrict) implies that water use is the consumption, and the legal water availability limits its value at the analyzed site. In the second scenario (Unrestricted), Withdrawal is considered for water use and is not limited by legal water availability. Restricted and Unrestricted scenarios are assessed in two periods: reference and future.

The reference period uses water use estimates for 2020 and Q90 estimated with data from 1971 to 2001. In the second period, water use is estimated for 2040, and Q90 is calculated using discharges from 2021 to 2050.

3.2. Water availability

The discharges were estimated by MGB hydrologic model in each unit-catchment, in which the basins were divided. The MGB is a mathematical model that simulates several hydrological processes at the unit catchment scale, such as evapotranspiration (canopy and soil), surface, subsurface, water under the surface, and discharges. The MGB (COLLISCHONN et al., 2007; Pontes et al., 2017) has been used in several studies in South

America (Siqueira et al., 2018) and worldwide (Fleischmann et al., 2018). In this study, the water availability is considered the Q90 flow.

The pre-processing phase is the first step to simulate the hydrological processes in the basin. An algorithm separates the watershed into unit catchments, delimited according to the digital elevation model (DEM). A set of topological characteristics for each unit-catchment is obtained, including geometrical river features (width, depth, and length), Manning roughness coefficients, drainage area, flooded area estimations, climate data, and percentage of land use/cover and soil type (hydrological response units-HRUs). The data used are shown in Table 2.

The PMIMB was divided into 2233 unit-catchments, while the IRB was divided into 1246. The stage–area–volume curve for each of these units from both basins was estimated using the Shuttle Radar Topography Mission (SRTM) Bare Earth Data (O'Loughlin et al., 2016) and the HAND model (Nobre et al., 2011).

Table 2. The data source used in the hydrological modeling of Itacaiúnas River Basin (IRB) and Pindaré, Mearim, Itapicuru, and Munim basin (PMIMB).

Data	IRB	PMIMB
DEM	Alos World 3D (Takaku et al., 2016); SRTM Bare Earth Data (O'Loughlin et al., 2016)	Hydrosheds DEM (https://www.hydrosheds.org/); SRTM Bare Earth Data (O'Loughlin et al., 2016)
Soil type	Digital Soil Map of the World (http://www. fao.org/geonetwork)	EMBRAPA (https://www.embrapa.br /solos/sibcs/solos-do-brasil)
Land use and land cover	(Souza-Filho et al., 2018), based on Landsat imagery	MapBiomas (http://mapbiomas.org/).
Vegetation data	(Pontes et al., 2019)	(Faria et al., 2018; OLIVEIRA et al., 2018; Rodrigues et al., 2016; Siqueira et al., 2018)
Precipitation (1971-2001)	Water and Global Change Forcing Data (WFD) (https://esgf-index1.ceda.ac.uk/)	Water and Global Change Forcing Data (WFD) (https://esgf-index1.ceda.ac.uk/)

Temperature (1971-2001)	Climate Research Unit (https://lr1.uea.ac.uk/cru/data)	Climate Research Unit (https://lr1.uea.ac.uk/cru/data)
Precipitation and temperature (2021-2050)	GCM data from: Earth System Grid Federation (https://lr1.uea.ac.uk/cru/data)	GCM data from: Earth System Grid Federation (https://lr1.uea.ac.uk/cru/data)
Wind speed, solar radiation, relative humidity, and air pressure	Climate Research Unit (https://lr1.uea.ac.uk/cru/data)	Climate Research Unit (https://lr1.uea.ac.uk/cru/data)

The hydrological behavior in the HRUs is described through soil characteristics, land use, and land cover and climate data. The vegetation data includes height, leaf index area, albedo, and superficial resistance.

The MGB model simulates the water-energy balance and water budget in each HRU, resulting in streamflow values. These variables are routed to the rivers, described by a rectangular geometry. Cross-sections are represented using geomorphic relationships: $w = 3 \times (0.91 \times A^{0.476})$ for the IRB and $w = 0.571 \times A^{0.46}$ for the PMIMB, where "w" is the river reach width (m); "A" is the drainage area (m^2); $d = 0.547 \times w^{1.146}$ (IRB) and $d = 0.091 \times A^{0.31}$ (PMIMB), where "d" is the full depth of the river reach (m). The routing method is a linear reservoir scheme (COLLISCHONN et al., 2007), using a constant Manning's coefficient of 0.025 for the IRB river reaches and 0.03 in the PMIMB.

For the reference period (1971-2001), mean climate data (Air temperature, wind speed, solar radiation, relative humidity, and air pressure) were obtained from Climate Research Unit, and daily precipitation was obtained from Water and Global Change Forcing Data (WFD) product. For the future period, only mean air temperature and precipitation were changed accordingly in five GCM models (GFDL-ESM2 M, HADGEM2ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1 m) in the RCP 8.5. The bias correction method (trend-preserving statistical bias correction method based on quantile-mapping functions) used in the GCM projections adjusts the long-term monthly mean of temperature and precipitation. All data have 0.5° × 0.5° of spatial resolution.

The MGB simulated the hydrological processes of both basins satisfactorily. For IRB, calibration and validation results were considered satisfactory (Pontes et al., 2019). The MGB was calibrated in the basin outlet (unique parameters set) in this first study. The performance metrics were Nash–Sutcliffe efficiency, Nash–Sutcliffe logarithmic discharges, and long-term relative error values. The calibration was performed in 1987-1989 (the land cover was mainly natural forests) and 1998-2007 (pasture lands replaced 30,000 km² of the native forest). Nash–Sutcliffe efficiency, Nash–Sutcliffe logarithmic discharges, and long-term relative error values were 0.66, 0.70, and 17% (first period) and 0.39, 0.70, and 21% (second period). Later, the same model was compared to observed discharges in eight in-situ stations along the basin and confirmed the model quality to represent the discharges in IRB, even with a unique set of parameters for all unit catchments (Melo et al., 2022). For PMIMB, the MGB was calibrated and validated in four in-situ stations, representing four sub-basins with 75% of the total basin area. Each one owns a unique set of parameters. The mean Nash–Sutcliffe efficiency, Nash–Sutcliffe logarithmic discharges, and long-term relative error values were 0.63, 0.61, and 13%, respectively, also indicating that the MGB model represents the discharges satisfactorily in this basin.

3.3. Water withdrawal and consumption data

Data on water withdrawal and Consumption (m³/s) were obtained from the Handbook of Consumptive Water Use in Brazil (Brazilian National Water and Sanitation Agency - https://metadados.snirh.gov.br/). The water uses are available at the unit catchments estimated by Otto Pfastetter's method codification, named here as Otto basins. The Otto basins used here have rivers larger than 50 km² drainage area. The water uses (Domestic, Industry, Livestock, and Agriculture) were estimated for 2020 and 2040. The information on water use of each otto basin is transferred for each MGB unit catchment using a simple area relationship. It is a crucial step because it allows the estimates of water scarcity, where the discharges are estimated by hydrological modeling.

4. Results

4.1. Water use

Figure 2 presents the water withdrawal and consumption for each use and year in the basins. The total water withdrawal estimate in the IRB varies from 11.5 m³/s in 2020 to 21 m³/s in 2040. The industry is the primary water use in this basin, followed by livestock, domestic, and agricultural activities. For the PMIMB, the total withdrawal varies from 6.4 m³/s in 2020 to 8.2 m³/s in 2040. In this basin, the primary water use is domestic, followed by agriculture, livestock, and industry.

On total water consumption, the estimative in IRB is 4.4 m³/s (2020) and 8.1 m³/s (2040). In the PMIMB, the water consumption varies from 3.6 m³/s to 4.6 m³/s over the years. In both watersheds, water is used for thermoelectricity, but It was neglected in this study because it isn't considered a consumptive use of water.

There are some interesting spatial patterns in water use in the basins (Figure 3 and Figure 4). The higher industry water use in IRB is mainly located in the Mosaic of Carajás, related to mining activity. Despite reaching 70% of the total withdrawal for 2020 (76% for 2040), this economic activity uses around 1% of the MoC area. Still, in the PMIMB, industrial water withdrawal corresponds only to 3% of total withdrawal, indicating the difference in industrialization processes in these watersheds. In the IRB, the second water use is livestock, spread in the basin, except inside the MoC. In the PMIMB, similar to the IRB, livestock water use is in almost the entire watershed, although being the only third water use.

Figure 2: Water withdrawal (W) and consumption (C) for each use and year in the basins: (a) IRB; and (b) PMIMB.

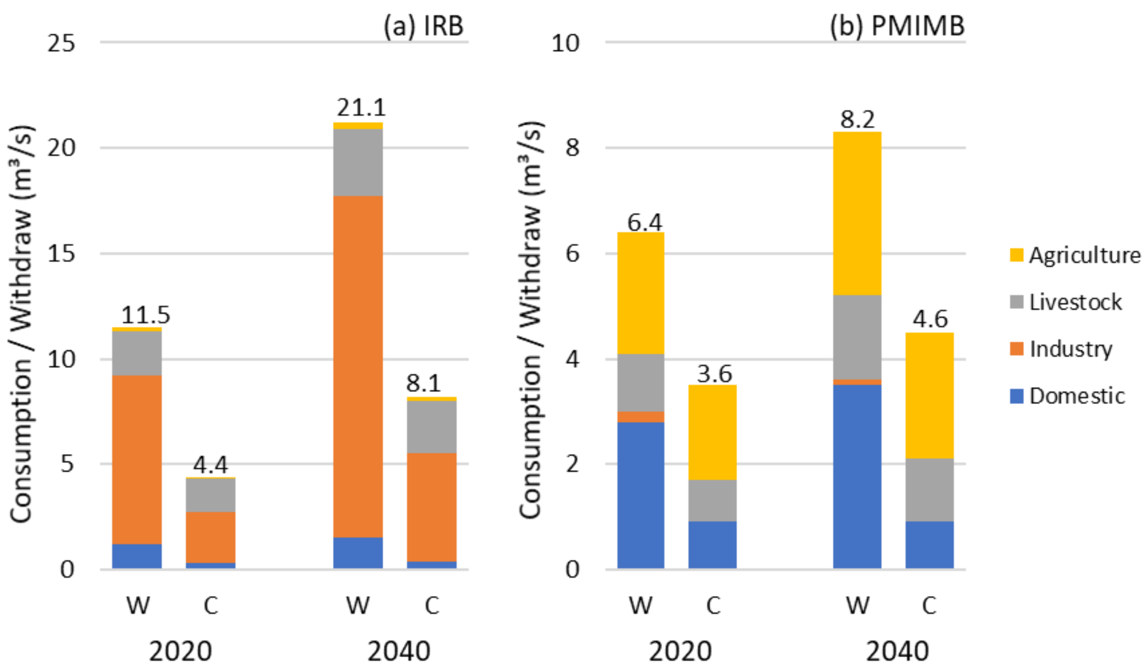


Figure 3: IRB's water withdrawal (2020) at unit-catchment scale for each use. Water consumption and the 2040 period are presented in the supplementary file.

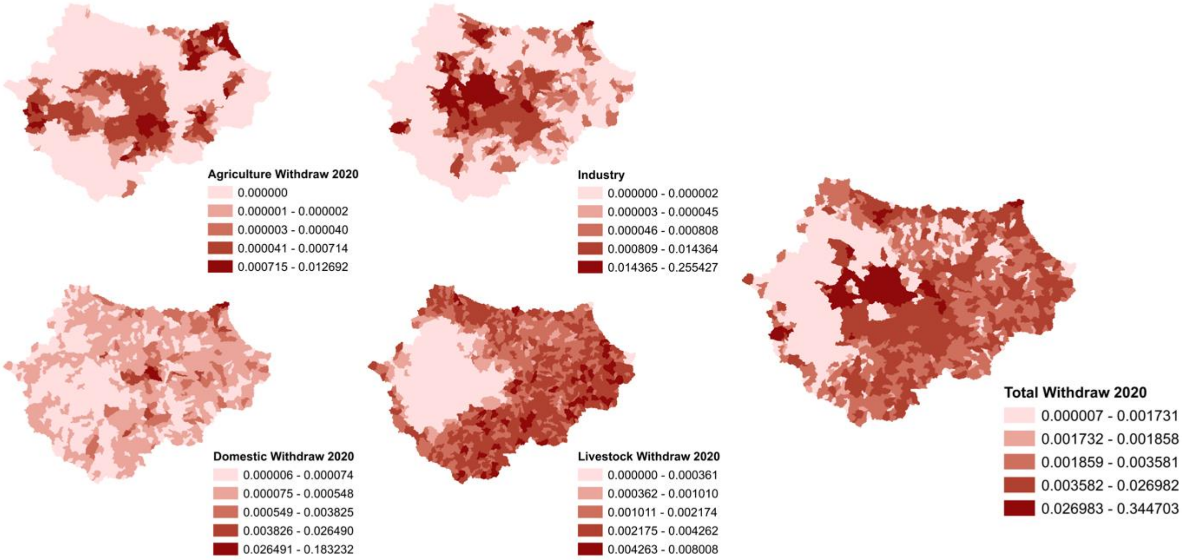
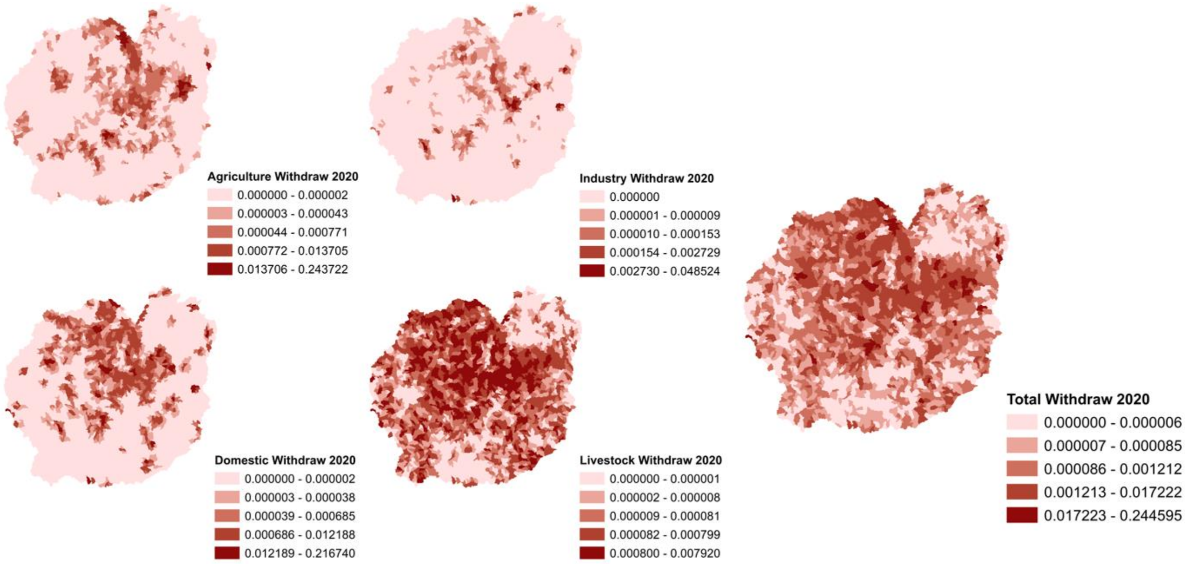


Figure 4: PMIMB's water withdrawal (2020) at unit-catchment scale for each use. Water consumption and the 2040 period are presented in the supplementary file.



4.2. Water availability

The water availability is considered in this study as Q90 flow (90% exceedance flow). For IRB (Figure 5), Q90 reaches 128 m³/s in the outlet for the reference period. Besides, the mean Q90 of the unit catchments is only 3.3 m³/s, indicating the high variation of discharges in the basin. Regarding the future period, the Q90 in the outlet decreased to 33.8 m³/s, and the mean Q90 of the unit catchments declined to 0.8 m³/s.

For PMIMB (Figure 6), the Q90 in the reference period reaches 238 m³/s. It corresponds to the sum of the Pindaré (31 m³/s), Mearim (120 m³/s), Itapicurú (56 m³/s), and Munim (31 m³/s) discharges. In the future period, the Q90 may decrease to 190 m³/s (a reduction of 31%, 14%, 11%, and 51% in each river, respectively, compared to the reference period). Similar to IRB, the mean discharge at the unit catchment scale is 3.45 m³/s, indicating the high variability of this variable.

Figure 5: A) Water availability (Q90) in the reference period at the unit-catchment scale for the Itacaiúnas river basin. B) Mean relative difference of Q90 in the future (mean of GCMs) and reference periods.

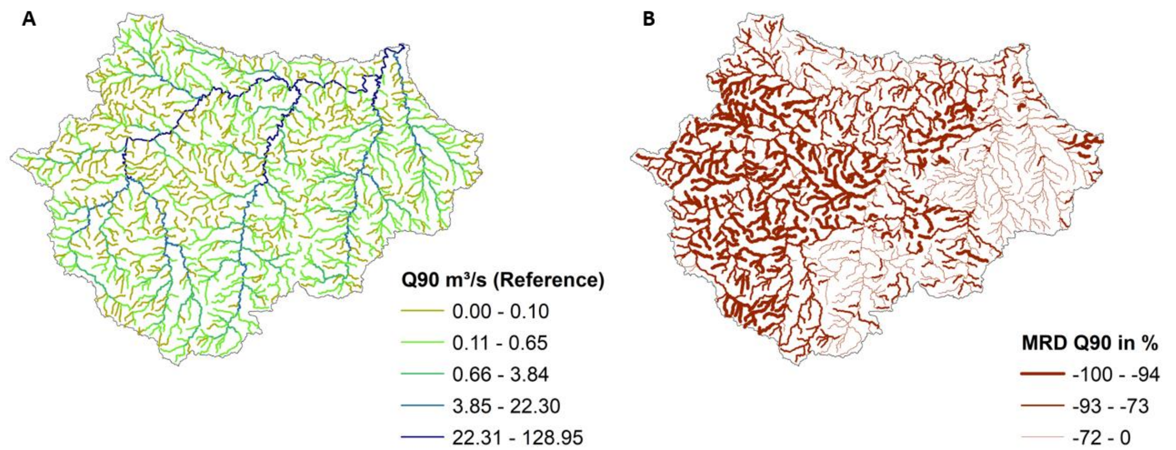
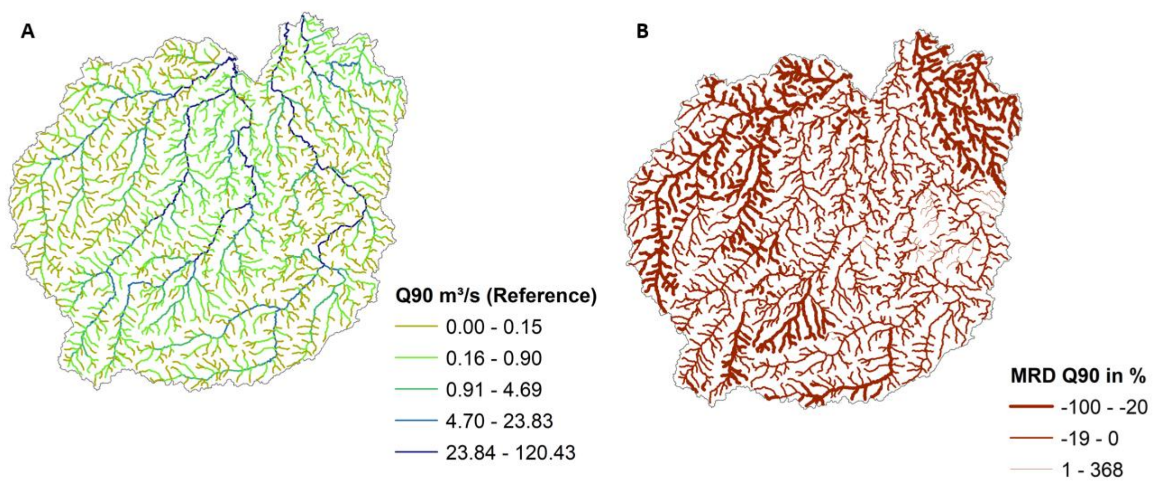


Figure 6: A) Water availability (Q90) in the reference period at the unit-catchment scale for the PMIMB. B) Mean relative difference of Q90 in the future (mean of GCMs) and reference periods.



4.3. Water scarcity

The spatial distribution of the WSI in the IRB indicates that the higher values are located mainly inside MoC, probably due to industry water use. Despite this, the WSI values suggest a comfortable situation in this basin. Around 90% (94%) of the unit catchments of IRB have a maximum WSI of 20% in the Unrestricted (Restricted) scenario. The simulation also reveals that 6% (2%) of unit catchments have a WSI upper to 80% in the Unrestricted (Restricted). The WSI can be worse in the future, meaning more unit catchments with a WSI upper of 80% (27.3% for the Unrestricted: 27.3%; Restricted: 18.6%) and fewer with a WSI limited to 20% (54% for the Unrestricted: 68.4%; Restricted: 18.6%), according to Table 3 and Figure 7. This result is evident in the spatial variability, in which worse values of WSI occur spread in the basin. The increase of WSI occurs mainly in the headwater of Itacaiúnas and Aquiri rivers, Paraupebas watershed tributaries, and Lower Itacaiúnas rivers. Table 3 also presents the first-order unit-catchments with WSI higher than 80% in both basins. The WSI condition for PMIMB is quite different from IRB. More than 99% of catchments own WSI between 0-20% in both Unrestricted and Restricted scenarios and periods, which means a more comfortable situation, according to Table 3 and Figure 8.

Figure: WSI values in the IRB for all scenarios and periods.

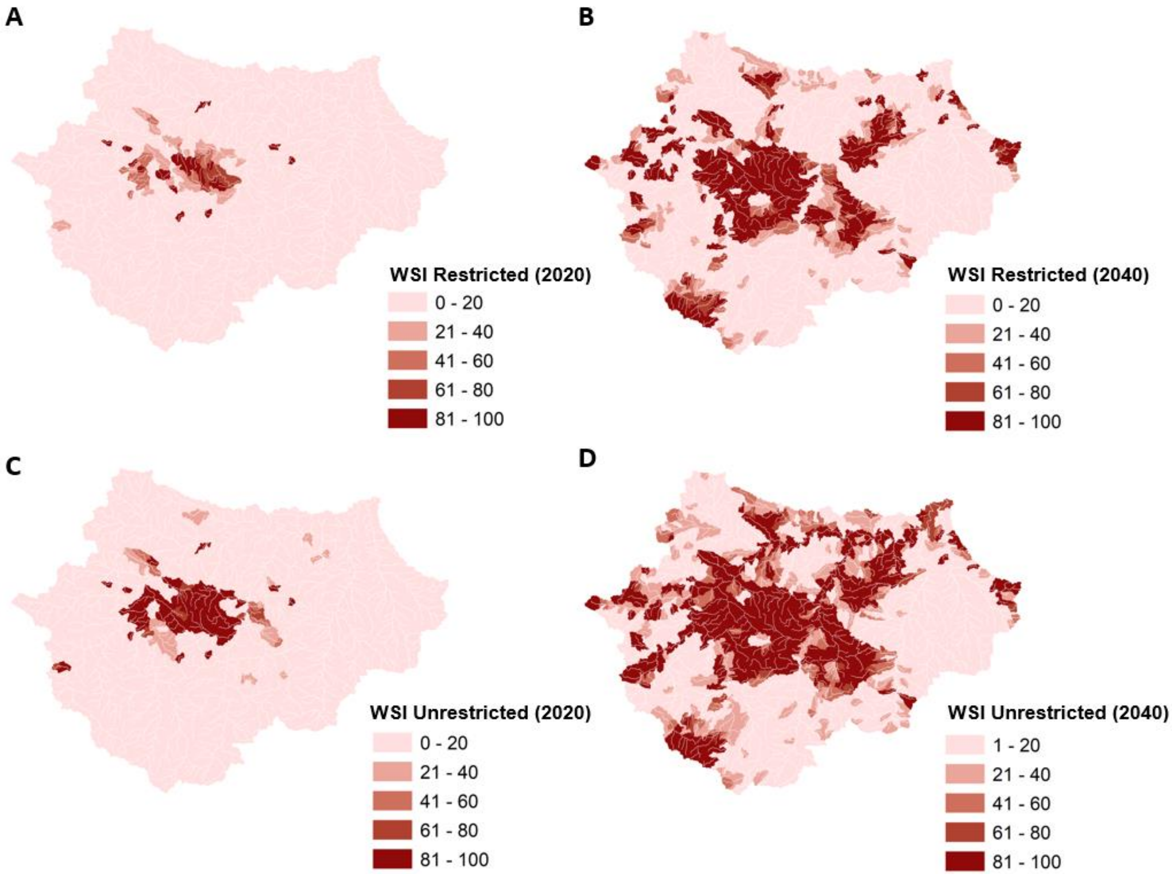


Figure: WSI values in the PMIMB for all scenarios and periods.

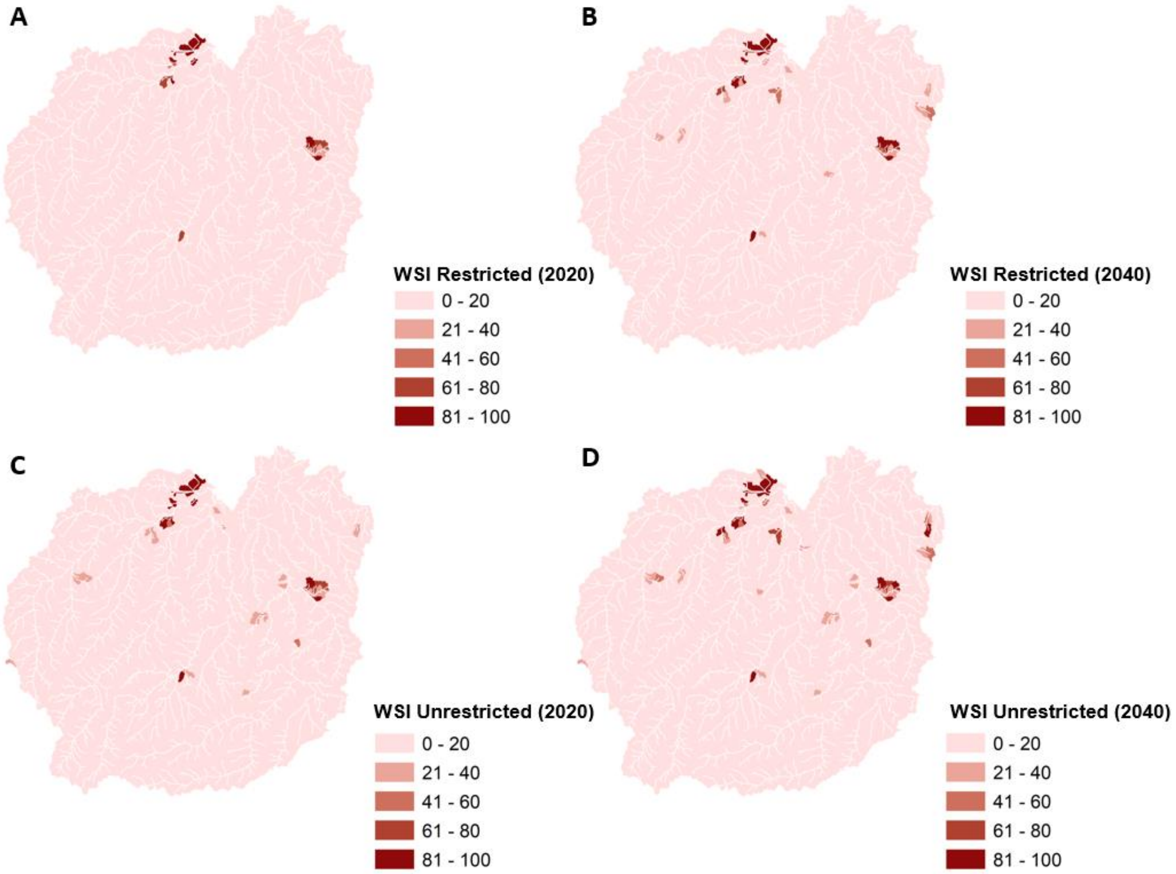


Table 3: Number of unit catchments in the IRB and PMIMB in each WSI class for all scenarios (Restricted and Unrestricted) and periods (2020 and 2040) considering all unit catchments and only first-order catchments with WSI higher than 80.

Unit catchments	WSI classes	IRB 2020 (2040)		PMIMB 2020 (2040)	
		Restricted	Unrestricted	Restricted	Unrestricted
All	0% - 20%	1172 (852)	1133 (674)	2210 (2191)	2189 (2174)
	20% - 40%	28 (101)	28 (146)	5 (18)	23 (27)
	40% - 60%	16 (35)	8 (60)	1 (5)	3 (8)
	60% - 80%	8 (25)	7 (26)	6 (1)	3 (4)
	80% - 100%	22 (233)	70 (340)	11 (18)	15 (20)
First order	80% - 100%	19 (157)	36 (165)	2 (5)	4 (5)

5. Discussion

5.1. Difference between global and regional WSI for the watersheds.

Several studies presented global WSI estimates (ALCAMO et al., 2007; Degefu et al., 2019; Huggins et al., 2022; Kiguchi et al., 2015; Liu et al., 2021; Munia et al., 2016, 2020; Smakhtin et al., 2004; Veldkamp et al., 2017). Despite the vantage of a global scale, in general, the WSI doesn't represent small-order rivers due to the coarse resolution of water use or water availability. On the water availability data, for instance, earlier studies used a spatial resolution of half-degree, which is satisfactory for transboundary or large basins but may neglect small rivers even in stressed basins (Degefu et al., 2019; Liu et al., 2021; Munia et al., 2020).

According to our results, first-order unit-catchments (mean drainage area of 30 km^2) with WSI higher than 80% vary from 19 to 36 in the 2020 period. Still, they may reach 165 in the 2040 period, indicating the need to represent these small basins. Also, earlier and global scale studies normally presented that there is low water stress (WSI < 0.3) in most parts of Brazilian basins, even in the future assessments (ALCAMO et al., 2007; Smakhtin et al., 2004), contradicting our results, which indicated rivers under high WSI, mainly in IRB. Unlike the IRB, the first-order unit-catchments in PMIMB are limited to 5, supporting that this basin does not experience high levels of water scarcity.

On a regional scale, the Brazilian Water and Sanitation Agency studied water security in Brazil. This study considers the same water use data and the Q95, estimated by flow regionalization techniques. The future flows were considered implicitly due to ongoing changes in observed flow data. Despite the similarity of WSI patterns, considering climate projections by GCMs is important to understand the possible critical future scenarios, even though it is challenging to implement in immediate water planning. Also, even with uncertainties related to these projections, the GCM data as input for hydrological models are widely used in literature (ALCAMO et al., 2007; Arnell, 2004; Dinar et al., 2019; Kiguchi et al., 2015; Liu et al., 2022; Munia et al., 2020). In the IRB, for instance, the mean Q90 estimated using the five GCMs indicates a reduction of 95 m^3/s compared to the reference period in the watershed outlet, confirming the importance of these projections (Pontes et al., 2022). The results showed that future Q90 decreased 100% compared to the reference period, mainly in the rivers of Mosaic of Carajás, where water use is more intense.

5.2. Uncertainties in WSI estimates

The use of water withdrawal or water consumption in the WSI estimates may cause essential changes in this index. (Liu et al., 2021; Munia et al., 2020). A recent study indicates that choosing withdrawal or consumption in the WSI estimates changed the estimate of the population living in water-stressed areas (Munia et al., 2020). Our study indirectly evaluates the influence of the withdrawal or consumption in WSI estimates in the scenarios, which can be noted in the number of unit catchments distributed by the WSI classes (Table X). In the IRB, for instance, the number of unit catchments with WSI > 80% is 22 (Restricted) and 70 (Unrestricted) in the 2020 period. These numbers represent 2% and 6% of the unit catchments of IRB, and the difference between the scenarios occurs mainly in the MoC, in small drainage areas with industrial use. Nevertheless, local water use significantly influences WSI estimates compared to upstream water use (Munia et al., 2020). Although water consumption is more faithful to reality than water withdrawal, the amount of water that is returned to the rivers may not be guaranteed for downstream uses due to other factors, such as pollution sources (Wada et al., 2011). Regarding PMIMB, the basin has 11 (Restricted) and 15 (Unrestricted), but the difference is more spatially noticeable in the IRB.

Another uncertainty concerns the water use (consumption or withdrawal) limited to Q90 (or other reference discharge used as water availability). For instance, the water withdrawal in a river can not exceed the Q90, but it can occur in practice due to the lack of water oversight. This uncertainty also is implicitly considered in our study in the Unrestricted scenario. In the IRB, the total water consumption in 2020 (2040) was 4.4 m^3/s (8 m^3/s), but the value considered in the WSI estimate is 89% (54%) of this total. This occurs because there are river reaches that have less Q90 than water consumption. It is important to mention that water use higher than environmental discharge may impact aquatic ecosystem services, such as fishery, recreation, and flood controls (Smakhtin et al., 2004).

There are other sources of uncertainties not considered in this study, such as the equations to estimate environmental flow (and consequently water availability) (Liu et al., 2021; Pastor et al., 2014) and water scarcity (Liu et al., 2017). A recent study evaluated how different environmental flow estimates (Q90, Q50, Q90/Q50, and Variable Monthly Flows - VMF method) could impact the population under water scarcity (Liu et al., 2021). The authors showed that the area under water scarcity ranged between 8% and 52% of the global land area, which means 28% to 60% of the global population living under water scarcity. In Brazil, water availability and environmental flows vary from state to state, and it is a function of the minimum flow (Q90, Q80, Q95, 7Q10) of the evaluated period. For instance, the water availability in a state can be 90% of Q90, which means that only 10% is reserved for the environment. Some studies indicate that the discharge required by a river to maintain its aquatic ecosystem services must be variable over time, considering the anthropic and natural changes (POFF et al., 2010; RICHTER et al., 1997; Richter, 2010). But these studies also indicate the difficulty of implementing the methods due to the lack of understanding about environmental flow benefits, water management difficulties, and the complexity of the proposed methods. Another limitation of our study is the use of only one index of water scarcity.

5.3. Future changes implications

Climate changes may impact water resources in different ways, such as increasing high flows and decreasing water availability (Alves et al., 2021; Brechin and Bhandari, 2011). Although the GCMs usually agree with the signal of future precipitation and air temperature changes, they have different results about the intensity (Brêda et al., 2020; Schewe et al., 2014). The uncertainties in climate variables reinforce the importance of using several GCMs to improve the results' goodness and magnitude of changes (Alfredo et al., 2016; Brêda et al., 2020). In IRB, climate changes (2021-2050) indicate a decrease in precipitation and an increase in air temperature, which means a reduction in water availability of 70% compared to the reference period (1971-2001) (Pontes et al., 2022). The highest differences in water availability can occur in the MoC region (Figure 5). Regarding PMIMB, most parts of the basin may experience a decrease in water availability, but others may experience an increase. Considering the sum of all outlets, the reduction in water availability is 20%. Despite the changes simulated by GCMs, decision-makers must not consider climate change as forecasts. In IRB, for instance, a recent study indicates a decrease in precipitation in the last 40 years, but it is not significant (Cavalcante et al., 2019). The authors showed that deforestation is mainly responsible for the basin's flow increase. In addition to climate, water use and population changes may threaten water security in watersheds (Draper and Kundell, 2007; Munia et al., 2020; Schewe et al., 2014).

6. Conclusion

We evaluated water scarcity, represented as WSI, using hydrological modeling and water use estimates (consumption and withdrawal) in Legal Amazon watersheds in Pará and Maranhão states.

The hydrological model used in this study – MGB – was considered well-adjusted for both regions and allowed water availability estimates in the basins, including first-order rivers, where water users usually exist in critical, such as industry. Also, because the model estimates water availability spatially, the WSI was calculated for more diffuse water use, such as livestock.

In the WSI estimates, our study also considered uncertainties related to water consumption or withdrawal and the water use limited to legal water availability. These uncertainties were evaluated in both scenarios (Restricted and Unrestricted). In general, WSI is less than 20% in most parts of unit-catchments of IRB and PMIMB, indicating a safe water situation. It is more evident in PMIMB, where the primary water use is agriculture and domestic. However, first-order unit-catchments in IRB need more attention due to WSI that surpasses 80%. High WSI values in first-order unit-catchments may compromise downstream water uses. The WSI was also estimated in future scenarios, considering projections of water availability and use. Although our results indicated a reduction in water availability in IRB and part of PMIMB, the watersheds can be considered safe regarding water security.

For a better uncertainties assessment, it is recommended in the subsequent studies to use more than one water scarcity approach, which may change the understanding of areas with more water-related risks. Also, it is recommended to use updated climate projections, which have been improved over the years. Finally, we agree that the results improve water management in the basin and allow identify and evaluate how water-related risks can impact these watersheds.

7. References

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