



## Hydrological modeling of LULC and climate change scenarios in a hydrographic basin in the semiarid region of Brazil.

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### ABSTRACT

This study aimed to evaluate the influence of future climate predictions associated with land use and cover scenarios on flow regimes (low, high and medium values) in the Pajeú river basin (Pernambuco/Brazil). The climate scenarios RCP 4.5 and 8.5 were simulated with the regional model Eta/CPTEC nested within global circulation models. The future LULC scenarios were defined using the Land Change Modeler in TerrSet and LULC maps from Mapbiomas. The hydrological simulation for streamflow estimation in the basin was performed using the MGB model. The 1985 LULC map was used to define the hydrologic response units, the period 1973-1982 for calibration, and 1983-1990 for validation. The calibration of the MGB was assessed by comparing the variables streamflow, evapotranspiration, and soil moisture. The simulations showed the impacts of the changes considering the LULC scenarios individually and the combination with the climate change scenarios. The increment of streamflow after the replacement of caatinga by agriculture and pasture can intensify or compensate the impacts of climate change, depending on the GCM has a trend to produce more or less precipitation.

Keywords: land use and cover, Pajeú river basin, MGB, hydrological variables.

## Modelagem hidrológica de cenários LULC e de mudanças climáticas em uma bacia hidrográfica do semiárido do Brasil.

### RESUMO

Este estudo teve como objetivo avaliar a influência de cenários climáticos futuros associados a cenários de uso e cobertura da terra nos regimes de vazões (valores baixos, altos e médios) na bacia do rio Pajeú (Pernambuco/Brazil). Os cenários climáticos RCP 4.5 e 8.5 foi simulado com o modelo regional Eta/CPTEC aninhado em modelos de circulação global. E os futuros cenários LULC foram definidos usando o Land Change Modeler no TerrSet e os mapas LULC do Mapbiomas. A simulação hidrológica para estimativa de vazões na bacia foi realizada utilizando o modelo de grandes bacias (MGB). O mapa LULC de 1985 foi usado para definir as unidades de resposta hidrológica, o período 1973-1982 para calibração e 1983-1990 para validação. A calibração do MGB foi avaliada comparando-se as variáveis vazão, evapotranspiração e umidade do solo. As simulações mostraram os impactos das mudanças considerando os cenários LULC individualmente, e a combinação com os cenários de mudanças climáticas. O incremento da vazão após a substituição da Caatinga por agricultura e pastagem pode intensificar ou compensar os impactos das mudanças climáticas, dependendo do MCG ter tendência a produzir mais ou menos precipitação.

Palavras-chave: uso e cobertura da terra, bacia do rio Pajeú, MGB, variáveis hidrológicas.

### Introduction

In the last two decades, the water resources community has been investigating the potential effects of climate change on the water cycle and its impact on water availability and security. Such studies allow for assessing environmental vulnerability concerning climate alterations and their effects on human settlements. Although variability is a well-known component of climate

dynamics, its impact, even within the expected limits, can cause significant damage to several human activities (Nunes & Lombardo, 1995), including water availability for the food industry and agriculture (Frone & Frone, 2015), and water supply for the population, among others.

Studies have shown that unplanned land use and land cover (LULC) and deforestation can add to climate change and, consequently, damage

the development of human activities (Santos & Santos, 2013). The land-use change affects important processes such as precipitation patterns, terrestrial evaporation entering the atmosphere, and plant-available soil moisture dynamics (Wierik et al., 2021).

Masullo and Rangel (2012) concluded that LULC scenarios result in temperature increases that create heat islands. The same study verified that vegetation removal from pavements hinders water infiltration into the soil, interfering with groundwater recharge. Some studies have attempted to use models that generate future scenarios of LULC based on observed LULC, and new scenarios have been developed according to the pattern or trend of evolution over time (Andrade & Ribeiro, 2020, Santos et al., 2021; Silva et al., 2022).

Studies have shown divergent results in relation to the hydrological modeling of LULC scenarios. In this regard, Siqueira et al. (2022) found that maintaining vegetation cover led to an increase in average flow. Meanwhile, Brito Neto et al. (2021) and Kovalski et al. (2022) found that in the scenario with the smallest area occupied by natural vegetation there was an increase in the average monthly, total, maximum and minimum flows.

The Intergovernmental Panel on Climate Change (IPCC) predicts drier conditions in 60% of the Latin American region, increasing the number of countries experiencing water stress (Magrin et al., 2007). In addition, the climate of this region is particularly affected by El Niño Southern Oscillation (ENSO) (IPCC, 2012). Considering that ENSO dynamics can explain interannual hydroclimatic variability, its occurrence and magnitude predictions are essential for developing adaptive management strategies. Godin et al. (2011) corroborated this expectation after applying climate models in the Jaguaribe river basin (Ceará state). According to the authors mentioned above, climate change in this basin estimated by the model worked as an additional pressure in the water demand for irrigation because of the elevation of the reference evapotranspiration, which was due to temperature increase associated with precipitation reduction.

The future climate scenarios developed by the IPCC serve as input data for terrestrial climate models and show better results for continental scales; the future climate scenarios resulting from the simulations of terrestrial climate models are used to feed regional climate models, which predict changes in rainfall regimes depending on the climate scenario used (Fernandes et al., 2017;

Santos et al., 2021). The observed rise in temperature in certain regions and the result of hydrological modeling can lead to changes in surface runoff, evapotranspiration values and humidity (Santos, 2019; Vergasta et al., 2021).

Future climate change scenarios point to severe situations for several river basins located in Brazil (Arroio Junior & Mauad, 2015; Fernandes et al., 2017; Godin et al., 2011; Santos, 2019, Vergasta et al., 2021; Ferreira et al., 2023). For this reason, it is of the utmost importance to continue developing research in order to analyze the possible impacts imposed by future climate scenarios on river basins.

Arroio Junior and Mauad (2015) also verified the vulnerability to possible climate change in the Ribeirão Feijão river basin (São Paulo state) using the hydrological model SWAT. Future water availability problems are a significant challenge for this basin. In this regard, population growth, lifestyle change, environmental degradation, and climate change can reduce access to potable water and increase the variability and magnitude of climate events. Since there is less freshwater due to eutrophication in water bodies and a growing risk of extreme weather events, achieving sustainable water security will be increasingly difficult (Siska & Taraka, 2015).

Several studies have assessed future climate scenarios and found a decrease in rainfall and an increase in temperature (Alemayehu et al., 2020; Costa et al., 2022, Farinosi et al., 2019; Kosh et al., 2022; Nóbrega et al., 2022; Silva et al., 2023, Zákchia et al., 2021). These are components of the hydrological cycle that can affect the availability and quantity of water in river basins, especially in Brazil's semi-arid regions (Silva et al., 2020). Such projections end up placing greater demands on water resource management systems, especially in regions with a higher aridity index, since they are more vulnerable to climate change and the socio-environmental impacts caused by long periods of drought (Kimura, 2020; Marengo et al., 2020; Mutti et al., 2020).

Global circulation models (GCMs) predict adverse future climatological scenarios in South America, resulting in significant problems such as droughts and floods concerning water security and ecosystem maintenance (Chou et al., 2014b). Studies with the regional model Eta/CPTEC, nested in the Earth system model HadGEM2-ES, have shown trends in wetter conditions during the period 1961-1990 in most of South America (Chou et al., 2014a, Haylock et al., 2006). In contrast, simulations with the Eta/CPTEC model nested in

the GCMs MIROC5 and BESM generally exhibit drier conditions in most of South America, particularly in the north (Brito et al., 2019, Koch et al., 2020). Extreme rainfall can increase surface runoff, even in unsaturated soils, which can cause inundation, landslides, and structural damage. However, precipitation scarcity can affect Brazil's economic, social, and environmental sectors (Valverde & Marengo, 2014).

Various studies carried out worldwide in relation to climate change and water resources show three types of results: increases, decreases and no change in surface runoff, the first being found in regions with high latitudes and in part of the United States; and the second in West Africa, southern Europe and part of South America; there are also regions where no negative or positive changes are found in surface runoff (Bates et al., 2008; Costa et al., 2022; Santos et al., 2013; Silva et al., 2023). At the level of Brazil, the largest river basins have shown reductions in surface runoff and in others there is a tendency for an increase (Marengo, 2006), showing that the result can vary from river basin to river basin and from one region to another.

On the other hand, some studies have shown, based on indicators of climate extremes, that hydrological modeling using data from the regional Eta model, coupled to the HadGEM2-ES Earth system climate sample, shows trends towards wetter conditions in the period from 1961 to 1990 (baseline period) in a large part of the South American continent (Chou et al., 2014a; Haylock et al., 2006). On the other hand, modeling that used data from the Eta model coupled with climate samples from the MIROC5 and BESM Earth systems show drier climate trends for most of South America, particularly in the northern portion of the continent (Brito et al., 2019). In this sense, it is necessary to develop research that seeks to better understand the possible impacts of future climate scenarios on watersheds in semi-arid regions. This understanding can help when developing policies to combat and mitigate climate change.

This study made an effort to enhance the elaboration of future LULC scenarios to better characterize the changes in the following decades in contrast with studies that consider a stationary LULC map over time (Koch et al., 2020, Ribeiro Neto et al., 2014). Case studies like the Pajeú River Basin (PRB) can contribute to understanding the effects of global changes on the water resources of semiarid regions. Climate and LULC change are two of the main driving forces of global change, and the Brazilian semiarid is considered a hotspot region. In this regard, the present study aimed to

assess the influence of future climate scenarios associated with land use and land cover scenarios on streamflow regimes (low, high and average values) in the PRB in Pernambuco State, Brazil.

It also has the following hypothesis: the MGB model have the capacity to represent the effects of climate change associated with alterations to the LULC scenarios in a watershed in the semi-arid region. Since this hydrological model is not widely used in river basins with this climatological condition (Felix & Paz, 2016; Negreiros et al., 2007, Souza et al., 2017; Virões & Cirilo, 2019).

## Materials and methods

### Study area

The PRB (Figure 1) is the largest river basin in Pernambuco, covering 16,838.70 km<sup>2</sup> and corresponding to 17% of the state's territory (SRHS, 1998). The Pajeú river is a tributary of the São Francisco river, and its headwaters are located in the municipality of Brejinho (PE) at an altitude of 800 m near the borders of the Pernambuco and Paraíba states. The PRB includes 28 municipalities, and its main river is 347 km long with an outlet in the Itaparica reservoir in the São Francisco River.

Caatinga is the predominant vegetation cover in the basin, followed by pasture and agriculture. Caatinga is a forest formation characterized by thornscrub, cactus, and bunch grasses. Crystalline basement predominates in the basin, resulting in shallow soil and rock near the surface, characteristics that influence runoff generation, considering that, in those conditions, there is low capacity for storage in the soil and low flow regulation. The drainage network, including the main watercourse, exhibits an intermittent regime that interrupts the flow during the dry season due to irregular precipitation. The rainy season extends from January to May and is influenced by the Intertropical Convergence Zone, the main atmospheric system that regulates precipitation in this region. The dry season is between June and December.

The PRB exhibits susceptibility to desertification, classified as “moderate” and “high”, and vegetation suppression is the main stressor responsible for the development of the desertification process (Ferreira et al., 2014). The predominant climate in the basin area is BShw according to the Köppen-Geiger climate classification, characterized by a hot semiarid climate with spring-summer rains. However, in some regions of highlands, where humidity is higher due to a decrease in evaporation rates triggered by milder temperatures, the climate

characteristics are different with these areas classified as tropical humid and semi-humid. Annual rainfall ranges from 300 to 1200 mm, with the highest values occurring at Alto Pajeú, while

the lowest annual accumulated values are found in areas close to the São Francisco River; therefore, semi-aridity is very pronounced (Assis et al., 2015).

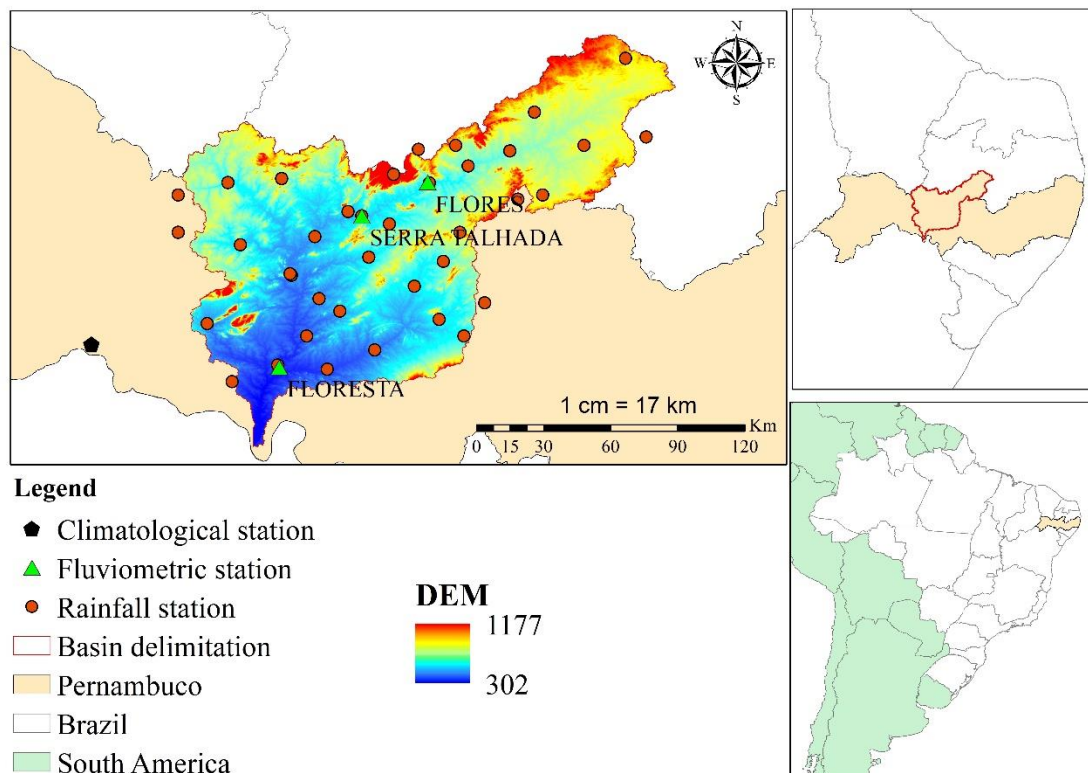


Figure 1. Location of the PRB with the DEM, rain gauges, climatological station, and streamflow gauges Flores, Serra Talhada, and Floresta (from north to south).

### Hydrological simulation

The MGB is a distributed hydrological model for large basins (Collischonn et al., 2007). It comprises modules of evapotranspiration, water balance in the soil, surface, sub-surface, baseflow, and routing in the drainage network.

The water balance in the soil is accomplished using a method based on the surface flow generation regulated by the excess storage capacity and the relationship between soil moisture and the fraction of area with saturated soil. The version of the model used in this study simulates flow routing in the channels using the Muskingum-Cunge method and spatial discretization based on unit catchments.

Calculating potential evapotranspiration in the MGB requires air temperature, relative humidity, net radiation, wind speed and atmospheric pressure (obtained from the Cabrobó weather station).

In the simulations with the MGB model, it is acceptable to use climatological normal to calculate evapotranspiration. This is useful when there are many missing data in the time series of

the climatological variables (like the Cabrobó station).

The simulations had daily time steps, including calibration, validation, and scenarios. However, in the calibration and validation process, the daily streamflow was converted to a monthly time step over 18 years: 1973-1982 for calibration and 1983-1990 for validation. Three stream gauges were selected in the Pajeú river to calibrate the MGB (Flores, Serra Talhada, and Floresta).

The results will be presented monthly. The calibration period was chosen based on the oldest LULC map available. So that the model was calibrated with data from the same period.

After calibration, the model was run to compare the baseline (1961-1990) and future scenarios of the Eta/CPTEC model, corresponding to the period from 2041 to 2070. Therefore, the aim was to compare the streamflow calculated by the MGB using climate forcing from the 20th century and LULC and climate scenarios from the 21st century.

MGB has a set of fixed parameters that can be estimated based on the physical characteristics of the region. For the PRB, these parameters were

estimated based on the estimation of Felix and Paz (2016) for the Piancó Basin because both study areas have similar physiographic characteristics. A unique set of values was calibrated for the entire basin for the other adjustable parameters (Table 1).

The parameters calibrated are:  $W_m$  - maximum water storage in the upper soil layer (mm);  $b$  - represents the statistical distribution of the soil water storage capacity;  $K_{bas}$  - gives the percolation rate for groundwater in the case of saturated soil (mm.day<sup>-1</sup>);  $K_{int}$  - gives the subsurface drainage of water from the soil layer (mm. day<sup>-1</sup>);  $XL$  - soil porosity index;  $CAP$  - maximum value of upward flow in the soil (mm.day<sup>-1</sup>);  $W_c$  - storage limit for upward or downward flow (mm);  $CS$  - surface propagation parameter;  $CI$  - subsurface propagation parameter;  $CB$  - baseflow propagation parameter (days);  $QB_{M3/S/KM2}$  - specific baseflow given in cubic meters per second per square kilometer.

The parameters were manually fitted based on a comparison between the measured and simulated discharges. Three criteria were used to evaluate the performance of the model: error of volume (EV), Nash-Sutcliffe coefficient (NS), and Nash-Sutcliffe coefficient of the logarithm of discharge (NSlog). The closer to 1 the values of NS and NSlog, the more robust the simulation, and an EV near zero means well-adjusted discharges. The NS is influenced by the peak of the streamflows and the NSlog allows to measure the fit of low streamflows. In addition to the assessment with observed streamflow, the soil moisture and evapotranspiration were compared with other estimations. The average soil moisture in the PRB can be estimated using the European Space Agency Soil Moisture Climate Change Initiative (ESA CCI SM) with a spatial resolution of 0.25° (Chung et al.,

2018). The soil moisture was compared after the calculation of its normalized values:

$$nsm(\%) = \frac{SM_i - SM_{min}}{SM_{max} - SM_{min}} \cdot 100 \quad (1)$$

Where:  $nsm$  is the normalized soil moisture,  $SM_i$  is the soil moisture of the month  $i$ ,  $SM_{min}$  is the minimum value and  $SM_{max}$  is the maximum value. These values are the average corresponding to the drainage area of the stream gauge Floresta and for the MGB and ESA CCI SM time series. The annual actual evapotranspiration was estimated, making the difference between precipitation and streamflow ( $P - Q$ ).

*Future LULC scenarios – definition of the hydrologic response units (HRU)*

The combination of the LULC map and soil type map characterizes the hydrologic response units used in the MGB. The LULC map was provided by the MapBiomas project (Souza et al., 2020), which uses automatic cloud processing classifiers developed and operated on the Google Earth Engine platform to generate historical time series of annual land-use maps in Brazil. Three years (1985, 2000 and 2017) were selected to evaluate the evolution of land use in the PRB.

These maps were used as a reference to create future LULC scenarios in the land change modeler (LCM) integrated into the TerrSet software. Firstly, the maps of 1985 and 2000 were used to simulate the map of 2017, considering the transition from caatinga to agriculture i.e., this is to validate the LCM (illustrated in Figure 2). Then the maps of 1985 and 2017 were used as a reference to create future LULC scenarios.

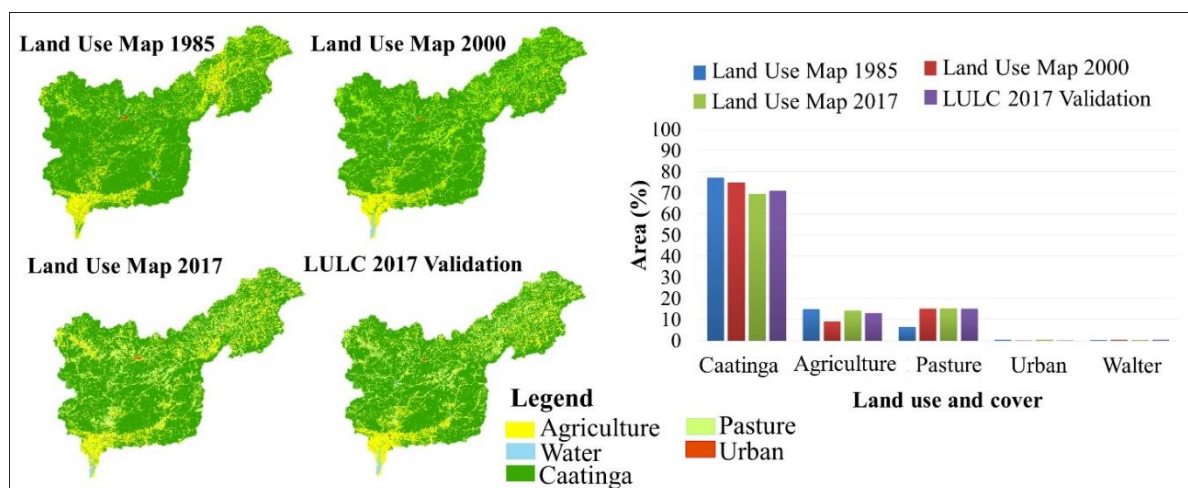


Figure 2. Assessment of the LCM: LULC maps on the top and bar graph of the classes. All maps are from MapBiomas, except the “LULC 2017 Validation” (estimation of the LCM).

The simulations for the calibration of the MGB used the 1985 land use map, and the set of parameters was repeated in the simulation of all scenarios. The LULC change's effects are considered according to the proportion of the HRUs change in the basin. The land use scenario referring to 1985 was chosen for the simulation because it represents the period selected for the calibration and validation.

The LCM measures changes in LULC by considering the losses and gains of the area per class of use. In addition, the LCM can predict future LULC, identifying areas that are well-established and in transition from one class  $n$  to another  $p$  (Eastman, 2016; Uddin et al., 2015). The multilayer perceptron (MLP) neural network model available in the LCM was adopted in this application. The MLP model has some advantages; for example, user intervention is not required, and it provides detailed information about the contribution of the explanatory variables (Eastman, 2016; Estoque et al., 2019; Folharini & Oliveira, 2020; Leta et al., 2021; Xavier & Silva, 2018)

Two LULC future scenarios in the PRB were defined for the year 2055. Both future scenarios have more pessimistic characteristics, that is, an increase in anthropic interventions but considering the possible transitions of classes from the current reality. For future scenario 1, the criterion was to define the transition from caatinga

and pasture to agriculture. Scenario 2 considers the transition from caatinga to pasture and agriculture. In addition, the LULC of 1985 was considered the reference because of its good condition, as it presents little human intervention.

Figure 3 reveals the resulting maps for the LULC scenarios, showing the significant variation of the caatinga class. In 1985, approximately 60% of the basin was occupied by caatinga and shallow soil, which reduced to 49.8% in scenario 1 and 42.4% in scenario 2. The transition of the agriculture class ranged in 1985 from 6.5% to 24.4% in scenario 1 and 21.6% in scenario 2 (Figure 4). These results demonstrate that the LCM, according to the criterion of the approximate region and the potential of transition of the LULC maps between 1985 and 2017, found a greater probability of occurrence of scenario 2 than of scenario 1, considering that the area occupied by the caatinga in the latter scenario was greater than that in the former scenario.

It is important to note that urban expansion was not remarkable in future scenarios because LCM uses the criterion of class transition potential. According to information from MapBiomass, there was little evolution of urban areas in the PRB until 2017, which, by conforming to LCM simulations, resulted in little probability of occurrence of intense urbanization until the middle of the 21st century.

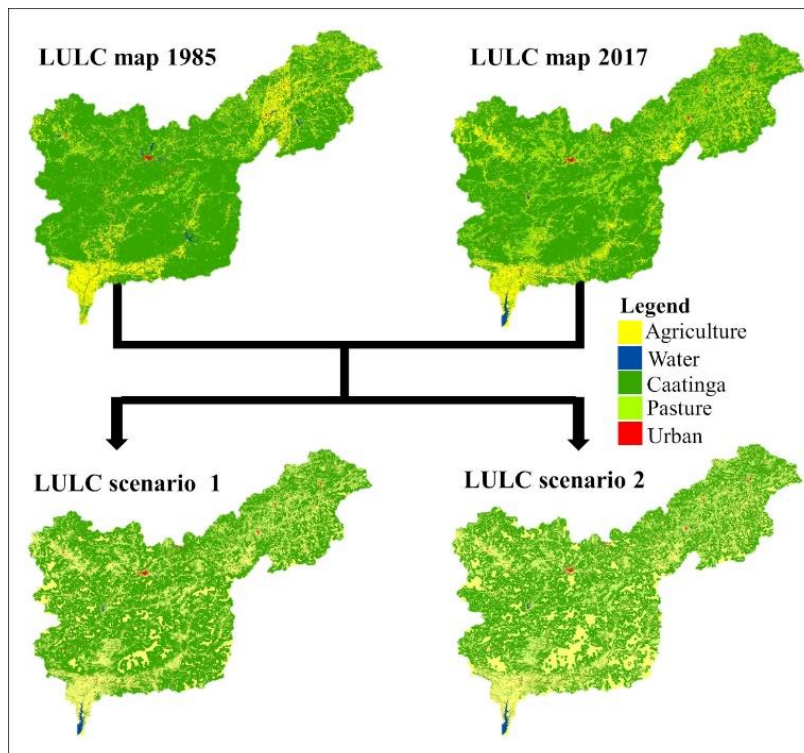


Figure 3. Maps of the current and future LULC scenarios for the PRB.

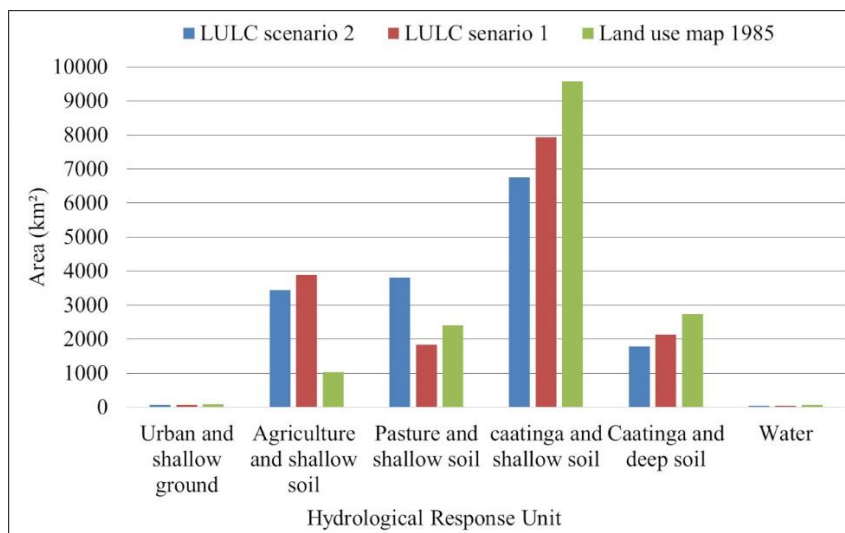


Figure 4. The surface area of classes for the current and future LULC scenarios.

### Future climate scenarios

The future climate scenarios adopted were projections from the Eta/CPTEC RCP 4.5 and 8.5, a regional climate model that uses GCM output as a boundary condition to downscale climate change scenarios (Chou et al. 2014a; Chou et al. 2014b; Lyra et al., 2017). The GCMs used in the downscaling were the Brazilian Earth System Model (BESM) (Nobre et al., 2013), Canadian Earth System Model version 2 (CanESM2) (Christian et al., 2010), Hadley Center Global Environment Model version 2 (HadGEM2-ES) (Collins et al., 2011), and Model for Interdisciplinary Research on Climate version 5 (MIROC5) (Watanabe et al., 2010). After downscaling with the Eta/CPTEC model, the output data are referred to as Eta-BESM, Eta-CanESM, Eta-HadGEM, and Eta-MIROC. The data selected for the hydrological simulation were air temperature at 2 m above the Earth's surface ( $^{\circ}\text{C}$ ), atmospheric pressure at the Earth's surface (hPa), total precipitation (mm), wind speed at 10 m (m/s), relative humidity (%), and average incident radiation at the Earth's surface ( $\text{W}/\text{m}^2$ ). The time step was daily for precipitation and monthly climatological normal for the other variables. The bias correction of precipitation was performed using the quantile-quantile mapping method (Bárdossy & Pegram, 2011), and the air temperature was corrected using the delta-change method (Adam et al., 2017). To make it compatible with the time horizon of the LULC scenario (2055), the simulations covered the period of 2041-2070. The streamflows simulated with the MGB model using these data are called MGB-Eta-BESM,

MGB-Eta-CanESM, MGB-Eta-HadGEM, and MGB-Eta-MIROC.

In order to assess the influence of the LULC and climate change scenarios over the streamflow regime, three values were considered: one representative of the period of peak flow ( $Q_{10}$ ), one representative of the minimum streamflow during the rainy season ( $Q_{95\text{-sea}}$ ), and the mean streamflow. The  $Q_{95\text{-sea}}$  is obtained from the flow duration curve built with the mean annual streamflow referred to as the rainy season (January to April). The base for comparison is the "Baseline + LULC 1985", which means simulation with GCM data for 1961-1990 and the LULC map of 1985. The other simulations are the GCM data for 2041-2070 and the LULC map of 1985, LULC scenarios 1 and 2.

### Results and discussion

The results were evaluated regarding calibration and validation of the MGB model by considering the hydrograph and the criteria NS, NSlog, and EV. Simulations of future climate change and LULC scenarios were analyzed regarding streamflow and precipitation.

#### *Hydrological modeling – calibration and validation*

The MGB model was calibrated and validated only with the HRU for 1985, and the parameter set was repeated for all future scenarios. The set of calibrated and fixed parameters are shown in the Tables 1. The names of the classes refer to land use and soil type respectively. For example, "Urban\_shallow" is the combination of land use Urban and shallow soil. Collischonn et al.

(2007) describes in detail the parameterization of the model MGB. Six out of seven parameters had the same value for all classes of HRUs. The parameter  $W_m$  (representing the soil water storage capacity) had different values according to the LULC and soil type combination. Based on other MGB applications, we assumed that there is a direct relationship between  $W_m$  and the HRUs, i.e., greater values of  $W_m$  for deeper soils and forest land cover like caatinga in this study.

The MGB satisfactorily simulated the hydrograph's seasonal variation and rising and falling streamflows. Figure 5 shows the simulated and measured streamflows after calibration and validation at the three stream gauges. Table 2 lists the statistics of the simulations for the calibration and validation corresponding to the three stations selected in the PRB.

**Table 1.** Set of parameters calibrated.

Classes	$W_m$	$b$	$K_{bas}$	$K_{int}$	$XL$	$CAP$	$W_c$
Urban_shallow	200.0	0.12	0.01	4.00	0.67	0.00	0.10
Agriculture_shallow	400.0	0.12	0.01	4.00	0.67	0.00	0.10
Pasture_shallow	100.0	0.12	0.01	4.00	0.67	0.00	0.10
Caatinga_shallow	2600.0	0.12	0.01	4.00	0.67	0.00	0.10
Caatinga_deep	2800.0	0.12	0.01	4.00	0.67	0.00	0.10
Water	0.0	0.10	0.01	4.00	0.67	0.00	0.10
CS	20.0						
CI	50.0						
CB	8000.0						
QB_M3/S/KM2	0.0010						

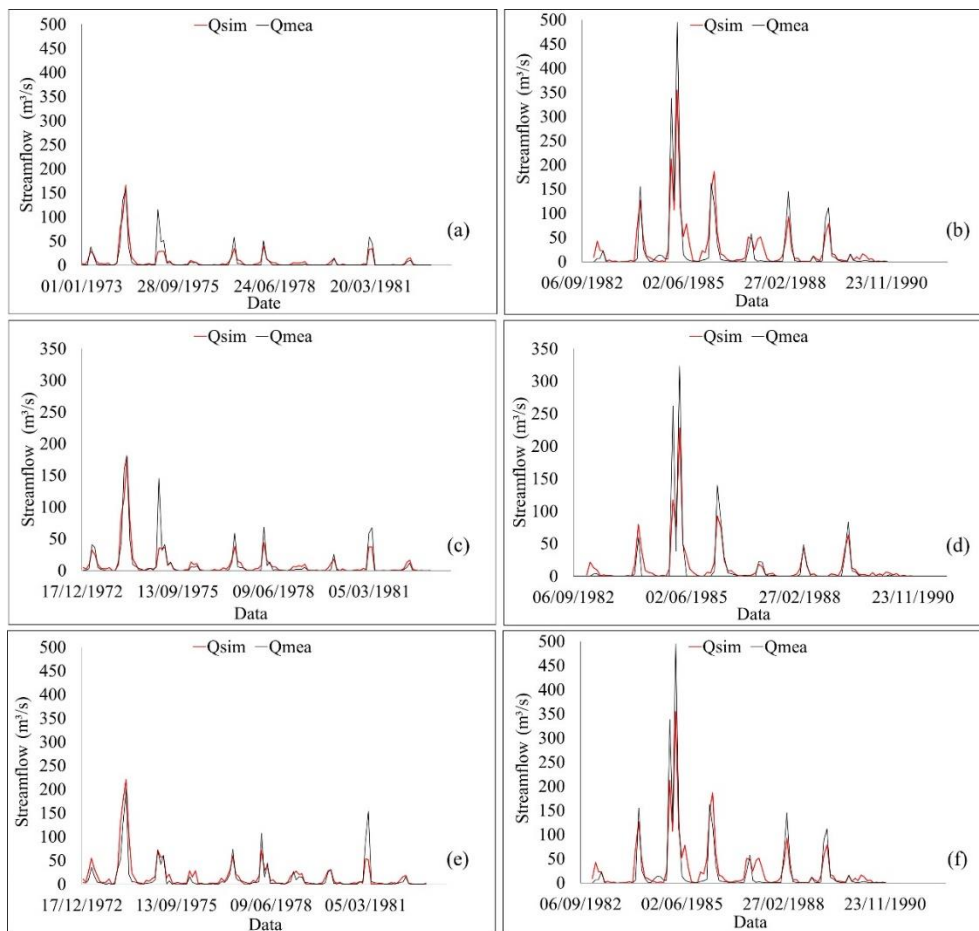


Figure 5. Hydrographs for the calibration (1973-1982) and Validation (1983-1990), respectively, for the stations Flores (a, b), Serra Talhada (c, d), and Floresta (e, f).

**Table 2.** Statistics of the MGB model for the calibration and validation periods using monthly data.

Stream gauges	Calibration (1973–1982)			Validation (1983–1990)		
	NS	NSlog	EV (%)	NS	NSlog	EV (%)
Flores	0.79	0.77	-0.64	0.89	0.49	-6.96
Serra Talhada	0.78	0.97	2.91	0.81	0.67	-1.10
Floresta	0.70	0.53	-25.93	0.84	0.64	-11.37

The simulated peak flow was underestimated in both periods compared with the measured peak flow. It is also important to mention the lack of capability of the model in representing the low flow, especially, for the validation period considering the decrease of the NSlog values. The metrics, however, are comparable to other studies conducted in basins located in the northeast semiarid region and presenting similar characteristics in terms of drainage area, climate, soil type and vegetation. In these studies, the NS metric varied between 0.52 and 0.89: Piancó basin (Escarião et al., 2012; Felix & Paz, 2016; Souza et al., 2017), Capibaribe basin (Ribeiro Neto et al., 2014), Piranhas-Açu basin (Silva & Medeiros, 2018).

Besides the streamflow evaluation, other variables simulated by the MGB were also analyzed after parameter calibration. Figure 6

presents the assessment of the soil moisture (entire PRB) and evapotranspiration considering the average for the drainage area of the stream gauge Floresta. The soil moisture was underestimated, following the trend presented in the comparison of streamflow. More investigations must be done to understand the possible factors influencing this underestimation and improve the simulation of the soil moisture. For drought studies, for example, it is important that the values of soil moisture be well simulated to capture the critical periods and estimate characteristics like duration and frequency of the events. Notwithstanding the soil moisture underestimation, the model simulated well the seasonal variation and the magnitude of the variation compared with the ESA-CCI-SM database (Figure 6a). The annual evapotranspiration was also well represented by the MGB (Figure 6b).

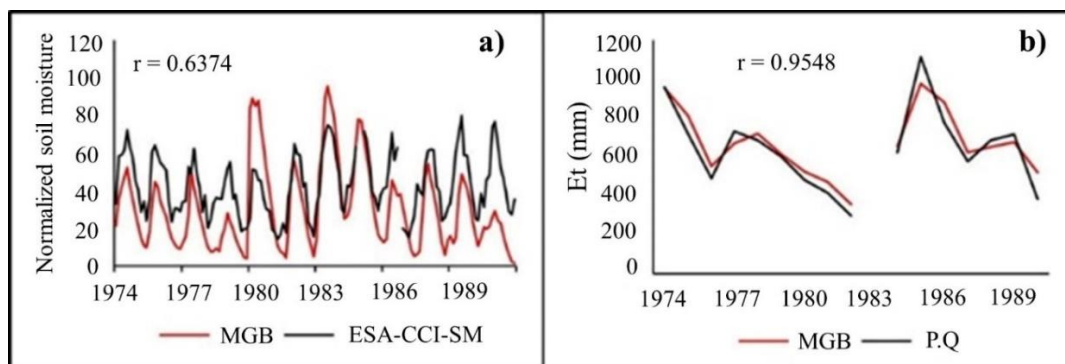


Figure 6. Normalized monthly soil moisture (1979–1990) (a) and annual evapotranspiration (1974–1990) (b).

*Hydrological simulation of the LULC scenarios*

To verify the impact of the LULC scenarios, the MGB was simulated using the climate variables corresponding to the calibration period (1973-1982) and the LULC maps of 1985, scenario 1 and scenario 2. As demonstrated in Figure 7a, the streamflow was greater in the scenario with the smallest forest area (scenario 2). This result is similar to what is reported in other studies (Bayer & Collischonn, 2013; Brito Neto et al., 2021, Magalhães et al., 2018; Perazzoli et al.; 2013; Sirqueira et al., 2022), i.e., areas occupied by pasture tend to generate greater runoff when compared to areas occupied by arboreal vegetation. According to the simulations, the actual

evapotranspiration (Figure 7b) and soil moisture (Figure 7c) were less affected.

However, Lins et al. (2024) report that vegetation restoration would compensate for reductions in water availability in a semi-arid, Brazilian experimental basin. Likewise, Sirqueira et al. (2022) found an increase in flows that coincides with an increase in natural forest cover, also using the MGB-IPH model.

Research carried out using the MGB model to simulate LULC scenarios has shown divergent results, sometimes showing that replacing natural vegetation with agriculture or pasture causes a decrease in flow and at other times that the opposite

situation occurs (Brito Neto et al. 2021; Jati & Silva, 2017; Sirqueira et al., 2022).

It is necessary to better understand the issue of model parameterization which, in turn, is

closely linked to the level of evolution of the LULC scenarios. Since the size of the URH classes will indicate the value of the  $W_m$  (maximum water absorption capacity of the soil).

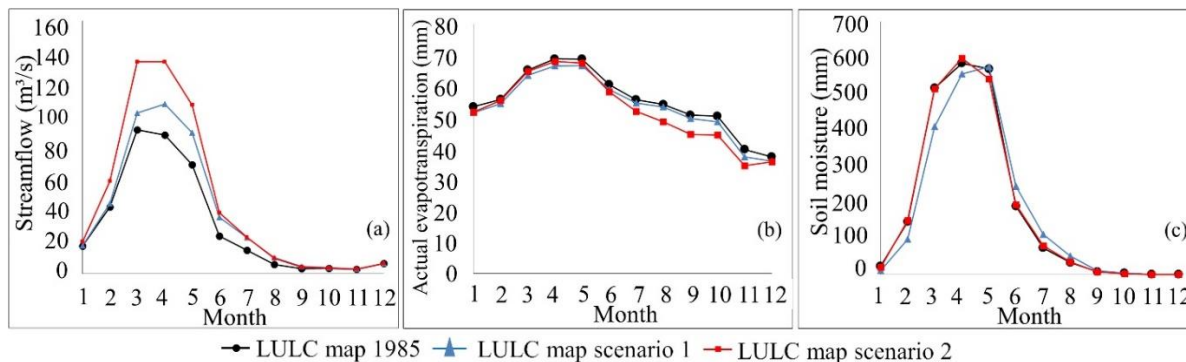


Figure 7. Long-term average streamflow at the basin outlet (a), actual evapotranspiration (b), soil moisture (c) referring to LULC scenarios and observed climate variables (1973-1982).

*Hydrological simulation of the LULC and climate scenarios*

Regarding modeling scenarios with the MGB, there was a change in the flow concerning the various combinations of climate scenarios and land use analyzed. The hydrological simulation with the Eta-BESM RCP 4.5 combined with the LULC scenarios showed a tendency for higher streamflow to occur when the Eta-BESM RCP 4.5 scenario is associated with LULC scenario 2 (Figure 8a).

This behavior was also found by Costa et al. (2022) using the MGB model for the Doce River basin when employing climate scenarios, but it is divergent from that reported by Brito et al. (2019) and Marengo (2004) when claiming that the BESM scenario shows a drier climate trend in most of South America.

And also by Gomes (2020) when analyzing data from the BESM scenarios on the Madeira River, which also showed an increase in rainfall. Silva et al. (2021) also found that the Eta-BESM scenario shows an increase in precipitation in both RCP 4.5 and RCP 8.5 in semi-arid regions of the state of Paraíba/BR.

However, Brito et al. (2019) found that the BESM showed a drier climate trend for most of South America, particularly in the northern part of the continent. This result differs slightly from that found in the current study.

It was also possible to observe the same behavior for the Eta-HadGEM RCP 4.5 (Figure 8b). A similar result was found by Schuster et al. (2020) for the Laguna dos Patos transboundary using data from the HADGEM model. For the RCP 8.5, the Eta-BESM simulates a great volume of precipitation, resulting in excessive generation of

streamflow (e.g., the peak flow doubles from the baseline to “RCP 8.5 + land use map 1985” simulation) (Figure 9a). The opposite occurred for the Eta-HadGEM considering the RCP 8.5, with significant reduction of precipitation, impacting the generation of streamflow (all scenarios presented values lower than the baseline) (Figure 9b).

The hydrological simulation with the MGB-Eta-CanESM and MGB-Eta-MIROC showed a higher streamflow in the baseline period because of the greater volume of precipitation in the baseline compared to the Eta-MIROC and Eta-CanESM RCP 4.5 scenario (Figure 8c and 8d). It can also be observed that LULC scenario 2 had the highest flow, showing that streamflow tends to increase in scenarios with less conservation of natural vegetation. In the RCP 8.5, there is a slight increase of streamflow generation for the Eta-MIROC (Figure 9c), and an intensification of reduction for the Eta-CanESM (Figure 9d).

The MGB-Eta-CanESM and MGB-Eta-MIROC runs are closer to what Tibúrcio et al. (2023) found for the Amolar Creek catchment, located in the semi-arid region of Pernambuco. With a significant reduction in water availability in the basin and a reduction in base flow. This result is in line with that reported by Brito et al. (2019), who found that MIROC tends towards a drier climate.

This result differs slightly from that obtained by Andrade et al. (2020), who found that the forecasts of the Eta-MIROC5 and Eta-HadGEM2 models showed that the seasonal flow will decrease in the Mundaú river basin, both in the rainy and dry seasons, except in the medium term for Eta-HadGEM. Chou et al. (2014a) found that Eta model simulations conducted by HadGEM2-

ES show wet trends, while Eta conducted by BESM and MIROC5 show trends towards drier conditions.

It is worth noting in this study that the differences in the streamflow between the LULC scenarios 1 and 2 occurred mainly due to the fixed parameters of the MGB model. When calibrating the MGB, we considered that the parameter  $W_m$  is influenced by the soil type and the vegetation

cover, i.e., there is a direct relation between vegetation height and the value of  $W_m$ . Following this guidance, the soil storage capacity has ascendant values for pasture, agriculture and caatinga. In this sense, as the model generates runoff from the moment the soil reaches its storage capacity, lower values of  $W_m$  are expected to provide a greater volume of surface runoff which reaches the river channel more quickly.

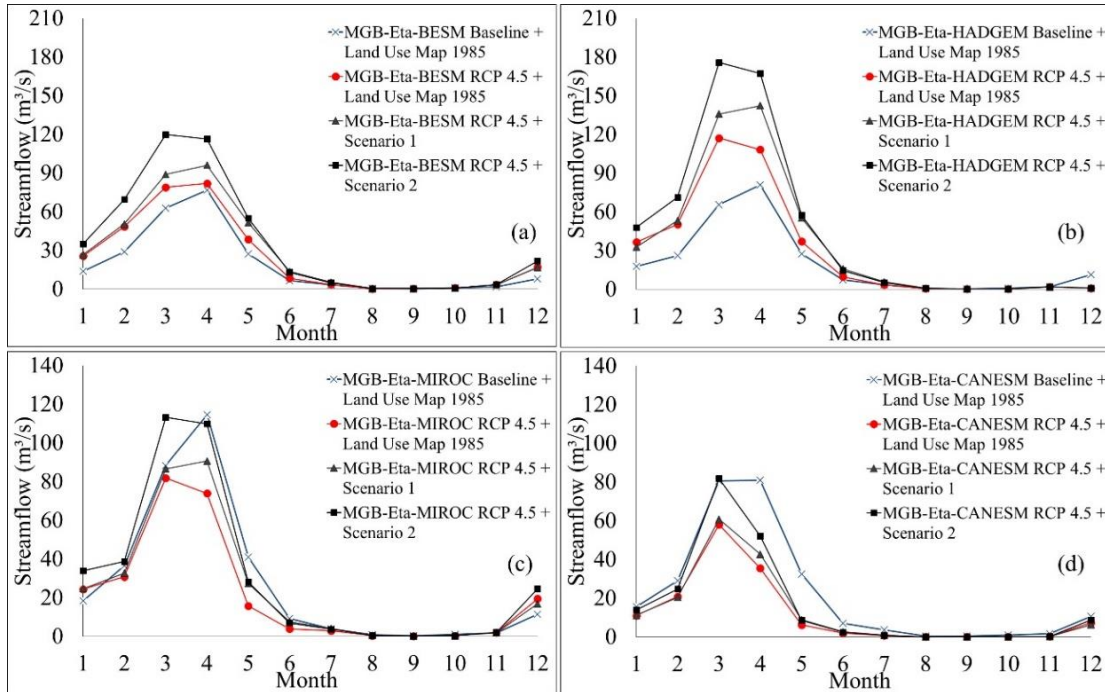


Figure 8. Long-term monthly average streamflow at the basin outlet for LULC and climate scenarios (a) MGB-Eta-BESM; (b) MGB-Eta-HadGEM; (c) MGB-Eta-MIROC; (d) MGB-Eta-CanESM. Baseline is the period 1961-1990, and RCP 4.5 is the period 2041-2070.

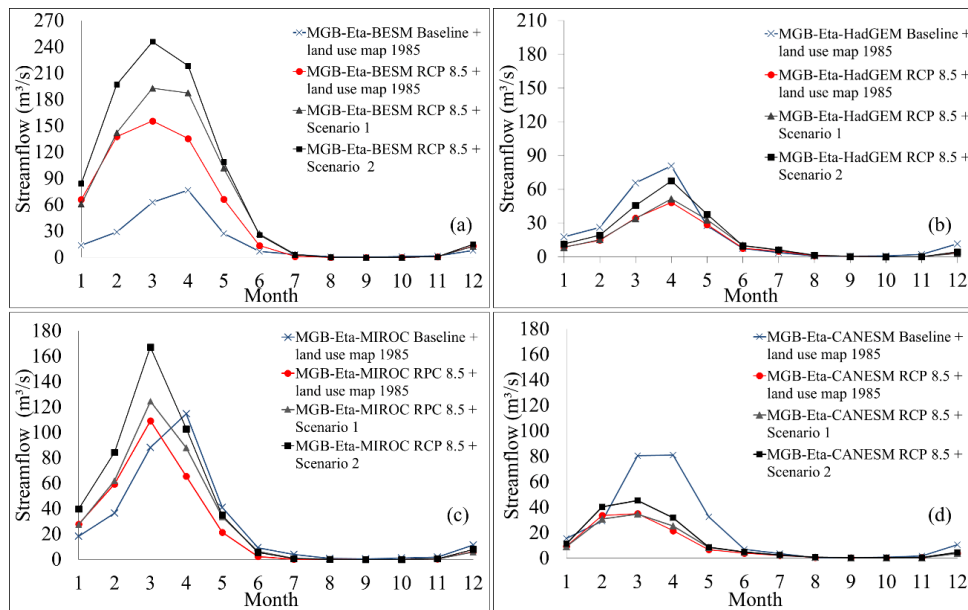


Figure 9. Long-term monthly average streamflow at the basin outlet for LULC and climate scenarios (a) MGB-Eta-BESM; (b) MGB-Eta-HadGEM; (c) MGB-Eta-MIROC; (d) MGB-Eta-CanESM. Baseline is the period 1961-1990, and RCP 8.5 is the period 2041-2070.

Figure 10 exhibits the climatology of the precipitation in the PRB for the climate models considering the periods baseline and RCPs. There is an increase in precipitation for the Eta-BESM and Eta-HadGEM models and a decrease for Eta-MIROC and Eta-CanESM in the RCP 4.5 (Figure 10a). The Eta-BESM and Eta-CanESM keeps the sign of the change in the RCP 8.5, however, the Eta-HadGEM and Eta-MIROC switch the sign (Figure 10a). Indications of seasonality shift were observed, especially for the RCP 8.5, and the models Eta-BESM, Eta-MIROC, and Eta-CanESM (rain season starts earlier). The Eta-HadGEM shows a possible intensification of the precipitation regime, increasing in the wet season and decreasing in the dry season for the RCP 4.5, not observed in

the RCP 8.5, probably, because of the uniform decrease of the precipitation.

Porto et al. (2022) analyzed the rainfall data from the Eta-HadGEM regional model for the Pajeú river basin and found that the values are closer to the observed rainfall between 2006 and 2037. However, rainfall was higher between 2038 and 2068.

Jati and Silva (2017) tested the sensitivity of the MGB model to changes in rainfall volumes in the Caruá-Una basin and found that a 50% decrease in rainfall reduced flow by between 14% and 32% and a 50% increase in rainfall increased it by 218.6%, showing the model's strong sensitivity to positive or negative changes in the rainfall regime.

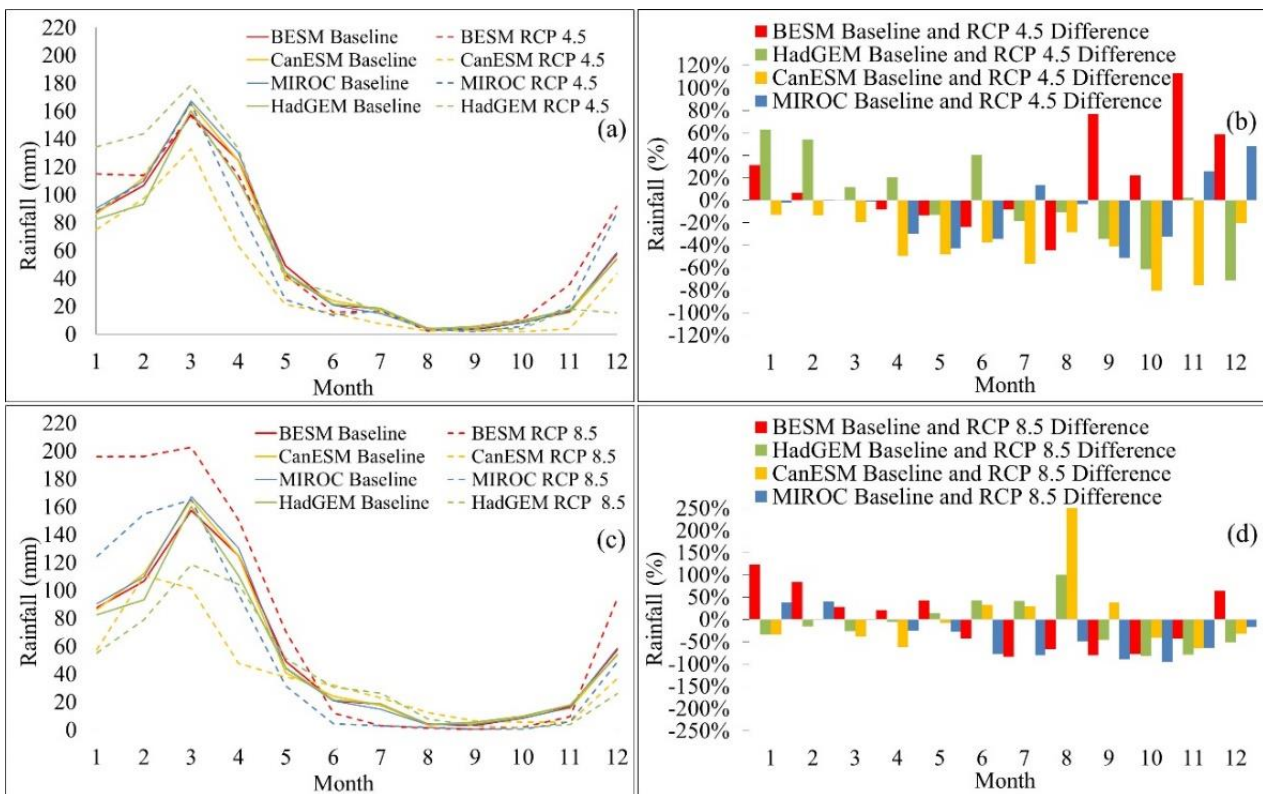


Figure 10. Long-term average precipitation in baseline, RCP 4.5 (a, b), and RCP 8.5 (c, d) climate scenarios.

The alterations of the streamflow regime are summarized in Figure 11, considering the average (10a),  $Q_{95-sea}$  (10b), and  $Q_{10}$  (10c). Observing the simulation of the GCMs with the LULC 1985, there was an increase of the streamflow for the MGB-Eta-BESM (both RCPs) and MGB-Eta-HadGEM (RCP 4.5) and a decrease for the MGB-Eta-CanESM (both RCPs) and MGB-Eta-HadGEM (RCP 8.5) (from the baseline to future scenarios). The Eta-MIROC had the smallest changes in the streamflow regime. Owing to the change of the vegetation cover, all categories of streamflow (average,  $Q_{95-sea}$  and  $Q_{10}$ ) increased for

the simulation “RCP + LULC 2” in all models in comparison to “RCP + LULC 1985”.

The observation of the influence of the LULC scenarios without climate scenarios allowed to verify the trend of increase of the streamflow in the PRB. This is corroborated by other studies conducted in the Brazilian semiarid (for example, Magalhães et al., 2018). The sign of the change was positive for the average,  $Q_{95-sea}$  and  $Q_{10}$ , but with greater magnitude for the average and the LULC 2 scenario. This behavior differs from that found by Wu et al. (2020) for the Luanhe river basin, located in the Chinese semiarid region. There was an increase in the base flow in the dry season

associated with the vegetation coverage expansion. In our study, the reduction of forest (caatinga) increased the streamflow.

The influence of changes in the LULC may be insignificant when the scenario simulated is restricted, a case reported by Blainski et al. (2014) where the alteration considered only the recovering of riparian vegetation. In the review of paired-watersheds experiments, Andréassian (2004) shows that it is obvious that deforestation increases annual flow, however, the effects are highly variable. The intrinsic variability of the watershed can define the degree of dependence on LULC (Blainski et al., 2017). Paired-watersheds experiments evaluate the impacts of the LULC change by monitoring two watersheds as similar as possible in terms of size, morphology, geology and climatic forcing (Andréassian, 2004).

Two simulations had the trend to increase the streamflow in this ascending order: “Baseline + LULC 1985”, “Future + LULC 1985”, “Future + LULC 1”, “Future + LULC 2”. The simulations of the RCPs presented an intensification of the shift sign from 4.5 to 8.5, increase with the MGB-Eta-BESM and decrease with the MGB-Eta-CanESM. The MGB-Eta-HadGEM switched the sign, from increase (RCP 4.5) to decrease (RCP8.5), and the MGB-Eta-MIROC had little changes. Koch et al. (2020) also identified similar behavior in the PRB with the HadGEM (switch of the sign) and MIROC (slight increment of the average streamflow from the RCP 2.6 to 8.5). The intensification of changes by the combination of climate and LULC scenarios was also verified by Silva et al. (2022) in the Salgado river basin (in the Brazilian semiarid region) and by Santos et al. (2021) in the Tapacurá river basin (Pernambuco).

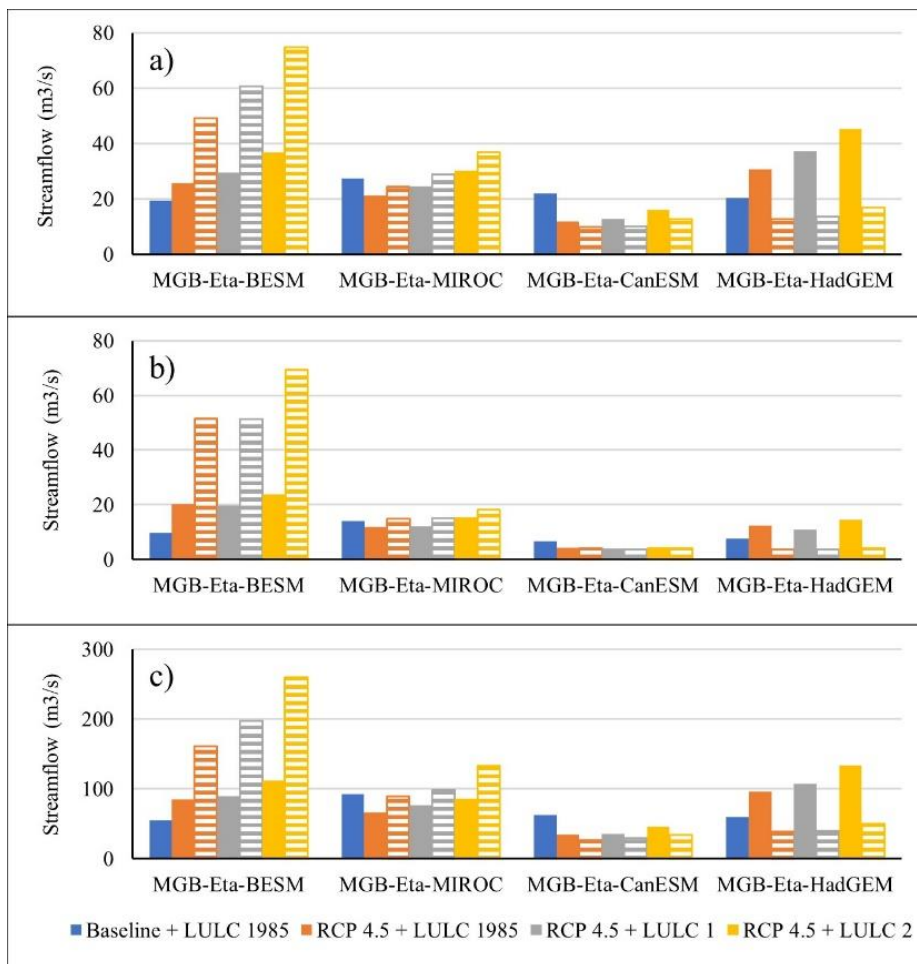


Figure 11. Streamflow in the PRB: average (a),  $Q_{95-sea}$  (b), and  $Q_{10}$  (c). The hatched bars refer to the RCP 8.5.

This result is similar to that found by Alemayehu et al. (2020) for Ethiopia, which found an increase in rainfall. And to that found by Diki et al. (2015) who found that the HadGEM2-ES model projects a wetter climate for South Africa and Nigeria. It is expected the increase of

streamflow when caatinga is removed. This characteristic affects the result after simulation with the GCMs. The CanESM, for example, has a negative precipitation anomaly. In this case, the LULC change would compensate the decrease in streamflow. On the other hand, the BESM has a

positive precipitation anomaly. In this case, the LULC change would intensify the increase of streamflow.

However, it is important to mention the key role of the soil moisture in the hydrological cycle and the difficulty of simulating it with the MGB in the PRB. The improvement of the soil moisture simulation could strengthen the arguments in favor of the compensation of streamflow generation verified between LULC scenarios and GCMs. The influence of the LULC scenarios without the RCP climate scenarios is shown in the Figure 12.

Figure 11 presents the streamflow simulation of the LULC scenarios without the RCP climate scenario. This shows the influence of the LULC change alone. Figure 12 exhibits the ensemble of the four GCMs combined with the LULC scenarios. It is noticeable the influence of the GCMs that simulates large volume of precipitation (especially BESM for the RCP 8.5).

Regarding seasonal streamflow, the results did not reveal different patterns of changes like those presented in the average streamflow. The alteration in the  $Q_{95-sea}$  and  $Q_{10}$  streamflow had the

same sign and a similar magnitude to the average streamflow (Figure 11).

The LULC and climate changes are two important drivers that affect the streamflow regime, especially in semiarid regions. The results presented in this study contribute to improving the comprehension of these impacts in the Brazilian semiarid region, showing how the PRB responds to the scenarios. For example, this approach should be considered in elaborating water resources master plans, assuming that these environmental changes interfere with processes like erosion, reservoir sedimentation and water availability.

The streamflow time series from the LULC and climate change scenarios can be used as input of allocation models and reservoir operation models to evaluate the impact of the alterations on the water supply for the human, agriculture, and animal uses (Koch et al., 2020, Ribeiro Neto et al., 2014). After simulation with allocation and reservoir operation models, adaptation measures can be elaborated to ensure water security in the region.

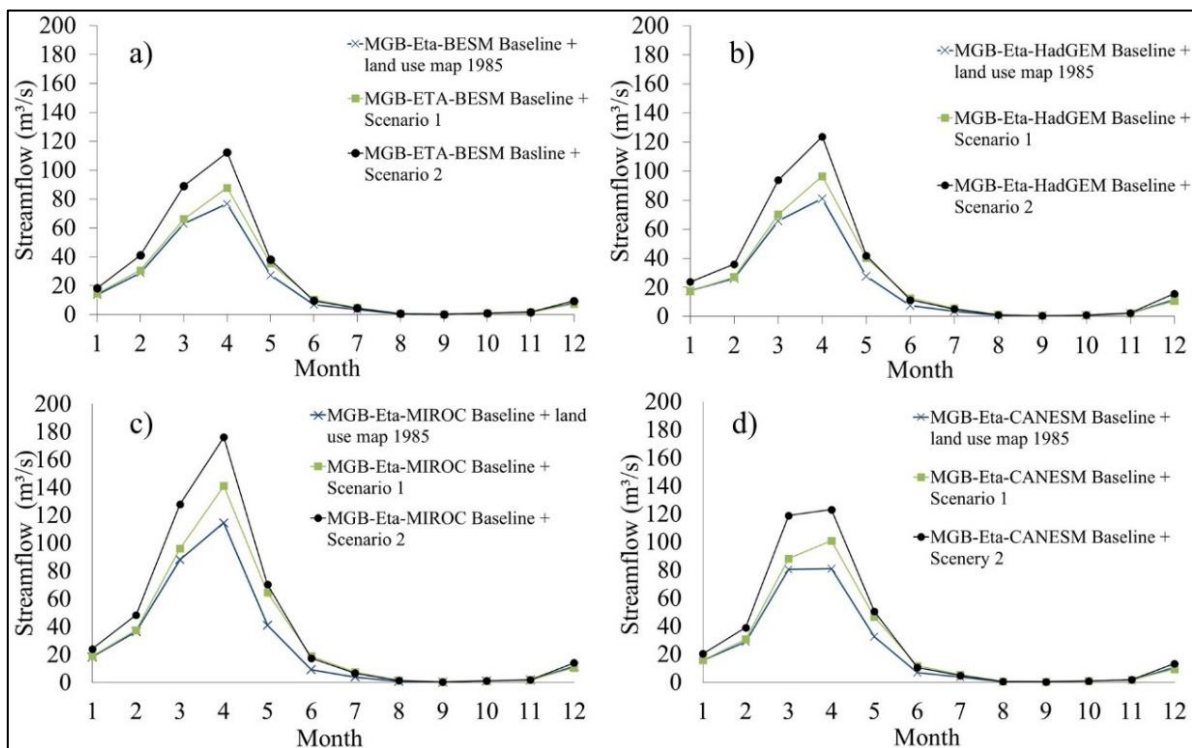


Figure 12. Simulation of the baseline for the GCMs and LULC scenarios.

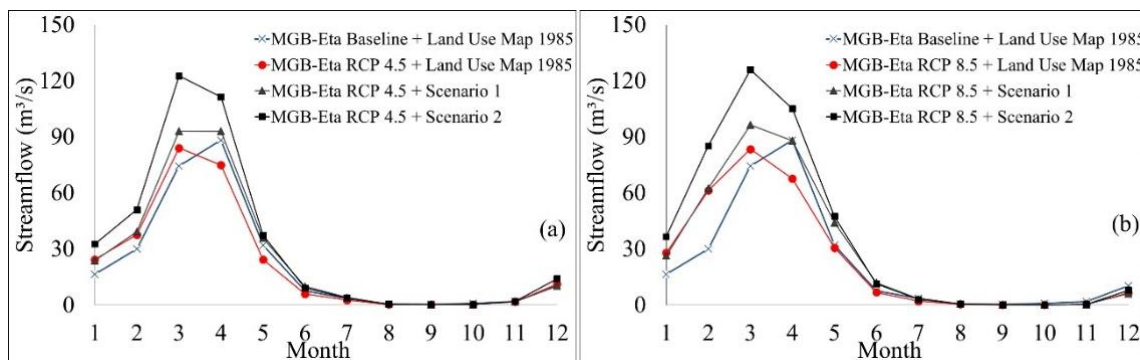


Figure 13. Ensemble of the four GCMs considering the RCPs 4.5 (a) and 8.5 (b).

Despite the coherence of the sign of the change in the simulation of the LULC scenarios, there is still uncertainty evolving the climate scenarios. Individually, the GCMs present results contradictory with shifted signs (increase of streamflow in one part of the GCMs and decrease in the other). The ensemble of the models is presented in the Figure 13. However, the influence of the GCMs that simulates large volume of precipitation (especially BESM for the RCP 8.5) could induce to excessive values of streamflow.

## Conclusions

This study aimed to evaluate the influence of future climate predictions associated with land use and cover scenarios on flow regimes (low, high and medium values) in the Pajeú river basin (Pernambuco/Brazil). Consistently, the simulations with the MGB-Eta-CanESM had a severe streamflow decrease in the future scenarios, in opposition to the consistent increase with the model MGB-Eta-BESM. The streamflow simulated by the MGB-Eta-HadGEM agreed with the MGB-Eta-BESM in the RCP 4.5 and with the MGB-Eta-CanESM in the RCP 8.5. Intermediate values obtained with the MGB-Eta-MIROC could indicate the more likely path of the streamflow regime in the region.

Systematically, the simulations indicated increase of discharge for the LULC scenarios that assume the expansion of agriculture and pasture. Based on the simulations of the MGB, the increment of streamflow after the replacement of caatinga by agriculture and pasture can intensify or compensate the impacts of climate change, depending on the GCM has a trend to produce more or less precipitation. Considering the relevance of this conclusion, we understand the importance of improving the soil moisture simulation to ratify the synergy verified between LULC scenarios and GCMs.

Complementary investigations are needed to reduce the uncertainties associated with the results produced by the GCMs to obtain more robust conclusions. Reduction of uncertainties can be reach increasing the number of models and identifying those with better performance in the region. Nevertheless, the simulations of scenarios have shown the importance of knowledge about the power of drivers like LULC and climate change in inducing environmental alterations.

In addition, it was possible to observe that the simulated scenarios behaved similarly to other studies that used data from the same climate model for regions with the same climatology. However, it is important to point out that more in-depth analyses need to be carried out in order to better understand which future climate scenarios are heading in the right direction. This understanding is of great importance for adopting measures to mitigate the effects of climate change.

It was also possible to see that the MGB hydrological model is capable of satisfactorily representing climate change scenarios associated with LULC scenarios, producing plausible results.

## Acknowledgments

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