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Climate change impact assessment in a tropical headwater basin

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ABSTRACT

Changes in precipitation and air temperature may produce different impacts on the hydrological regime, compromising water supply. This study focuses on climate change impacts in the Verde River Basin (VRB), a tropical headwater basin in southeast Brazil, located in the state of Minas Gerais. The Variable Infiltration Capacity model (VIC) was calibrated and validated in the Verde River Basin. The downscaling (Eta Regional Climate Model, at 20-km resolution) of three Global Circulation Models (CanESM2, HadGEM2-ES and MIROC5) were used to drive the VIC for a historical baseline (1961-2005) and three time-slices (2011-2040, 2041-2070 and 2071-2099), under RCPs 4.5 and 8.5 scenarios. The scenarios were used as input in the hydrological model after bias correction. The hydrological model (VIC) showed satisfactory statistical performance in calibration and validation, with CNS varying from 0.77 to 0.85 for daily and monthly discharges; however, it overestimated some peak flows and underestimated the recession flows. Multi-model ensemble means predict increases of the minimum and maximum monthly average temperature for the investigated area at the end of the century. The Eta-CanESM2 indicated greater warming, mainly for RCP8.5 at the end the century, whereas Eta-HadGEM2-ES showed higher reduction in the precipitation for RCP4.5 at the beginning of the century and for RCP8.5 at the end the century, negatively impacting the evapotranspiration and discharge. Among the Regional Climate Models (RCMs), the Eta-MIROC5 showed minor changes in the components of the hydrological cycle. This study suggests that Global Circulation Models represent an additional uncertainty, which should be accounted for in the climate change impact assessment.

Keywords: climate changes, RCP4.5, RCP8.5, VIC model.

Avaliação do impacto da mudança climática em uma bacia hidrográfica tropical de cabeceira

RESUMO

Mudanças na precipitação e na temperatura do ar podem produzir diferentes impactos no regime hidrológico, causando colapso no abastecimento de água. Este estudo focaliza nos impactos das mudanças climáticas na bacia do Rio Verde (VRB), uma bacia hidrográfica de cabeceira no sudeste do Brasil, localizada em Minas Gerais. O modelo hidrológico *Variable Infiltration Capacity* (VIC) foi calibrado e validado na bacia do Rio Verde. O *downscaling* (Modelo de Clima Regional Eta, com resolução de 20 km) de três Modelos de Circulação Global (CanESM2, HadGEM2-ES e MIROC5) foram usados no VIC com dados históricos (1961-2005) e em três intervalos de tempo (2011- 2040, 2041-2070 e 2071-2099), nos cenários RCPs 4.5 e 8.5. Os cenários foram usados como entrada no modelo hidrológico após a correção do viés. O modelo hidrológico (VIC) apresentou desempenho estatístico satisfatório na calibração e validação, com CNS variando de 0,77 a 0,85 para as vazões diárias e mensais; no entanto, superestimou alguns fluxos de pico e subestimou os de recessão. A média do conjunto de modelos prevê aumentos da temperatura média mensal mínima e máxima no final do século. O Eta-CanESM2 indicou maiores temperaturas, principalmente para RCP8.5 no final do século, enquanto Eta-HadGEM2-ES apresentou a maior redução na precipitação para RCP4.5 no início do século e para RCP8.5 no final do século, impactando negativamente na evapotranspiração e vazão. Entre os Modelos Climáticos Regionais (MCRs), o Eta-MIROC5 apresentou pequenas alterações nos componentes do ciclo hidrológico. Este estudo sugere que Modelos de Circulação Global representam incertezas adicionais, que devem ser consideradas na avaliação do impacto das mudanças climáticas.

Palavras-chave: modelo VIC, mudanças climáticas, RCP4.5 e RCP8.5.

1. INTRODUCTION

Changes in precipitation and air temperature associated with greenhouse gas emission increases have been studied through simulations accomplished by Global Climate Models (GCM). These simulations are essential for understanding future climate change and represent temporal and spatial variability of the climate in a land-ocean-atmosphere system (Chou *et al.*, 2014a; Oliveira *et al.*, 2017).

However, the study of climate change on the regional scale depends on regional physical processes and geographical characteristics, thus, the downscaling of the GCM simulations (Regional Climate Models, RCM) have been applied to assess regional hydrological variations caused by climate change (Rajib and Rahman, 2012; Chou *et al.*, 2014b). Regional hydrological responses to global climate change are strategic for water-resource management, agricultural and energy production, water availability, and for flooding and drought forecasting (Byun *et al.*, 2019).

Based on the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) (IPCC, 2014), the increase in global mean temperatures for 2081-2100 relative to 1986-2005 are limited in the range from 0.3 to 1.7°C (RCP2.6), 1.1 to 2.6°C (RCP4.5), 1.4 to 3.1°C (RCP6.0), and 2.6 to 4.8°C (RCP8.5). The potential impacts of climate change on hydrological regimes have been discussed widely.

Worldwide, numerous studies have applied the Variable Infiltration Capacity (VIC) hydrological model to study effects of climate change on the hydrological cycle (Chawla and Mujumdar, 2015; Bozkurt *et al.*, 2017; Wang *et al.*, 2019; Yang *et al.*, 2019; Dang *et al.*, 2020). Wang *et al.* (2019) assessed the impact of climate change on hydropower potential in the Nanliujiang River Basin, China, considering five GCMs under all RCPs scenarios. Dang *et al.* (2020) analyzed the effect of future climate on discharges in the upper Mekong River Basin, China, for five GCMs under RCPs 4.5 and 8.5 for the two selected models calibrated without and with reservoirs. Bozkurt *et al.* (2017) applied the VIC model driven by 26 GCMs under RCP8.5 to analyze the impact of climate change on four basins in Andes Cordillera, Chile.

Chawla ad Mujumdar (2015) examined the effects of climate change on discharge in the Upper Ganga Basin, India, for 6 GCMs under RCPs 4.5 and 8.5. Yang *et al.* (2019) assessed future climate change effects on extreme discharges in the Yangtze River, China, using seven GCMs under the highest emission scenario (RCP8.5). Global Circulation Models could impact the magnitude and change direction of hydrological response. A multi-model ensemble approach can improve the reliability of model predictions and better assess the hydrological modeling uncertainty.

In Brazil, the Grande River Basin (GRB), in the southeastern region, is essential for hydropower generation due to topography and abundant water availability, being, therefore, highly vulnerable to climate change (Alvarenga *et al.,* 2017). Some studies have investigated the impacts of climate change on the Grande River Basin headwater, indicating that both temperature and precipitation affect the discharge and total runoff magnitude (Viola *et al.*, 2015; Alvarenga *et al.,* 2016b; 2018; Oliveira *et al.*, 2017). In this region, these studies compared climate impacts on the future water cycle with Eta-HadGEM2-ES and MIROC5 inputs (Alvarenga *et al.*, 2016b; 2018; Oliveira *et al.*, 2017).

As reported by Alvarenga *et al.* (2016b), who used the Distributed Hydrology Soil Vegetation Model (DHSVM), the simulated discharge over the 21st century in a small watershed in Mantiqueira Range region (Grande River headwaters) indicated drastic changes under the RCP8.5 scenario, with reduction of mean monthly and annual discharge of 77 and 69%, respectively. In another study carried out at the same region, Oliveira *et al.* (2017) used the Soil and Water Assessment Tool (SWAT) hydrological model to assess the impacts of climate change on discharge and hence on hydropower potential, verifying mean monthly discharge reduction from 49.6 to 69.4% for RCP8.5, which implies serious problems in the potential of hydroelectricity generation. Viola *et al.* (2015), using the Lavras Simulation of Hydrology (LASH) model forced by A1B scenario emission (4th Assessment Report, AR4), simulated the hydrological changes in four headwater basins of the Grande River, wherein the results showed a reduction in the annual discharge for the first time-slice (2011-2040) and a substantial increase after 2041. In AR4, the A1B scenario is considered an intermediate scenario between high (A2 scenario) and low (B2 scenario) greenhouse gas emissions.

Independent of the considered scenario, it is well known that the water supply is closely related to climate patterns. In this way, climate changes modify the rainfall regime and increase the occurrence of extreme hydrological events, such as maximum discharges and long periods of drought. According to Nobre *et al.* (2011), although there is a considerable level of uncertainty regarding precipitation projections, there is significant convergence in the scenarios of a generalized increase in average air temperature and the frequency of heatwaves and hot nights (Marengo, 2007), thus impacting and consistently increasing water loss through evaporative processes and contributing to reduced water availability.

In this context, this research evaluated the hydrological impacts projected by two future scenarios (RCP4.5 and RCP8.5) using the downscaling of three GCMs (CanESM2, HadGEM2-ES and MIROC5) by the Eta Regional Climate Model, in the Verde River Basin, southeast Brazil. The VIC model has been widely used worldwide at basin macro-scales and has proved to be an effective tool for assessing climate change effects on a hydrological cycle. The novelty in this research is applying the VIC model on a micro-scale in a tropical headwater basin and evaluating the impacts projected by different GCMs in the headwater Grande River Basin. In addition, in order to improve the reliability and robustness of future projections, ensembles of hydrological models will be evaluated.

The VIC model has been used in larger scales; however, calibrating and validating a smaller scale basin can be helpful for analyzing model performance in representing local hydrological processes, as headwater basins in Brazil are not as monitored as larger watersheds. Thus, extrapolating for a larger-scale is expected to facilitate parametrization. Besides model performance, the impacts of climate changes on smaller-scale can be helpful for management policies; i.e., the Rio Verde Basin (RVB) has its own Basin Committee, and it is responsible for administrating water uses.

2. MATERIAL AND METHODS

2.1. Study Area

The Verde River Basin (VRB) has a drainage area of approximately 4,100 km2, with an elevation ranging from 809 to 2,742m, and is located in the headwater of the Grande River Basin, draining to the Furnas Hydropower Plant Reservoir, which has an installed capacity of 1,216 MW, the most important facility in southeast Brazil (Figure 1). The Grande River Basin is an important Brazilian river for hydroelectric production in the country (Viola *et al.*, 2014; Oliveira *et al.*, 2018; Bueno *et al.*, 2020). In this study, the wet season encompasses the period between October and March, while the dry season runs from April to September. The hydrological year extends from October to September of the following year.

According to the Köppen classification, Cwb predominates in the basin. The mean annual rainfall is approximately 1,500mm, and the annual mean temperature is 18°C, with a dry winter season (Mello *et al.*, 2012). The dominant soil classes in the highest parts of the Verde River Basin are Argisol (65.3%), Latosol (23.3%) and Cambisol (8.9%), with rocky outcrops (1.3%) and Fluvic Neosol (1.2%) in the lower parts (watershed lowlands). Main land uses include Pasture (69.2%), Forest (21.3%), Eucalyptus (0.2%), Agriculture (7%) and Urbanization (0.6%).

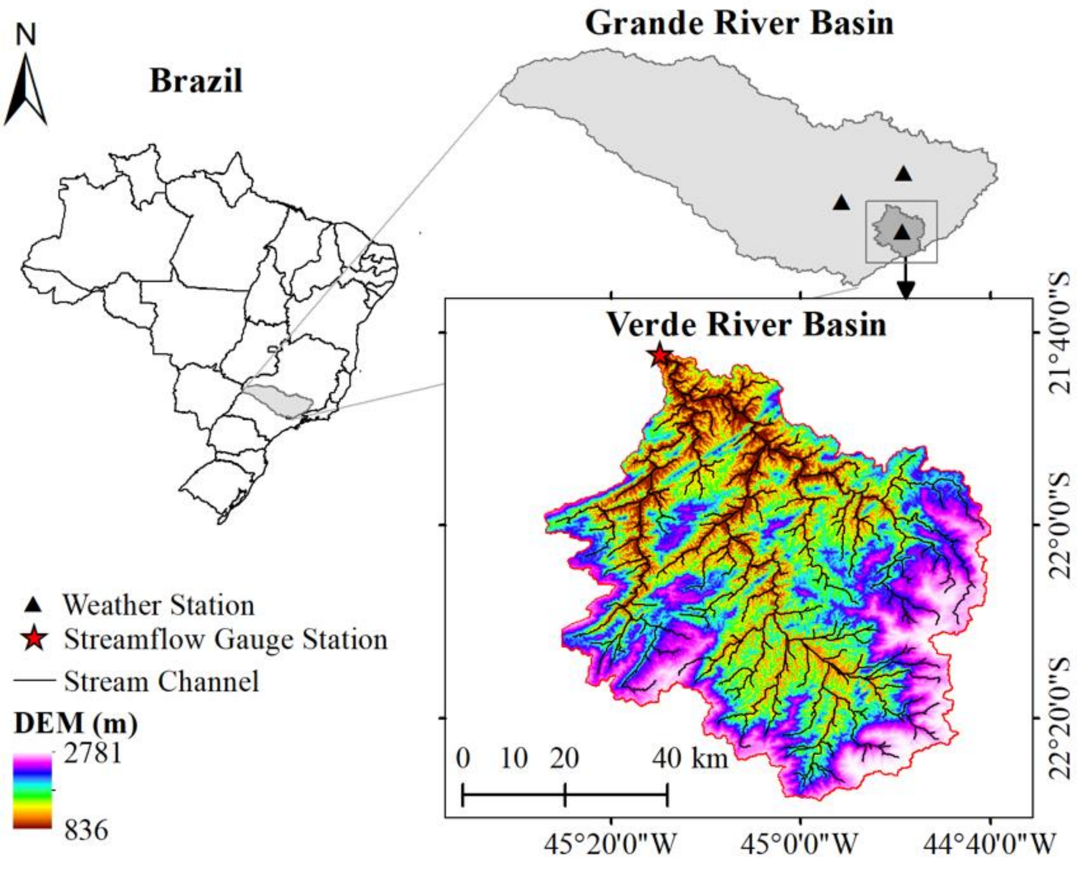

Figure 1. Geographical location of the Verde River Basin outlet in the Paraná River Basin and Grande River Basin, Minas Gerais state, southeast Brazil; and its Digital Elevation Model (DEM) and geographical location of the weather and streamflow gauge stations.

2.2. VIC model and set-up for the study area

The VIC model is a grid-based macroscale semi-distributed land surface hydrological model, which consists of two modules: (i) rainfall-runoff (Liang *et al.*, 1994; 1996; Liang and Xie, 2001) that simulates the water and energy fluxes that govern the terrestrial hydrological cycle; and (ii) routing model (Lohmann *et al.*, 1996; 1998) that calculates the discharge using linearized de Saint-Venant equations.

The VIC model calculates water balance on grid cells using a three-layer soil column. In the upper soil layer, the variable soil moisture capacity curve controls infiltration and surface runoff, and the lower soil layer controls the baseflow generation, using ARNO model formulation (Todini, 1996).

The VIC model was manually calibrated and implemented at a spatial resolution of 0.01° x 0.01° (3768 grid cells), and daily and monthly temporal resolution. ASTER sensor data with a 30-m resolution was used to obtain the Digital Elevation Model (DEM). Images of the Landsat 8 sensor with 30-m resolution were used to obtain the land-use/cover map through supervised and object-oriented classification techniques, and the soil class map was provided by the State Foundation for the Environment. The atmospheric variables in the calibration phase (daily precipitation, maximum and minimum temperatures, and wind speed) were obtained from the meteorological stations of National Institute of Meteorology (Figure 1). The same variables were obtained from the climate models in the baseline period (1961 – 2005) and in radiative forcing future scenarios (2011 – 2099).

The study period, from 1990 to 2005, was divided into three parts: warm-up (1990–1992), calibration (1993–1999), and validation (2000–2005). The assessment of model performance was carried out using daily discharge data observed at the "Três Corações" gauge station, obtained from the National Water Agency and Basic Sanitation (Figure 1).

2.3. Statistical tools for model evaluation and metrics for assessment of the hydrological changes

In order to evaluate the VIC model performance in reproducing observed daily discharge, four precision statistics were calculated: (i) coefficient of determination (R^2) that describes the variance between simulated and observed discharge; (ii) Nash-Sutcliffe efficiency coefficient (CNS) that reflects the matching degree between simulated and observed discharge (Nash and Sutcliffe, 1970); (iii) Relative error (Pbias) that is employed to measure the mean tendency of the difference between simulated and observed discharges (Gupta *et al.*, 1999); and (iv) Kling-Gupta efficiency (KGE) that is a decomposition of the CNS into three components: correlation coefficient (r), bias (β), and variability (α) (Gupta *et al.*, 2009).

KGE addressed by Gupta *et al.* (2009) relies upon two facts in using CNS to assess model performance: (i) bias is normalized by the standard deviation of the observed values, and for cases where the variability in the observed discharge is high, having less importance in the computation of CNS; and (ii) the maximum value of CNS is obtained when $\alpha = r$; therefore, since r will always be less than 1, when using CNS to evaluate performance of the model, we tend to select a value that underestimates the variability of discharge. According to Moriasi *et al.* (2007), R^2 and CNS values greater than 0.50 are considered acceptable, and Pbias less than |25%| presents satisfactory results.

In order to assess the VIC model capability to simulate discharge, when forced with climate models simulations, Flow Duration Curve (FDC) indices were used, following the "signature measures" of Yilmaz *et al.* (2008). To characterize the information in an FDC, we partitioned the curve into three different segments: (i) high-flow segment volume (MWH) with exceedance probabilities lower than 0.02, which presents watershed response to large precipitation events; (ii) low-flow segment volume (MWL) with exceedance probabilities higher than 0.9, which shows long-term sustainability of discharge; and (iii) mid-segment slope (MS) with exceedance probabilities between 0.2 and 0.7. Additionally, we appraised the seasonal variability between wet and dry season discharges (Season), according to Ley *et al.* (2011). For assessing climatic change, the variability between baseline period and radiative forcing scenarios (RCP4.5 and RCP8.5) was determined.

2.4. Climate Models, Downscaling and Bias Correction

The climate simulations used in this study were based on the dynamical downscaling of three GCMs (Table 1) simulations using the Eta regional climate model, referred to as Eta-HadGEM2-ES, Eta-CanESM2, and Eta-MIROC5. According to Chou *et al.* (2014a; 2014b; 2018), in a study on South America, these models showed better performance in representing the current climate. It should be highlighted that uncertainty analysis inherent to climate change scenarios should consider several models (Knutti and Sedláček, 2013). Once uncertainties are inherent to the climate change projections, the impact assessments should prioritize multi-model climate projections to generate a range of plausible scenarios (Taylor *et al.*, 2012). This multi-model approach is called "ensemble mean".

Table 1. Global circulation models (GCM) descriptions.

GCM	Horizontal resolution (lat x long)	Vertical resolution	Reference
CanESM2	2.75º x 2.8125º	35 levels	Arora *et al.* (2011)
MIROC5	150 km x 150 km	40 levels	Watanabe *et al.* (2010)
HadGEM2-ES	1.274º x 1.875º	38 levels	Collins *et al.* (2011) Martin *et al.* (2011)

The Eta model has been adapted by the Center for Weather Forecast and Climate Studies for studies in Central and South America (Pesquero *et al.*, 2010; Chou *et al.*, 2012; Mesinger *et al.*, 2012; Marengo *et al.*, 2012). The vertical discretization at horizontal geodetic levels is critical for weather models, especially when applied in regions of steep topography (Mesinger *et al.*, 2012). The atmosphere is represented vertically up to the pressure level of 25 hPa with 38 layers (Black, 1994).

The downscaling method provided simulations with spatial resolution of 20-km covering the period from 1961 to 2005 for baseline, and future scenarios (RCP4.5 and RCP8.5) that were divided in three time-slices: near-future (2011–2040), mid-century (2041–2070), and end-century (2071–2099). The daily variables simulated by the Eta model used to assess the potential hydrological impacts on the Verde River Basin were precipitation, maximum and minimum temperatures, and wind speed.

However, simulations from RCMs, such as the Eta model, are subjected to systematic biases (Graham *et al.*, 2007; Rodrigues *et al.*, 2020), mainly caused by errors in conceptualization, discretization and spatial resolution of climate variables within a grid-cell (Teutschbein and Seibert 2012). Therefore, biases of RCM variables were corrected based on observed meteorological data from two stations within the Verde River Basin area. The linear scaling method was used for precipitation, maximum and minimum temperatures as proposed by Lenderink *et al.* (2007), and for wind speed as proposed by Haddeland *et al.* (2012). The corrections are based on the differences between mean data observed in meteorological stations and data simulated from RCM in the baseline period (Teutschbein and Seibert, 2012).

2.5. Future Scenarios

The RCP4.5 scenario represents a stabilization scenario, consolidating the radiative forcing at 4.5 W m^{-2} in the year 2100 (Thomson *et al.*, 2011), and CO_2 concentrations smaller than 550 ppm (Wise *et al.,* 2009). This scenario assumes that climate change policies are included in the countries' political-economic-social planning, as well as the development of technologies combined with the expansion of renewable energy (Thomson *et al.,* 2011) and reduction of fossil fuel consumption and emissions (Clarke *et al.,* 2007; Wise *et al.,* 2009).

On the other hand, the RCP8.5 is the most pessimistic scenario for the 21th century, with CO_2 concentrations equivalent to 1370 ppm (van Vuuren *et al.,* 2011), following high disorderly growth demographic, low development of technologies to reduce pollution and the absence of public policies (Riahi *et al.,* 2011). According to van Vuuren *et al.* (2011), the increase in energy demand and the excessive use of non-renewable energies, mainly mineral coal,characterize the worst scenario of greenhouse gas concentrations in 2100.

3. RESULTS AND DISCUSSION

3.1. VIC Model Performance

Table 2 shows the precision statistics values for calibration and validation for the daily and monthly discharges in a micro-scale tropical headwater basin. According to Moriasi *et al.* (2007), the statistical indices showed "good" and "satisfactory" performances of the VIC model for predicting the daily discharges in calibration and validation periods. The KGE presented as better than CNS for daily discharge for both calibration and validation periods, wherein the component representing the bias (β) was dominant for better performance.

Table 2. Precision statistics of the VIC model for daily and monthly mean discharge.

Statistics Index	Calibration (1993-1999)		Validation (2000-2003)	
	Daily	Monthly	Daily	Monthly
R^2	0.85	0.92	0.85	0.91
CNS	0.79	0.85	0.77	0.80
Pbias	14.85	14.99	14.48	13.79
KGE	0.83	0.83	0.78	0.76

The VIC model performance for Verde River Basin is similar to that in studies accomplished in the Grande River Basin headwater (Viola *et al.,* 2014; Alvarenga *et al.,* 2016a; Oliveira *et al.,* 2017; 2018), as well as studies worldwide using this model for different purposes (Chawla and Mujumdar, 2015; Wang *et al.,* 2019; Yang *et al.,* 2019; Dang *et al.,* 2020).

Daily hydrographs for calibration and validation periods are presented in Figure 2. The comparison between simulated and observed discharge shows overestimation in some peak flows and, for the recession period, the simulated discharges are underestimated. In general, other studies have shown difficulties in simulating peak and recession flows with different hydrological models. In studies in the Grande River Basin headwater, Viola *et al.* (2014) and Oliveira *et al.* (2017), using LASH and SWAT models, respectively, showed underestimation of the simulated discharges during the validation period. In the same region, Alvarenga *et al.* (2016b), applying the DHSVM model, presented underestimation during the dry season and overestimation during the wet season.

3.2. Hydrologic responses to climate change

Figure 3 shows projected changes of monthly hydrological variables (ensemble mean) including precipitation, maximum and minimum temperatures, evapotranspiration, total runoff and discharge for three time-slices (2011-2040, 2041-2070, and 2071-2099), under two emission scenarios (RCP4.5 and RCP8.5), relative to baseline period (1961 - 2005).

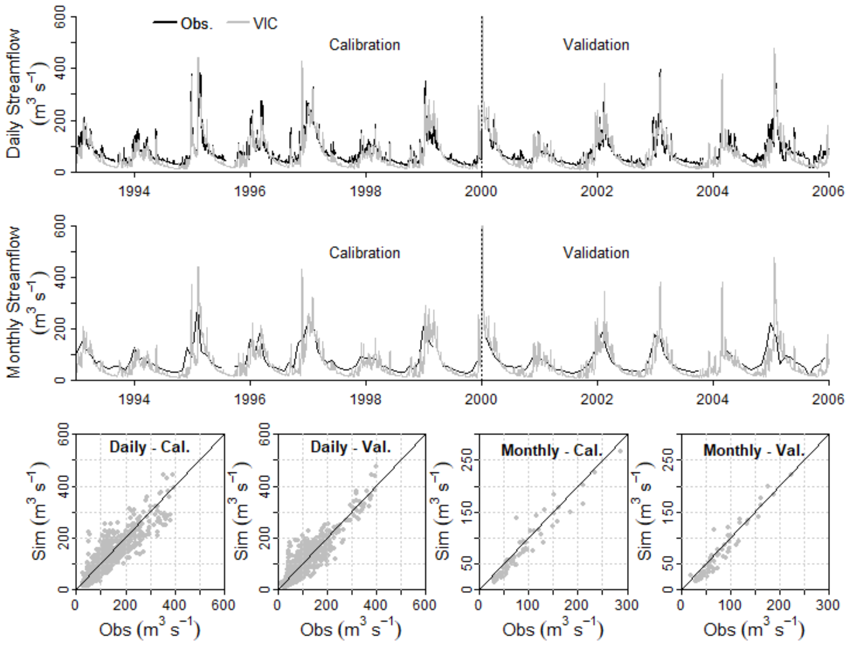

Figure 2. Observed and simulated daily and monthly discharges during calibration (1993-1999) and validation (2000-2005) periods.

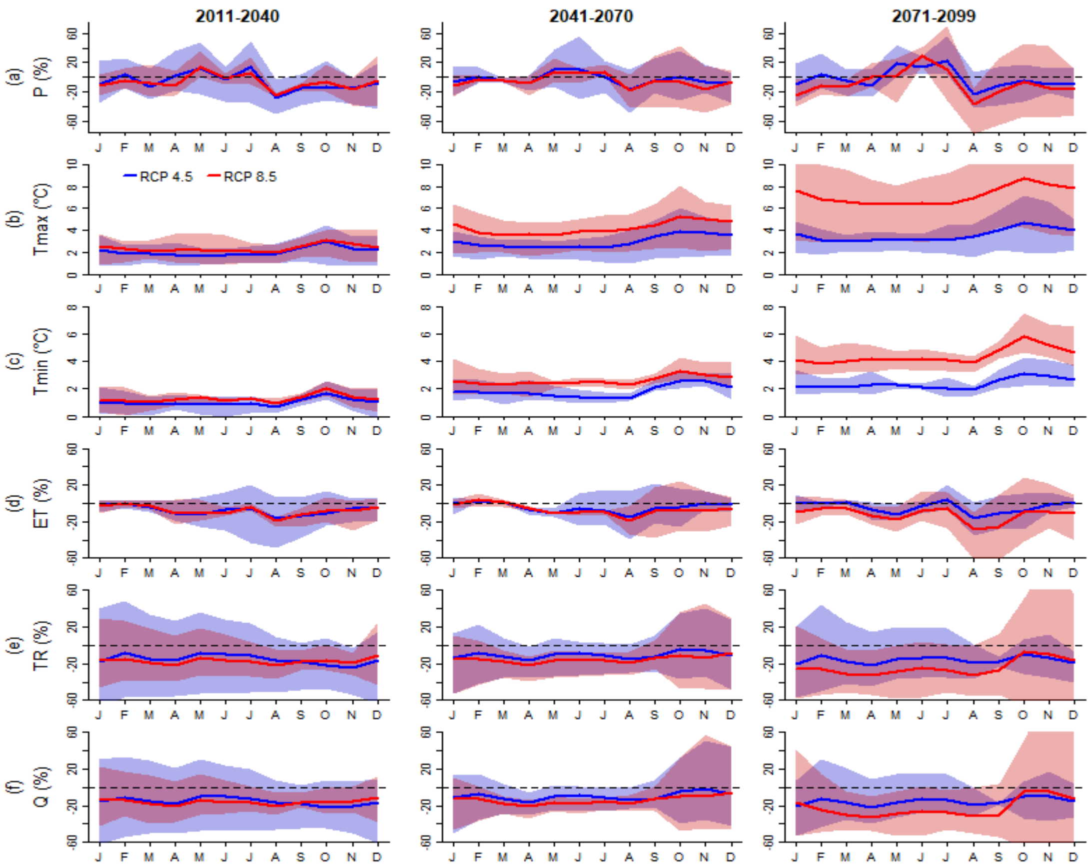

Figure 3. Projected monthly changes in hydrometeorolgical variables of three RCMs (ensemble mean): (a) Precipitation (P); (b) Maximum Temperature (Tmax); (c) Minimum Temperature (Tmin); (d) Evapotranspiration (ET); (e) Total Runoff (TR); and (f) Discharge (Q). P, Tmax and Tmin are derived from meteorological forcing data while ET and TR are simulated by the VIC model and Q by the Routing Model. Each shaded range is bounded by the minimum and maximum of the three RCMs under RCP4.5 (blue) and RCP8.5 (red).

Regarding the ensemble mean of precipitation (Figure 3a), the RCP4.5 scenario presented a wider range for the 2011 to 2040 period, mainly during the dry season (April-September). On the other hand, the RCP8.5 indicated a wider ensemble range from July to December by the end-century, which may imply impacts on agriculture, reduction of underground recharge, reduction of baseflow and hence water supply during the dry season.

Overall, there is a change in seasonality between radiative scenarios, with the RCP4.5 showing higher variability in the dry season from 2011 to 2040, while RCP8.5 at the beginning of the wet season from 2071 to 2099. At the end of the century, both scenarios showed stronger changes in August, with a reduction of 23.7% (RCP4.5) and 36.6% (RCP8.5). Among the RCMs, the Eta simulations driven by HadGEM2-ES showed higher impact in annual precipitation, mainly during the wet season, indicating a reduction of 17.4 and 32.3% for RCPs 4.5 and 8.5, respectively.

Maximum temperature (Figure 3b) and minimum temperature (Figure 3c) changes produced similar ensemble ranges in the near-future (2011-2040), indicating minimum difference between radiative scenarios and RCMs. However, at the end of the century, the RCMs projected strong warming in all months, mainly under RCP8.5. From September to January, the ensemble mean showed warming varying from 3.7 to 4.8°C (RCP 4.5) and 7.6 to 8.7°C (RCP8.5) for maximum temperature, and from 2.3 to 3.1°C (RCP4.5) and 4.1 to 5.7°C (RCP 8.5) for minimum temperature.

Between 2071 and 2099, the Eta-CanESM2 presented increased change in mean annual maximum and minimum temperatures, with a mean increase of 4.7 and 3.1°C for RCP4.5, respectively. Under RCP8.5, the ensemble mean indicated a mean increase of 10.2 and 5.4°C, respectively. The climate models were highly correlated at near and mid-future; however, the results in the end-future presented a wider range, indicating low reliability.

The ensemble mean of evapotranspiration (Figure 3d) showed similar behavior to that of precipitation, with the RCP4.5 indicating increased variation during the dry season from 2011 to 2040, and RCP8.5 from July to December by the end the century, wherein August and September indicated increased changes with a decrease of 28.6 and 26.0%, respectively. At the end of the century, the Eta-CanESM2 and Eta-HadGEM2-ES indicated stronger changes in mean annual evapotranspiration under RCP8.5, with a decrease of 20.6 and 21.0%, respectively, while Eta-MIROC5 presented an increase of 9.0%.

Total runoff (Figure 3e) indicated impacts in all months, with ensemble mean varying from -21.6 to -10.1% (RCP4.5) and from -32.7 to -6.9% (RCP8.5) by the end of the century (2071 to 2099). The Eta-HadGEM2 showed stronger decreases in the mean annual total runoff, with reduction of 57.8, 39.2 and 42.3% under RCP4.5, and 38.2, 41.3, and 54.0% under RCP8.5 during 2011 to 2040, 2041 to 2070, and 2071 to 2099, respectively.

With the routing model, the ensemble mean of discharge (Figure 3f) showed similar behavior to that of total runoff, indicating negative changes for all months, wherein two first time-slices (2011-2040 and 2041-2070) showed small changes between RCPs 4.5 and 8.5. However, at the end the century, the ensemble mean of RCP8.5 presented a decrease varying from 24.5 to 32.2% between February and September, while RCP4.5 showed a reduction from 12.4 to 22.0% for the same period.

Although a three-model ensemble is a limitation in uncertainty analysis in these projections, it gives an indication of the conditions in which models agree or diverge (Chou *et al.*, 2014a). Overall, the models agree in a tendency to increasing maximum and minimum average temperatures. Changes in precipitation estimation over VRB are uncertain. This is also observed in regional scale projections by RCMs worldwide, due to model uncertainty while simulating plants' water-use response to changes of CO_2 concentration (Lehner *et al.*, 2019). Thus, changes in simulated discharge and total runoff reflect these uncertainties of precipitation simulations by RCMs (Mello *et al.*, 2021).

The impacts of climate change on the hydrology of the Verde River Basin are investigated by assessing the changes in mean monthly and annual discharges for three future time-slices (2011–2040, 2041–2070 and 2071–2100) under the RCP4.5 and RCP8.5 scenarios relative to the baseline (1961-2005). Figure 4 shows the mean monthly discharge for the RCMs Eta-CanESM2, Eta-HadGEM-ES and Eta-MIROC5, under future projections (RCP4.5 and RCP8.5) and changes relative to the baseline period.

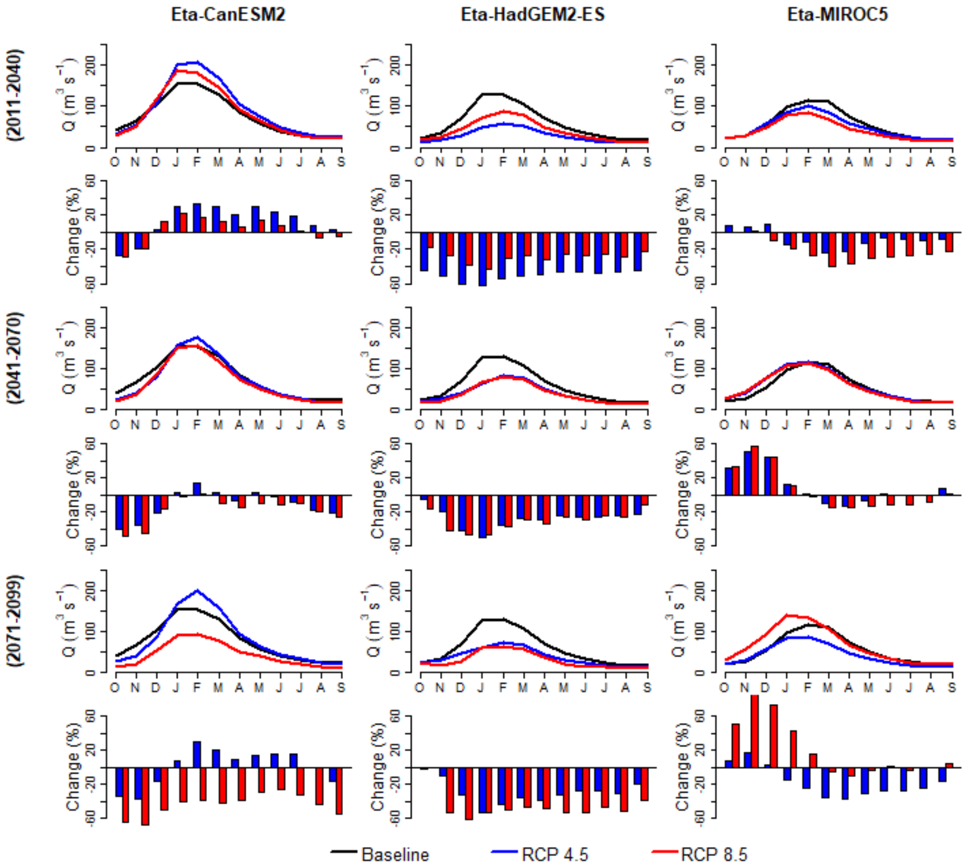

Figure 4. Mean monthly discharge (Q) simulated by the VIC model forced by RCMs Eta-CanESM2, Eta-HadGEM2-ES, and Eta-MIROC5 for the three time-slices (2011-2040, 2041-2070, and 2071-2099) under RCP4.5 (blue) and RCP8.5 (red), and changes (%) of both scenarios relative to the baseline period (1961-2005).

At the beginning of the century (2011 to 2040), the annual mean discharge projected based on Eta-MIROC5 decreased 11.7 and 26% for RCP4.5 and RCP8.5, respectively, whereas Eta-CanESM2 indicated an increase of 18.5 and 8.8% under RCP4.5 and RCP8.5, respectively. The Eta-HadGEM2 showed more impact for all the periods, mainly for the near-future (2011-2040) under RCP4.5 (-53.4%) and end-century (2071-2099) under RCP8.5 (-49.2%). This more pronounced impact was expected, since Eta-HadGEM2-ES projected reduction on precipitation throughout the year, especially during the wet season. Thus, other studies have also reported higher impacts by reduced discharge in watersheds over Central and Southeast Brazilian regions based on Eta-HadGEM2-ES (Ribeiro Neto *et al.*, 2016; Oliveira *et al.*, 2017; 2019).

From January to March, the mean monthly discharge of Eta-CanESM2 under RCP4.5 showed an increase for all periods, with changes varying from 29.6 to 33.7% for the near-future (2011-2040), from 3.0 to 14.2% for the mid-century (2041-2070), and from 8.1 to 30.5% for the end-century (2071 to 2099). Also, this behavior was observed in the first time-slice under the RCP8.5 (varying from 12.7 to 22.9%). In contrast, at the end of the 21st century, the Eta-

CanESM2 under RCP8.5 presented reductions varying from 26.2 to 67.2%, with the beginning of the wet period (October and November) presenting greater impacts.

As opposed to Eta-HadGEM2-ES, the Eta-CanESM2 projections indicate an increase in precipitation during the wet season, especially in RCP4.5. As a result, discharge predictions indicate an increase in the mean monthly value for this season. In a study for watersheds in southern Brazil, Resende *et al.* (2019) observed an increase in extreme discharge events for RCP4.5 and RCP8.5 scenarios from discharge simulations also using Eta-CanESM2 data.

Regarding Eta-MIROC5, both scenarios showed few changes during the beginning of the wet season (October-December) from 2011 to 2040, varying from 6.7 to 9.1% (RCP4.5) and -8.9 to 1.4% (RCP8.5). However, from October to December at the end of the century, the RCP8.5 indicated a stronger increase, ranging from 50.6 to 107.7%, whereas RCP4.5 presented behavior similar for the near-future (2011-2040).

3.3. FDC Signatures

Figure 5 shows variability between baseline (1961-2005) and time-slice (2011-2040, 2041-2070 and 2071-2099) signature indexs of the Flow Duration Curve (FDC) in Verde River Basin, and Figure 6 presents daily discharge simulated by the VIC model using data of future scenarios (RCP4.5 and RCP8.5) projected by the Eta-CanESM2, Eta-HadGEM2-ES, and Eta-MIROC5.

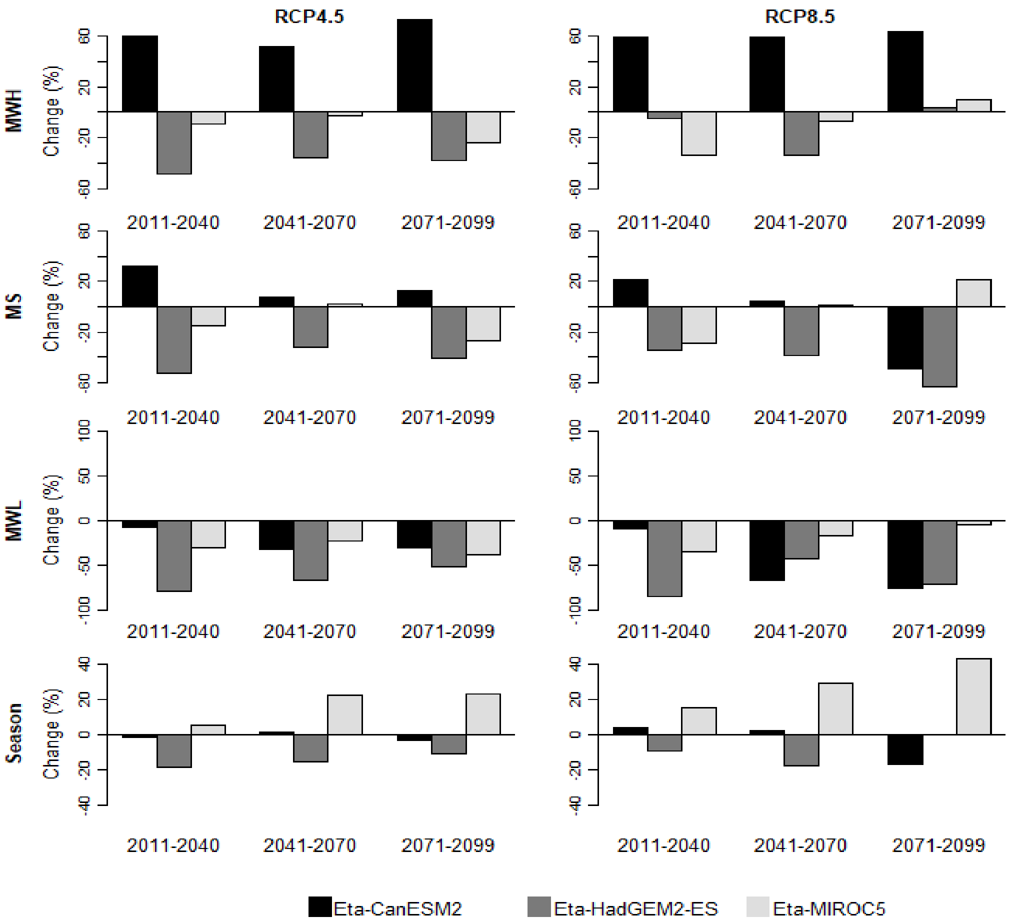

Figure 5. Change (%) between baseline (1961-2005) and time slices (2011-2040, 2041-2070 and 2071-2099) signatures of the Flow Duration Curve (FDC) in the Verde River Basin. Simulated discharges are the result of hydrological model simulations using data of future scenarios (RCP4.5 and RCP8.5) projected by the RCMs (Eta-CanESM2, Eta-HadGEM2-ES and Eta-MIROC5). High flow segment of the FDC (MWH); low flow segment of the FDC (MWL); slope of the FDC at the medium range (MS); differences between wet and dry season discharges (Season).

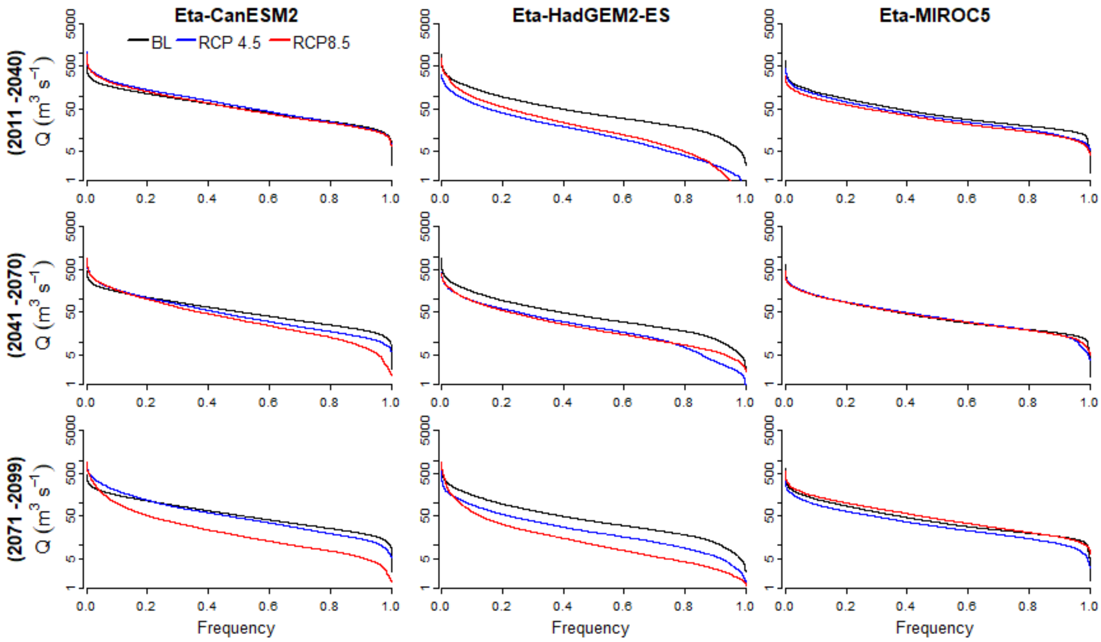

Figure 6. Flow Duration Curve (FDC) of daily discharge (Q) simulated by VIC using data of baseline (BL) and future scenarios (RCP4.5 and RCP8.5) projected by the RCMs (Eta-CanESM2, Eta-HadGEM2-ES and Eta-MIROC5).

The basin hydrological response showed an increase towards greater precipitation events under Eta-CanESM2 for all the time-slices, wherein RCP4.5 indicated an increase of 60.3, 52.0 and 73.5%, and RCP 8.5 increased 58.7, 58.9 and 63.5% from 2011 to 2040, 2041 to 2070, and 2071 to 2099, respectively. In contrast, the Eta-HadGEM2-ES and Eta-MIROC5 presented a reduction in different magnitudes, except for third time-slice under RCP8.5, which showed an increase of 4.0% (Eta-HadGEM2-ES) and 10.4% (Eta-MIROC5). However, there is a consensus among discharge simulations from RCMs projections in the Verde River Basin for the low-flow segment of the FDC (MWL), indicating reduction in dry season discharge. This result is consistent with an Oliveira *et al.* (2017) study in the Grande River Basin headwaters. Thus, these reductions in the low flow regime in the tropical headwater basin can impact the region with long and extreme droughts (Oliveira *et al.*, 2017).

Concerning the mid-segment slope, the Eta-HadGEM2-ES showed a higher decrease, with MS varying from -32.1 to -52.5% under RCP4.5, and from -34.4 to -63.0% under RCP8.5. This impact also occurred for the recession flows (MWL), in which Eta-HadGEM2-ES indicated a reduction of 79.2% (RCP4.5) and 85.6% (RCP8.5) for near-future (2011-2040), and 51.6% (RCP4.5) and 72.0% (RCP8.5) at the end-century (2071-2099). Figure 6 clearly shows the changes in the FDC and steep slope of the curve, indicating lower long-term sustainability of discharge, and, consequently, longer dry periods.

According to Yilmaz *et al.* (2008), a steep mid-segment slope indicates lower soil storage capacity and, hence, larger surface runoff, while a flatter slope is associated with watersheds having slower groundwater flow response. Moreover, in relation to components of water balance, the Eta-HadGEM2-ES showed larger changes, mainly during the spring season.

Regarding the Season index, the Eta-MIROC5 showed high variability and seasonality, indicating greater difference between the wet and dry seasons of future projections (RCPs 4.5 and 8.5) when compared to the baseline period, which may influence the water supply in the dry season throughout the century. Despite indicating a steep slope of the curve (Figure 6), the EtaHadGEM2-ES presented low variability between seasons (dry and wet) both RCP4.5 and RCP8.5.

Overall, the Eta-CanESM2 indicated an increase in the maximum discharge (MWH) and a reduction in the recession flows (MWL), i.e., smaller natural-flow regulation capacity, impacting on the water-resource management in the basin. The Eta-MIROC5 showed a slight reduction of MWH, MS and MWL under RCP4.5, and an increase of MWH and MS for RCP8.5 by the end of the century. Regarding the Eta-HadGEM2-ES, the signatures of FDC showed stronger impact on both maximum and minimum discharges.

4. CONCLUSION

The VIC was combined with three climate models and two radiative forcing scenarios in order to evaluate the changes in hydrological response in the Grande River Basin and the relative importance of each different input of the hydrological model.

Overall, the VIC model was effective in simulating a micro-scale tropical headwater watershed for climate change studies. This is especially important in studies for large-scale watersheds as the model is able to represent hydrological processes at local conditions, as headwater watersheds are not as monitored in Brazil. The hydrological model showed satisfactory statistical performance, overestimating, however, some peak flows, and underestimating the recession flows.

The ensemble mean of precipitation showed small changes between radiative forcing scenarios. However, in August, precipitation showed a stronger decrease at the end of century in RCPs 4.5 (-23.7%) and 8.5 (-36.6%). Furthermore, for precipitation, only from August to December shows a decrease in mensal values, while in other months the predict change signal is not clear. Regarding temperature changes, the Eta-CanESM2 indicated greater warming, mainly under RCP8.5 at the end of the century, with an increase of 5.4 and 10.2°C for mean annual temperature minimum and maximum, respectively. The analysis of uncertainties showed that in general the largest share of uncertainty is related to climate models (the same radiative forcing, different models simulate different changes), and radiative forcing scenarios, due to the uncertainty of future radiative forcing and, hence, climate. Thus, exploring these uncertainties at the regional scale can enhance the reliability of climate change impact projections for watersheds.

The climate model choice remained the dominant factor for mean discharge, as well as in the signatures of the Flow Duration Curve (FDC). Signal of reduction in the majority of the signatures of the FDC is clearer for the simulated discharge using data of Eta-HadGEM2-ES than for the remaining two climate models. Regarding mean monthly discharge, the Eta-HadGEM2-ES showed higher reductions for all periods under both radiative forcing scenarios, wherein RCP4.5 presented more impact at the beginning of the century, and under RCP8.5, at the end of the century. The results indicated high vulnerability of the region regarding water uses in the future, mainly for Eta-HadGEM2-ES projections, negatively impacting water availability, agriculture and livestock production, and potential for hydro-electric generation.

5. ACKNOWLEDGEMENTS

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