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Impacts of Climate Change on the Hydrology of a Small Brazilian Headwater Catchment Using the Distributed Hydrology-Soil-Vegetation Model

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Abstract

Climate change is one of the greatest issues for human society. The objective of this study is to assess the impacts of future climate change on seasonal average discharge and monthly water budget in a small headwater catchment, located on the Grande River basin, in Minas Gerais, Brazil. The assessment is carried out using the hydrology model, DHSVM. The atmospheric forcing to drive the Distributed Hydrology-Soil-Vegetation Model (DHSVM) is derived from the downscaling of the HadGEM2-ES projections by the Eta Regional Climate Model, at 5-km high resolution. The projections assume the RCP4.5 and RCP8.5 IPCC AR5 emission scenarios. Baseline period was taken between 1961 and 1990. The projections are assessed in three time slices (2011-2040, 2041-2070 and 2071-2099). The climate change is assessed in time slices of 30 years and in comparison against the baseline period to evaluate the hydrological changes in the catchment. The results showed differences in the hydrological behavior between the emission scenarios and though time slices. Reductions in the magnitude of the seasonal average discharge and monthly water budget may alter the water availability. Under the RCP4.5 scenario, results show greater reductions in the water availability in the first time slice, whereas under RCP8.5 scenario greater reductions are indicated in the third time slice.

Keywords

Climate Changes, RCP4.5 and RCP8.5 Scenarios, Hydrological Model, Discharge

1. Introduction

The Southeast region of Brazil is extremely relevant for the social and economic development of the country. The Grande River basin is located in southeastern Brazil and the Tropical Atlantic Forest in its headwater region (Mantiqueira Range), should be highlighted as one of the most important biodiversity hotspot of the world [1] [2]. In this basin, the annual variability of precipitation and temperature can be critical for human water consumption, irrigation, and hydropower generation [3] [4].

Southeastern Brazil, in the hydrological years of 2013/2014 and 2014/2015, experienced the worst water crisis yet observed due to rainfall much below average and high temperatures in the summer [5] [6] [7]. That water crisis may be associated with a number of factors, such as: socio-spatial disparities, losses in the water distribution networks, poor infrastructure, inadequate political actions for socioeconomic development and environmental education, and deforestation of the Atlantic Forest [7] [8] [9] [10].

The spatial-temporal patterns that characterize the hydrological response of a catchment can be altered due to climate changes. These changes may vary in intensity according to climatic characteristics, land surface saturation and with the magnitude of the change [11]. Climatic changes may impact the water balance in several ways, such as changes in the evapotranspiration, soil moisture content, groundwater storage and discharge regime [12] [13] [14] [15].

[11] evaluated precipitation, evapotranspiration, discharge, and soil moisture changes on the Brazilian major National Hydrographic basins using downscaling projections of HadGEM2-ES and MIROC5 under two RCP scenarios, and the MGB-IPH hydrological model. The assessment of the water availability shows projected reduction in almost the entire country, except in the south of Brazil. The results suggest that the projected changes may trigger the occurrence of natural disasters such as droughts and flash floods, which could increase vulnerability of people living in risk areas.

Some studies on climate changes and their effects on the Grande River basin have indicated that both temperature and precipitation would affect discharge and surface runoff in different hydrographic basin scale [12] [16] [17]. As reported recently by [12], projected discharges throughout the 21st century in the Lavrinha catchment, located in Mantiqueira Range region show drastic changes. These authors used the Distributed Hydrology-Soil-Vegetation Model (DHSVM) driven by the downscaling projections of the Eta/HadGEM2-ES under RCP8.5 scenario. Moreover, the use of a physically based fully distributed hydrologic model, e.g. DHSVM, is essential for quantitatively evaluating climate change impacts on hydrology of headwater catchments. The projected changes resulted in a monthly and annual average reduction of the discharge of up to 77% and 69%, respectively.

The changes in the context of different scenarios are valuable for assisting management of water resources. The objective of this research is to investigate the possible changes on seasonal average discharge and monthly water budget

using the DHSVM. The novelty of this research is the evaluation of the hydrological impacts projected by two RCP4.5 and RCP8.5 scenarios using the downscaling of the HadGEM2-ES by the Eta Regional Climate Model at high resolution, in a 6.76 km^2 catchment's drainage area, located in the Grande River basin headwater region. Furthermore, this is the second survey using DHSVM to analyze possible hydrological impacts under AR5 emission scenarios in Brazil.

2. Material and Methods

2.1. Site Description

This study was carried out in Lavrinha Creek Catchment (LCC), a headwater basin located in the Mantiqueira Range region, in Southeastern Brazil (Figure 1). LCC, shelters the last remnants of the ecologically important Upper Montane Tropical Forest. In addition, the Atlantic forest in these areas is an important biome in danger of extinction [1]. The choice for studying this basin is the vulnerability due to the possible climate changes in the basin scale. Table 1 shows the characteristics of the LCC.
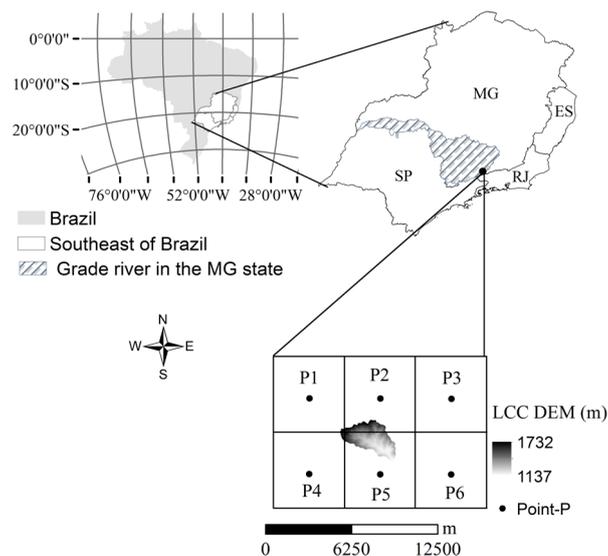
Figure 1. Location, topography and Eta model grid boxes around LCC catchment.

Table 1. Characteristics of the LCC.

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Area	6.76 km^2
Elevation	1137 to 1733 m
Climate	Cwb (according to Koppen classification method)
Average annual temperature	17˚C
Average annual rainfall	2045 mm
Vegetation types	Atlantic Forest and Grassland
Soil types	Haplic Cambisol, Fluvic Neosol and Haplic Gleisol

2.2. DHSVM and Spatial and Hydrometeorological Data

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a physically based, spatially distributed hydrology model, developed by [18]. In this model, the spatial distribution of soil moisture with multilayer unsaturated soil and a saturated subsurface, evaporation with two-layer canopy representation for interception and evaporation; runoff production with generation through saturation excess and infiltration excess mechanisms; within the stream, the linear reservoir routing method is used for each river segment; and simulated at hourly time steps. This model subdivides a catchment into uniform cells (30 m in this study) to capture the spatial variability of the physical characteristics of the catchment at the spatial resolution of a DEM-Digital Elevation Model (**Figure 1**). To run the model, input soil and vegetation parameters are required for each pixel. Digital elevation data are used in the model for flow routing, estimation of soil depth distribution, and meteorological data extrapolation. The meteorological station is located in the coordinates of 22˚07'S and 44˚27'W within the LCC (in the average elevation). Meteorological inputs required by DHSVM includes: precipitation (m), temperature (˚C), wind speed (m s^{-1}), relative humidity (%), and shortwave and longwave solar radiation (W m^{-2}) (hourly in this study). Long wave radiation was calculated as described by [19].

DEM for the catchment was obtained from a 1:50,000 contour map at a spatial resolution of 30 m (Instituto Brasileiro de Geografia e Estatística—IBGE, 1973). The DEM was used to define the LCC. The stream network was generated using the flow routing module based on DEM. Soil depth data were calculated according to the water table depth observations in the LCC [20], being estimated, respectively, the minimum and maximum values, as 2.5 and 5.0 m. Parameters used to represent the vegetation and soil for the DHSVM simulations are listed in [3]. The soil type data in 30-m spatial resolution was obtained from [21]. Two vegetation classes, grassland and Atlantic Forest, were derived from an ALOS (Advanced Land Observing Satellite) image from 2008, using a maximum likelihood supervised classification with ground-based validation points (**Figure 2**).

2.3. DHSVM Simulations

LCC was monitored and studied from 2005 to 2010, within the scope of a wider research and development project sponsored by CEMIG to study the hydrology of the Upper Grande River basin. From information obtained in the field surveys and laboratory analysis, it was possible to obtain the data required to use the Distributed Hydrology Soil Vegetation Model (DHSVM) on a GIS platform. The meteorological record from January 2005 to December 2010 has been run through the DHSVM (hourly). One year and 9 months period was chosen for warm up DHSVM continuous simulations, aiming to reduce uncertainties about initial soil moisture condition to reach equilibrium. Monthly discharge output from the DHSVM simulations were compared against the observed data for the same period. The hydrological year in the region encompasses October of one
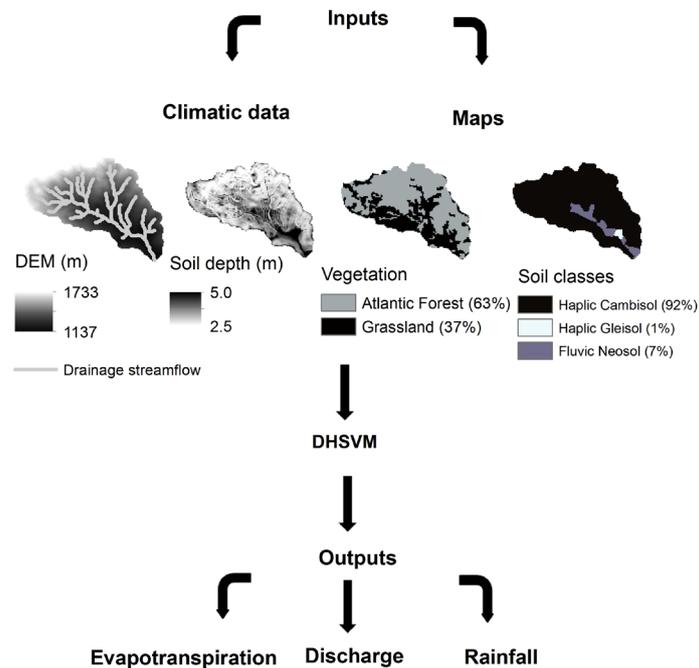
Figure 2. Inputs and outputs of the DHSVM.

year to September of the following year. The accuracy of DHSVM in simulating monthly discharge was evaluated using the coefficient of efficiency E (Nash and Sutcliffe), coefficient of determination—R^2 and Percent bias-P_{bias}, defined as follows:

$$E = 1.0 - \frac{\sum_{i=1}^{N}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{N}(Q_{oi} - \overline{Q}_o)^2} \qquad (1)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}(Q_{Qi} - \overline{Q_O})(Q_{Si} - \overline{Q_S})}{\sum_{i=1}^{N}\left[(Q_{Qi} - \overline{Q_O})^2\right]^{0.5}\left[(Q_{Si} - \overline{Q_S})^2\right]^{0.5}} \right\}^2 \qquad (2)$$

$$P_{bias} = \frac{\sum_{i=1}^{N}(Q_{oi} - Q_{si})}{\sum_{i=1}^{N}(Q_{oi})} \times 100 \qquad (3)$$

where Q_{Oi} is the observed value, Q_{Si} is the simulated value, and N is the number of data points corresponding to the number of time steps in a given simulation period. The $\overline{Q_O}$ and $\overline{Q_S}$ denotes the average value of a variable over the entire evaluation period.

The future projections of discharge changes in the LCC were generated with DHSVM forced by Eta-HadGEM2-ES for RCP4.5 and RCP8.5 scenarios until 2100. The study area was covered with central six points of the Eta model grid boxes and climatic data were extracted to feed the DHSVM. The DHSVM inverse-distance weighting scheme was used to transfer climate data from multiple locations.

2.4. The Downscaling of HadGEM2-ES under RCP4.5 and RCP8.5 Scenarios

Eta is a regional climate model used to produce weather and climate forecasts for South America by the Brazilian National Institute for Space Research (INPE). [22] [23] used a modified version of the Eta obtained from [24]. The model simulations (5-km horizontal resolution) were produced from the Eta model which was nested into the HadGEM2-ES and these simulations were output at intervals of three hours [9]. The HadGEM2-ES global model was used in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) forced by all RCPs scenarios. The HadGEM2-ES exhibits a good representation of the atmospheric conditions over South America, especially in the summer (December, January and February). The high-resolution simulations allowed describing regions with complex topography and with small scale catchments.

The Representative Concentration Pathways, RCP4.5 and RCP8.5, were taken in this study. The RCP4.5 scenario has radiative forcing of 4.5 W m^{-2}; the radiative forcing increases almost linearly up to 2060 when the increase rate slows until the end of the 2100, where it stabilizes. The RCP8.5 scenario, with radiative forcing of 8.5 W m^{-2}, is characterized by a continuous increasing greenhouse gas emission beyond 2100 [25].

3. Results and Discussion

3.1. DHSVM Performance

To evaluate performance of the DHSVM, the sensitivity of the simulations to the soil parameterization was studied. Vegetation parameters were not changed in the calibration. The presented vegetation and soil (Figure 2) and respective parameters were extrapolated for future simulations (scenarios) to evaluate the impacts on the hydrological regime only as a result to the climatic changes.

The model was calibrated and validated to the monthly mean observed discharge at the outlet of LCC by adjusting the lateral and vertical hydraulic conductivity and the exponent for decreasing the lateral hydraulic conductivity with the depth through soil parameters. After calibration, all parameters were updated in DHSVM, and the model simulated the validation period. A more detailed description of DHSVM calibration can be found in [3].

Monthly average hydrograph for the calibration and validation periods are presented in Figure 3. The comparison of the simulated and observed hydrographs reveals: 1) that the observed and predicted monthly discharge hydrographs showed reasonable agreement for both calibration and validation periods; 2) the simulation closely estimates the peak flows and the recession period. According to [26], DHSVM performance is considered "good" for the calibration and validation periods ($R^2_{calibration}$ = 0.70; $E_{calibration}$ = 0.63; $P_{bias\ calibration}$ = 3.13 and $R^2_{validation}$ = 0.85; $E_{validation}$ = 0.77; $P_{bias\ validation}$ = −13.21). Thus, these results suggest that DHSVM may be useful for simulations of the hydrological impacts under RCP4.5 and RCP8.5 scenarios, *i.e.*, with focus on the long-term trend.
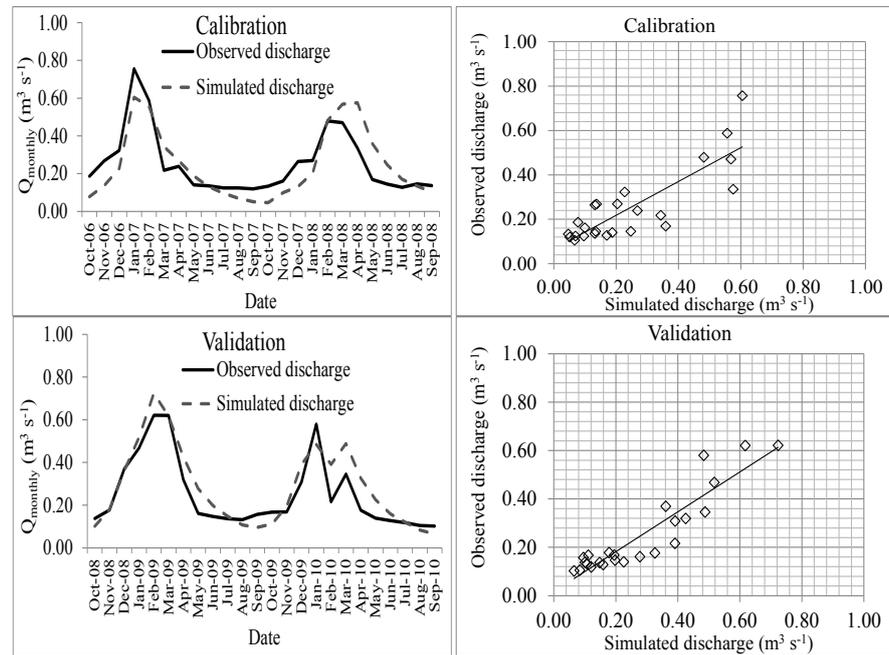
Figure 3. Observed and simulated discharge (m³s⁻¹) during model calibration and validation periods.

3.2. Changes Projected by DHSVM Driven by the 5 Km Eta Simulations

The baseline period simulations and observed data from regions around LCC are in agreement, which gives confidence in the up of future RCPs scenarios to force DHSVM and to simulate the impacts in water resources in the region [12]. In addition, an important aspect of these simulations is that high-resolution 5-km Eta model can capture topographic features and extreme values better than the resolution 20-km. In general, these high-resolution runs resulted in a bias reduction [27]. Temperature and precipitation was analyzed in the LCC, for the HadGEM2-ES in the RCP4.5 and RCP8.5 scenarios, throughout the 21st century, in comparison with the baseline period. The results showed that both scenarios presented an increase in the seasonal average air temperature (summer, autumn, winter and spring). The impacts simulated under the RCP8.5 scenario are larger, with an increase in the temperature over 5°C by the end of the 21st century, in all seasons. In addition, summer showed greater impact, indicating an increase in temperature over exceeding 6°C. Considering the RCP4.5 scenario, there were increases in temperature between 2.0°C and 3.0°C, for the four seasons. Regarding the projected precipitation, there is no clear trend in the autumn, winter and spring for the RCP4.5 and RCP8.5 scenarios, but a sign of reduction in the summer in both scenarios toward the end of the century.

These results are consistent with the studies carried out by [23] and [9]. In a study of climate change in South America using Eta/HadGEM2-ES projections, [23] showed increase in temperature in summer, from about 3.5°C and 5.0°C under RCP4.5 scenario, and over 7.0°C under RCP8.5 scenario, in the Center

South region of Brazil. In addition, for the winter season, in the same region, these authors obtained temperature increases from about 2.5˚C to 4.0˚C under RCP4.5 and over 7.0˚C under RCP8.5. In the study of impacts on tropical forest of Central America, the projections of Eta/HadGEM2-ES indicate an increase in the annual average temperature at the end of the 21st century (2071 to 2099), when compared with the baseline period between 1961 and 1990 [9]. These projections show warming of about 3.0˚C and 3.5˚C under RCP4.5 and 6.0˚C and 7.0˚C under RCP8.5. [23] also found more uncertainties in the precipitation projections than temperature projections in South America.

The average changes in discharge projected by DHSVM simulations, for the three time slices, and under RCP4.5 and RCP8.5 scenarios, are shown in Table 2, split in summer (DJF), autumn (MAM), winter (JJA) and spring (SON). The discharge projections show a clear sensitivity of seasonal average discharges to temperature and precipitation changes. The major reduction of average discharge (%) was found in DJF, considering all time slices and RCPs, in comparison with the other seasons. This discharge reduction in the summer follows the tendency of temperature increase and precipitation reduction throughout the 21st century. The sensitivity of the runoff to climate changes under both RCPs scenarios was more highlighted for the time slices of 2011-2040 and 2071-2099.

This research also suggests underestimation bias of the simulated discharges, as can be seen in the Table 2 (1961-1990) when compared to observed discharges (2006-2010) in the Figure 3. These differences are likely because of an underestimation of precipitation from the Eta model. Despite the uncertainties of the simulated projections *i.e.* climate data without bias-corrected and simulations using only a Global Model, DHSVM reasonably simulated discharge in the baseline period. Climate change related risk involves uncertainty about the severity of the impacts in the Mantiqueira Range region. It should also be highlighted that, since 2013, this region has suffer with annual observed rainfall values below average. Thus, effects of drought have been critical, indicating the importance of these results, despite all the limitations.

3.3. Water Budget Responses

Table 3 shows the water budget at LCC simulated by DHSVM for the baseline period and under RCP4.5 (a) and RCP8.5 scenarios (b). For the baseline period (1961-1990), the water budget indicated a water deficit in April, May, June, and July months. Observed data (Rainfall-Evapotranspiration) from a meteorological station in the LCC, during the years 2006 to 2010, although it is a shorter period, also showed negative water budget in May, June, July and August months. In general, the water deficit of the simulated data (baseline period) coincides with these observed data along with the dry season in the studied region [12] [28].

Regarding RCP4.5 scenario, the largest water deficit occurred in the first time slice of the 21st century (2011-2040), when the dry period extended from March

Table 2. Change in the seasonal average discharge (m³s⁻¹) (%), projected by DHSVM, under RCP4.5 and RCP8.5 (time slice), in comparison with the baseline period.

Season	Baseline (1961-1990)	2011-2040 (RCP4.5)	2041-2070 (RCP4.5)	2071-2099 (RCP4.5)	2011-2040 (RCP8.5)	2041-2070 (RCP8.5)	2071-2099 (RCP8.5)
Summer (DJF)	0.229	0.045 (−80.35%)	0.065 (−71.62%)	0.078 (−65.94%)	0.094 (−58.95%)	0.08 (−65.07%)	0.059 (−74.24%)
Autumn (MAM)	0.231	0.058 (−74.89%)	0.071 (−69.26%)	0.074 (−67.97%)	0.083 (−64.07%)	0.083 (−64.07%)	0.065 (−71.86%)
Winter (JJA)	0.104	0.029 (−72.12%)	0.073 (−29.81%)	0.038 (−63.46%)	0.042 (−59.62%)	0.044 (−57.69%)	0.039 (−62.50%)
Spring (SON)	0.090	0.021 (−76.67%)	0.042 (−53.33%)	0.05 (−44.44%)	0.043 (−52.22%)	0.06 (−33.33%)	0.041 (−54.44%)

Table 3. Monthly average rainfall (R), evapotranspiration (ET) and water budget (R-ET) (mm month⁻¹), simulated by DHSVM at LCC, for baseline (1961-1990), and RCP4.5 (a) and RCP8.5 (b) scenarios, in three time slices (2011-2040, 2041-2070 and 2071-2099).

(a)

Month	Baseline (1961-1990)			2011-2040 (RCP4.5)			2041-2070 (RCP4.5)			2071-2099 (RCP4.5)		
	R	ET	R-ET	R	ET	R-ET	R	ET	R-ET	R	ET	R-ET
Oct	130.0	106.8	23.2	96.5	87.3	9.3	105.8	91.1	14.7	119.9	94.9	25.0
Nov	158.0	103.6	54.4	108.6	86.8	21.7	114.5	92.6	21.9	121.8	93.3	28.6
Dec	200.2	126.1	74.1	123.3	115.0	8.2	119.5	112.9	6.5	140.3	126.9	13.4
Jan	198.4	129.2	69.1	142.7	121.5	21.2	138.7	107.2	31.6	145.5	121.6	23.9
Feb	159.9	113.6	46.3	140.0	105.1	34.9	131.8	110.0	21.9	131.6	110.2	21.4
Mar	137.2	107.6	29.5	99.0	101.5	−2.5	108.8	102.5	6.3	114.5	110.9	3.6
Apr	70.3	88.7	−18.4	62.6	78.8	−16.1	58.6	75.8	−17.2	53.8	86.5	−32.7
May	38.1	79.2	−41.1	32.1	54.9	−22.8	27.1	58.7	−31.6	38.1	59.1	−21.0
Jun	30.2	42.3	−12.1	21.2	30.9	−9.7	20.9	28.1	−7.2	29.2	37.9	−8.6
Jul	52.7	55.8	−3.1	32.3	36.7	−4.4	46.2	39.8	6.5	52.4	47.0	5.4
Aug	76.4	61.8	14.6	42.9	45.6	−2.7	65.8	53.9	11.9	52.1	50.4	1.7
Sep	104.9	85.9	19.0	65.8	60.5	5.3	77.4	72.7	4.7	96.9	73.8	23.1

(b)

Month	2011-2040 (RCP8.5)			2041-2070 (RCP8.5)			2071-2099 (RCP8.5)		
	R	ET	R-ET	R	ET	R-ET	R	ET	R-ET
Oct	102.8	80.1	22.7	97.5	89.8	7.7	101.2	76.0	25.2
Nov	100.1	79.8	20.3	79.6	74.8	4.9	68.9	74.3	−5.4
Dec	101.6	97.9	3.7	130.1	98.0	32.0	89.6	77.2	12.4
Jan	149.3	104.5	44.8	155.6	111.0	44.6	115.6	87.5	28.2
Feb	123.7	103.2	20.5	154.8	119.6	35.2	113.9	95.6	18.3
Mar	111.0	101.7	9.3	115.8	116.1	−0.3	92.9	88.4	4.5
Apr	46.7	72.5	−25.8	64.8	84.5	−19.7	50.0	66.9	−16.9
May	26.9	50.3	−23.4	34.3	66.1	−31.9	18.2	35.5	−17.3
Jun	33.3	27.9	5.4	33.9	33.6	0.3	45.2	28.9	16.3
Jul	61.1	45.2	15.9	56.7	48.8	7.9	85.8	60.2	25.6
Aug	63.9	65.1	−1.2	71.5	61.3	10.2	60.8	63.5	−2.8
Sep	81.5	67.7	13.8	104.2	74.6	29.6	67.4	65.5	1.9

to August. In subsequent time slices, 2041-2070 and 2071-2099, negative vertical water budget (R-ET) occurred from April to June. These results indicate lower water availability in the LCC from 2011 to 2040 under RCP4.5 scenario. On the other hand, RCP8.5 scenario showed some more variability, ranging from positive to negative change, in the monthly vertical water budget signals throughout the 21st century. Additionally, the time slice of 2071-2099, under RCP8.5, shows less water availability, with drastic reductions in the monthly runoff (Table 3).

These results are in agreement with those obtained by [11], who also found increasing changes from the first to the last time slice, considering Eta/HadGEM2-ES and RCP8.5, which suggests increase in the variability of water budget signals (R-ET). In addition, this study suggests a risk of water supply shortages affecting human consumption, hydropower and agriculture, in the Grande River basin. This shown shortage should increase in the 2011-2040 and 2071-2099 time slices, under RCP4.5 and RCP8.5 scenarios, respectively.

4. Conclusions

The results indicated a seasonal discharge reduction during all the simulated periods and all RCPs when compared to the baseline period in the LCC using DHSVM. Under RCP4.5 and RCP8.5, runoff showed a decrease in the summer by −80.35% and −74.24%. The most critical situation regarding water deficit is expected for the 2011-2040 and 2071-2099 time slices, for the RCP4.5 and RCP8.5 scenarios, respectively.

The assessment of the average annual water budget, in comparison with the baseline period, shows a projected water availability reduction by 83%, 73% and 67% and 59%, 53% and 65% during three time-slices (2011-2040, 2041-2070 and 2071-2099) of the RCP4.5 and RCP8.5, respectively. The findings of this study highlight the need for a further and more extensive assessment of the potential climate change impact on the local circulation and water resources using future emission scenarios of AR5.

The climate changes may cause human health problems, alter ecosystems and cause more natural disasters; the changes may also cause a water availability reduction and freshwater security risk, as well as affect food and electricity generation prices in this region. Thus, more research in conservation practices and adaptation strategies should be conducted.

Acknowledgements

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