ISSN:1984-2295

Revista Brasileira de Geografia Física

Homepage: www.ufpe.br/rbgfe

Simulation of Green and Blue Water Impacts Caused by Climate Changes in the Apucarantina River Watershed, Southern Brazil

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Article received in 15/11/2014 and accepted in 06/05/2015

ABSTRACT

Climate changes may generate significant impacts in the hydrological cycle. It is important to recognize modifications in green water (water stored in soil followed by the consumption of the vegetation) and blue water (water that flows into rivers, lakes, wetlands and shallow aquifers) availability in consequence of climate change modifications. The mathematical modelling is used to simulate the effect of climate change scenarios in hydrological processes in watersheds. This study aimed to evaluate the impacts of climate change in blue and green water in Apucarantina River Watershed, Southern Brazil, considering the climate scenarios A2 and B2, pessimistic and optimistic, respectively, about greenhouse gases emissions developed by IPCC. SWAT was calibrated and validated using daily streamflow from 1987 to 2012. Climate scenarios A2 and B2 were used to simulate the hydrological conditions for the period 2071-2100. The model presented satisfactory fit compared to the observed data allowing the simulation of the current hydrological conditions, therefore permitting the simulation of future climate change impacts on green and blue water. We found that despite the increase in potential evapotranspiration of 19% and 12% for A2 and B2 scenario respectively, caused by the increase in temperature, the reduction in rainfall amount induced to a reduction in actual evapotranspiration, which correspond to green water, and a reduction of 21% for A2 scenario and 14% for B2 scenario in blue water availability.

Keywords: Green Water; Blue Water; SWAT Model; Climate Change; Southern Brazil.

Simulação dos Impactos da Água Verde e Azul Causados pelas Mudanças Climáticas na Bacia Hidrográfica do Rio Apucarantina, Sudeste do Brasil

RESUMO

Mudanças climáticas podem gerar impactos significativos no ciclo hidrológico. É importante reconhecer as modificações na água verde (água armazenada no solo seguida de consumo pela vegetação) e água azul (água que flui em rios, lagos, pântanos e aquíferos rasos) disponibilidade em consequência das modificações resultantes das alterações climáticas. A modelagem matemática é usada para simular o efeito de cenários de mudanças climáticas nos processos hidrológicos nas bacias hidrográficas. Este estudo objetivou avaliar os impactos das mudanças climáticas na água azul e verde na bacia hidrográfica do rio Apucarantina, Sudeste do Brasil, considerando os cenários climáticos A2 e B2, pessimista e otimista, respectivamente, sobre emissões de gases de efeito estufa desenvolvido pelo IPCC. O SWAT foi calibrado e validado utilizando vazão diária de 1987 a 2012. Os cenários climáticos A2 e B2 foram usados para simular as condições hidrológicas para o período de 2071-2100. O modelo mostrou ajuste satisfatório em comparação com os dados observados, permitindo a simulação das condições hidrológicas atuais e de impactos futuros das mudanças climáticas nas águas verde e azul. Verificou-se que, apesar do aumento do potencial de evapotranspiração de 19% e 12% para os cenários A2 e B2, respectivamente, causado pelo aumento na temperatura, a redução da quantidade de chuva induziu a uma redução na evapotranspiração real, que correspondem à água verde, e uma redução de 21% para o cenário A2 e 14% para o cenário B2 quanto à disponibilidade de água azul.

Palavras-chave: Água verde; Água azul; Modelo SWAT; Mudança climática; Sudeste do Brasil.

Introduction

The interaction between climatic and hydrologic components involves multiple competing processes (Luo,

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2013). It is known that climate variability may influence hydrological processes, considering that the main climate variables such as precipitation, radiation, and temperature, have an inseparable role in water balance. Eckhardt and Ulbrich (2003) reported that the main consequences of

elevation in atmospheric CO₂ concentration are the increase in mean temperatures and changes in temporal and spatial distribution of precipitation, which should be accompanied by an increased risk of intense events of rainfall and droughts. Climate changes are expected to have effects on precipitation variability patterns (Dufek and Ambrizzi, 2008), streamflow (Zang and Liu, 2013; Ficklin et al., 2009), evapotranspiration (Rockström et al., 2009; McKenney and Rosenberg, 1993) and hydro-sedimentological processes (Nearing et al., 2005; Lu et al., 2013; Iensen et al., 2014). Long-term changes in evapotranspiration may conduct to significant modifications on the hydrologic processes, having critical implications for water availability (Chattopadhyay and Hulme, 1997).

Actual evapotranspiration (AET) is a physical process of water transfer to the atmosphere by evaporation from soil and, water bodies and transpiration through vegetation. AET constitutes an important component in the hydrologic balance, which is determined by climatic factors, including temperature, radiation, humidity, and wind speed and by the availability of water in soil (McKenney and Rosenberg, 1993).

Rockström and Gordon (2001) reported that most of water resources assessment tends to focus primarily on the evaluation of liquid portion in hydrologic budget, emphasizing the amount of water that flows into rivers, lakes, and groundwater. Therefore, little attention is paid to the role of evapotranspiration or vapor flows of water balance, and its importance in the hydrological cycle, sustaining terrestrial ecosystems. According to Fennessey and Kirshen (1994) in regions with humid climate, it is recognized that actual evapotranspiration may account for over than half of the average of annual water balance, and this amount of water tend not to be considered in water resources assessment.

To improve the knowledge about hydroclimatic processes in watersheds Falkenmark (1995) first proposed the green and blue water concept. By definition, blue water consists of the water amount that flows through rivers, aquifers, lakes, and wetlands. Green water comprises the amount of water that comes from precipitation and is stored in soil and then consumed by vegetation. Xu (2013) describe Green water flow as equivalent to the actual evapotranspiration (AET). The concept of green and blue water are important considering the wide view of water balance inputs and outputs provided by this approach.

The green and blue water concepts of Falkenmark (1995) were improved by Falkenmark and Rockström (2004), distinguishing flow from storage of green and blue water. Thus, Falkenmark and Rockström (2004) describe blue water storage as the amount of water stored in aquifers. Green water storage is defined as the soil moisture. These authors also differentiate blue water flow

that refers to the water flowing in rivers, aquifers and lakes and green water flow refers to the vapor amount that return to the atmosphere as evapotranspiration.

Recognizing the importance of green and blue water dynamics and to elucidate the effects of climate change on environmental processes in watershed, many studies that have been conducted concluded that any changes in climatic variables might affect significantly green and blue water availability. (Xu, 2013; Rockström and Gordon, 2001; Zang and Liu, 2013; Faramarzi et al., 2009; Falkenmark and Rockström, 2004; Gerten et al., 2005; Hoff et al., 2010; Liu and Yang 2010).

McKenney and Rosenberg (1993) reported that due to modifications in precipitation patterns it is expected that water storage in soil also decreases, and hence the reduction in actual evapotranspiration occurs, these modifications might influence the amount of water available to grow crops, to water animals, and to supply human needs. Also, Pruski and Nearing (2002) describes that changes in temperature could change evapotranspiration rates, affecting soil moisture and, therefore, infiltration and runoff.

The prediction of the effect of climate change on blue and green water it is important to make a quantitative assessment thought hydrological modeling is emphasizing the importance of this assessment for future management of the watershed. The magnitude of climate change effect on environmental dynamics varies, depending on the region analyzed and considered climate scenario (IPCC, 2007). Due to the heterogeneity of climate conditions predicted by the scenarios, it is necessary to regionalize assessment of climate change impacts. Thus, this paper proposes the use of Soil and Water Assessment Tool (SWAT), to estimate potential regional impacts of climate change scenarios on blue and green water in the Apucarantina River watershed located in southern Brazil.

Material and Methods

Study area

The Apucarantina River watershed drains an area of 504 km² and is located in southern Brazil (50°56'W and 23°42'S) (Figure 1). The local geomorphology consists of smooth hills, with elevation ranging from 660 m to 1210 m. The average slope of the Apucarantina River watershed is approximately 11%.

Land use in the watershed is predominantly agriculture (63%), with soybean and wheat as major crops. The climate is classified as Humid Subtropical Climate or Cfa (Köppen, 1948), characterized by high temperature and high rainfall in summer months. The average annual precipitation in the Apucarantina River watershed is 1,634 mm.

Figure 1. Geographical localization of the Apucarantina River watershed in Southern Brazil.

SWAT model application

The SWAT model is a hydrological model developed in 1996 by U.S. Agricultural Research Service, Texas A & M University and other federal agencies (Neitsch et al., 2005). It is a watershed-scale model that simulates monthly and daily streamflow, nutrient loading, and sediment yield resulting from the interaction of weather, soil properties, stream channel characteristics, agricultural management and crop growth (Nearing et al. 2005). SWAT requires the input of climate data such as precipitation, temperature and humidity and therefore is used to investigate climate change effects on plant growth, evapotranspiration, snow and runoff generation (Eckhardt and Ulbrich, 2003; Zang and Liu, 2013; Luo et al., 2013). SWAT model has been successfully used to predict hydrological cycle and scenario simulation in many watersheds of different sizes and environmental conditions (Schuol et al., 2008; Gerten et al., 2005; Faramazi et al., 2009; Luo et al., 2013).

SWAT estimates runoff using the Curve Number method by SCS (Soil Conservation Service, 1972). To predict potential evapotranspiration SWAT offers three equations: Priestley-Taylor (1972), Hargreaves (Hargreaves and Samani, 1985), and Penman-Monteith (Allen et al., 1989). In this study, the Penman-Monteith method was used. This method requires data on vegetation and climatic data of radiation, humidity and wind speed.

SWAT requires spatially distributed data and time series of climatic and hydrological data. Data used in this study were obtained from the climate and rain gauge station located near the studied area. Rain gauge and Stream gauge stations are shown in Figure 1. Time series of temperature, radiation, air relative humidity and wind speed were obtained in the Instituto Agrônômico do Paraná (IAPAR). The weather station is located 40 km of the Apucarantina River watershed.

The land use data was obtained by supervised classification of digital images of LANDSAT 7 ETM +1, bands 5, 4 and 3, which spatial resolution is 30m. Definition of soil types and their physical and hydrological characteristics were obtained in EMBRAPA (1984) mapping in scale 1:600,000. The DEM had a spatial resolution of 30 m and was made contour and point elevation data of topographic maps in scale 1:50,000.

The watershed was partitioned in 43 sub-watersheds of equivalent size. Each sub-watershed was divided into Hydrological Response Units (HRU), which are combinations of homogeneous soil types, land use, slope and management (Neitsch et al., 2005). The 43 sub-watersheds were divided in 350 HRU.

Streamflow from the Apucarantina River watershed was calibrated and validated with daily measured data from 1987 to 2012. Calibration was made with observed data from 2000 to 2012 and validation from 1987 to 2000. The model was calibrated in two steps. First, a

manual calibration was done to adjust the main components of water balance; then an automatic calibration was done using SWAT-CUP (Abbaspour, 2011) to achieve a good model fit.

The goodness of fit was evaluated visually as well as with Nash-Sutcliffe coefficient efficiency (COE, Nash and Sutcliffe, 1970), Percent Bias (PBIAS) and RSR (RMSE-observations standard deviation ratio). According to Moriasi *et al.* (2007) a satisfactory calibration consists in having a COE > 0.50, an RSR < 0.70, and if PBIAS +/- 25% for streamflow.

Climate change scenarios

After model calibration, climate scenarios A2 and B2 were used as input data in SWAT modeling. The scenarios were generated with spatial resolution of 50 km (0.5° latitude x 0.5° longitude) and with daily time step, using the regional climate model HadRM3P of the Hadley Centre, UK, and downscaled using Integrated System of Regional Modelling PRECIS - Providing Regional Climate for Impact Studies (Marengo *et al.*, 2009).

Climate scenarios were based on possible trends of CO₂, population growth, socio-economic development and technological changes (Marengo, 2007). The scenarios developed by IPCC compartmentalize the world in several large cells. The downscaling technique is used to regionalize data. Through downscaling, the climate and weather information are regionalized to present details of the particularities of each region.

The A2 scenario describes a pessimist scenario for climate change that the CO₂ concentration approximately will fold until 2100. Also, it is predicted an increase of 2°C to 5.4°C in temperature by 2100 (IPCC, 2007). The B2 scenario describes an optimistic scenario for climate change in which the increase in temperature varies between 1.8°C to 3.8°C and CO₂ concentration increase 50% by 2100. Also, A2 and B2 emissions scenarios

indicate that the general tendency of global average water vapor, evaporation and precipitation are projected to increase, although at the regional scale both increases or decreases are seen (IPCC, 2007).

Blue and green water

To estimate the percentage of precipitation that is transformed in actual evapotranspiration we used the green water coefficient (Equation 1) described by Xu (2013), which herein is the equivalent of the evapotranspiration coefficient. The use of C_{gw} emphasizes the rate of transformation from precipitation to green water or actual evapotranspiration.

$$C_{gw} = \frac{Q_{green}}{P} = \frac{(P - Q_{blue})}{P} \quad (\text{Equation 1})$$

where C_{gw} is the coefficient of green water. Q_{green} is the green water amount. P is precipitation. Q_{blue} is the amount of blue water.

In this study, green water flow is considered the amount of actual evapotranspiration (AET). Green water storage is defined analyzing the variation of water stored in the soil. Still, blue water flow is considered the sum of surface runoff, lateral flow contribution to stream flow and groundwater contribution to streamflow. Due to limitations in SWAT output, we could not define blue water storage. Thus, this concept will not be evaluated in this paper.

Results and Discussion

Calibration and validation

According to literature, some of SWAT parameters were altered to permit an adequate reproduction the actual hydrological conditions in the Apucarantina River watershed. The parameters and values used in the calibration process are presented in Table 1.

Table 1. Parameters modified for simulation of runoff, their description and the adopted value.

Parameters	Description	Calibrated value
Cn2	SCS runoff curve number for moisture condition II;	-25%*
Alpha_bf	Base flow Alpha factor (days);	0.7
Esco	Soil evaporation compensation factor;	0.33
Sol_awc	Available water capacity of soil layer (mm/mm);	50%*
Gw_delay	Groundwater delay time (days);	120
Gwqmn	Threshold water depth in shallow aquifer for flow (mm);	400
Gw_revap	Groundwater re-evaporation coefficient;	0.15
Canmx	Maximum canopy storage (mm);	Forest= 5 Pasture=2 Agriculture= 2
Sol_K	Saturated hydraulic conductivity (mm/hr);	50%*
Revapmn	Threshold depth of water in the shallow aquifer for “revap” to occur (mm);	200
Slsbbasin	Average slope length (m);	30%*

*percentage of change applied to the initial value.

Table 2 shows the statistical test values obtained in the process of calibration and validation for streamflow. As verified by statistical methods, the simulated streamflow has a valid fit to the observed data in calibration and

validation periods. Therefore, the model with the calibrated parameters can represent the hydrological processes of Apucarantina watershed and can be used to evaluate the current and future climate conditions.

Table 2. Evaluation of calibration and validation process.

Stage	Time Step	Runoff		
		COE	RMR	PBIAS
Calibration	Daily	0.71	0.54	2.68
	Monthly	0.86	0.18	2.64
	Daily	0.72	0.41	-6.8
Validation	Monthly	0.82	0.42	-6.85

Climate change impacts

On both scenarios, the main variation was observed in the temperature, which increases in both scenarios and in the precipitation that decreased 365.9 mm and 451.9 mm for the scenarios A2 and B2, respectively, as could be observed in the Table 3.

In the Apucarantina River watershed it was found that 67% of precipitation is transformed into the green water flow, or actual evapotranspiration (AET). This result indicates that more than half of water balance is not explicitly considered in water resources management in the studied area.

Table 3. Comparison of values of climate variables for baseline conditions and the climate scenarios used. TMAX = Average maximum temperature; TMIN = average minimum temperature; RAD = Average radiation; HMD = Average of relative humidity of the air; WND = Average of wind speed.

Scenario	TMAX	TMIN	RAD	HMD	WND	Annual Mean Precipitation
	(°C)	(°C)	(MJ/m ² -day)	(%)	(m/s)	(mm)
Baseline	27.9	17.3	14.54	68.9	2.35	1634.3
A2	30.05	20.88	14.48	71.1	3	1268.4
B2	28.79	19.6	14.56	72.9	2.62	1182.4

Temperature and precipitation are not the only variables that may affect the hydrological cycle although it is considered that these are the main variables influencing water availability and evapotranspiration. Martin *et al.* (1989) found that the effect of temperature is unlikely to be the only climatic element affected by greenhouse warming, however, changes in other climatic elements can offset or intensify the effects of rising temperature on evapotranspiration.

The main results obtained in the simulation of climate change scenarios in the Apucarantina River watershed are presented in Figure 2. In consequence of the increase in temperature, potential evapotranspiration (PET) increased 19% under scenario A2 and 12% under scenario B2 (Figure 2d), the most expressive variation occurred between July and October. According to Katul *et al.* (2012), PET is expected to increase by 6.8% for each 1°C increase in air temperature.

Although the increase in PET, it was observed a reduction in precipitation of 19% and 23% (Figure 2a) for scenario A2 and B2, respectively. With the significant reduction in precipitation amount, soil moisture became limited presenting a reduction of 13% in the A2 scenario and 7% in the B2 scenario. In this context, with the reduction in water availability, there was less water to streamflow and to be stored in soil (Figure 2c). This modification in soil moisture is alarming considering that the agricultures the predominant land use of Apucarantina river watershed.

The decreasing trend in precipitation and soil water content, induce, reduction of 16% under A2 scenario and 33% under a B2 scenario in AET or green water flow (Falkenmark and Rockstrom, 2006). We found that blue water flow also showed a general decrease of 21% to the A2 scenario and 14% to the B2 scenario.

Figure 2. Simulation results for the current climate condition and scenarios A2 and B2. a) Mean Precipitation (mm). b) Mean blue water flow (mm). c) Mean green water storage (mm). d) Mean green water flow (mm).

According to McKenney and Rosenberg (1993), in many water balance models, the actual evapotranspiration (AET) is assumed to follow a linear function of soil moisture content. When soil moisture becomes limited, AET would be less sensitive to changes in temperature, solar radiation, humidity, and the wind than would PET. By implication, climate effects in the runoff would follow the same patterns of changes in PET if soil moisture content remains high and does not limit AET. In Apucarantina River watershed, it was observed that despite the increase in PET, actual evapotranspiration did not follow the same upward tendency because of a decrease in precipitation amount. With less water stored in the soil, AET also becomes limited.

These results could be compared to those obtained by Eckhardt and Ulbrich (2003), these authors found that the increase in potential evapotranspiration associated with decreased precipitation may reduce groundwater recharge and streamflow by more than 50%. Luo et al. (2013) also reported that higher temperature is expected to increase potential evapotranspiration and decrease water yield in watersheds. Luo et al. (2013) also described that these changes in average annual streamflow predicted by

SWAT were significantly correlated with precipitation changes, in addition, the seasonality of precipitation change was significantly magnified in the resultant seasonality of streamflow.

In order to evaluate the monthly time series generated by the simulations of baseline conditions A2 and B2 scenarios, it was elaborated a box plot graph (Figure 3) to analyze general variation of green and blue water flow.

Green water flow (Figure 3a) showed a reduction in the median, minimum and maximum values for both climate scenarios. This situation was caused by the reduction of precipitation, which implies that less water is available to be stored in soil and consumed by vegetation as actual evapotranspiration.

Blue water flow (Figure 3b) presented an increase in maximum and absolute minimum values for both climate scenarios indicating the occurrence of more extreme and intense events. Scenario A2 presents the largest amplitude. Scenario B2 showed a higher frequency of blue water below the median value indicating that in the climate condition predicted by this scenario is expected the increase in months characterized by low flows.

Figure 3. Box plot for baseline climate condition and scenarios A2 and B2. a) Green water flow; b) Blue water flow.

Conclusion

SWAT model was able to reproduce the current hydrological conditions of the watershed enabling the simulation of climate scenarios to assess the impacts on the hydrological dynamics.

The importance of AET as the main output term in the water balance of most watersheds, mainly in a humid climate. As such, estimation of actual evapotranspiration conditions is a crucial component for evaluating watershed response to future climates.

By the simulation of climate change impacts, it was observed that the increase in temperature induced to an increase of 19% and 12% for A2 and B2 scenario, respectively. Although the increase in potential evapotranspiration, the decrease trend in precipitation (19% for A2 and 23% for B2) culminate to a decrease of 13% in A2 and 7% in B2 in soil moisture, which correspond to green water storage. As a consequence of less water stored in the soil, AET, which represents green water flow, reduced 16% in the A2 scenario and 33% in the B2 scenario. Blue water flow, which refers to water that flow meanwhile river and aquifers showed a reduction of 21% for A2 scenario and 14% for the B2 scenario. Also, the results showed the seasonality of climate data and its consequences in blue water flow and green water flow and green water storage in the Apucarantina River watershed.

Analyzing green and blue water flow series it was observed the general trend of reduction in median values in green water and an increase in the amplitude in blue water for both climate change scenarios.

Acknowledgements

We thanks the National Council for Scientific and Technological Development (CNPq) for the scholarship to the first author, the Coordination of Improvement of Higher Education Personnel (CAPES) for scholarship support to the second author. The authors thank Prof. Dr. Claudia Camargo Campos Guimarães (UDESC) and Prof. Dr. José A. Marengo (INPE) who provided the climate change scenarios data in the scope of the Study on Climate Change in Southern Brazil (CLIMASUL) Project.

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