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Impacts of land use and climate changes on surface runoff in a tropical forest watershed (Brazil)

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Abstract

Surface runoff generation capacity can be modified by land use and climate changes. Annual runoff volumes have been evaluated in a small watershed of tropical forest (Brazil), using SWAT model. Firstly, the accuracy of SWAT in runoff predictions has been assessed by default input parameters and improved by automatic calibration, using 20-year observations. Then, the hydrological response under land uses (cropland, pasture and deforested soil) alternative to tropical forest, and climate change scenarios has been simulated. SWAT application has showed that, if forest was replaced by crops or pasture, the watershed's hydrological response would not significantly be affected. Conversely, a complete deforestation would slightly increase its runoff generation capacity. Under forecasted climate scenarios, the runoff generation capacity of the watershed will tend to decrease and will not be noticeably different among the representative concentration pathways. Pasture and bare soil will give the lowest and highest runoff coefficients, respectively.

Keywords: surface runoff; hydrological model; cropland; pasture; deforestation; Global Circulation Model.

1. Introduction

Tropical forests, the richest terrestrial ecosystems in biodiversity and structural complexity terms (Whitmore 1990), are essential for maintaining the ecological integrity of watersheds (Ataroff & Rada 2000; Neill et al. 2001). However, the negative effects of land use and climate changes threaten these delicate environments.

Land use is a critical issue that affects primarily the hydrological cycle and the water balance of an ecosystem (Sui 2005), since the land cover influences potential evapotranspiration, infiltration, surface runoff and sediment yield in a watershed (Durães et al. 2011). Land use is subject to changes at several spatial scales, which significantly affects ecological systems (Vitousek 1994; Piniewski et al. 2014). For instance, a heavy decrease in land cover of tropical areas, such as deforestation of upstream watersheds and urbanization pressure, generally leads to more intense stormflow and erosion events with higher impacts on the water balance (de Paulo Rodrigues da Silva et al. 2018). In tropical conditions the effects of changes in land use and cover on the hydrological response of a watershed is still controversial (dos R. Pereira et al. 2016a); regarding deforestation risk, researches are not unanimous on how the lack of tree cover due to human actions impacts hydrology in tropical watersheds (Baker and Miller 2013; Chandler 2006).

In addition, climate change, resulting from the increase in greenhouse gas emissions, determines modifications of the hydrologic response of a watershed, and these impacts on the water resources availability (Arnell 1999).Future climate trends on a planetary scale show a significant increase in the temperature and a reduction in annual rainfall (Estrela et al. 2012; Senent-Aparicio et al. 2017). The increase in global temperature, modifying the evapotranspiration rates (Paparrizos et al. 2016; Urrutia & Vuille 2009), will significantly change the frequency and magnitude of hydrological events (i.e., floods and droughts) and will heavily influence the hydrological processes at local and global scales.

In general, the hydrological impacts of climate change have been widely investigated using General Circulation Models (GCMs), which provide information about historical, current and future climate (Gonzalez et al. 2010; Jing et al. 2015). The impacts of change impacts on hydrology are commonly evaluated using a pre-processed output from one or several GCMs as climatic input to hydrological models (Piniewski et al. 2013). Future precipitation and temperature data forecasted by GCMs give insights on future potential changes in the hydrological response of a large-scale territory (Hoomehr et al. 2016). Different greenhouse gases emissions (GHGs) scenarios can be projected, following the so-called Representative Concentration Pathways (RCPs) of the Intergovernmental Panel on

Climate Change 5th Assessment Report (IPCC 2014; Almagro et al. 2017). According to the latest IPCC report (IPCC 2014), the global mean surface temperature increased by 0.85 °C from 1880 to 2012.

The simulation of watershed hydrology is perhaps the most important tool for water resource planning and management, since it helps to evaluate and predict by a quantitative approach the hydrological processes that control water movement at various time scales (Spruill et al. 2000). More specifically, watershed hydrology can be simulated to estimate freshwater availability and distribution (Piniewski et al 2017), to predict stream flows, and to evaluate the hydrological response due to changes in land use and cover (dos R. Pereira et al. 2016a), and also under simultaneous scenarios of climate change. Computer models are essential for simulating hydrologic processes and their responses to both natural and anthropogenic factors at watershed scale (Lironga & Jianyuna 2012) and for developing water management strategies (de Paulo Rodrigues da Silva et al. 2018). Hydrological computer models can be coupled to GCMs to produce potential scenarios of climate change effects on water resources. By this combination, the effects of climate change can be linked to the hydrological response of a watershed, estimating water runoff, sediment yield and impacts on water quality (Ficklin et al. 2009).

A number of watershed-scale models able to simulate surface runoff, soil erosion and sediment/pollutant transport have been developed in the last decades. These models vary in complexity and data input requirements (Borah & Bera 2004). Among the available models, SWAT is one of the most used to determine streamflow response to changes in land cover conditions, agricultural operations, and natural rainfall trends. However, in spite of its great potential as powerful tool for analyses about watershed hydrology, SWAT remains yet to be fully exploited for hydrological and predictions in tropical regions (de Paulo Rodrigues da Silva et al. 2018). Therefore, in order to consolidate its use in delicate and complex environments, SWAT still requires implementation in watersheds with climate and soil typical of tropical conditions (dos R. Pereira et al. 2016b). Previous applications in these environmental contexts have shown that, after calibration and validation, SWAT provides satisfactory performances in simulating annual and monthly stream flows (Dourado-Hernandes et al. 2018). These results make the model an effective means for hydrological predictions of water yields at the watershed scale (Douglas-Mankin et al. 2010; Gassman et al. 2007).

However, although research has mainly focused on streamflow using the SWAT model for temperate zones, less attention has been paid to evaluations of watershed hydrology under land cover and climate change scenarios in Brazil (de Paulo Rodrigues da Silva et al. 2018). Only limited applications of hydrological models to assess the effects of climate and land use changes on the hydrological response of a tropical areas are available (e.g., dos R. Pereira et al. 2016a; Almagro et al. 2017; Dourado Hernandes et al. 2018; de Paulo Rodrigues da Silva et al. 2018). This is especially important in watersheds with low availability of environmental data (Fukunaga et al. 2015; Zema et al. 2018). These applications are instead important for a region where hydrology has a high level of complexity, sourcing from both natural variability and human influences (de Paulo Rodrigues da Silva et al. 2018). This is the case of the Atlantic forest, the most threatened biome in Brazil, where the hydrological functions in forest ecosystems have had little attention by researchers (Zema et al. 2018), also because of the scarcity of hydrological observations (De Mello et al. 2016; Marmontel et al. 2018). The basic hypothesis of this study is that the hydrological response of a tropical watershed, as modified by land use and climate changes at basin scale, can be simulated and predicted by the SWAT model. To address this hypothesis, this paper has evaluated the SWAT accuracy in simulating the surface runoff in a watershed of South-East Brazil, which is representative of the very small and numerous watersheds of Mata Atlantica tropical forest. A large temporal scale was adopted to evaluate the watershed's runoff generation capacity, simulated by the model at the daily scale, under changed climate and land use in successive dry and wet years. First, the applicability and reliability of SWAT have been verified using a 20-year (1993-2014) database of observations. Then, the model has been used at the annual scale to simulate the watershed hydrological response under land uses (cropland, pasture and deforested soil) alternative to tropical forest and climate change scenarios. These latter have been predicted using an ensemble of three GCMs (MIROC5, GISS-E2-H and MRI-CGCM3). By this modelling exercise, indications about the most sustainable land use for water resource protection in this delicate ecosystem on the long term and under climate change forecasts can be given to land planners.

2. Materials and methods

2.1 Study area

The “A” micro-watershed (Figure 1) is located in the Parque Estadual da Serra do Mar (Cunha Municipality, Sao Paulo State, Brazil). It is a headwater, which is a tributary of the Paraibuna river, which, in turn, flows into the main Paraíba do Sul river (East Atlantic region).The region is covered with the Mata Atlantica rainforest, which is ecologically important for the conservation of biodiversity and endemic species disappearance (Galindo-Leal and Câmara 2005).

The studied area consists of a mountain plateau at an altitude of 1000-1200 m. The examined micro-watershed covers an area of 0.38 km^2, characterized by steep hillslopes (mean slope of 22%). The main channel (whose mean slope is 12%) rises at 1171 metres a.s.l. and flows after 930 metres into the Paraibuna river (outlet coordinates 23°15'28"S, 45°2'26"W) at a height of 1062 m (Figure 1). According to Kirpich (1940), the concentration time of the watershed (that is, the time required by runoff to reach the closure section from the farthest hydraulically distant point, Chow et al., 1964) is estimated in 0.14 hours. The climate of the area is "Cwa", humid subtropical climate (Köppen classification). Precipitation is well distributed throughout the year (on the average 2200-2300 mm/year), and the maximum occurs in summer, while winters are dry. The average annual temperature is 19.1 ºC, while the evapotranspiration is 682 mm/year (National Institute of Meteorology of Brazil, INMET). The latter is mainly due plant transpiration, since water evaporation from soil is quite negligible in Mata Atlantica (Fujieda et al. 1997).

Except on the case of very intense storms, the water course shows a constant hydrological regime, which is typical of tropical streams.

The area of the watershed is totally covered by tropical rain forest, an evergreen cover with a uniform canopy 20-m high, but some trees can reach 40 m (according to surveys by the Brazilian Institute of Geography and Statistics, IBGE) (Table 1). Since forest has been subjected to logging for more than 50 years, secondary vegetation is now recovering (Aguiar et al. 2001).

According to the taxonomic classification of the IBGE, the soil of the watershed is CX3 type (CX Tb Dystrophic + LVA Dystrophic), , which corresponds to the Ferralic Cambisol and Rhodic Ferralsol classes of the FAO classification (Klam and Van Reeuwijk, 2000). Its texture is sandy loam (54% of sand, 16% of silt and 30% of clay, with 3.4% of organic matter) in the upper layer (350 mm) and clay (40% of sand, 7% of silt and 53% of clay, with 0.6% of organic matter) in the lower layer (350 to 1850 mm). The saturated hydraulic conductivity is 2 mm/h for both layers and the soil's hydrological group is "C" according the USDA-SCS classification (1986).

2.2 The hydrological database

Meteorological data were recorded by a weather station (Meteodata model) located at the watershed outlet. The station consisted of a rain gauge, a hygrothermograph, a pyranometer, a weather vane and an anemometer (Table 1).

Precipitation and runoff volumes were measured in 22 years (January 1993 to December 2014). Precipitation data was recorded at the daily scale, while discharge data were continuously measured at the watershed outlet by an ultrasonic flow meter (WR-11Z model, NAKAASA corporation, precision 0.5 cm) (Table 1). The measured flow depths were converted into water discharge by a regression equation, as detailed in the studies of Cicco et al. (1987) and Zema et al. (2018). Finally, the daily runoff volume was estimated from the discharge.

Observations of precipitation and runoff daily data simulated by SWAT were aggregated at the annual scale for modelling purposes. The hydrological response of the watershed was quantified by the annual runoff coefficient (hereinafter "RC"), equal to the ratio between the runoff volume and the cumulative precipitation of the same year.

2.3 Hydrological modelling

2.3.1 The SWAT model

SWAT is a time-continuous, long-term, distributed-parameter, process-based hydrological model that was developed to simulate surface and subsurface flow, soil erosion as well as sediment and nutrient movement through a watershed (Arnold et al. 1998). Although SWAT has been mainly used to study the hydrology of medium to large watershed (Piniewski et al. 2013), several applications are found also in small watersheds (e.g., Meaurio et al. 2015; Qiu et al. 2012; Kang et al. 2006; Licciardello et al. 2011).

In the SWAT model, a watershed is delineated into multiple sub-watersheds topologically connected by stream networks (Strauch & Volk 2013). Each sub-watershed is further divided into lumped hydrologic response units (HRUs). The HRUs are formed by overlaying maps of land use, soil type, and topography (Neitsch et al. 2010), each one resulting of unique combination of these features (De Mello et al. 2017).

The model simulates the hydrologic cycle separately for the "land phase" and "channel" or "routing phase" processes (Strauch et al. 2013). The land phase, including water flow, nutrient transport, and vegetation growth, is simulated at the HRU level (Strauch & Volk, 2013). Water, sediments and nutrients are summed for all HRUs of a sub-watershed and the resulting flows are then conveyed in the channel phase routing through channels, ponds, and reservoirs to the watershed outlet (Ficklin et al. 2009). Therefore, land phase and channel processes are integrated by SWAT at the sub-watershed level (Strauch & Volk, 2013).

In each HRU, SWAT estimates the components of the hydrological cycle (such as surface runoff, baseflow, evapotranspiration, infiltration, and soil moisture change, Lironga & Jianyuna, 2012) using the following water balance equation (de Paulo Rodrigues da Silva et al. 2018):

$$SW_t = SW_0 + \sum_{t=1}^{T} \left(R - S_n - ET - W_a - R_f \right) \quad (1)$$

where:

SW_t = final soil water content on day *t* (mm)
SW_o = initial soil water content on day *i* (mm)
T = time (days)
R = precipitation depth on day *i* (mm)
S_n= surface runoff volume on day *i* (mm)
ET = evapotranspiration depth on day *i* (mm)
W_a = amount of water entering the vadose zone from the soil profile on day *i*
R_f = amount of return flow on day *i*.

To estimate the components of the hydrological cycle, SWAT requires as input the daily data of precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed (de Paulo Rodrigues da Silva et al. 2018). Each hydrological component is estimated through SWAT sub-models related to climate, hydrology, erosion, land cover and plant growth, nutrients, pesticides, and land management (Neitsch et al. 2005). Surface runoff and infiltration volumes are simulated from daily precipitation using the Soil Conservation Service (SCS) Curve Number (CN) method (SCS, 1972).

2.3.2 Model implementation, calibration and validation

SWAT was implemented in the “A” micro-watershed, based on morphometry, climate, soil and land use input data, and evaluated across a period of 22 years (1993 to 2014).

A 30-m resolution Digital Elevation Model (produced by a Shuttle Radar Topography Mission) was used to generate the topography (Table 1). Thus, the watershed was discretised in SWAT into HRUs and its stream network was segmented into channels.

Climate data were provided by the meteorological station (Table 1) and input into the SWAT climate subroutines. Following Chow et al. (1964), surface runoff was separated from baseflow by the linear method applied to the observed streamflow records.

Soil parameters were derived from the Brazilian soil map prepared by IBGE in 2001 (Table 1). Two different soils (prevalently, sandy loam from surface to 350 mm, and clay from 350 mm to 1850 mm) were assumed. The land use was tropical rain forest.

The hydrological SWAT sub-model was run at the daily scale and its hydrological predictions evaluated at the annual scale by temporal aggregation. The default soil parameters were initially given to the model (Table 2). A default value of CN (equal to 70) of forest was first assumed, according to the standard procedure set by USDA (1972). The years of 1993 and 1994 were appended before the simulation period and used to warm up the model, in order to setup the soil's water content (Licciardello et al. 2007; von Stackelberg et al. 2007; Zhang et al. 2007; dos R. Pereira et al. 2016).

The model was calibrated and validated using the split-sample technique (Klemes 1986), applying the input parameters previously calibrated for a given period (calibration period, 1993-2004) to another period (validation period, 2005-2014) (dos R. Pereira et al. 2018). Prior to the calibration and validation process, the most sensitive parameters of the SWAT model for estimating surface runoff were identified by a sensitivity analysis, using SWAT-CUP (Calibration and Uncertainty Programs, Abbaspour 2007).

According the SWAT-CUP user's manual, the most sensitive parameters were identified using the "p-value" of a t-Student distribution, which tests the null hypothesis that each input parameter has not any effects on the model's output. A low p-value ($p = 0.05$ is the generally accepted threshold) indicates that this null hypothesis can be rejected. Therefore, if $p < 0.05$, the changes in the parameter are associated with changes in the surface runoff and that parameter is very sensitive.

SWAT-CUP was also used for the automated calibration of the model, adjusting the most influential parameters for streamflow simulation, as identified in the previous steps. More specifically, the automatic calibration was carried out (Fukunaga et al. 2015; Abbaspour 2007) as follows: (1) a threshold of the Nash & Sutcliffe coefficient (E, see below) higher than 0.4 was adopted as objective function; (2) physically meaningful absolute minimum and maximum ranges for the parameters being optimised were assumed using the values suggested in SWAT and SWAT-CUP guidelines; (3) one parameter at a time, all the parameters were varied between the minimum and maximum values until the highest value of E was achieved.

2.3.3 Evaluation of the runoff prediction capacity of the model in current conditions

Both for calibration and validation processes, the runoff prediction capability of SWAT was evaluated on the annual scale, due to the need of long-term (i.e., decadal) predictions required by this study.

SWAT performance was evaluated by (i) visually comparing the observed and simulated values of runoff volumes in scatterplots; and (ii) adopting a set of quantitative criteria, commonly used in hydrological modelling:

- the main statistics (i.e. the maximum, minimum, mean and standard deviation of both the observed and simulated values)
- the coefficient of determination (r^2)
- the coefficient of efficiency of Nash & Sutcliffe (1970, E)
- the Coefficient of Residual Mass (CRM, also reported as "percent bias", PBIAS).

The equations for their calculations are reported in the works of Moriasi et al. (2007), Zema et al. (2016), and Van Liew & Garbrecht (2003). The optimal values of these criteria are summarised as follows:

- the closer the statistics, the more accurate the model predictions;
- r^2 ranges from 0 (no agreement between model and data variance) to 1 (perfect agreement); values over 0.5 are acceptable (Santhi et al. 2001; Van Liew et al. 2003; Vieira et al. 2018);
- E, the most common measure of model accuracy, varies from $-\infty$ to 1; the model accuracy is "good" if $E \geq 0.75$, "satisfactory" if $0.36 \leq E \leq 0.75$ and "unsatisfactory" if $E \leq 0.36$ (Van Liew & Garbrecht 2003);
- CRM (or PBIAS), if positive, indicates model underestimation, whereas, if negative, overestimation (Gupta et al. 1999); an absolute value below 25% is considered fair (Moriasi et al. 2007).

2.3.4 Analysis of the watershed's hydrological response to land use and climate changes

Regarding land use changes, four scenarios were evaluated under the current weather conditions to assess the effect of land cover change on the hydrological response of the watershed. The differences of surface runoff generated by these scenarios in the period 1993-2014 were compared to the current landscape. In more detail, we simulated the hydrological effects of the replacement of native tropical forests (baseline scenario) with: (a) pasture (tropical herbaceous species); (b) crop cultivation (corn species); (3) bare soil (which is the effect of the total deforestation of the watershed) (Table 3). The choice of these scenarios is justified by the fact that areas previously covered by natural vegetation have been replaced by pasture or agriculture in most of the tropical semiarid regions of the world, resulting in a substantial increase in degraded or intensively cultivated areas. Hence, the scenarios analysed by the SWAT model can be helpful to identify conservation measures of natural resources and to recover degraded areas in Brazil and in tropical regions (de Paulo Rodrigues da Silva et al. 2018). The hydrological effects of these land use changes were input in SWAT by modifying the initial CNs. The values related to the land uses alternative to forest were derived from the USDA-SCS guidelines for the soil hydrological group "C".

Regarding the future weather projections, the climate changes forecasted for the next 80 years were estimated by an ensemble of three Global Circulation Models (GCMs), which mathematically represents the general circulation of a planetary atmosphere or ocean (Zhang et al. 2016). The GCM numerical structure is based on integration of many equations describing fluid dynamics and chemical processes (Krisanova et al. 2016). In this study, we used the following GCMs:

- MIROC5 (Atmosphere and Ocean Research Institute, University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan)
- GISS-E2-H (NASA Goddard Institute for Space Sciences, USA)
- MRI-CGCM3 (Meteorological Research Institute, Tsukuba, Japan).

Since GCMs usually provide global data at a rather coarse resolution (grid size about 100-200 km), GCM simulations were downscaled at a finer resolution suitable for regional or sub-regional hydrological modelling (25-50 km). Following Zhang et al. (2016), the Statistical Downscaling Method (SDSM), developed by Wilby et al. (2002), was applied to downscale the results for each GCM in terms of regional climate forcing, i.e., the SWAT model input data over the watershed. SDSM application consisted of five steps: 1) predictant (observed data) and predictor (large-scale atmospheric variable) selection; 2) model calibration; 3) weather generator; 4) model validation; and 5) future climate scenario generator.

Future monthly values were simulated and then transformed into daily values using the weather generator of SWAT. The use of the internal weather generator of SWAT, instead of the climate model outputs at the daily scale, allowed by-passing the not ease availability of data at the lowest time scales of GCMs.

GCMs are driven by atmospheric GHG concentrations. As GHG emission scenarios, the so-called Representative Concentration Pathways (RCPs 2.6, 4.5, 6.0 and 8.5) were adopted (IPCC, 2013; Krisanova et al. 2016). The radiative forcing level in 2100 of RCP8.5 is the highest while that of RCP2.6 is the lowest (Li and Fang, 2016).

From each GCM and RCP, the monthly precipitation and maximum and minimum temperatures for four 20-year periods (2020-2039, 2040-2059, 2060-2079 and 2080-2099) were forecasted, in order to simulate surface runoff for the experimental watershed under the current tropical forest or the other simulated land uses (pasture, cropland and bare soil) (Table 3).

Henceforth, these two conditions (actual precipitation, 1993-2014, and current land use, tropical forest) will be indicated as "baseline" scenarios.

The baseline scenario (1993-2014) with the observed data may not agree with the same period projected by the GCMs. If so, adjustments must be considered in the simulations of future climate change scenarios, with data corrections to minimize the existing bias. These corrections are based on the differences between observed and historical simulated values (Lenderink et al., 2007; Santos et al., 2019). Therefore, the surface runoff was simulated by the calibrated SWAT model, using the historical precipitation data of the three GCMs (available for the period 1993-2005). These runoff simulations were finally compared to the corresponding values, simulated using the historical data of observed precipitation for the same baseline period.

2.3.4 Statistical analysis

The statistical analysis was carried out using ANOVA. One-way ANOVA was applied to evaluate the significance of differences: (i) in precipitation among the RCP scenarios of future climate change; and (ii) in runoff volume and coefficient predicted by SWAT among the land uses. Then, using two-way ANOVA and pairwise comparison by Tukey's test (at $p < 0.05$), we evaluated whether the mean runoff volumes and coefficients (response variables) predicted by the model were different among land use and climate change scenarios (independent factors). In order to satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to normality test or were square root-transformed whenever necessary. All the statistical tests were carried out by XLSTAT software.

3. Results

3.1 Evaluation of the runoff prediction capacity of SWAT model in current conditions

The values of the statistics and indexes used to assess the SWAT model performance in predicting the surface runoff in the "A" micro-watershed are reported in Table 4. Although r^2 (equal to 0.82) and CRM (0.15) were acceptable (> 0.50 and < 0.25, respectively) when model run with default input parameters, the E value was unsatisfactory (= 0.35, thus < 0.36). The positive CRM indicates that the model tends to underestimate the observed annual runoff. Comparing the statistics of predicted and observed runoff volumes, the errors were -15.4% and -35.5% for the average and maximum values, respectively (Figure 2a).

The comparison of surface runoff values observed at the watershed outlet and predicted by SWAT showed that, when the model run with default input parameters, its runoff prediction capability was at the limit of acceptance. Using the SWAT-CUP procedure for SWAT calibration, the model's performance noticeably improved. The good model performance given by the calibration process was confirmed in the validation period. SWAT-CUP identified ten input parameters, to which the model showed the highest sensitivity (Table 2 and Figure 3). After calibration, the tendency to runoff underestimation was reduced, as shown by the CRM decreased to a value close to zero). The changes in the input parameters let runoff predictions be closer to the corresponding observations (Figures 2a and 4). More specifically, the mean, minimum and maximum runoff volumes came very close to the corresponding observations and the differences were lower than 3.5%. The E index (equal to 0.83) became good and the appreciable value of r^2, achieved in model's runs with default parameters, increased to 0.86 (Table 4).

In the validation period, the degree of correlation between runoff observations and predictions ($r^2 = 0.70$) decreased compared to the calibration period. The model's tendency to underestimate the runoff in the calibration period turned to overestimation (CRM < 0) for the validation period. The model efficiency, lower than in the calibration phase, remained however satisfactory (E = 0.70). The predicted mean and maximum runoff volumes were practically equal to the observations (differences of 1.7% and 2.8%, respectively). The prediction error increased only for the minimum values (about 10%) (Table 4 and Figure 2b).

The difference between the precipitation, and runoff volume and coefficient simulated by the SWAT model with the observed data and the corresponding simulations using the three GCMs for the baseline period (1993-2005) was always lower than 1% and not statistically significant (at p

< 0.05) (Table 5). Therefore, no adjustments were considered in the simulations of future climate change scenarios.

3.2 Evaluation of the watershed hydrological response to land use and climate changes

3.2.1 Land use changes in the baseline period (1993-2014)

Compared to the baseline value (1321 mm/yr, years 1993-2014), when the forest was the actual soil cover, and under the same rainfall input (on the average 1847 mm/yr), land use change to pasture would give the lowest surface runoff (on the average 1290 mm/yr, -2.32%), while the worst hydrological response (that is, higher runoff) would be produced by a soil left bare due to total deforestation (1437 mm/yr, +8.81%). Replacing the forest cover by agricultural activities, the runoff would undergo a very slight change (1329 mm/yr, +0.63%) (Table 6).

3.2.2 Climate and land use changes in the future (2020-2099)

Under the mean values of future climate projections, averaged among the adopted GCMs, and assuming as baseline the actual land use (tropical forest, 1402 mm/yr of surface runoff), if the hydrological variables are averaged among all the simulated climate change scenarios, crop cover and soil left bare would increase of the surface runoff (1486 mm/yr, +6.0%, and 1562 mm/yr, +11.4%), while pasture would slightly reduce runoff volume (1486 mm/yr, -1.6%) (Table 6). Almagro et al. (2017) report that South-East Brazil (where the studied watershed is located) will be one of the most greatly affected regions in terms of rainfall erosion, since a decrease (−5% to −41%, depending on the GCM adopted) in mean rainfall erosivity is forecasted.

Referring to the different RCPs, RCP 4.5 is expected to give the highest precipitation (averaging the three GCMs adopted, 1976 mm/yr, +7.0% compared the average value of the baseline period, 1847 mm/yr, years 2003-2014), while RCP 8.5 will provide the lowest precipitation input (1936 mm/yr, +4.8%). Under the other RCPs, the precipitation increase will be lower (1945, RCP 2.6 and 1944, RCP 6.0, mm/yr) (Table 6 and Figures 5a to d). Compared to the baseline value (on the average 1321 mm/yr), RCP 4.5 will presumably produce the highest runoff volumes in the 80-year period (on the average 1478 mm/yr, +11.9%). Conversely, the minimum surface runoff will be achieved under RCP 2.6 and RCP 8.5 (1449 mm/yr, +9.7%, for both RCPs) (Table 6 and Figures 5a to d).

4. Discussions

4.1 Evaluation of the runoff prediction capacity of SWAT model

The automated calibration procedure has demonstrated the importance of the tree canopy interception ("CANMX.hru" parameter) in tropical forests, whose value was increased during calibration. Shares of tree canopy interception close to 15-20% has been quantified by several studies in tropical forests (e.g., Franken et al. 1982a; 1982b; Zema et al. 2018). Also Strauch et al. (2012, in Brazil) as well as Zhang et al. (2016, in China) and Raneesh & Thampi Santosh (2011, in India) found that SWAT is strongly sensitive to this input parameter.

Also water infiltration in the soil was modified, decreasing the available water capacity of the soil ("SOL_AWC().sol") and increasing the fraction of the infiltrating water into the deep aquifer percolation fraction ("RCHRG_DP.gw") as well as the soil evaporation compensation factor ("ESCO.hru") (Table 2). The increase of the latter parameter allowed the model to reduce the evaporative demand from lower soil levels, when it accounts for the effect of the capillary action, crusting and cracks. "SOL_AWC().sol" and "ESCO.hru" were among the most sensitive parameters in SWAT model applications in the same environmental contexts (Strauch et al. 2012; De Mello et al. 2016) and in other climate conditions (e.g., Tan et al. 2017, in Malaysia; Zhang et al. 2016, in China; Raneesh et al. 2011, in India; Senent-Aparicio et al. 2017, in Spain). The initial CN for antecedent moisture condition II ("CN2.mgt"), a basic parameter for accurate surface runoff prediction for almost all the prediction models using the SCS-CN hydrological component (Licciardello et al. 2007; Strauch et al. 2013; Zema et al. 2017), was increased from the default value of 70 to 77.3. This change increased the soil's aptitude to produce surface runoff and thus reduced the model's tendency to its underestimation (Table 4). A similar increase was needed in the study of Strauch & Volk (2013), in order to reach a better fit to peak flows observed in a watershed under the same environmental conditions (Cerrado bioma, Brazil). Conversely, Strauch et al. (2012; 2013) reported the need to decrease CN2 parameter in Brazilian basins, since the soil physical properties and practices (such as the infiltration capacity and management activities) were not properly reflected in initial CN2 and the initially assumed reference values were too high (Fukunaga et al. 2015). Also De Mello et al. (2016) and Strauch et al. (2012) found a high sensitivity of SWAT model to "CN2.mgt" parameter under the same environmental conditions as those of this study.

Other minor changes needed by SWAT-CUP to improve runoff prediction capacity of SWAT were applied to the moist bulk density ("SOL_BD().sol"), effective hydraulic conductivity in tributary channel alluvium ("CH_K1.sub"), lateral flow travel time ("LAT_TTIME.hru"),

462 Manning's coefficient "n" value for overland flow ("OV_N.hru") and saturated hydraulic
463 conductivity ("SOL_K().sol"). All these parameters were noticeably increased, since under default
464 simulations many of these were assumed as null (Table 2). It is interesting to highlight that the
465 calibrated value of the saturated hydraulic conductivity set by SWAT-CUP may be unrealistic, but
466 it must be also noted that: (i) the model's sensitivity to this input parameter was quite limited; and
467 (ii) the calibrated value came from a mathematical optimisation rather than a physically-based
468 optimisation.

469 It should be also evidenced that other input parameters that were identified by SWAT-CUP
470 as the most influential in SWAT applications of other studies (for instance, "ALPHA_BF" =
471 Baseflow recession constant, "GW_DELAY" = Groundwater delay time, "GWQMN" = Water
472 depth in shallow aquifer for return flow, "CH_N2" = Manning's "n" value for the main channel,
473 "RCHRG_DP" = Deep aquifer percolation fraction) (De Mello et al. 2016; Strauch et al. 2012; Tan
474 et al. 2017; Zhang et al. 2016; Raneesh et al. 2011; Senent-Aparicio et al. 2017) were not
475 considered as sensitive parameters in this study (Figure 3). The low sensitivity of SWAT to these
476 parameters is quite surprising, since the hydrological processes which many of these factors govern
477 (for instance, deep percolation, sub-surface flow, filtration in deeper layers of soil) have a large
478 importance in the hydrological cycle of small forest watersheds under tropical conditions (Fujieda
479 et al. 1997; Zema et al. 2018). This indicates that autocalibration should be done within relatively
480 strict parameter ranges set after manual calibration or using additional hydrological observations
481 such as evapotranspiration or soil moisture. Moreover, this confirms again that SWAT-CUP
482 calibration often lacks realistic links to the physical processes.

483 Overall, the evaluation over the entire period of more than 20 years (1993-2014) showed
484 that, provided that the model is calibrated: (i) SWAT slightly underestimates the observed runoff
485 volumes (CRM = 0.01); (ii) the model is able to give very accurate annual predictions of surface
486 runoff, as shown by r^2 and E, both close to 0.82; (iii) the differences between the observed and
487 predicted means are negligible (lower than 2-3%) (Table 4). As the results of calibration and
488 validation procedures have demonstrated, the predicted runoff volumes on the annual scale were
489 very close to the observations, approaching to the identity line of the scatter plot, with very few
490 exceptions (Figure 4). Model performance was more satisfactory in the calibration period than for
491 validation, as shown by the higher values of the evaluation criteria adopted in this study. This is due
492 to the fact that the parameter values are specifically optimised for the calibration period and thus the
493 validation period may have different conditions that cause the calibrated parameters to be less than
494 optimal (Fukunaga et al. 2015).

Almost all the previous evaluations of SWAT model in the same climatic and geomorphological conditions were carried out by comparing the observed and predicted daily and monthly stream flows rather than the annual values as in this study. SWAT prediction capacity of runoff at the daily scale, beyond the aims of this study, was not satisfactory in the experimental watershed, as highlighted by the large difference in the majority of the evaluation criteria (mean, E and CRM, data not shown) adopted for model's performance evaluations (under the acceptance limits suggested by literature). The values of the Nash and Sutcliffe coefficient were in the range 0.41 (Strauch et al. 2013) to 0.82 (Dourado-Hernandes et al. 2018), while the maximum absolute value of PBIAS (5.9) was found by Strauch & Volk (2013). All the authors reported that SWAT model predicted high stream flows better than low flow conditions (de Paulo Rodrigues da Silva et al. 2018). Regarding the only model's application at the annual scale at the authors' knowledge, De Mello et al. (2017) found r^2 of 0.82, E of 0.71 and PBIAS of -12.1 in the calibration period, and r^2 of 0.76, E of 0.37 and PBIAS of -16.7 in the validation period in SWAT implementation in Sarapuí River watershed (southeast Brazil) for water quality predictions.

4.2 Evaluation of the watershed hydrological response to land use and climate changes

The hydrological response of the watershed to land use and climate changes were quantified in this study by adopting the annual runoff coefficients of each land use and climate scenario. This allows the assessment of the water resource dynamics, which is governed by the succession of wet and dry years, in the natural and delicate ecosystem of the studied watershed. The analysis of a multidecadal scale is in accordance to Krysanova et al. (2016), who suggests comparisons of outputs of hydrological models, driven by climate model data, for the reference and future scenario periods, using 30-year average annual and monthly outputs.

4.2.1 Land use changes in the baseline period (1993-2014)

The actual forest cover of the watershed determined a runoff coefficient, averaged in the period 1993-2014, of 0.71. This value is about 9% lower (and significant at $p < 0.05$) than for bare soil (RC = 0.78), which simulates a complete deforestation of the watershed. This increase shows the role of vegetation cover in the influence of the hydrological balance of the watershed. As a matter of fact, the presence of tropical forest increases water losses, providing greater water infiltration and storage in soil, replenishing groundwater and improving flow regularity (Zema et al. 2018). More generally, forests increase canopy interception, transpiration of plant tissues, evaporation from soil and water infiltration; thus, the share of precipitation that turns to surface runoff is reduced. Furthermore, forest vegetation and in particular riparian complexes play positive effects for conservation of water quality in tropical headwater watersheds, where, instead, agriculture and pasture may represent a threat against natural resource preservation (Marmontel et al. 2018).

A conversion of the current land use (forest) to cropland or pasture would determine a slight increase (RC = 0.72, +0.63%) or decrease (RC = 0.70, -2.32%), respectively, of the runoff coefficients; these variations were not significant at $p < 0.05$. This means that the experimental tropical watershed does not show a so high sensitivity to land use, regardless of the type of the change introduced. In other words, a slight decrease of water losses, expected under pasture and agricultural activities, would not significantly affect the water balance of the watershed.

The lower runoff generation capacity of pasture compared to the other land uses is in accordance with findings of de Paulo Rodrigues da Silva et al. (2018), who applied SWAT in a tropical river basin of Eastern Brazil. These authors showed that: (i) the smallest runoff was generated in areas with pasture cover; (ii) its replacement by maize cultivation increased the surface volume drained to the regions; and (iii) the runoff increased by 70% in areas with bare soil. These results indicated an increasing trend in runoff from pasture to cropland and areas without vegetation cover. Conversely, Dourado-Hernandes et al. (2018) found that a limited expansion of cropland (namely sugarcane) should have no effect on stream flows generated in a watershed of Cerrado biome (same tropical conditions), also under climate change scenarios (until 2030). The slightly higher runoff generation capacity simulated by SWAT in tropical forest in comparison with pasture cover may be quite surprising and however would deserve deeper investigations. A possible explanation has been found here by an analysis of the different components of the hydrological cycle simulated by SWAT. It emerged that pasture supports a higher evapotranspiration compared to forest (on the average 483 against 460 mm/yr, respectively). The more intense evapotranspiration rate of pasture may be supported by both the higher re-evaporation from the shallow aquifer (97 against 92 mm/yr) to the root zone and the lower percolation (80 against 72 mm/yr) into groundwater, presumably due to the denser basal area of the pasture cover of the root zone. This is accordance to Wolf et al. (2011), who report that in tropical environments the fraction of evaporation from the soil is higher in the pasture than at the forest sites. Furthermore, in tropical regions, grassland has the potential to transport as much or more water vapour to the atmosphere than forest does (Brauman et al. 2015). Santos et al. (2015) report that, compared to forest, higher levels of compaction may have favoured greater water loss in pasture areas of tropical areas (Southwestern Amazonia).

The increase of runoff generation capacity in a deforested area suggested by SWAT in the studied micro-watershed agrees with the results of dos Reis Pereira et al. (2014; 2016b). These authors studied the impacts of deforestation on a watershed on the Brazilian east coast and found an increased water flow in the analysed river due to decreased evapotranspiration.

4.2.2 Climate and land use changes in the future (2020-2099)

Under the future climate projections, a decadal variability of runoff coefficients was forecasted as watershed responds to variations of input precipitation in time windows of 20 years. More specifically, while an almost constant runoff coefficient may be expected throughout the 80-year period, the related values fluctuate for all the studied land uses with a similar shape. In spite of these fluctuations, the negative slope of the regression lines of RCs indicates that across the forecast period the runoff generation capacity of the experimental watershed will slightly decrease (Figures 6a to 6d). Among the different RCPs, the hydrological response of the watershed soil will be more intense under RCP 4.5 for all the investigated land uses, except for the pasture cover (Figures 6 and 7). The differences in precipitation and runoff coefficient were not significant at $p < 0.05$ among the RCP scenarios, while runoff was significantly different among some RCPs. Moreover, while the runoff was significantly different between forest and pasture on one side, and cropland and bare soil on the other side, all the evaluated land uses gave significantly different runoff coefficients (Table 6).

If the runoff coefficients of the observation period (1993-2014) are assumed as reference, a combined analysis of the effects of climate and land use changes on the future hydrological response of the watershed can be made.

Firstly, the mean runoff generation capacity of the experimental watershed is expected to slightly decrease in pasture for all the RCPs analysed (on the average by -0.9%), while an increase can be forecasted under forest (+0.8%), except for RCP 2.6, and crop (+6.8%) covers. If the soil will be bare (e.g., for a deforested watershed), this increase will be the highest (+12.4%) among the analysed land uses (Figure 7a). This indicates that, compared to tropical forest or cropland, pastureland is more efficient to govern the hydrological response of the watershed.

Secondly, the maximum runoff coefficients will increase (positive variations compared the baseline, on the average +23.3%) under all the land use and climate change scenarios. Since the highest RCs can be expected in occasion of years with floods (that is, when the soil is saturated and the runoff capacity generation gets its maximum value) and is linked to soil erosion, this means that in the future the climate change will determine an aggravation of the flood and soil erosion risks in this tropical watershed. However, although flooding is one of the problems of the studied watershed, the flood risk is not the most critical. While it is obvious that over bare soil this increase will be the highest (+33.3%), less expected is the fact that agricultural activities and forest cover will induce higher RCs (+25.8% and +18.3%, respectively) compared to pasture (+15.9%) (Figure 7b).

Thirdly, it is well known that a minimum runoff generation is vital for surface water body recharge and thus to feed potable water to population and irrigation resources to crops, when groundwater is not exploited. Small watersheds of tropical forests must have an adequate water supply to compensate the high evapotranspiration rates of forest throughout the year (Zema et al. 2018). If the availability of surface water is related to the minimum values of runoff coefficients, from the future predictions of surface runoff provided by SWAT model it is evident that a pasture cover will produce the highest reduction of surface runoff (on the average -2.8%). Conversely, the minimum runoff generation capacity will remain constant under tropical forest (-0.84%), while it will increase in cropland (+3.7%) and in particular in bare soil (+9.6%) (Figure 7c).

Comparisons of our results with other literature experiments are quite hard, due to the lack of similar studies analysing the effects of climate change in tropical watersheds. Regarding other SWAT applications in other environmental contexts, we should consider modelling experiences in USA, Spain, China, Malaysia and India. The study of Ficklin et al. (2009), carried out in an agricultural watershed of California, showed its high sensitivity to the climate change, indicating that not only temperature and precipitation have significant effects on all hydrological components of the water cycle, but also that these effects are complicated by the activities of irrigated agriculture. In the headwater of the Segura River basin (South-eastern Spain), Senent-Aparicio et al. (2017) showed that, compared the baseline period (1971-2000), the negative and positive trends of precipitation and temperature, respectively, will lead to a decrease in the availability of water resources by between 2 and 5% in this important water supplying basin. Raneesh & Thampi Santosh (2011) implemented SWAT in an Indian watershed (humid tropics) with forest and agricultural land uses and predicted that stream flow will undergo a declining trend under future climate change scenarios. However, the effect will not adversely affect agricultural production in the watershed, because the future temperature increase will be compensated by an expected storm intensity increase in the summer and pre-monsoon periods. A mountainous large watershed of China was monitored and modelled using SWAT by Zhang et al. (2016), who noticed relatively slight changes in stream flows in both RCP 2.6 and RCP 4.5, but increases under RCP 8.5. However, these authors suggested that future projections given by GCM emission scenarios must be considered with caution. As a matter of fact, GCMs generally cannot fully capture the interactions between atmospheric and hydrological processes and thus the effects of future climate changes on stream flows are largely uncertain (Knutti & Sedláček 2013). Tan et al. (2017) got to the same conclusions (that is, larger surface runoff changes under the RCP 8.5 compared to the RCP 2.6 and RCP 4.5, and large uncertainties in GCMs and RCPs), applying SWAT to a large watershed dominated by tropical rainforest and rubber and oil palm plantations in Malaysia.

From a social approach, the evaluation of land use and climate impacts on future management of water resources at the watershed scale indicates that deforestation must be avoided. Leaving the soil bare would increase the flood risk in urban areas (with possible lost of lives and infrastructure damages) and this would be a very large impact under the forecasted climate change. Moreover, although the SWAT simulations have demonstrated that a land use change from forest to pasture or cropland would have a moderate impact on the runoff generation capacity, this conversion would determine a significant lost of biodiversity in highly natural watersheds of the tropical environment; society should not accept that this hazard may happen in one of the most delicate ecosystems in the world. Finally, the risk of water resource reduction in tropical rivers can be expected in some of the simulated climate scenarios, and this could lead to the reduction of clear water availability for potable uses.

Overall, since the study has shown that SWAT is able to delineate the hydrological response of tropical watersheds to natural (e.g., climate change) or anthropogenic (e.g., land use modification) forcing, this model represents a useful tool for land planners and, more in general, socio-economic stakeholders, in order to adopt the most suitable measures for water resource and soil protection.

5. Conclusions

Once the applicability and reliability of SWAT model in predicting surface runoff have been verified at the annual scale and improved by calibration in a tropical forest watershed, its hydrological response under four alternative land uses (forest, cropland, pasture and bare soil) and forecasted climate changes has been simulated. The results of model application showed that the tropical watershed under investigation does not show a high sensitivity to land use, regardless of the type of the change introduced, provided that the soil is not left bare. If forest was replaced by crops or pasture, slight increases or decreases of the runoff coefficients would be expected, but the watershed's hydrological response would not significantly been affected. Conversely, a complete deforestation, leaving the soil bare, would increase the runoff generation capacity of the watershed.

Despite the uncertainty of future weather projections, under forecasted climate change scenarios, the most conservative and sustainable land use on the long term basically will depend on water management purposes established by land planners. More specifically, the runoff generation capacity of the watershed will tend to decrease and will not be noticeably different among the four climate change scenarios simulated throughout the next 80-year period. In the RCP 4.5, which will produce the most intense hydrological response in the watershed, pasture and bare soil have been found to give the lowest and highest runoff coefficients, respectively. To protect the watershed from floods and soil erosion, the most "hydrologically" efficient land use is pasture, since the conversion from forest to a natural herbaceous cover (as pasture is) will allow a decrease of the maximum values of the runoff coefficient. Finally, since the minimum runoff generation capacity will remain basically constant under tropical forest, the presence of the current tree cover will be suitable to assure surface water body recharge and thus to feed potable water to population and irrigation resources to crops. The societal implications of the forecasted changes in tropical forest watersheds go from the aggravation of the flood risk to the reduction of water resource availability for potable uses.

Overall, the study has confirmed the good accuracy in runoff predictions of the SWAT model, and provided useful indications about the sustainability of water resource management in tropical watersheds under climate and land use change scenarios. The model can support land planners' strategies in view of the conservation of the delicate ecosystems of tropical forests.

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TABLES

Table 1. Values and source of the input data for implementation of the SWAT model at "A" micro-watershed (Brazil).

Input data	***Source***	***Notes***
Topography	Topodata project of the National Institute if Spatial Investigation (INPE) of Brazil, based on data from the Shuttle Radar Topography Mission (SRTM)	Spatial resolution of 30 metres
Soil	Soil map of 2001, prepared by the Brazilian Institute of Geography and Statistics (IBGE)	Ferralic Cambisol Rhodic Ferralsol
Land use	Land use map of 2014, prepared by the Brazilian Institute of Geography and Statistics (IBGE)	Tropical rain forest
Weather	Meteorological station installed in the watershed	Hygrothermograph Pyranometer Weather vane Anemometer
Hydrology	Precipitation measured using a rain gauging station (W11-00-60 model, NAKAASA Instruments Company Ltd., Japan)	Precision 0.5 mm
	Water flow depth measured by ultrasonic flow meter (WR-11Z model, NAKAASA Instruments Company Ltd., Japan)	

Table 2. Input parameters with default values and calibrated by SWAT-CUP procedure in SWAT model implementation at the "A" micro-watershed (Brazil).

Parameter		***Measuring unit***	**Value**	
Name	*SWAT acronym*		*default*	*calibrated*
Initial SCS runoff curve number for moisture condition II	CN2.mgt	(-)	70	77.3
Baseflow alpha factor	ALPHA_BF.gw	1/days	0.91	0.93
Groundwater delay time	GW_DELAY.gw	days	31	367
Threshold depth of water in the shallow aquifer required for return flow to occur	GWQMN.gw	mm H_2O	1000	1725
Groundwater "revap" coefficient	GW_REVAP.gw	(-)	0.02	0.19
Soil evaporation compensation factor	ESCO.hru	(-)	0.95	0.99
Plant uptake compensation factor	EPCO.hru	(-)	1	0.73
Manning's coefficient "n" value for the main channels	CH_N2.rte	(-)	0.014	0.251
Effective hydraulic conductivity in main channel alluvium	CH_K2.rte	mm/hr	0	498
Available water capacity of the soil layer	SOL_AWC().sol	mm H_2O/mm soil	0.06	0.03
Moist bulk density	SOL_BD().sol	g/cm^3	1.40	2.34
Saturated hydraulic conductivity	SOL_K().sol	mm/hr	2	1152
Threshold depth of water in the shallow aquifer required for "revap" or percolation to the deep aquifer to occur	REVAPMN.gw	mm H_2O	750	96
Manning's coefficient "n" value for overland flow	OV_N.hru	(-)	0.60	13.6
Deep aquifer percolation fraction	RCHRG_DP.gw	(-)	0.05	0.23

Maximum canopy storage	CANMX.hru	mm H_2O	0	0.15
Surface runoff lag coefficient	SURLAG.bsn	(-)	2	21.4
Average slope length	SLSUBBSN.hru	m	15.2	130
Lateral flow travel time	LAT_TTIME.hru	days	0	18.8
Initial groundwater height	GWHT.gw	m	1	21.5
Effective hydraulic conductivity in tributary channel alluvium	CH_K1.sub	mm/hr	0	69.8
Manning's coefficient "n" value for the tributary channels	CH_N1.sub	(-)	0.01	18.9

Table 3. Scheme of the land use and climate change Representative Concentration Pathways (RCPs) adopted for evaluation the hydrological response of the "A" micro-watershed (Brazil) by the SWAT model.

		Land use scenarios			
		Forest (baseline)	*Cropland*	*Pasture*	*Bare soil*
Climate change scenarios	*Baseline (1993-2014)*	X	X	X	X
	RCP 2.6 (2020-2099)	X	X	X	X
	RCP 4.5 (2020-2099)	X	X	X	X
	RCP 6.0 (2020-2099)	X	X	X	X
	RCP 8.5 (2020-2099)	X	X	X	X

Note: RCP = Representative Concentration Pathways.

Table 4. Statistics and model evaluation criteria for the surface runoff observations and predictions by the SWAT model at the "A" micro-watershed outlet (Brazil).

Surface runoff	**Model input parameters**	**Mean**	**Std. Dev.**	**Min**	**Max**	**r^2**	**E**	**CRM (PBIAS)**
		(mm/yr)						
Calibration (1993-2003)								
Observed	-	1309	312	862	1712	-	-	-
Predicted	Default	1108	326	556	1583	0.82	0.35	0.15
	Calibrated	1265	257	874	1657	0.86	0.83	0.03
Validation (2004-2014)								
Observed	-	1347	271	912	1843	-	-	-
Predicted	Validated	1370	251	1002	1895	0.71	0.70	-0.02
Whole period (1993-2014)								
Observed	-	1328	286	862	1843	-	-	-
Predicted	Default	1180	309	566	1848	0.62	0.25	0.11
	Calibrated/ validated	1321	253	875	1881	0.78	0.78	0.01

Table 5. Difference (%) between the hydrological data simulated by the SWAT model with observed and projected precipitation (provided by three GCMs) for the baseline period (1993-2005) at the "A" micro-watershed outlet (Brazil).

Statistics	**Global Circulation Model**								
	MIROC5			GISS-E2-H			MRI-CGM3		
	Rainfall	Runoff	Runoff coeff.	Rainfall	Runoff	Runoff coeff.	Rainfall	Runoff	Runoff coeff.
Mean	0.05	-0.56	0.03	-0.61	-0.95	0.30	-0.13	0.20	0.99
Minimum	-0.98	-0.84	0.14	-0.98	-0.66	0.32	-0.62	0.38	1.00
Maximum	0.71	0.89	-0.12	0.95	0.41	-0.83	0.82	0.90	-0.22
Standard deviation	0.31	0.64	-0.27	1.02	-0.54	0.52	0.67	0.64	0.52

Note: all differences are not statistically significant after one-way ANOVA (at $p < 0.05$).

Table 6. Statistics (mean ± std. dev. among GCM models) of the surface runoff predictions by the SWAT model under climate and land use change Representative Concentration Pathways (RCPs) at the "A" micro-watershed outlet (Brazil).

Climate scenario		Precipitation (mm)	Surface runoff (mm)					Runoff coefficient				
			Land use scenario					*Land use scenario*				
			Forest (baseline)	*Cropland*	*Pasture*	*Bare soil*	*Mean*	*Forest (baseline)*	*Cropland*	*Pasture*	*Bare soil*	*Mean*
1993-2014 (baseline)		1847	1321 a	1329 a	1290 a	1437 a	1344	0.71 a	0.72 a	0.70 a	0.78 b	0.73
2020-2099	*RCP 2.6*	1945 ± 27 A	1391 ± 18	1480 ± 16	1368 ± 16	1557 ± 17	1449 ± 17 A	0.72 ± 0.004	0.76 ± 0.006	0.70 ± 0.004	0.80 ± 0.006	0.75 ± 0.005 A
	RCP 4.5	1976 ± 30 A	1421 ± 21	1509 ± 18	1397 ± 18	1587 ± 30	1478 ± 22 B	0.72 ± 0.004	0.77 ± 0.005	0.71 ± 0.005	0.81 ± 0.006	0.75 ± 0.005 A
	RCP 6.0	1944 ± 22 A	1398 ± 15	1483 ± 14	1377 ± 14	1555 ± 14	1453 ± 14 AB	0.72 ± 0.004	0.76 ± 0.006	0.71 ± 0.004	0.80 ± 0.006	0.75 ± 0.005 A
	RCP 8.5	1936 ± 42 A	1398 ± 28	1471 ± 26	1377 ± 26	1550 ± 28	1449 ± 27 A	0.72 ± 0.0005	0.76 ± 0.006	0.71 ± 0.005	0.80 ± 0.007	0.75 ± 0.006 A
	Mean	1950 ± 30	1402 ± 20 a	1486 ± 19 b	1380 ± 18 a	1562 ± 22 c	-	0.72 ± 0.004 a	0.76 ± 0.006 b	0.71 ± 0.005 c	0.80 ± 0.006 d	-

Note: Different lowercase and capital letters indicate significant differences among land use and climate change scenarios, respectively, after two-way ANOVA and Tukey's test (at $p < 0.05$).

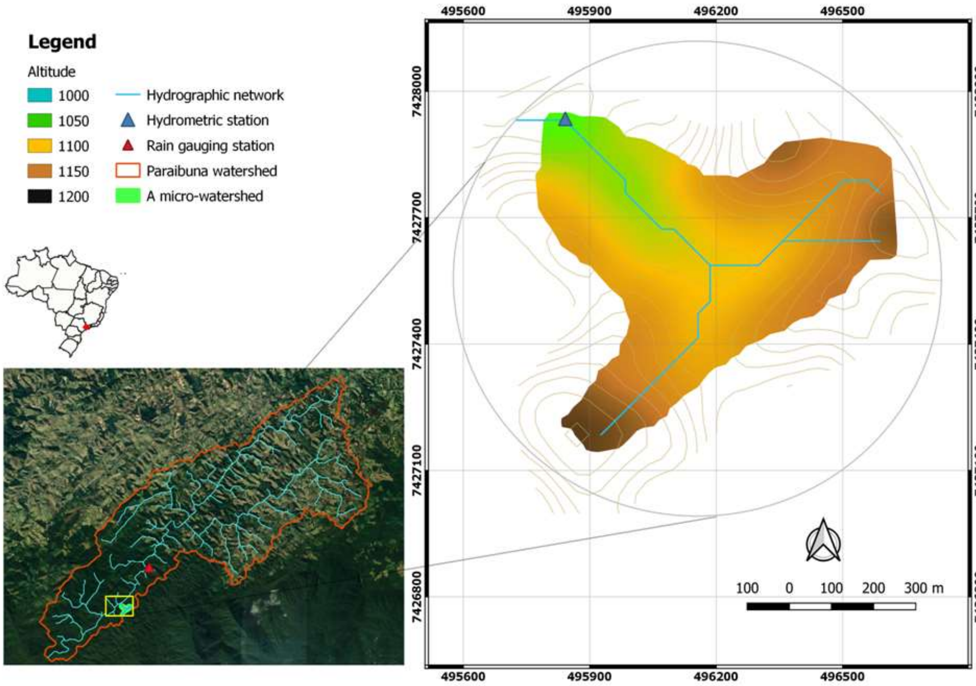

Figure 1. Geographical location (a) and land use map (b) of the "A" micro-watershed (Brazil).

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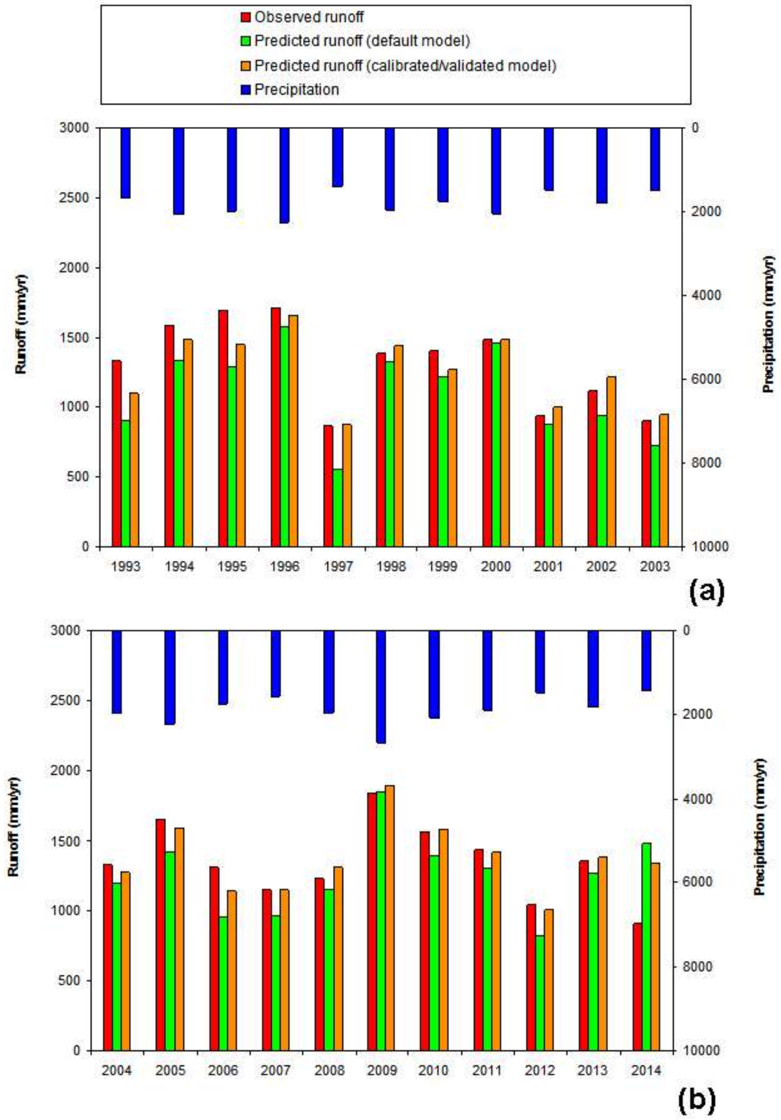

Figures 2a, b. Annual precipitation and surface runoff volumes observed at the outlet and simulated by the SWAT model (run with the default and calibrated input parameters) in the "A" micro-watershed (Brazil) - (a) calibration period, 1993-2003; (b) validation period (2004-2014).

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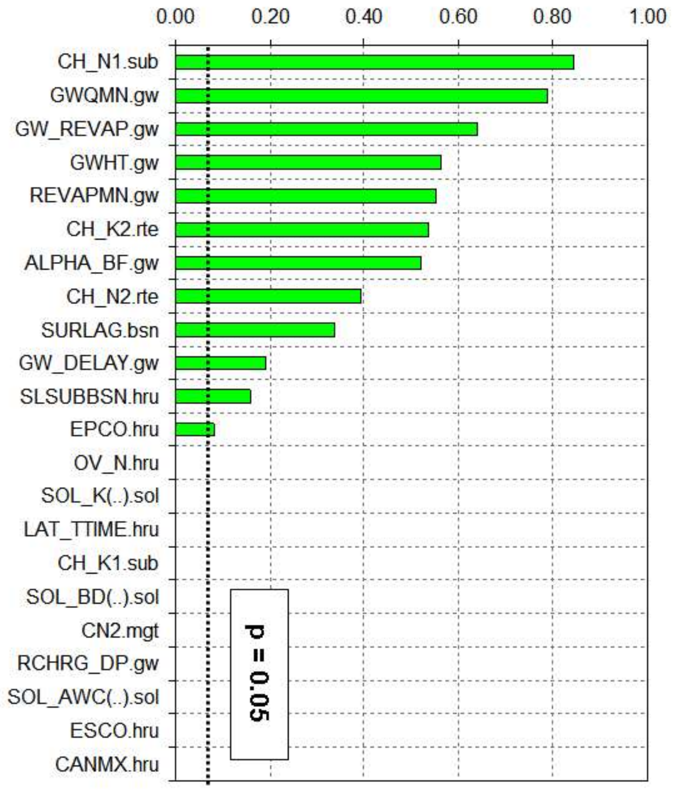

Figure 3. p-values of the input parameters of the SWAT model given by SWAT-CUP procedure applied to simulate surface runoff in the "A" micro-watershed (Brazil) - the most sensitive input parameters correspond to a p-values < 0.05.

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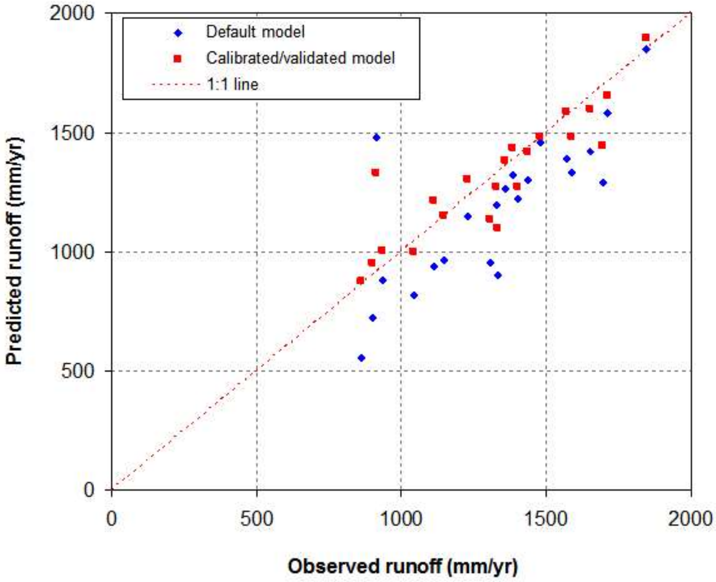

Figure 4. Scatter plots of annual runoff volumes observed at the outlet and predicted by the SWAT model in the "A" micro-watershed (Brazil).

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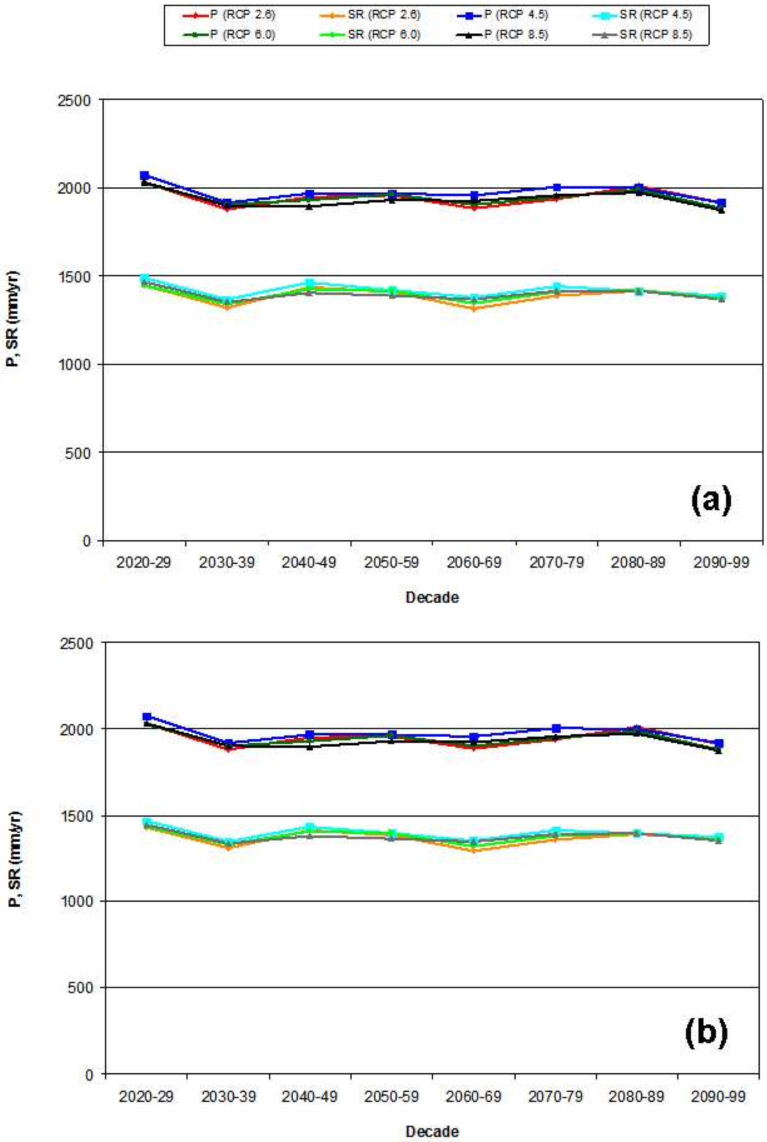

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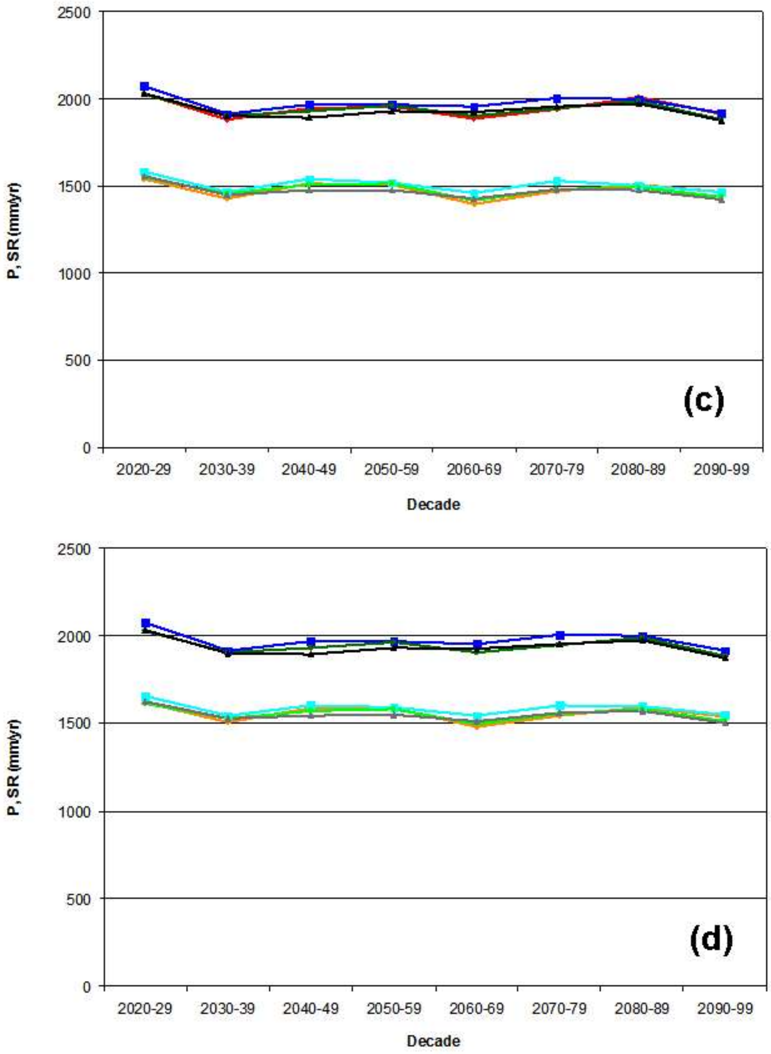
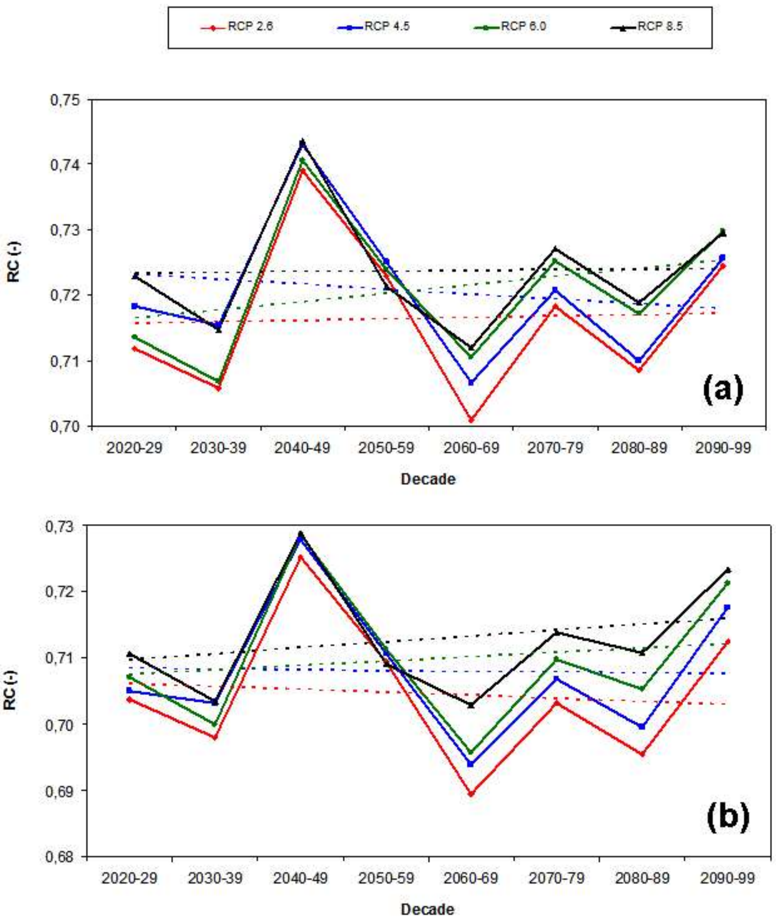


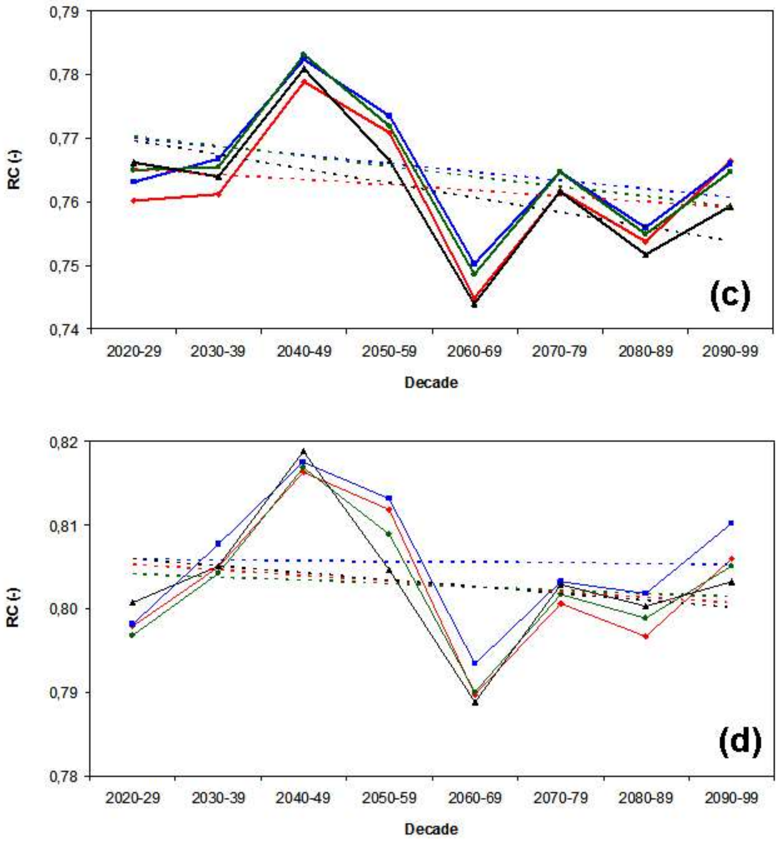
Figures 5a, b, c and d - Annual precipitation (P) and surface runoff (SR) volumes simulated by the calibrated SWAT model under climate (four RCPs) and land use change scenarios in the "A" micro-watershed (Brazil) - (a) forestland; (b) pasture; (c) cropland; (d) bare soil (standard deviations among the evaluated GCMs are not shown due to the small scale).

190x254mm (96 x 96 DPI)



Figures 6a, b, c and d - Runoff coefficients (RC) at the annual scale simulated by the calibrated SWAT model under climate (RCP) and land use change scenarios in the "A" micro-watershed (Brazil) - (a) forestland; (b) pasture; (c) cropland; (d) bare soil. The dashed line is the linear regression model.

190x254mm (96 x 96 DPI)



Figures 6a, b, c and d - Runoff coefficients (RC) at the annual scale simulated by the calibrated SWAT model under climate (RCP) and land use change scenarios in the "A" micro-watershed (Brazil) - (a) forestland; (b) pasture; (c) cropland; (d) bare soil. The dashed line is the linear regression model.

190x254mm (96 x 96 DPI)

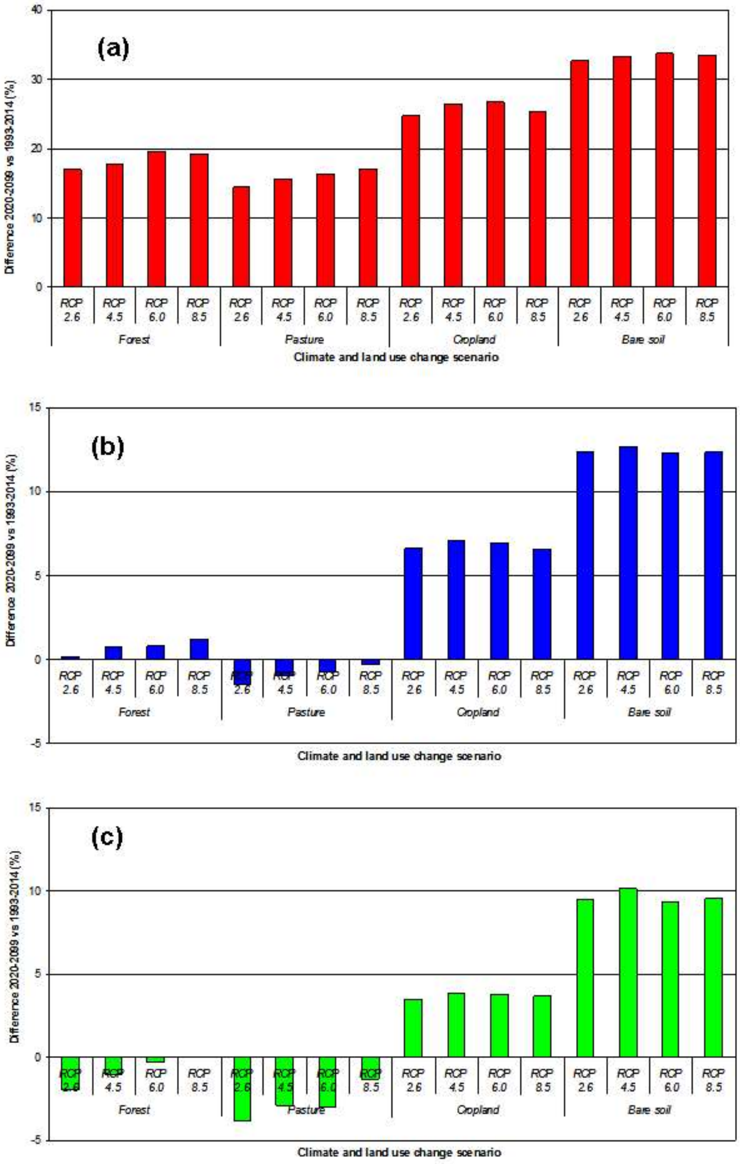


Figure 7a, b and c - Difference between the mean (a), maximum (b) and minimum (c) runoff coefficients at the annual scale observed in the period 1993-2014 and simulated by the calibrated SWAT model under climate (RCP) and land use change scenarios in the "A" micro-watershed (Brazil).

190x254mm (96 x 96 DPI)