Article

Impacts of Land-Use and Climate Changes on Hydrologic Processes in the Piracicaba Basin, Brazil

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ABSTRACT

Climate and land use changes are two factors affecting the hydrology of watersheds. The greatest effect of climate change is probably the change in the hydrological cycle, thus water availability for human consumption, industry, and power generation. While the change in land use can cause changes in the hydrological components of the basin, such as evapotranspiration, runoff, and groundwater recharge. From these projections, it is necessary to understand the processes involved in climate change and land use and its impact on water systems. In this context, the objective of this study was to simulate climate change scenarios combined with the land use change and to analyze the impacts on the hydrology in the Piracicaba basin. Two periods were selected based on the preliminary result of detection of the abrupt change point of the annual flow series, using Petitt's non-parameter test. The first period selected prior to the occurrence of the point of the change was from 1985 to 2000. The other period after the point of the change was 2001 to 2015. Land use maps of the years 1990 and 2010 were used to represent the two periods. The results showed a good performance of the SWAT model. The NS (Nash-Sutcliffe coefficient) was 0.88 in calibration for both periods. In the validation, the NS was 0.92 and 0.94 for the first and second periods respectively. We then simulate climate and land use changes scenarios and compare them to the current scenario (baseline). The simulation results showed that the hydrological processes in the Piracicaba basin in the period 1985-2015, had more intense responses to land use change than climate.

Keywords: hydrologic modelling; Pettit method; SWAT; surface runoff; water yield

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), over the last century, global climate changes that impacted water resources through changes in precipitation, temperature and energy balance. Increased evaporation, combined with changes in precipitation, has the potential to affect the flow dynamics along the basins, the frequency and intensity of extreme events such as floods and also changing the characteristics of transport and dispersion of pollutants in water (IPCC, 2007a; IPCC, 2007b; IPCC, 2013).

From different perspectives, recent studies have analyzed the impacts of climate change in hydrology of the watershed and its consequences on agricultural production and variation in the qualitative and quantitative availability of resources (Bekele et al, 2019; Leta et al, 2016; Lobanova et al, 2018; Wang et al, 2018). According to the results of these studies, changes in the dynamics of the basins, which includes among other components precipitation, runoff, evaporation, temperature and extreme events are closely associated with climate change.

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However, land use change and management practices also affect the hydrology of the watershed. Some studies have quantified the combined effects of climate variations and land use in hydrology (Pervez, 2015; Tu, 2009; Guo et al., 2008; Lahmer et al., 2001; Mander et al, 1998). The results of these studies showed several effects of land use and management on the hydrological components of the watershed and the increase of such effects under different climatic conditions. Other studies too investigated the combined effect of land use and climate impacts on the response rivers and basins in different parts of the world (D'Agostino et al., 2010; Wetterhall et al, 2011; Wang et al, 2013; Bossa et al, 2014; Wang et al, 2014; Pechlivanidis et al, 2015; Heo et al, 2015).

Among the various methodologies currently applied in the research area hydrometeorological, the potential impacts of future climate change and the land use can be quantified for a specific watershed through use of a hydrological simulation model integrated with climate projections derived from Global Climate Models (GCM's) and land use change scenario modelers. The results of climate projections of GCM's such as precipitation and temperature, feed hydrological models to analyze scenarios of the effects of climate change on water resources. Hydrological models establish a link between climate change and water production through simulation of the hydrological processes in basins. Various simulations can be done from according to the user's needs (Ficklin et al., 2009). Confidence in results simulations varies greatly and depends largely on the methods and structure of the climate scenario as well as the hydrological model used and the assumptions adopted in modeling. Assessments with various climate change scenarios can provide valuable information on the sensitivity of hydrological systems to changes in climate (Arnell & Liv, 2001; Karlsson et al, 2016).

One of the most used simulation models in hydrographic basins today is the SWAT model (Soil and Water Assessment Tool), which allows a great flexibility in the configuration of watersheds (Peterson & Hamlett, 1998). At SWAT model applications have shown promising results, for example, hydrological assessments, impacts of climate change, assessment of the best management practices, estimating the load of pollutants, determining the effects of change land use, sediment production, among others (Yan et al, 2013; Welde et al, 2017; Leta et al, 2018; Wang et al, 2018; Teklay et al, 2019). The model was developed for be applied in large river basins and has often been used as a tool to analyze the effects of climate change and land use in the response of the watershed, and impacts on water demand and availability throughout the world (Abbaspour et al, 2009; Montenegro & Ragab, 2010; Rossi et al, 2009; Schuol et al, 2008; Siderius et al, 2013 apud Pervez & Henebry, 2015; Zhao et al, 2015; Napoli et al, 2017; Ahiablame et al, 2017; Tamm et al, 2018; Sahoo et al, 2018).

The hydrological changes mentioned have had a pronounced impact on many sectors of the society since the reduction of water availability, whether quantitative, qualitative or both, it has become a serious problem that many communities and nations around the world already face and that may be aggravated due to changes in the associated climate to the rapid increase in human population (Kundzewicz et al, 2007). It is evident that both climate and land use changes are important drivers of change in the hydrology of basins, although the relationship of these effects is difficult empirical separation. Therefore, it is important to assess changes in the land use together with the impacts of climate change to predict availability long-term water supply.

Taking into account the facts and issues presented and that there is a limited number of studies on the combined effect of the impact of changes climate change and land use change in the quantity and quality of water for Brazilian conditions, this work aims to simulate through the model SWAT climate and land use

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changes scenarios in the Piracicaba basin and carry out comparisons regarding the impacts on the flow resulting from the simulations with the current scenario (baseline).

2 MATERIAL AND METHODS

2.1 General Description of the Study Area

The study area is the Piracicaba basin located between the UTM coordinates 150,000, 412,500 West and 7,424,000, 7,557,000 South, Zone 23S, 45° central meridian (Figure 1). The basin has a drainage area of approximately 12,570 km², with an approximate length of 300 km in the East-West and 100 km in the North-South direction, 90% of which are located in the State of São Paulo and the rest in the State of Minas Gerais.

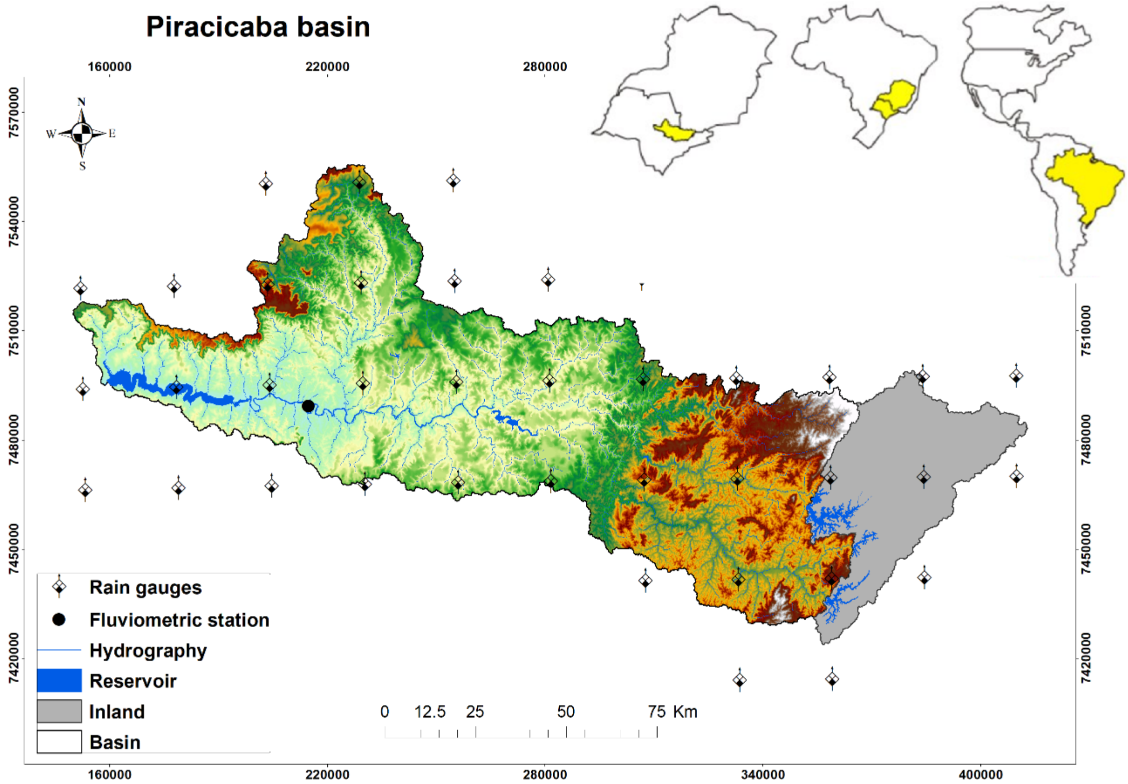

Figure 1 – Location of the Piracicaba basin.

The climate of the Piracicaba basin, according to Alvares et al. (2013), is the Climate Wet Subtropical, showing the variations: (i) Subtropical climate with dry winter and mild summer (Cwb) in its extreme east, the Serra da Mantiqueira; (ii) Weather Subtropical with no dry season and mild summer (Cfb) in the portion between the East and the center of the basin; (iii) Subtropical climate without dry season and hot summer (Cfa) in the portion between the center and the outflow of the basin (West); and, (iv) Subtropical climate with dry winter and with hot summer (Cwa) in the northwestern portion. Precipitation varies between 1,195 mm and 1,609 mm, with an annual average of 1440 m with a typical regime of the subtropical region with summer rainy season, from October to March, and dry winter, from April to September (PROFILL-RHAMA, 2018).

Economically, the Piracicaba basin stands out for its accentuated development of the sugarcane agroindustry and the presence of an industrial center in the Metropolitan Region of Campinas with chemical, textile, metallurgical industries, electronics, automotive, pulp and paper, in addition to a wide range of

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services. The Piracicaba basin have Gross Domestic Product (GDP) valued at 316.2 billion reais, representing 17% of the State of São Paulo's GDP Paulo in 2014 (PROFILL-RHAMA, 2018; IBGE, 2016).

Currently, the Piracicaba basin is characterized by the increasing increase in pressures exerted on water resources. In the upstream region of the basin, there is the transposition of part of its waters to supply the greater São Paulo through the Cantareira Water Production System (SPAC), the main conflict factor in the use of water in the basin. SPAC is a set of dams and hydraulic structures capable of providing, at normal operating levels, a flow of 33 m³/s for greater São Paulo (ANA and DAEE, 2017), currently meeting the demand of a population of 5.4 million people. For the Piracicaba basin, in turn, the SPAC allocates a flow of 5.5 m³/s, destined for public and industrial supply, drainage of domestic effluents and industrial, irrigation, electricity generation and recreation, highlighting the supply of approximately 5.5 million people in the metropolitan region of Campinas (PCJ Basin Agency, 2014).

The transposition by SPAC, therefore, is one of the main reasons for conflict by water in the Piracicaba basin as it reduces the water availability of the basin which is estimated at 970 $m^3.hab^{-1}$ $year^{-1}$ (PCJ, 2020), a value considered critical according to the agency manager (PCJ Basin Agency, 2018).

2.2 Change point detection in hydrological data series

The identification of change points in hydrological series is one of the methods important analytical tools to investigate the effects of climate change and human activities (Zuo et al., 2014). The method developed by Pettitt (1979) is commonly applied in climatic and hydrological series of continuous data (Karabork et al., 2007, Martinez et al., 2010, Zuo et al., 2014). O Pettitt's method indicates the value and place (time) of breaking the trend of a series temporal, when the exact time of change is unknown (Júnior & Landim, 2014). Pettitt's method has the advantage of being non-parametric, that is, it does not require the data conform to any probability distribution.

The Pettitt test uses a version of the Mann-Whitney test (Freund, 2006), in which it is verified whether two samples $Y_1, Y_2..., Y_t$ e $Y_{t+1}, Y_{t+2}..., Y_T$ are or are not of the same population. The null hypothesis of the Pettitt test is the absence of the shift point. The statistic $U_{t,T}$ counts the number of times a member of the first sample is larger than a member of the second sample, which can be written according to the equation:

$$U_{t,T} = U_{t-1,T} + \sum_{j=1}^{T} sgn(Y_i - Y_j) \quad (t = 2, \dots, T) \qquad \text{equation 1}$$

being:

$$\begin{aligned} sgn(Y_i - Y_j) &= 1, \quad \text{para } (Y_i - Y_j) > 0 \\ sgn(Y_i - Y_j) &= 0, \quad \text{para } (Y_i - Y_j) = 0 \\ sgn(Y_i - Y_j) &= -1, \quad \text{para } (Y_i - Y_j) < 0 \end{aligned} \qquad \text{equation 2}$$

The $K(t)$ statistic, which locates the point at which there was a change in a series temporal, and the probability (p) associated with its significance can be calculated, respectively, by:

$$K(t) = max_{1 \le t \le T} |U_{t,T}| \qquad \text{equation 3}$$

$$p \cong 2 \cdot e^{\left(\frac{-6 \cdot [K(t)]^2}{T^3 + T^2}\right)} \qquad \text{equation 4}$$

The abrupt change point is the one at which the value of t occurs to the maximum of $K(t)$. To be more carefully evaluated, levels of significance of 5% and 10% to detect any change in the hydrological variable in study.

In the present work, the Pettitt test was used to detect the possible trend change points in the observed minimum and maximum annual flows of the Artemis station (prefix 4D-007). The flow station is located near the outlet of the basin at coordinates UTM 214.839m E, 7,489,331m N, zone 23. The period of analysis of the series temporal was between 1985 and 2015.

2.3 The SWAT Model

The SWAT model, acronym for *Soil and Water Assessment Tool*, is a model deterministic, semi-distributed, physically based and continuous simulation based daily temporal (NEITSCH et al., 2009). The model stands out for presenting the capacity to assess the effects of different decisions on the components of the water balance and the presence of pollution sources, punctual or not (ABBASPOUR et al., 2015), predicting the impact of land management practices, such as changes in land use and occupancy or application of chemical products in crops (NEITSCH et al., 2009) and for presenting integration with Geographic Information Systems (GIS) *software* (MARTIN et al., 2005).

The SWAT model is based on topography to discretize the watershed in sub-basins which are connected to the drainage network. Then to evaluate the effects of different uses and occupations on heterogeneous soils, each sub-basin is then discretized into hydrological response units (HRU), as a function of topography, land use and slope. Finally, hydrological processes, such as runoff surface and evapotranspiration, are calculated in each HRU, with the calculation of the balance water divided into surface and runoff propagation phases (NEITSCH et al., 2009; RAFEE et al., 2019).

The surface phase controls the amount of water, sediment, nutrients and loads of pesticides in the main channel of each sub-basin (NEITSCH et al., 2009). the phase of flow propagation, in turn, simulates the flow and transport process of sediments, nutrients and pesticide loads from the main channel of the stretch in question to outflow from the watershed (NEITSCH et al., 2009).

These characteristics make the SWAT model robust to be used in different water resources management studies, such as: plant growth (Luo et al, 2008), water availability assessment (ROUHOLAHNEJAD et al., 2014; FUKUNAGA et al., 2015; CUCELOGLU; ABBASPOUR; OZTURK, 2017), measurement of changes in behavior
hydrological resulting from changes in land use (ZHU; LI, 2014; MACHADO; RIBEIRO; LOPES, 2015; NAPOLI; MASSETTI; ORLANDINI, 2017), estimate of erosion (Tibebe & Bewket, 2011), nutrient transport (Baltokoski et al., 2010), sediment transport (Machado et al., 2003) and water management (Debele et al., 2008).

Input data required to represent the study area in the model SWAT were: (1) the Digital Elevation Model (DEM) of the *Shuttle Radar* project *Topography Mission* (SRTM) with 30 m spatial resolution (USGS; NGA; NASA, 2013); (2) the Soil Map with spatial and tabular data prepared by Rossi (2017); (3) the Land Use and Occupation Map; (4) time series of climate data observed as precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity.

For the Piracicaba basin, the Land Use and Occupation Maps were elaborated in function of the trend change points (Item 2.2). The data series in turn, were obtained from meteorological stations located along of the basin under the responsibility of the National Institute of Meteorology (INMET), of the Center for Meteorological and Climatic Research Applied to Agriculture (CEPAGRI) from the State University of Campinas (UNICAMP), from the School of Agriculture “Luiz de Queiroz” (ESALQ) and data interpolated from the work of Xavier et al (2016) (Figure 1).

The areas upstream of the SPAC reservoirs were considered as "*Inland"*, portions of the watershed that are not directly modeled, but that provide an inflow that must be propagated through the channel network for the purpose of water balance, reducing computational processing time (WINCHELL et al., 2013). This was necessary by difficulty of representing areas upstream of the SPAC due to the lack of precipitation data and to account for the water balance in the reservoirs. How the outflows of the reservoirs are provided by the SPAC operator, the hydrological modeling was performed only for the downstream regions (Figure 1).

The model has been used due to its ability to model impacts future weather conditions. Some studies on the impacts of climate change on water resources have used this model (eg Hanratty and Stefan, 1998; Rosenberg et al., 1999; Cruzeiro et al., 1999; Stonefelt et al., 2000; Fontaine et al., 2001; Eckhardt and Ulbrich, 2003; Chaplot, 2007; Schuol et al., 2008, Zhang et al., 2016).

2.4 Parameterization, Calibration and Validation of the SWAT model

The study area was parameterized in the SWAT model through the survey of parameters related to soil/management, groundwater, sub-basins and main channel that may influence hydrological processes and their intervals of variation suggested in technical literature (ABBASPOUR et al., 2015; BRIGHENTI; BONUMA; CHAFFE, 2016; RAFEE et al., 2019). We did the Analysis of Global Sensitivity (ASG) to assess which are the most sensitive parameters in the area of study, as described by Abbaspour (2014), and therefore used for the model calibration.

The calibration process consists of adjusting the values of input parameters considered sensitive and the initial and boundary conditions of the model within plausible intervals until the values simulated by the model are close to the observed in the field (ZECKOSKI et al., 2015). Validation, in turn, consists of check if the calibrated model is able to properly reproduce a set of field observations other than those used in calibration or predicting future conditions without further adjustments to the calibrated parameters (C. ZHENG et al., 2012; MORIASI et al. al., 2015).

For the execution of the SWAT model calibration and validation procedures, the *software* used was the SWAT-CUP (*Soil and Water Assessment Tool: Calibration and Uncertainty Programs*) (Abbaspour, 2012), with the chosen algorithm being S*equential Uncertainty Fitting Version*2 (SUFI-2) due to its extensive use in technical literature (ROUHOLAHNEJAD et al., 2014; KAMALI et al., 2017; RAFEE et al., 2019).

The SUFI-2 algorithm is characterized by representing all sources of uncertainty in the model in the parameters to be calibrated, expressing them in intervals with uniform probability distributions of occurrence. During the calibration process, SUFI-2 iteratively tries to capture most of the observed data and optimize the objective function chosen by modifying the parameter ranges to be calibrated, presenting the output variables within a 95% prediction range of uncertainty (95PPU). 95PPU is calculated using the accumulated probability between the 2.5% and 97.5% levels of significance obtained through Hipercube sampling Latino (ABBASPOUR et al., 2007, 2015).

The two measures used to measure the quality of the calibration process of SUFI-2 are the P-value and R-value. The first refers to the fraction of observed data which is within the 95PPU range, with the value of 100% indicating the calibration perfect. The R-value, in turn, refers to the ratio between the average width of the uncertainty and its standard deviation. Technical literature recommends P-values greater than 0.70 and R-value less than 1.5 (ABBASPOUR; JOHNSON; VAN GENUCHTEN, 2004; ABBASPOUR et al., 2007, 2015).

The data from the Artemis flow station were used to carry out the procedures for calibration and validation of the Piracicaba basin in SWAT-CUP. This flow station is located near the outlet and its

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contribution area represents 86.8% of the total area of the basin, reflecting the possible effects of the change in use of land over the water regime. The division of calibration and validation periods was defined considering the possible points of trend change (Item 2.2).

The objective function used for calibration and evaluation of simulated data was the Nash-Sutcliffe Efficiency Coefficient (NSE). This coefficient is the statistic normalized of the variance of the residuals on the variance of the observed data (NASH;
SUTCLIFFE, 1970; MORIASI et al., 2015), being calculated by:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{OBS(i)} - Q_{SIM(i)})^2}{\sum_{i=1}^{n}(Q_{OBS(i)} - \overline{Q}_{OBS})^2} \quad \text{equation 5}$$

Where $Q_{OBS(i)}$ and $Q_{SIM(i)}$ correspond to the observed and simulated monthly flow, respectively (m³/s); $\overline{Q}_{OBS}$ is the average monthly flow observed in the simulation period;
and *n*, the number of events.
NSE values can vary between -∞ and 1, with 1 being indicative of a perfect adjustment. According to Moriasi et al., (2007), NSE values greater than 0.5 indicate a satisfactory model performance and values below zero a performance unacceptable.
In addition to the NSE, the *Percent Bias* statistic (PBIAS) was calculated, which measures the average trend of how much the model underestimates (positive values) or overestimates (negative values) the simulated data in relation to the observed:

$$PBIAS[\%] = \frac{\sum_{1}^{n}\left(Q_{OBS(i)} - Q_{SIM(i)}\right)}{\sum_{i=1}^{n}\left(Q_{OBS(i)}\right)} \times 100 \quad \text{equation 6}$$

The calibration process was performed until satisfactory P-values are obtained value and R-value and values considered at least as "Satisfactory" of the statistics NSE and PBIAS, as presented in Table 1.
Table 1 – Performance ranges of NSE and PBIAS functions for monthly discretization.

Função	**Very good**	**Good**	**Satisfactory**	**Unsatisfactory**
PBIAS	| PBIAS |< 10%	10% ≤ | PBIAS | <15%	15% ≤ | PBIAS | < 25%	| PBIAS | ≥ 25%
NSE	NSE > 0,75	0,65 < NSE ≤ 0,75	0,50 < NSE ≤ 0,65	NSE ≤ 0,50

Source: Kouchi et al. (2017).

2.5 Scenarios generation using hydrological modeling

Scenario generation is one of the most important applications of modeling hydrological because it helps decision makers to analyze the potential impacts of human actions. In this case, climate change scenarios combined with land use change are simulated and the impacts on the hydrological characteristics of the basin analyzed. Assessing the impacts of climate change on hydrology and water quality has become one of the main challenges of hydrological modeling in using the SWAT model.

To differentiate the effect of climate change and land use on the flow and analyze the efficiency of the SWAT model to properly simulate these and future changes, we use the one change factor approach, keeping it if the other constants (Tan et al., 2015). Two periods were selected based on in the preliminary result of detection of the abrupt change point of the flow series yearly. The first period selected was before the occurrence of the probable point of change, from 1985 to 2000, representing the 1990's. The other period,

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after the point of change, was from 2001 to 2015 (representing 2000's). 1990 and 2010 land use maps were used to represent land use patterns for the two periods.

We assess the following conditions:

1. Baseline (C1): 1990 land use and weather conditions from 1985 to 2000;
2. Land use change only (C2): land use pattern in 2010 and weather conditions from 1985 to 2000;
3. Only climate change (C3): land use pattern for the year 1990 and weather conditions from 2001 to 2015;
4. Land use and climate change (C4): land use pattern for the year 2010 and weather conditions from 2001 to 2015.

Therefore, scenarios 1 and 4 represent, respectively, past conditions and current in the Piracicaba basin, being used to carry out the steps of calibration and validation. As recommended by some researchers (Arnold et al., 2000, 2012; Thampi et al., 2010), before running the simulations in the SWAT model, the set of meteorological and hydrological data was divided into two subsets: 1985 to 2000 (1985 to 1995 for calibration and 1996 to 2000 for validation) and 2001 to 2015 (2001 to 2010 for calibration and 2011 to 2015 for validation), represented by conditions C1 and C4, respectively. Due to the uncertainties of the ignorance of the condition's initial hydrological conditions at the beginning of the simulation, especially regarding the initial moisture of the soil (Mello et al., 2008), the 5 years prior to these periods were used for heating the model ("warm up"). Thus, from 1980 to 1984 for scenario C1 and from 1996
to 2000 for scenario C4, were reserved for heating in the steps of calibration and validation.

Thus, 3 analysis scenarios were created:

• (C1 and C4) indicates the current condition during the respective analysis periods;
• S2 (C2 – C1) depicts the effects of land use change on the water regime;
• S3 (C3 – C1) depicts the effects of climate change on the water regime;
• S4 (C4 – C1) describes the combined effects of land use change and climate in the water regime.

The impact of climate change and land use change on the regime water was evaluated by comparing the flows that result from the simulation of the current scenario (baseline) after calibration and validation with simulation data resulting from the projections scenario. The statistical criterion used to compare current and future scenarios is the deviation from analyzed event (Dv). With this method, the smaller the value of Dv, the smaller the deviation between scenarios (ASCE, 1993):

$$Dv[\%] = \frac{\sum_{1}^{n}(S_{SIM} - S_{CU})}{\sum_{i=1}^{n}(S_{CU})} \times 100 \qquad \text{equation 7}$$

Being, S_{SIM} represents the events of the scenarios of the projections and S_{CU} represents the events considered as the current scenario (baseline) in the period analyzed. The calculation of the deviation of the analyzed event (Dv) is important because it considers the potential deviation between the data compared.

3 RESULTS

3.1 Change point detection in hydrological data series

For both Artemis flow station series, we observed, with 90% confidence statistic, that there is a trend change in the maximum flows from the year 1999 (Figure 2), with an average increase of 21%, and in minimum flows from the year 2000 (Figure 3), with an average decrease of 21.5%.

These results complement the trend analyzes carried out by Moraes et al. (1997) and Frederice & Brandão (2016). The authors measured the effects of the installation of the SPAC in the average daily flows from the main rivers in the Piracicaba basin for the periods from, 1930 to 1995 and 1944 to 2012.

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According to Moraes et al. (1997), precipitation in the basin showed a positive trend in the period between 1947 and 1991, although not statistically significant, and the flow, in turn, a negative trend statistically significant from 1979. That is, despite the increase in rainfall from around 100 mm in the period, the flows reversed by SPAC decreased the flow produced by the basin, the impacts being more pronounced in the Jaguari and Atibaia rivers, main SPAC trainers. Frederice & Brandão (2016), in turn, quantified these changes, estimating a decrease in the measured mean flow of the basin at the Artemis station by 14% from 148.84 m^3/s to 127.33 m^3/s after 1984. For minimum flow of 7 days with 10 years of return time, reference flow for granting use of surface water resources in the Piracicaba basin, the authors noted the decrease in the median by approximately 15%, from 45.57 m^3/s to 38.50 m^3/s.

These authors analyzed the effects of the construction of SPAC on values flow rate of the Piracicaba River. However, in this research, the period analyzed it was from 1985 to 2015, that is, after the construction of SPAC in 1982 and, thus, posterior to the trend breakpoints observed by the aforementioned authors. Therefore, the detection of the occurrence of rupture points in the maximum and minimum flows about 18 years after the implementation of SPAC correlates to new factors not previously considered: changes in land use, which were measured in the present research through the analysis of satellite images, and the climate, estimated through of hydrological modeling in SWAT.

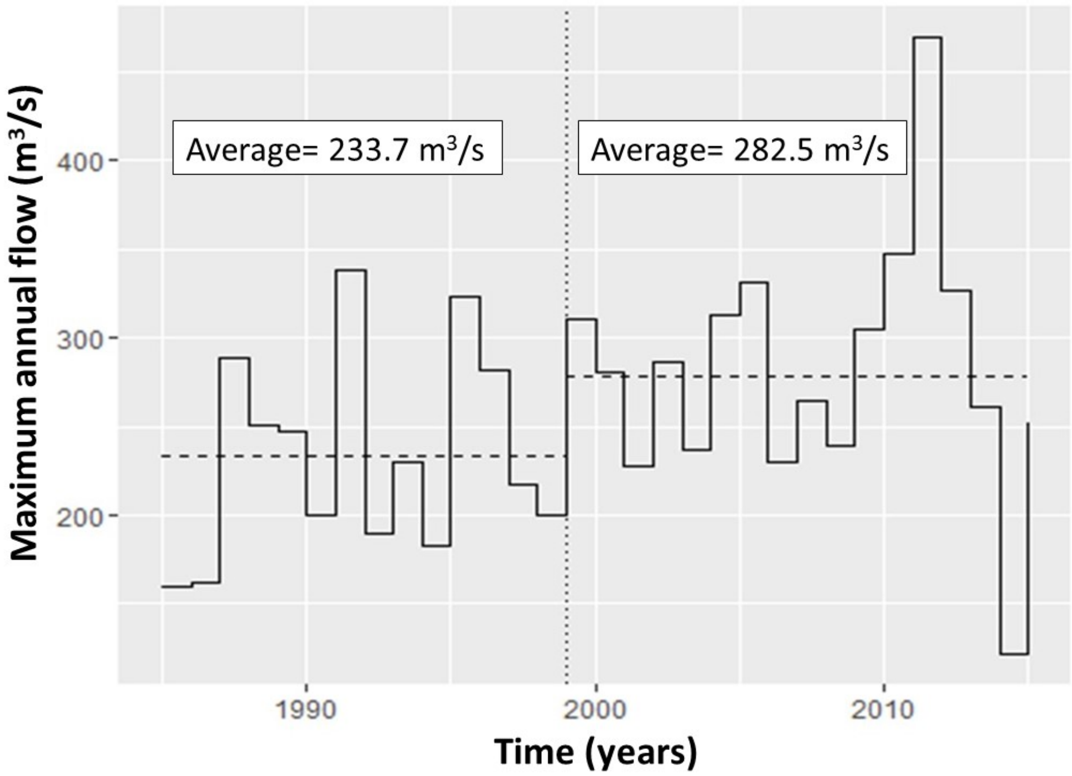

Figure 2 – Variation in the maximum annual flow of the Artemis flow station located in the Piracicaba basin in the period from 1985 to 2015. It is possible to identify the year 1999 as the year when the trend of maximum flows. The average of the maximum flows in the period from 1985 to 1998 is 233.7 m^3/s. In the period of 1999 to 2015 the average of the maximum observed flows is 282.5 m^3/s.

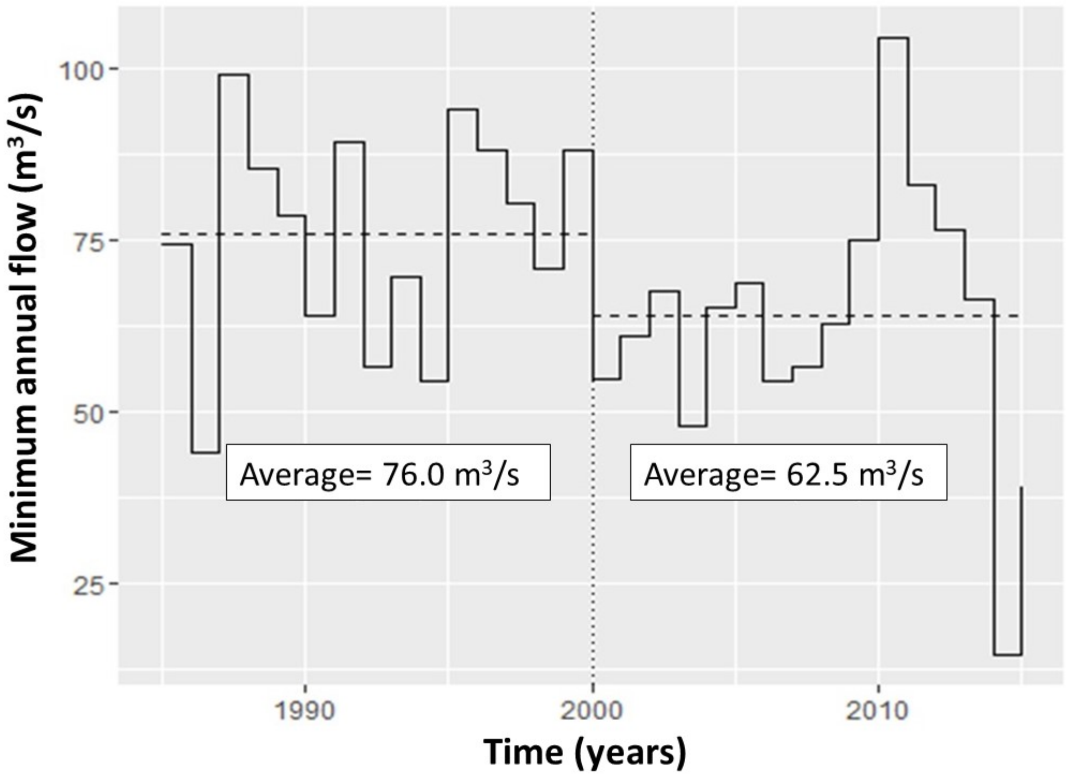

Figure 3 – Variation of the minimum annual flow of the Artemis flow station located in the Piracicaba basin in the period from 1985 to 2015. It is possible to identify the year 2000 as the year when the trend of minimum flows. The average of the minimum flows in the period from 1985 to 1999 is 76.0 m^3/s. In the period 2000 in 2015 the average minimum flow was 62.5 m^3/s.

3.2 Analysis of land use changes between 1990 and 2010

The survey done by Molin (2014) from satellite images was used to represent the land use in the two different periods based on the test result of Pettitt. The period before the change point, from 1985 to 2000, was represented by the 1990 land use survey. The period after the change point, from 2001 to 2015, was represented by the survey in 2010. Figure 4 presents the land use maps and Table 1 the total and relative areas of occupation of each land use in the Piracicaba basin for the two periods.

Comparing land uses in the two periods, there is an increase in areas destined for the planting of commercial species due to the expansion of the sugarcane area (12.6%) and perennial crops (115.6%) concomitantly with the reduction of pastures (-15.9%). This change in areas destined for agricultural production is explained due to the government incentives in the period, especially for ethanol production, and agricultural mechanization. As for natural vegetation, there was a reduction in native vegetation (-10.4%), but with an increase in reforestation (81.9%). This characteristic probably reflects the current demands of society regarding compliance with environmental legislation, especially on the part of agricultural producers for subscription to financing lines. finally, there was an increase of 28% in urban areas in the second period in relation to the first, although the total percentage of urban areas in the Piracicaba basin is less than 10%. This information ratifies the agricultural vocation of the basin, since 65.1% of the basin is occupied by plantation areas (perennial crops, sugarcane and pastures) and possible effects on agricultural productivity due to climate change can have considerable impacts on the social and economic aspects of the basin.

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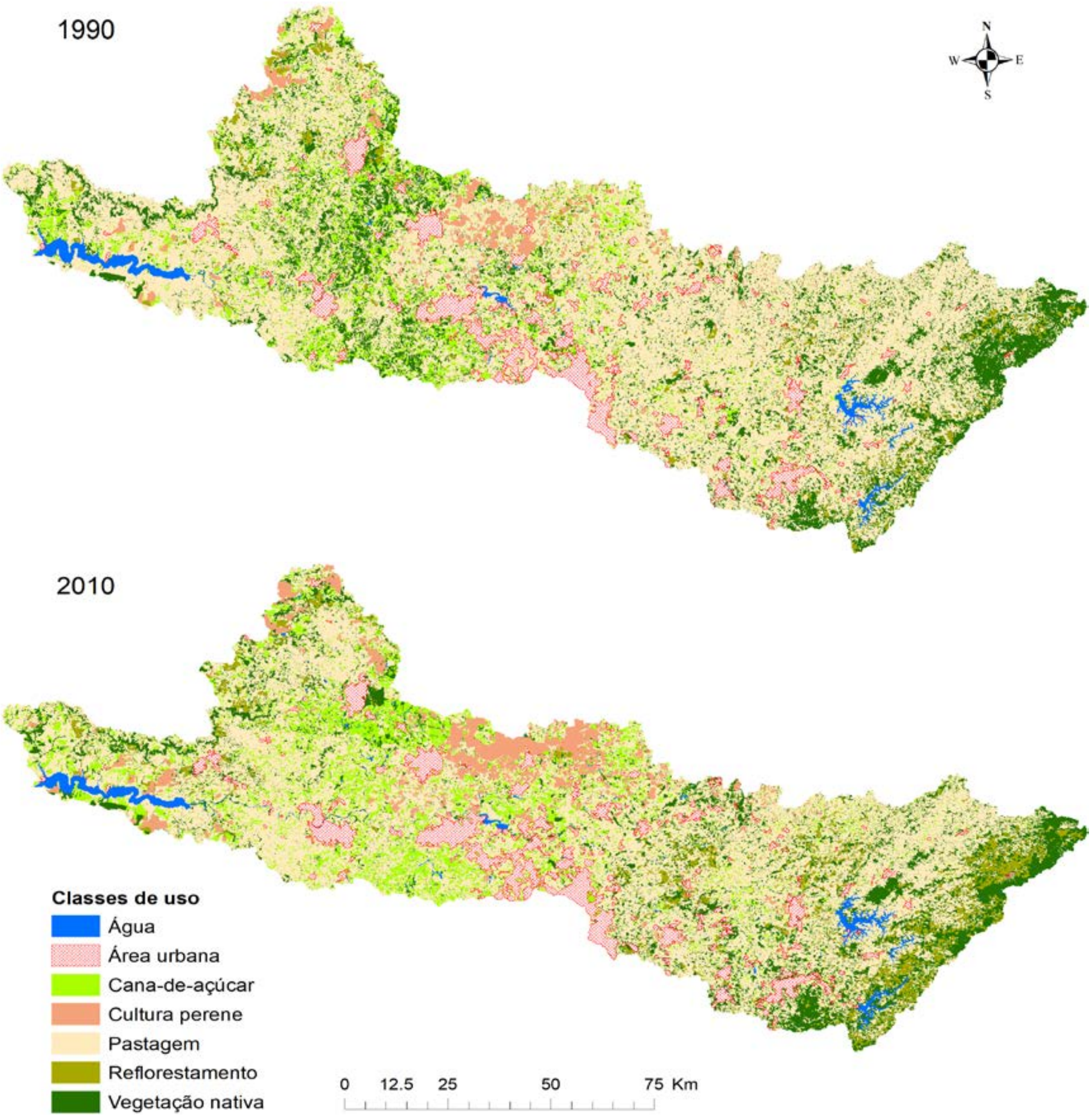

Figure 4 – Land use in the Piracicaba basin for the periods 1990 and 2010 (Molin, 2014).

Table 2 – Classes and land use change in the Piracicaba basin from 1980 to 2010.

Land uses	1990		2010		Change (2010–1990)	
	Area (km^2)	(%)	Area (km^2)	(%)	Area (km^2)	(%)
Water	182	1,4	209	1,7	27	14,8
Urban area	722	5,7	924	7,3	202	28,0
Sugarcane	3.008	23,9	3.386	26,9	378	12,6
Perennial culture	244	1,9	526	4,2	282	115,6
Pasture	5.085	40,4	4.274	34,0	-811	-15,9
Reforestation	293	2,3	533	4,2	240	81,9

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Native vegetation	3.049	24,2	2.732	21,7	-317	-10,4

3.3 SWAT model performance evaluation

In the parameterization we analyzed 16 parameters related to the behavior of the surface flow and base flow, which were subjected to the procedure of ASG, 7 of which presented sensitivity for the study area. The Table 2 presents the results of parameterization and ASG, being the results measured through the T-Stat and P-value indices. The first index identifies the relative significance of each parameter, with the higher the value absolute greater the sensitivity (MENDONÇA DOS SANTOS; PROENÇA DE OLIVEIRA; DI LOLLO, 2020). The P-value, in turn, evaluates the hypothesis that the angular coefficient of the line formed by the evaluated parameter is equal to zero, that is, it evaluates whether or not the parameter is sensitive. If the P-value is greater than 0.05, the parameter, with 95% statistical confidence, has no sensitivity (ABBASPOUR; VAGHEFI; SRINIVASAN, 2017).

The results of the sensitivity analysis (Table 3) showed the importance of parameters such as SOL_AWC, CH_K2, CN2 and ALPHA_BF in the flow in the basin. The CN2 parameter is related to the amount of runoff and is based on in the use and type of soil and in the previous conditions of humidity. Other parameters may have greater or lesser sensitivity, depending on the hydrogeomorphological characteristics and land use of the basin. According to Arnold et al. (2012), the most used parameters in flow calibration surface and base flow are CN2, SOL_AWC, ESCO, EPCO, SURLAG, GW_ALPHA, GW_REVAP, GW_DELAY, GW_QMN, REVAPMIN and RCHARG_DP.

Calibration of scenarios 1 and 4 was performed through 4 iterations of 500 simulations for the 7 parameters considered sensitive and, subsequently, the validation. The results of these steps are shown in Figure 5 and Figure 6, which illustrate, respectively, the monthly data of precipitation and simulated flows and observed in the calibration and validation period for conditions C1 and C4, displaying a similar pattern of variation between simulated and observed values.

Table 2 - Parameters used in the sensitivity analysis.

Parameter	Description	sensitivity	t-Stat	P-Value
SOL_AWC	Available water capacity of soil layer	1	19.10	0.00
CH_K2	Effective hydraulic conductivity of the channel	2	-13.70	0.00
CN2	Initial Curve Number for antecedent moisture II	3	8.65	0.00
GWQMN	Shallow aquifer water limit for baseflow occurrence	4	8.34	0.00
GW_REVAP	Coefficient of water rise to the saturated zone	5	6.83	0.00
SOL_K	Soil saturated hydraulic conductivity	6	4.75	0.00
ALPHA_BF	Baseflow Recession Coefficient	7	2.77	0.01
EPCO	Plant water absorption coefficient	8	-1.12	0.26

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CANMX	Maximum amount of water intercepted by vegetation	9	-0.62	0.53
SURLAG	Delay coefficient of runoff	10	0.42	0.68
REVAPMN	Soil water limit for the occurrence of capillary rise	11	0.25	0.81
SOL_ALB	Albedo of the soil	12	-0.25	0.81
GW_DELAY	Time interval for aquifer recharge	13	-0.22	0.83
ESCO	Soil water evaporation compensation coefficient	14	-0.19	0.85
CH_N2	Manning number	15	0.04	0.97
SLSUBBSN	Average slope length	16	-0.03	0.97

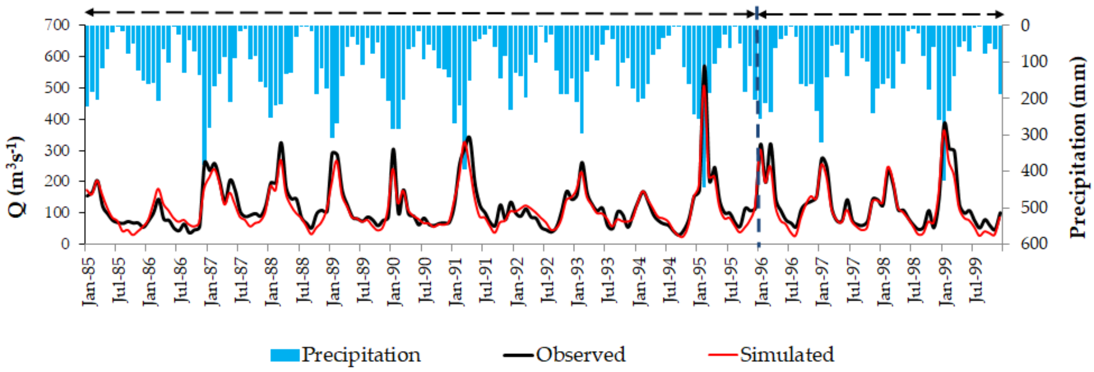

Figure 5 – Comparison of the observed and simulated flow in the Piracicaba basin in condition C1. The calibration was carried out in the period from 1985 to 1995 and the validation in the period from 1996 to 2000.

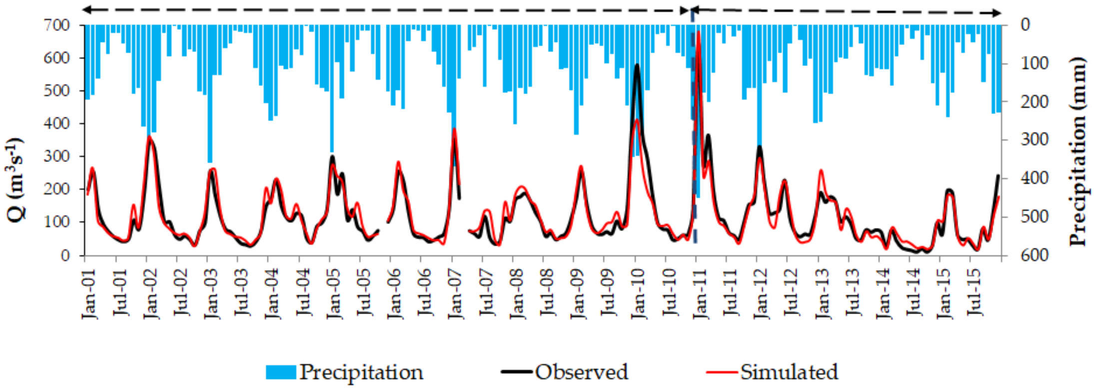

Figure 6 – Comparison of the observed and simulated flow in the Piracicaba basin in condition C4. The calibration was carried out from 2001 to 2010 and validation from 2011 to 2015.

Table 3 shows the result of statistical indices for evaluating the model's performance. SWAT adequately simulated the monthly flow for both conditions. The NSE values for the validation period were higher than the values found for the calibration, being 0.88 for the calibration of both periods and from 0.92

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to 0.94 for the C1 and C4 periods of validation. NSE values above 0.7 indicate a very good performance of the model (Moriasi et al., 2007).

As for the result of the variation between simulated and observed flows (PBIAS), the model underestimated the flow by 6.7% in the calibration and 11.0% in the validation for condition C1 and overestimated the flow by 2.9% in the calibration and underestimated by 2.8% in the validation period for condition C4 (Table 3). The values of |PBIAS| ≤ ± 10% indicate very good model accuracy (Van Liew et al., 2007).

The p-factor value was 0.96 for calibration and validation, and the r-factor was 1.07 for calibration and validation, in condition C1. For condition C4, the p-factor ranged from 0.85 (calibration) to 0.67 (validation), and the r-factor ranged from 0.51 (calibration) to 0.38 (validation). Abbaspour et al. (2015), recommend adopting a p-factor value greater than 0.7 and an r-factor value less than 1.5. However, the authors point out that these values can vary depending on the adequacy of the input data and the model's calibration.

These results show that the model after calibration and validation adequately simulated the hydrological processes in the Piracicaba basin for the scenarios of land use change and climatic variations.

Table 3 - SWAT model evaluation indices for conditions C1 and C4, during periods of proposed calibration and validation.

Indexes	**C1**		**C4**	
	Calibration	Validation	Calibration	Validation
NSE	0,88	0,92	0,88	0,94
PBIAS	6,7	11,0	-2,9	2,8

3.4 Assessing the effects of climate variations and land use change on hydrological processes

The Table 4 shows the simulated values of the average annual flow conditions land uses and climate C1, C2, C3 and C4 and the average annual values for the analysis. S2 scenario (C2 – C1) show the effects of land use change in the regime, S3 scenario (C3 – C1) show the effects of climate variability on the water regime and S4 scenario (C4 – C1) describes the combined effect of land use change and the climatic variability in the water regime.

Table 4. Simulated average annual flow for conditions C2, C3 and C4 with different patterns of land use and climatic conditions in relation to condition C1.

	land use	**climate**	$\overline{Q}$ **(m³/s)**	**Scenarios**	**ΔQ (m³/s)**	**Dv (%)**
C1	1990	1985-2000	1387,7	–	–	–
C2	2010	1985-2000	1711,2	S2 (C2 - C1)	323,6	23,3
C3	1990	2001-2015	1288,0	S3 (C3 - C1)	-99,6	-7,2
C4	2010	2001-2015	1422,5	S4 (C4 - C1)	34,9	2,5

By analyzing Table 4, the increase in flow caused by the change in the land use - S2 (C2 - C1), was more significant (23.3%) than the decrease caused by climate variability - S3 (C3 – C1), reduction of 7.2%.

S2 scenario, characterized by land use change, but maintaining the climatic conditions, the flow increased by 323.6 m^3/s, which represents a variation 23.3% (Table 4). The impact of land use change on runoff is presented in Figure 7. For the entire period analyzed, the variation was positive.

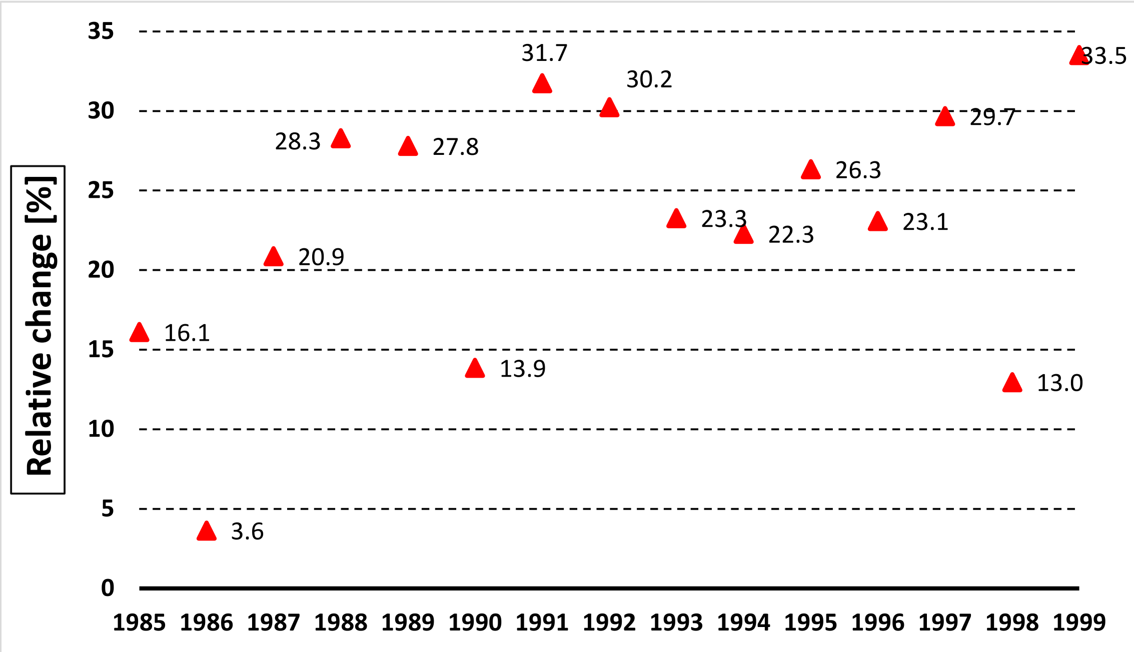

Figure 7 – Percentage change in runoff for scenario S2.

The decrease in native vegetation concurrently with the increase in urban area and other agricultural uses are possibly the cause of the positive variation (Table 1). The area of native vegetation decreased by 10.4%, while the urban area almost tripled (28%).

Changes in land use make it possible to explain in parts the changes in hydrological trend of maximum and minimum flows detected in this research. Commercial crops such as sugarcane are characterized by rapid growth and, consequently, by the greater demand for water, reducing the flows produced in the basin, especially the minimum flows (VIOLA et al., 2014). The canopy and the roots of these crops, as well as pastures, do not favor the phenomena of interception or rain infiltration, unlike forest vegetation, increasing runoff surface and, in this way, magnifying the maximum flow rates and the production of sediments (Mendonça dos Santos et al., 2020; Liu et al., 2012).

S3 scenario assesses the impact of climate variability on runoff, flow decreased by 99.6 m3/s, showing a negative variation of 7.2% (Table 4). A one of the probable causes was the decrease in the average annual precipitation of the basin by 44 mm (-3.5%) in the 2000s compared to the 1990s. Annual average precipitation in the basin of 1432 mm between 1985-2015 and the randomness of the variable's climate, this variation was negligible.

The percentage variation of the flow in scenario S3 (Dv S3) and the absolute variation of the precipitation (Dv P) are illustrated in Figure 8. Percentage changes in runoff followed the trend of absolute variation in rainfall only in the years of events extremes, positive or negative. The result of this scenario does not allow assigning a change in runoff due to the change in the precipitation pattern, but the natural climate variability.

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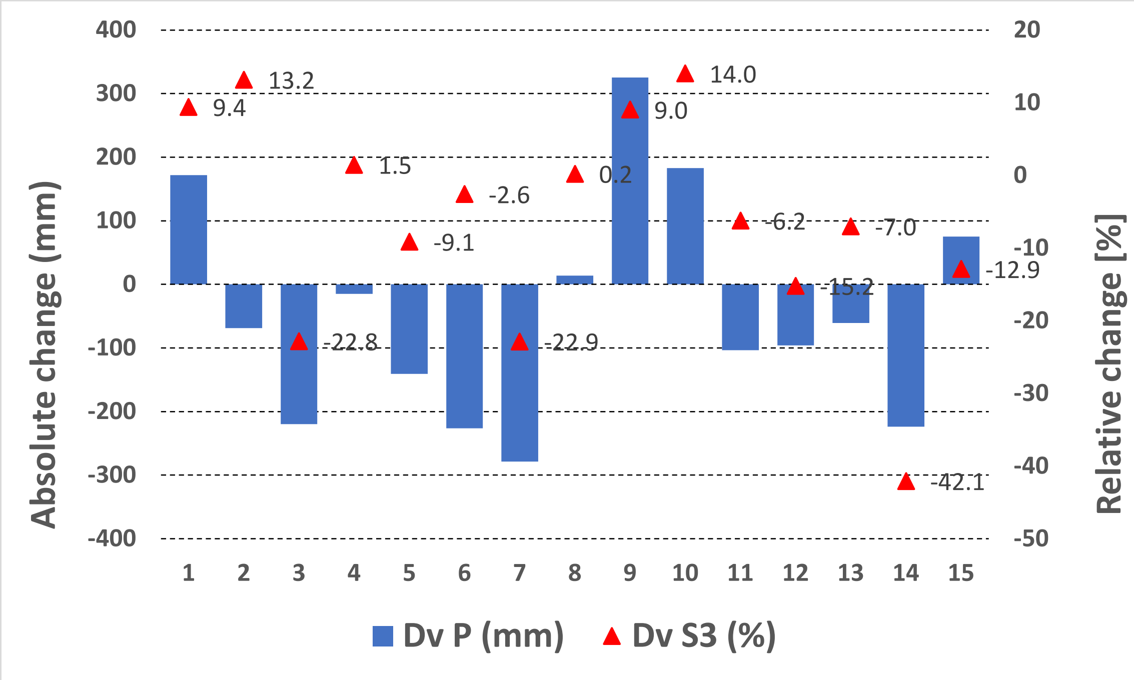

Figure 8 - Percentage variation in runoff for scenario S3 and the absolute variation in precipitation between the 2010's and 1990's in the Piracicaba basin.

The period between 2013 and 2015 was characterized by very low rainfall in relation to the annual averages for the period 1985-2015, which led to an unprecedented drought situation called water crisis (MARENGO et al., 2015). According to MARENGO et al. (2015), this situation was due to the presence of an intense, persistent and anomalous high atmospheric pressure system over the Southeast region during the summer of 2013 did not allow the action of rain mechanisms.

The resulting of this process was the critical level of the reservoirs and the reduction of the flow in the rivers (CBH-P CJ, 2017), the latter being observed in the values observed in the years of 2013 and 2014 of Dv of scenario S3 (-15.2% and -42.1%) and of Dv P (-61 mm and -228.3 mm). It is also observed that despite the year 2015 having presented rainfall higher than the average in 75.3 mm, the Piracicaba basin still presented flows 12.9% lower than the mean indicating that it was still under water stress.

In scenario S4, the combined effect of climate variability and change in land use, showed variation between conditions C4 and C1 positive (2.5%), with the combined effect of land use change and climate variability has increased the flow at 34.9 m^3/s (Table 4). These results went in the same direction as those induced only by the change in land use (S2) and opposed to the effects produced by the climate variability (S3). Therefore, the change in land use was more decisive than climate variability in the basin's water regime during the recent past (1985 to 2015).

The combined effects of land use change and climate variability are not a simple addition of the individual effects due to the complex interactions in the hydrological simulation process in the SWAT model (Wang, et al., 2014; Li et al., 2009). As shown in Table 4, the flow varied by 23.3% and -7.2% as an effect of land use change (S2) and climate variability (S3), respectively. Simply adding these results would produce the combined effect of land use change and climate variability. by 13.6%, a value 5.44 times higher than the effect of 2.5% measured in the S4 simulations. The results of the annual variation are shown in Figure 9.

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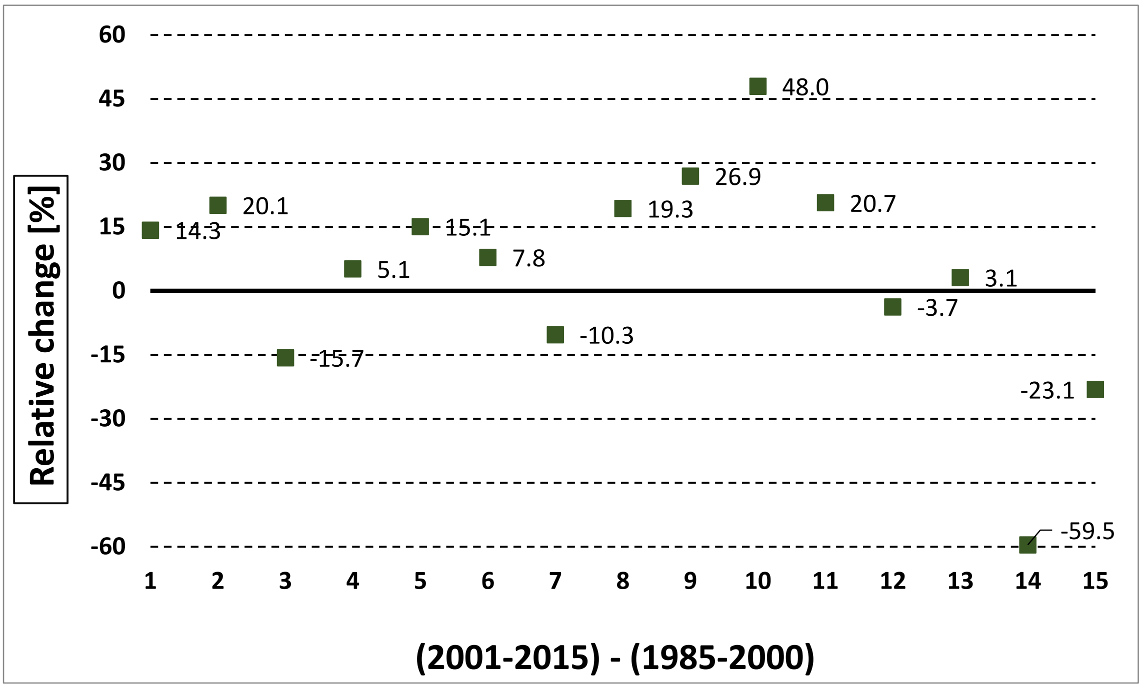

Figure 9 – Percentage change in runoff in scenario S4.

The S4 results are similar to those obtained in the S3 scenario, with variations in the flow either positive or negative. However, it is notable that the average range in S4 is much larger than S3, highlighting the intensification of the effects of the water crisis in the year 2014 by -59.5%. Therefore, from the simulation results in the SWAT model, it is inferred that the hydrological processes in the Piracicaba basin had more intense responses to land use change than climate variability.

Two additional considerations can be made from this result. The first is that the Dv index (Equation 7) cannot be analyzed by its value alone (Table 4), but by the individual analysis of each simulated year (Figure 9). Second MORIASI et al. (2015), the results of a hydrological model may overestimate in the same measure that they underestimate, producing deviation indexes close to zero, which does not correspond to reality, exactly what happened in this research.

The second consideration is that these results reinforce the need for constant simulations and evaluation of the effects of changes in land use and climatic variations in the Piracicaba basin as the region has several proposals for structural measures, such as the creation of dams (DAEE, 2015), and not structural, such as the reforestation of the banks of the main rivers (CONSÓRCIO PCJ, 2018), which may impact the flow produced in the basin. It should be noted that the analysis of impact of these measures, most of the time, does not include the effects of changes climate.

CONCLUSIONS

The initial objective of this work was to simulate the flow using the SWAT model and compare the results with the data observed in the Piracicaba basin and verify the model's performance through statistical tests. We then simulate climate change and land use scenarios and compared with the current scenario (baseline). Two analysis periods were defined, 1985-2000 and 2001-2015 from the detection of the changing point of the trend in maximum flows from the year 1999 and also the minimum flows from the year of 2000 from the Artemis fluviometric station (prefix 4D-007), using the non-parameter test of Petitt. The simulation results showed that the hydrological processes in the Piracicaba basin, in the period 1985-2015, had more intense responses to land use change than climate variability.

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