

## Hydrological simulation of a small forested catchment under different land use and forest management

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This paper describes the assessment of the SWAT hydrological model to reproduce continuous daily streamflow and simulate scenarios of forest management for a small catchment under tropical climate in Aracruz, Brazil. The main land use of the catchment consisted of eucalyptus cultivation. The SWAT parameters were calibrated and validated using daily hydrologic and meteorological data from 1997 to 2004. The statistical indices of SWAT validation (NS = 0.74, PBIAS = -14.34%, RSR = 0.51) show that SWAT performance was satisfactory in this application. Different land use and forest management scenarios were simulated with the aim of assessing their influence over the streamflow. The scenarios were: catchment under eucalyptus cultivation with three different forest managements and catchment under the native forest (Atlantic Rainforest). The scenarios simulations did not show significant changes in the long-term average streamflow. Minimum, maximum, and average annual streamflows were higher for eucalyptus scenarios compared to the native forest scenario. These results should be carefully applied to other watersheds as they reflect soil, landscape, and climate characteristics, as well as the geographic location, size, and use of water of the plantings and other vegetation.

**Keywords:** Hydrological Modeling, Soil and Water Assessment Tool (SWAT), Atlantic Rainforest, *Eucalyptus*

### Introduction

The alteration of landscapes by humans has led to a gradual increase in the scarcity of water and degradation of its quality (Mainali & Chang 2018). Over the last decades, there has been a growing consensus that the interaction between water and land use should be approached effectively in the pursuit of water sustainability, integrating territorial planning with the watershed scale management (Wang et al. 2016).

The maintenance of water resources is intimately related to the proper use of the soil and the land cover from a natural mechanism of dynamic equilibrium. There is a delicate interrelation between land use, soil, and water. When some interference occurs in that dynamic, the effects affect the system as a whole. The alteration of land use modifies the environmental

equilibrium affecting the hydrological processes in watersheds (Salemi et al. 2013, Fu et al. 2019).

The influence of land use on quantitative and qualitative aspects of water is difficult to quantify, especially in the long term and on a large scale, such as in a regional watershed, where complex interactions occur (Ferraz et al. 2013). In that sense, the characterization of the hydrological behavior of the watersheds due to land-use changes, in many cases, becomes unfeasible due to the complexity of the hydrological cycle processes.

When speaking about water quantity and quality, we often associate forests with water yield. Brazil is a forested country, with 494 million hectares (58% of its territory) of natural and planted forests, which represents one of the largest areas of for-

ests on the planet (Heino et al. 2015). Within the Brazilian forest sector, 98.5% are natural forests, while 1.5% are forest plantations. The planted forests are gaining more and more space in Brazil, and the concern about the development of forestry is related to the consequences of possible impacts from forestry activity on water availability and quality. These impacts are caused mainly by the export of nutrients and sediments by surface runoff and water consumption by the trees (Chandler et al. 2018).

Hydrological modeling is an essential tool that allows understanding water dynamics at catchments and foresees impacts of land-use changes over catchment hydrology (Bressiani et al. 2015). The results of modeling experiments would help to establish environmental impact assessment

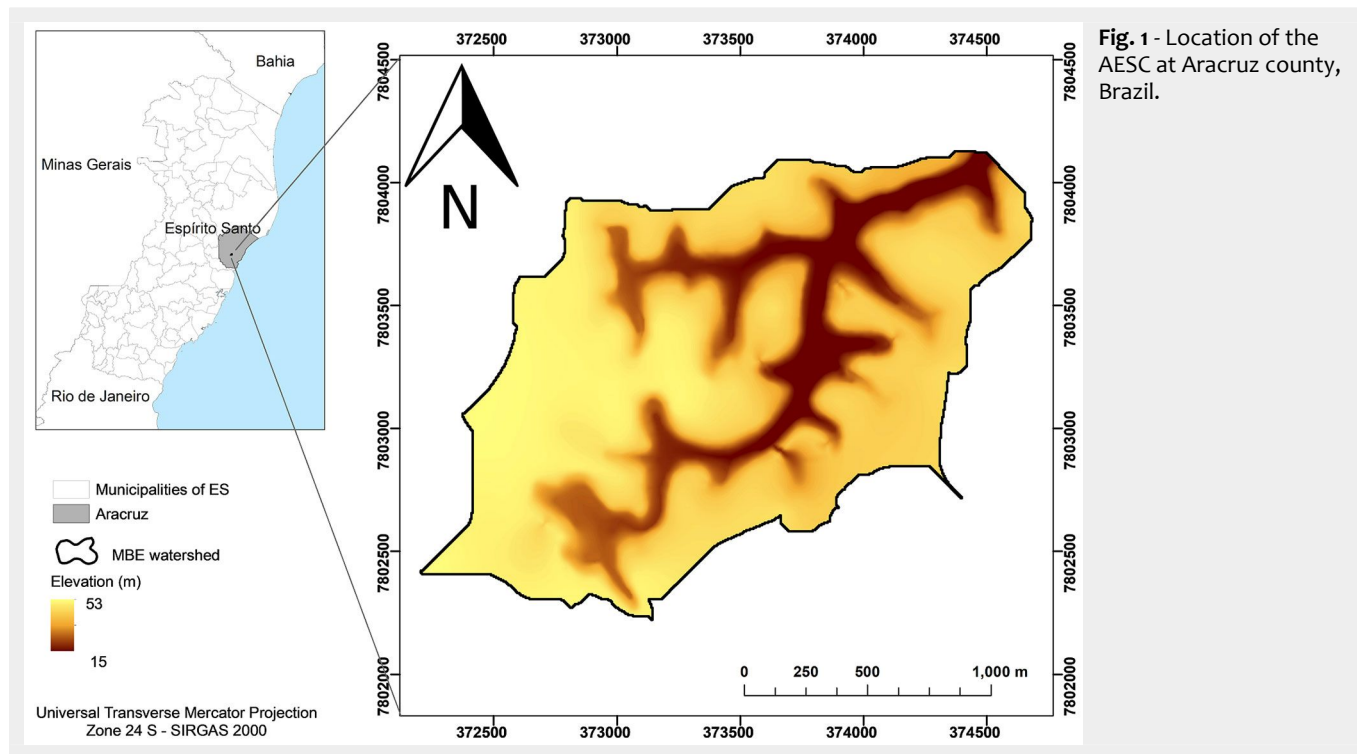
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**Fig. 1** - Location of the AESC at Aracruz county, Brazil.

procedures and adopt techniques that allow ensuring an increase in forest productivity, and an optimization of water use as well (Evaristo & McDonnell 2019). Among the hydrological models, the Soil and Water Assessment Tool (SWAT) has been applied worldwide, with satisfactory results in many catchments in Brazil (Gassman et al. 2007, Bressiani et al. 2015, Pereira et al. 2016). However, SWAT performance to simulate the hydrology of small forested catchments still needs to be assessed.

This paper has as the following objectives: (i) to assess the applicability of SWAT for the estimation of streamflow in a small tropical catchment (drainage area of 2.84 km<sup>2</sup>) where the primary land use is the cultivation of eucalyptus; (ii) to evaluate the impacts of different land use and forest

management systems over the catchment streamflow.

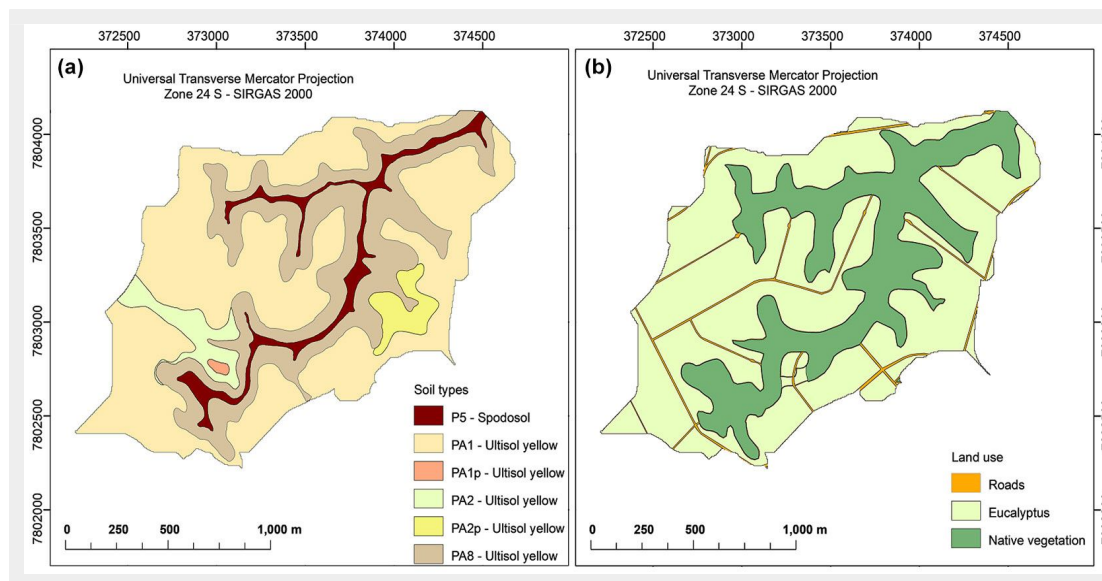
**Material and methods**

*Case study*

The case study was a small experimental catchment located in the city of Aracruz, State of Espírito Santo, Brazil, between the coordinates 19° 51' 16" S to 19° 52' 18" S, and 40° 11' 44" W to 40° 13' 15" W (Fig. 1). The Aracruz Experimental Small Catchment (AESC) has a drainage area of 2.84 km<sup>2</sup>, and its altitudes vary between 15 to 53 meters above the sea level. The local climate is Aw (Tropical savanna climate with dry-winter), according to the Köppen classification, with annual precipitation between 1000 and 1300 mm year<sup>-1</sup> and mean annual tem-

perature between 22° and 24° C.

The predominant types of soils are the Argisols and the Spodosols (Fig. 2a). In terms of soil cover (Fig. 2b), the vegetation is composed of eucalyptus plantations and native vegetation. Approximately 66% of the basin area is occupied by eucalyptus, with a production cycle of about 7 years, 30% by native vegetation in advanced and medium stages of regeneration, and 4% were ground roads to meet the needs of management of eucalyptus. In the areas of eucalyptus planting, gentle topography predominates, whereas in the native vegetation, steeper slopes are present. The areas of native vegetation configure the areas under permanent preservation (APP) around the streams.



**Fig. 2** - Map of soil types (a) and land use (b) of the AESC.

SWAT model

SWAT is a hydrological model developed to assess the impacts of changes in land use and land occupation on the hydrological cycle, sediment yield, and water quality in watersheds (Arnold et al. 2012). The model spatially simulates soil water content, surface runoff, soil erosion, nutrient cycling, crop growth, and management practices for each Hydrological Response Unit (HRU) with similar characteristics of topography, land use, and type of soil.

SWAT requires input data that includes daily meteorological data with information on precipitation, solar radiation, wind speed, relative humidity, and maximum and minimum temperatures. Input data is incorporated into the model using tables that contain information about the weather stations, soil, and land use. Based on these input data, SWAT establishes the water balance of each HRU and summarizes it for the whole catchment.

Input data

The SWAT input data, such as the digital elevation model (DEM) with 5 m of spatial resolution, soil map, land use map, and meteorological data, were obtained from the instrumentation and experiments in the AESC for hydrological analyzes and made available by the company Fibria Celulose S.A. The information about relief, land use, and soil types were processed using the software QGIS ver. 3.10 to create thematic images as input files required by the model. The sub-basins delineation and slope maps were derived from the DEM by SWAT processing.

Meteorological elements and streamflow on the outlet of AESC were determined on a daily scale from 1994 to 2004. For the meteorological measures, one automatic station was installed above the canopy, measuring precipitation, global radiation, wind speed, air temperature, and relative humidity. The streamflow was monitored by the use of a triangular weir equipped with an automatic water level sensor (pressure transducer).

The soil and land use maps (Fig. 2) were used as SWAT input. The soil physical and hydrological parameters necessary for the application of SWAT model were previously determined (Soares & Almeida 2001). The 35 vegetation parameters were obtained from the SWAT database, except the eucalyptus' parameters that were adapted according to Tab. 1.

The eucalyptus forest areas featuring different management practices were delineated according to personal communication with researchers at Fibria Celulose S.A. company, with areas for pulp production (7-year production cycle) and wood production for timber wood (14-year production cycle). The eucalyptus management for AESC was edited based on planting, fertilization, and harvesting operations. In this step, the curve number parameter (CN) has been updated for each management

**Tab. 1** - Eucalyptus input parameters modified in the SWAT crop growth database. Sources: (1) Soares & Almeida 2001; (2) Xavier et al. 2002; (3) Almeida et al. 2007; (4) Personal communication with researchers of the company Fibria Celulose S. A.

| Abbreviation | Description  | Value                |
|--------------|--|----------------------|
| HVSTI        | Harvest index for optimal growing conditions   | 0.9 <sup>(4)</sup>   |
| BLAI         | Maximum potential leaf area index  | 5 <sup>(2)</sup>     |
| CHTMX        | Maximum canopy height (m)  | 20 <sup>(4)</sup>    |
| RDMX         | Maximum root depth (m)   | 3 <sup>(4)</sup>     |
| TOPT         | Optimal temperature for plant growth (°C)  | 25 <sup>(4)</sup>    |
| TBASE        | Minimum (base) temperature for plant growth (°C)   | 8 <sup>(4)</sup>     |
| GSIC         | Maximum stomatal conductance at high solar radiation and low vapor pressure deficit (m s <sup>-1</sup> ) | 0.009 <sup>(1)</sup> |
| ALAIMIN      | Minimum leaf area index for plant during the dormant period (m <sup>2</sup> m <sup>-2</sup> )            | 1.5 <sup>(4)</sup>   |
| BIOLEAF      | Fraction of tree biomass accumulated each year that is converted to residue during dormancy              | 0.15 <sup>(4)</sup>  |
| MAT_YRS      | Number of years required for tree species to reach full development (years)                              | 7 <sup>(4)</sup>     |
| EXT_COEF     | Light extinction coefficient   | 0.8 <sup>(3)</sup>   |
| BMDIEOFF     | Biomass dieoff fraction  | 0.05 <sup>(4)</sup>  |

operation.

Calibration and validation of the SWAT model

The meteorological and hydrological data sets were separated into two different periods, one for the SWAT calibration (1994-2000) and the other for SWAT validation (2001-2004). SWAT-CUP software was used for sensitivity and automatic calibration analysis. SWAT-CUP algorithm accounts for the uncertainties by a measure known as the P-factor, which is the percentage of observed data within 95% of uncertainty prediction (95PPU). Later, manual calibration of the parameters that did not respond well to automatic calibration was performed.

The ability of the SWAT model to reproduce daily streamflow was assessed by the use of some statistical indices as well as by graphical analysis. The following statistical indices (Green & Van Griensven 2008, Bonumá et al. 2013) were calculated: Nash and Sutcliffe efficiency (NS – eqn. 1), percent bias (PBIAS – eqn. 2), and ratio of mean squared error to the standard deviation of the measured data (RSR – eqn. 3):

$$NS = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \tag{1}$$

$$PBIAS = 100 \cdot \frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n O_i} \tag{2}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^n (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \tag{3}$$

where n is the number of daily streamflow

data; O<sub>i</sub> is the observed daily streamflow; S<sub>i</sub> is the simulated daily streamflow;  $\bar{O}$  is the average of the observed streamflow.

Simulation of streamflows considering different land use and forest management scenarios

As a next step, simulations considering four different land use and forest management scenarios were run at SWAT. The scenarios consisted in: (i) NF – native forest: the whole catchment area covered with native vegetation (Atlantic Rainforest); (ii) CE – cellulose eucalyptus: the whole AESC area covered with eucalyptus plantation with management destined to the production of cellulose; (iii) TE – timber eucalyptus: the whole AESC area covered with eucalyptus plantation with management destined for timber wood; (iv) ME – mixed eucalyptus: reproduces the same forest management used in the calibration and validation of SWAT, in which the eucalyptus areas are managed for pulp production (7 years cycle) and timber wood (14 years cycle).

In all the scenarios, the areas under permanent preservation (APP) along the stream remained occupied by native vegetation, as preconized by Brazilian Forest Code.

The simulations of the scenarios occurred continuously for 35 years, using a synthetic series obtained by the statistics of the WGN Generator. Of the 35 years, 7 years were used to the model warm-up, and 28 years for the evaluation of the simulations. The purpose of this separation was to obtain cycles of approximately 7 years for the production of wood destined for cellulose and approximately 14 years for timber.

In the simulated period in each scenario, the following reference streamflows were determined: long-term average streamflow (Q<sub>mean</sub>), minimum streamflow that is ex-



**Tab. 2** - Values of the parameters used in the SWAT model calibration with the respective lower and upper limits, and the calibrated value. (\*): Mean value, as the CN<sub>2</sub> values vary depending of the soil type and land use; (1): Almeida & Soares 2003; (2): Micro-watershed Project Report.

| Parameters   | Limits     | Initial value | Calibrated value |
|--|------------|---------------|------------------|
| CN <sub>2</sub> (dimensionless)                      | ± 50%      | 35-59         | (-18%*)          |
| CANMX (mm) <sup>(1)</sup> Forest                     | 0-100      | 12            | 12               |
| Eucalyptus   | 0-100      | 24            | 24               |
| ALPHA_BF (days)                                      | 0-1        | 0.048         | 0.67             |
| GWQMN (mm)   | 0-5.000    | 500           | 357.81           |
| GW_DELAY (days) <sup>(2)</sup>                       | 0-500      | 31            | 15               |
| GW_REVAP (dimensionless)                             | 0.02-0.2   | 0.05          | 0.12             |
| REVAPMN (mm)   | 0-5000     | 1000          | 2923.44          |
| RCHRG_DP (fraction)                                  | 0-1        | 0.05          | 0.95             |
| SOL_AWC (mm H <sub>2</sub> O mm soil <sup>-1</sup> ) | ± 50%      | 0.05-0.14     | (+17.34%)        |
| SOL_K (mm h <sup>-1</sup> )                          | ± 50%      | 0.01-40       | (-19.53%)        |
| ESCO (dimensionless)                                 | 0.01-1     | 0.7           | 0.82             |
| SURLAG (dimensionless)                               | 1-24       | 4             | 15.87            |
| CNCOEF (dimensionless)                               | 0.5-2      | 0.5           | 0.85             |
| FFCB (fraction)                                      | 0-1        | 0.8           | 0.21             |
| EPCO (dimensionless)                                 | 0.01-1     | 1             | 0.28             |
| CH_N2 (dimensionless)                                | 0.025-0.15 | 0.014         | 0.087            |
| CH_K2 (mm h <sup>-1</sup> )                          | 0-130      | 0             | 11.25            |

**Tab. 3** - Statistical indices of calibration (before and after) and validation phases of the SWAT to AESC.

| Statistical index  | Before calibration | After calibration | Validation |
|--|--------------------|-------------------|------------|
| Nash-Sutcliffe efficiency (NS)   | -3.68              | 0.39              | 0.74       |
| Percent Bias (PBIAS, ×100)   | -2.51              | -0.18             | -0.14      |
| Ratio of the mean squared error to the standard deviation of the measured data (RSR) | 6.74               | 2.44              | 0.51       |

ceeded 90% of the time ( $Q_{90}$ ), and maximum streamflow with a return period of 10 years ( $Q_{max}$ ). These three reference flows were chosen due to its usage in most of the Brazilian Laws concerning the Water Resources Management. The Tukey test ( $\alpha = 0.01$ ) was applied to infer if the  $Q_{mean}$  calculated for the scenarios were different from each other.

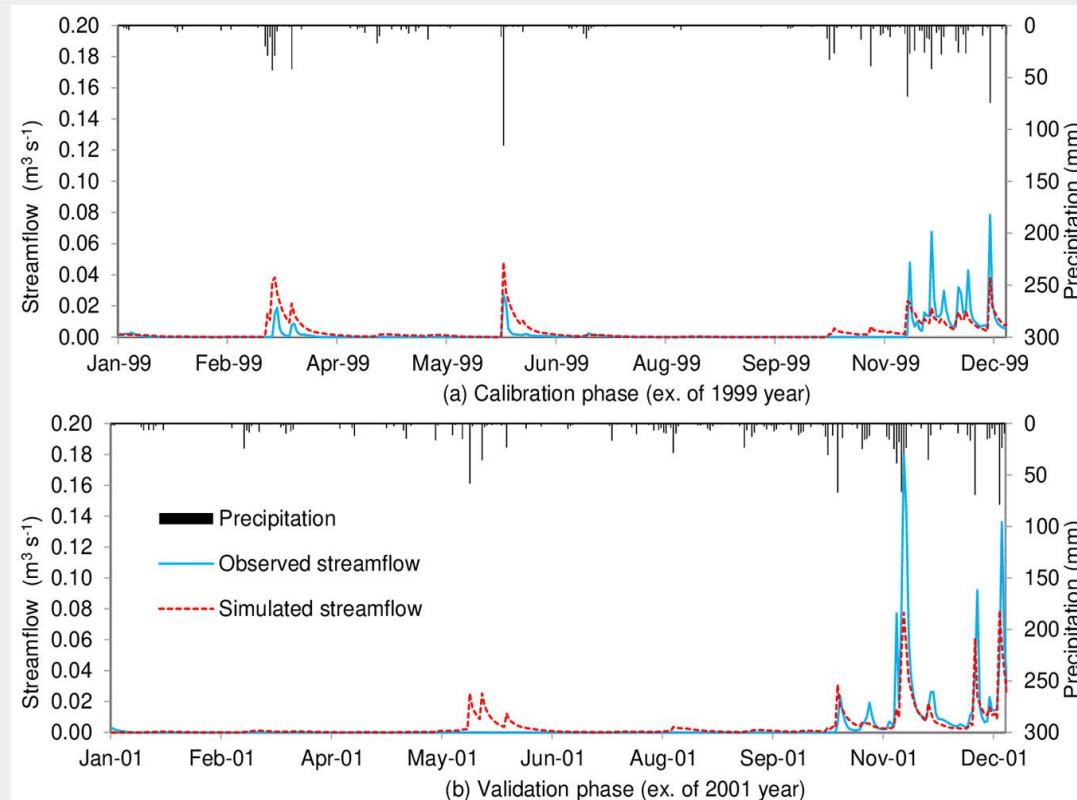
## Results

### Calibration and validation of the SWAT model

Tab. 2 shows the values of the SWAT calibrated parameters for the simulation of AESC daily streamflow. Tab. 3 presents the calculated statistical indices for the streamflow simulation, before and after calibration, as well as for the validation period. Fig. 3 shows the measured and simulated daily streamflows for the calibration (1997-2000) and validation (2001-2004) periods. Fig. 4 brings the comparison between the simulated and observed values of the daily streamflows, considering the calibration and validation periods.

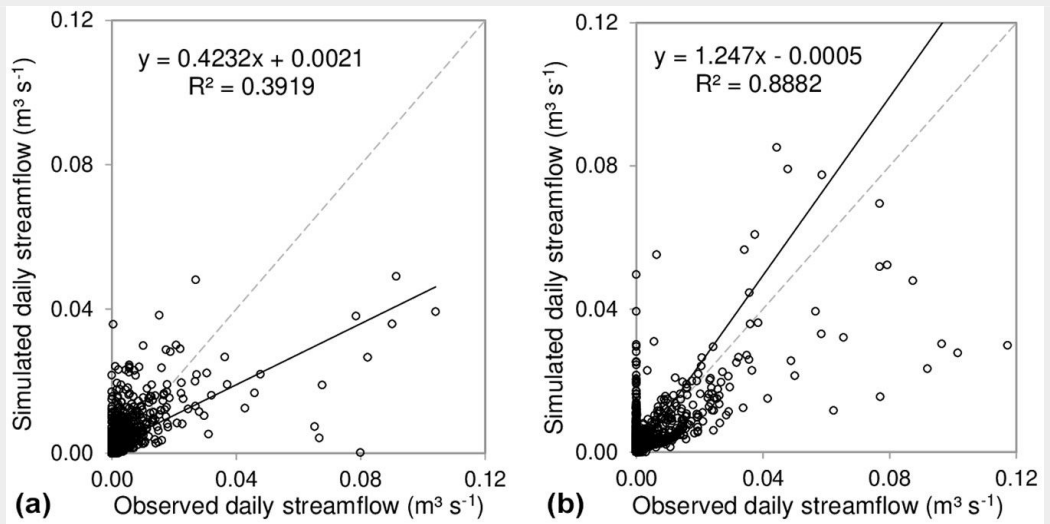
### Effects of land use and forest management on streamflow

The scenarios were elaborated to estimate the changes in streamflows due to land use and forest management modifications for 28 years, considering the calibrated parameters of the model, since the calibration and validation results were satisfactory. The hydrographs in Fig. 5 show the simulated average annual streamflows series. For each scenario, the mean, maxi-



**Fig. 3** - Hydrographs of the daily streamflow observed and simulated by SWAT for AESC. (a) Calibration period (example of year 1999); (b) validation period (example of year 2001).

**Fig. 4** - Relationship between the daily streamflow observed and simulated by SWAT for AESC for the calibration (a) and validation (b) periods.



imum, and minimum streamflows were calculated and presented in Tab. 4.

**Discussion**

*Calibration and validation of the SWAT model*

The CN2 parameter was calibrated to each soil type, and land use was reduced by about 18% (Tab. 2). This reduction occurred due to the physical properties of the soil and soil management that are not reflected by the SWAT standard CN2 values (Fukunaga et al. 2015). Similar reductions of CN2 from 9 to 50% were also observed in other Brazilian catchments (Andrade et al. 2013, Bonumá et al. 2013, Strauch et al. 2013, Fukunaga et al. 2015, Moreira et al. 2018, Cecílio et al. 2019).

The CANMX parameter, which controls the removal of water from the system by interception, was increased and, consequently, the evapotranspiration also increased. The calibrated value for the CANMX contributed to the increase in the initial abstractions and reduced the surface runoff and the peak streamflow. These values were close to those reported by other modeling studies using SWAT (Castro et al. 2016, Cecílio et al. 2019).

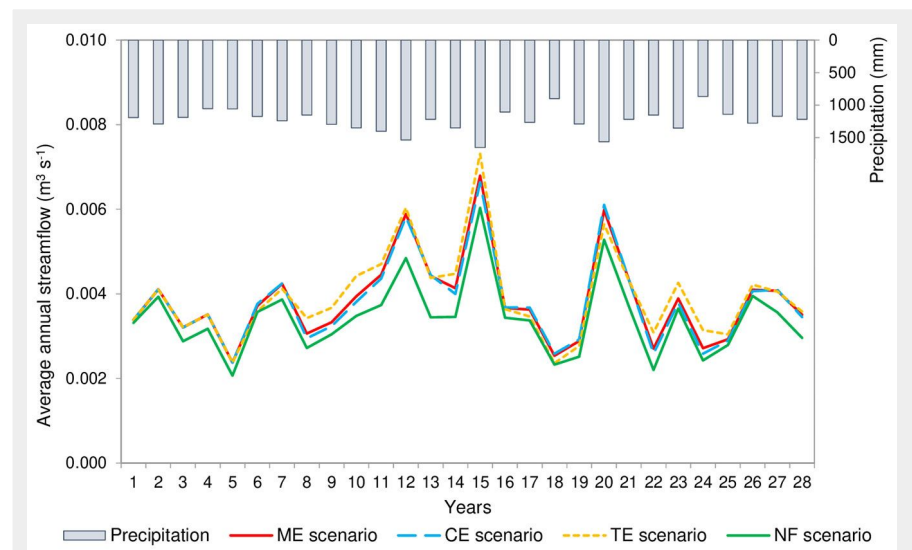
The ESCO and SOL\_K parameters, related to the groundwater dynamics, were also modified. The value of SOL\_K was decreased by 19.53%, aiming to reduce the water streamflow for lower layers of the soil profile, reducing percolation and baseflow. With a lower amount of water in the deeper layers of the soil, the value of the ESCO parameter (soil evaporation compensation factor) was increased to 0.82, close to values presented in other modeling efforts of Brazilian basins (Bonumá et al. 2013, Strauch et al. 2013, Cecílio et al. 2019).

The available water capacity in the soil (SOL\_AWC) was increased by 17.34%, as similarly observed to Brazilian catchments (Pereira et al. 2016). This augmentation leads the soil profile to increase its ability to store water, reducing runoff and base-

flow (Bonumá et al. 2013). The variation of the calibrated values can be considered small, taking into account the results found in other modeling studies carried out in Brazilian basins, varying from 40 to 90% (Andrade et al. 2013, Fukunaga et al. 2015, Moreira et al. 2018, Cecílio et al. 2019).

Other calibrated parameters were:

GWQMN, the water depth limit between the shallow aquifer and the surface; ALPHA\_BF, recession constant of the base streamflow; and RCHRG-DP, the fraction of percolated water; all related to groundwater. All these parameters were increased, being the GWQMN modified to adjust the shallow aquifer limit depth, in which the



**Fig. 5** - Hydrographs of average annual streamflow simulated for the scenarios of land use and forest management: mixed eucalyptus (ME), cellulose (CE), timber (TE) e native forest (NF).

**Tab. 4** - Reference streamflows simulated by the SWAT model at each land use and forest management scenario at AESC. Means followed by the same letter do not differ ( $p \geq 0.05$ ) from each other after Tukey test. ( $Q_{mean}$ ): long-term average streamflow; ( $Q_{90}$ ): minimum streamflow that is exceeded 90% of the time; ( $Q_{max}$ ): maximum streamflow with a return period of 10 years.

| Simulated scenario        | $Q_{mean}$ ( $m^3 s^{-1}$ ) | $Q_{90}$ ( $m^3 s^{-1}$ ) | $Q_{max}$ ( $m^3 s^{-1}$ ) |
|---------------------------|-----------------------------|---------------------------|----------------------------|
| Mixed eucalyptus (ME)     | 0.0038 <sup>a</sup>         | 0.0007                    | 0.102                      |
| Cellulose eucalyptus (CE) | 0.0037 <sup>a</sup>         | 0.0007                    | 0.106                      |
| Timber eucalyptus (TE)    | 0.0039 <sup>a</sup>         | 0.0008                    | 0.096                      |
| Native forest (NF)        | 0.0034 <sup>a</sup>         | 0.0005                    | 0.085                      |

water found below this limit starts to contribute to the base streamflow, and the ALPHA\_BF increased to allow a faster recession, with values close to those found in other works in Brazilian watersheds (Bonumá et al. 2013, Strauch et al. 2013). The parameter RCHRG-DP was increased so that more water of the base streamflow would be available for the aquifer recharge.

In addition, the GW\_REVAP and REVAPMN parameters, related to the shallow aquifer, were also increased. The value adopted for GW\_REVAP, equal to 0.12, was close to those found in other studies in Brazil (Fukunaga et al. 2015, Cecílio et al. 2019), representing a more substantial fraction of water from the shallow aquifer to the root zone, which may reflect on increased soil evaporation and transpiration of plants. Because of these increases, more water was available in the soil, which contributed to the increase in lateral subsurface streamflow, which is the major contributor to the final streamflow of the watercourses. The only parameter related to groundwater that had its value reduced was GW\_DELAY (groundwater delay time), altered to the value of 15 days (Almeida et al. 2007, Smethurst et al. 2015) in order to represent a faster response of groundwater to river discharge.

#### SWAT calibration and validation performance

The magnitude of the statistic shown in Tab. 3 indicates that SWAT changed from a non-recommended model ( $NS < 0$ ) to a model with satisfactory performance due to the calibration and validation of statistical indexes.

The simulation of the monthly streamflow series can be judged as satisfactory if  $NS > 0.50$  and  $RSR \leq 0.70$ , and if  $PBIAS < \pm 25\%$  (Moriassi et al. 2007). However, modeling efforts with the SWAT shows that the worst results occurred for daily prediction (Gassman et al. 2007). Some of the factors that could affect the SWAT performance of the model can be attributed to the fact that the calibration for small catchments does not allow the compensation of errors due to its rapid response to rainfall events. Therefore, when the hydrological models are evaluated on a daily scale, such as in the present paper, the limits of the statistical indexes can be less rigorous. In this context, SWAT considers that daily simulation can be taken as acceptable if  $NS > 0.33$  for small catchments (Green & Van Griensven 2008), as occurred in the present study.

The negative value of the PBIAS (Tab. 3) shows that the model overestimated the simulated streamflow during the calibration and validation periods, as shown in Fig. 3 and Fig. 4. The RSR value was larger than recommended after calibration; however, its value is acceptable for the validation phase. Thereby, with a lower RSR value, lower will be the standard error, and better will be the simulation, as evidenced by the hydrographs (Fig. 3).

The validation phase indexes were better than those obtained in the calibration phase, as also observed in other modeling studies (Vazquez-Amábile & Engel 2005). During the validation period (Fig. 3), it can be observed a large number of days without streamflow. This amount of days with very low or null surface runoff can increase the efficiency of the model since the errors associated with low values of streamflow tend to be lower than those related to high streamflow (Krause et al. 2005). Andrade et al. (2013) also observed that differences in the precipitations between the validation and calibration period of the SWAT model affect the NS statistical result. In the present study, the rainy period of the validation did not present the same rainfall concentration recorded during the calibration period (Legates & McCabe 1999).

SWAT model tended to overestimate the minimum streamflow in the dry seasons and underestimate the larger streamflows observed in the rainy seasons. Other modeling efforts (Fukunaga et al. 2015) also showed that the SWAT model has difficulties in reconciling dry and rainy season simulations.

#### Effects of land use and forest management on streamflow

We observed that the variation in the simulated streamflow strictly reflect the characteristics of the land use and forest management, which are input variables and composed the model databases. The results presented here should be seen as an initial assessment of the potential impact of land use and forest management on the streamflow of small catchments. As shown in Tab. 4, the simulations carried out with the four different scenarios did not show statistically significant changes in the  $Q_{mean}$ , as also observed in other Atlantic Forest watersheds (Mendes et al. 2018). The difference of  $Q_{mean}$  among the scenarios (NF compared to eucalyptus scenarios) was not superior to 15%. Other studies (Alvarez-Garreton et al. 2019) reported a decrease by about 2 to 8% in  $Q_{mean}$  due to the conversion of native to planted forests. The impact of forest cover variation on  $Q_{mean}$  is almost null when native forest suppression occurs over less than 50% of the basin (Cecílio et al. 2019). In the present study, due to the presence of APP in all the scenarios, native forest suppression (comparing NF to the other scenarios) affected about 66% of the catchment, justifying the small change in  $Q_{mean}$ . It also corroborates the evidence that forest management in catchments containing APP close to the stream might have little impact on streamflows (Smethurst et al. 2015).

It also can be seen that  $Q_{90}$  (minimum streamflow of reference) reached very low values for all the scenarios (Tab. 4). The eucalyptus scenarios presented higher  $Q_{90}$  (40 to 60%) than the native forest scenario (NF). The Brazilian public policies have consolidated the idea that forests always in-

crease the minimum streamflow due to the recovery of the hydrological functions of the soils under forests. However, many experimental data demonstrated the reduction of minimum streamflow when basins are forested with eucalyptus (Beskow et al. 2013) or native forests (Van Dijk & Keenan 2007).

Only little differences in  $Q_{max}$  were observed among the results of the different simulated scenarios. The NF scenario showed the lowest  $Q_{max}$  (Tab. 4), due to the higher rainfall interception provided by the Atlantic Rainforest (Van Dijk & Keenan 2007, Beskow et al. 2013) and the periods with less protection of the soil, right after the cutting and planting operations (Iroumé et al. 2006). Contrastingly, Eucalyptus scenarios presented  $Q_{max}$  from 13 to 25% higher than NF. According to some researches (Iroumé et al. 2006, Birkinshaw et al. 2011),  $Q_{max}$  can be increased from 32% to 100% due to harvesting of planted forests, depending on topographic, geological and rainfall characteristics. Among the eucalyptus scenarios, TE provided the lower  $Q_{max}$ . Higher maximum streamflow occurs in the eucalyptus managed for cellulose (CE), due to the shorter production cycle time and the longer exposure of the soil compared to ME and TE scenarios.

A lower average annual streamflows for the NF scenario is noticeable from Fig. 5. The native forest area improves the physical conditions of the soil and promotes the infiltration of water in the soil, thus favoring the recharge of groundwater and the reduction of the surface runoff. However, the native vegetation has a higher leaf area index and rainfall interception than eucalyptus plantations (Almeida et al. 2007), thus increasing the evapotranspiration in the areas under the native forest (Salemi et al. 2013).

The hydrographs of the eucalyptus scenarios (ME, CE, and TE - Fig. 5) show an increase of the average streamflows in the years of harvest and in the subsequent year (7/8, 14/15, 21/22, and 27/28). The increase of discharges for 1-2 years after the eucalyptus harvest was also observed in other studies in Brazil (Almeida et al. 2016). Moreover, the rise of average annual streamflow due to harvesting of planted forests can reach 110% of the  $Q_{mean}$  (Iroumé et al. 2006, Almeida et al. 2016). Forest harvesting decreases soil infiltration, leading to increased runoff (consequently increasing  $Q_{max}$ ) and sediment to streams (Punteney-Desmond et al. 2020). In addition, harvesting also reduces the evapotranspiration and, consequently, promotes the increase in the streamflows (Almeida et al. 2016). Meanwhile, during the years of eucalyptus growth, the annual average streamflow decreases.

Finally, these results should be carefully applied to other watersheds because they depend on local soil, landscape, and climate characteristics, as well as on the geographic location, size, and use of water of



the plantings and other vegetation.

## Conclusions

SWAT showed a satisfactory simulation of the streamflows of Aracruz small catchment, presenting the following statistical indexes associated with the validation of the model: NS = 0.74; PBIAS = -14%; and RSR = 0.51. The lowest streamflows were better simulated than the peak flows. Therefore, the SWAT model can be a useful tool also in modeling the streamflow of small forested catchments.

About the forest management scenarios simulated, differences in the long-term average streamflow due to changes in the land use and forest management were not statistically significant. Minimum streamflow ( $Q_{90}$ ) and maximum streamflow ( $Q_{max}$ ) were higher for the eucalyptus management scenarios compared with the native forest scenario. Native forest scenario presented lower annual streamflow than all the eucalyptus forest scenarios.

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