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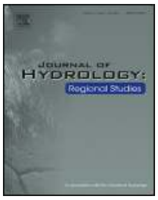

Hydrological simulation in a basin of typical tropical climate and soil using the SWAT model part I: Calibration and validation tests

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ABSTRACT

Study region: The study was developed for fhe Pomba River Basin, which is located in southeast region of Brazil in the continent of South America.
Study focus: This study aimed to (a) calibrate and validate the SWAT model for a sub-basin of Pomba River Basin, (b) validate it for use with upstream and downstream control sections and (c) validate it for sub-basins other than the one where calibration was performed. This was done with the goal of having a model that can be used for the estimation of water availability and the planning of soil use and occupation. The model was calibrated by trial and error during the period from January 1996 through December 1999, while validation was conducted during the period from January 2000 through December 2004. Estimated the maximum, average and minimum annual daily streamflows were evaluated based on the paired *t*-test and linear regression analysis.
New hydrological insights: The SWAT model was qualified for simulating the Pomba River sub-basin in the sites where rainfall representation was reasonable to good. The model can be used in the simulation of maximum, average and minimum annual daily streamflow based on the paired *t*-test, contributing with the water resources management of region, although the model still needs to be improved, mainly in the representativeness of rainfall, to give better estimates of extreme values.

1. Introduction

Recently, the Pomba River Basin has been under a significant degree of deforestation, mainly in its headwater areas, which face problems such as soil erosion, a decline in the quantity and quality of water in its sources and an increase in the occurrence of floods (AGEVAP, 2012). This situation is getting worse due to the lack of studies in the basin, which may help managers to plan and to better manage the water resources of the site.

The studies developed for the Pomba River Basin, which can help in this issue, are the one by Gonçalves et al. (2005), who carried out the hydrogeologic characterization of the Pomba River Basin through a quantitative correlation between

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surface water and groundwater, finding that the specific groundwater flows decrease from upstream to downstream from 13.7 to 10.9 $\mathrm{L\,s^{-1}\,km^{-2}}$. The other study was performed by Andrade et al. (2013b), who developed a computer system to assist in the management of the water resources of the basin using an ottocodifieds data produced by the National Water Agency (NWA) of Brazil and flow regionalization models. However, no study has been developed for the basin in hydrologic modeling, which is a very important tool that has contributed to understanding the hydrologic regime and better planning the soil use and the occupation of the basin.

Hydrologic modeling has been applied mainly to estimate water availability, for the prediction of short and medium term flows and to analyze the hydrologic response of the basin due to changes in soil use and occupation. Therefore, obtaining a hydrologic model with the ability to estimate with good accuracy the water regime of the basin in a fast, economical and safe way is important for better planning and management of water resources.

During recent decades, several distributed hydrological models have been developed to simulate hydrological processes in basins, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), the European Hydrological System (SHE) (Abbott et al., 1986), the Topography-based Hydrological Model (TOPMODEL) (Beven and Kirkby, 1979), and the Large Basin Hydrological Model (MGB-IPH) (Collischonn and Tucci, 2001), because they allow for an approximate characterization of the spatial variability of a basin by use of data and parameters in a point-grid network (Cao et al., 2006; Wang et al., 2012). Amongthe models mentioned above, the SWAT has excelled.

SWAT is a continuous in time, semi-distributed, process-based model (Arnold et al., 1998; Gassman et al., 2007) that may be applied to agricultural basins where quantitative and qualitative drainage aspects and erosion processes are to be studied, in addition to enabling the assessment of the hydrological behavior of basins facing changes in soil use and cover.

SWAT has been widely used worldwide (Gassman et al., 2007) in hydrologic simulations of basins with different climates, topography, geology, pedology, and vegetation conditions and with different drainage areas (Andrade et al., 2013a; Durães et al., 2011; Pereira et al., 2014a,b; von Stackelberg et al., 2007), yielding satisfactory results (performance) most of the time. However, for the SWAT to be broadly disseminated worldwide, it still requires studies in basins with climate and soil typical of tropical conditions and in highly irregular terrain, such as the Pomba River Basin in southeastern Brazil. This deficiency and the need for a hydrologic model to facilitate better planning and management of water resources of the Pomba River Basin were the reasons why we decided to carry out this study.

The model performance, which was previously mentioned, is assessed in many studies through a single test, the Split Sample Test, in which the model is calibrated using data from a period of time and applied with the parameters calibrated to another period (validation). However, further tests are required to assess the model in different applications so that a robust model with broader hydrological applicability can be obtained, which may be done through the Proxy-basin test (Klemes, 1986). In this test, the model is calibrated and validated in different sites, which may be in the same basin or in different basins with similar characteristics. This test is used, for example, to calculate the flow data in a site with no streamflow gauging stations.

In this sense, the objective was to calibrate the SWAT model, version 2005, for a sub-basin of the Pomba River Basin and validate it for the entire basin through different validation tests in order to obtain a model that can be used to estimate water availability and for planning the soil use and occupation of the basin.

2. Description of the study region

The present study was carried out in the Pomba River Basin, which has climate and soil typical of tropical conditions, located in southeastern Brazil, South America (Fig. 1), with a drainage area of approximately 8600 $\mathrm{km^2}$. The basin has a highly irregular terrain ranging from 52 to 1477 m and yearly rainfall of approximately 1400 mm. Its waters are used in several economic activities, among which agriculture, cattle farming, furniture manufacturing, fruit pulp industries, and hydroelectric generation, among others, stand out (Côrrea, 2006).

3. Material and methods

The study was split into three parts: (1) hydrological simulation of the Pomba River sub-basin with a control section in Astolfo Dutra, involving the calibration and validation of the model in this section; (2) application of the calibrated model to the sections upstream and downstream of the calibration section; and (3) application of the calibrated model to sections in sub-basins other than the one where the calibration was carried out.

In the SWAT model version 2005, the basin is divided into sub-basins that are then divided into Hydrological Response Units (HRUs) based on soil type and soil use. Thus, the Pomba River Basin was divided into 35 sub-basins (Fig. 2) based on the HCDEM (Fig. 1), and into 3,768HRUs based on soil use (Fig. 3A), on soil type (Fig. 3B), and on the terrain slope classes (Fig. 3C) in the basin.

3.1. Hydrological modeling

3.1.1. SWAT description

The hydrological components simulated in the SWAT model include: evapotranspiration, surface runoff, percolation, subsurface runoff (lateral runoff), and underground runoff (base runoff). When simulating evapotranspiration, the model

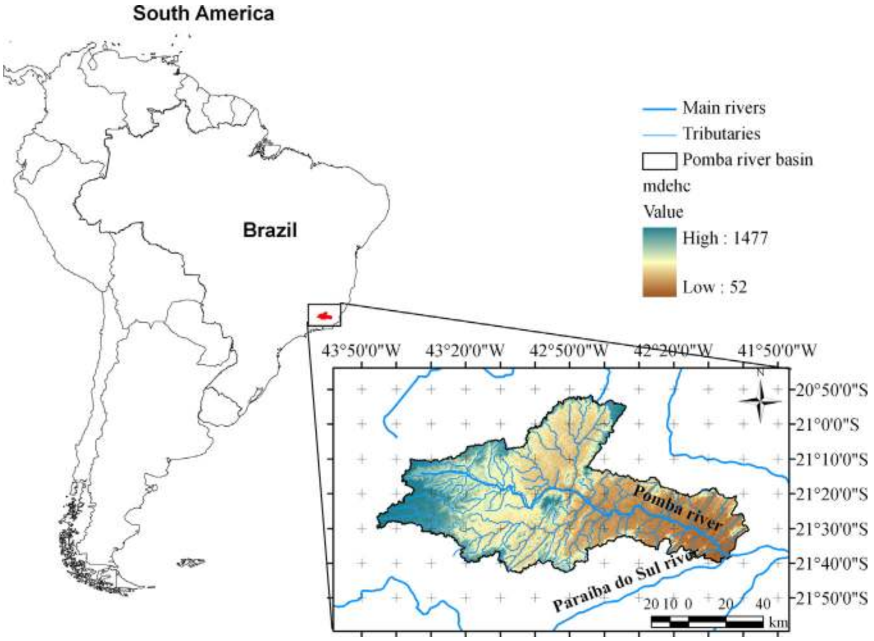

Fig. 1. Location of the Pomba River Basin in the national context.

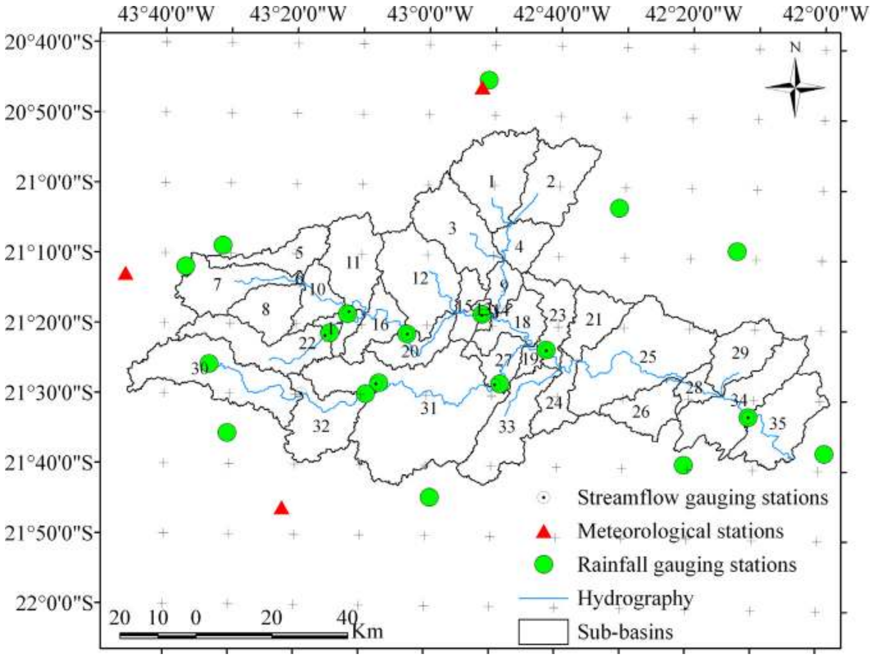

Fig. 2. Map of the sub-basins generated for the application of the SWAT model, in addition to rainfall, streamflow, and meteorological stations, used in the modeling.

separately estimates the evaporation of water in the soil and plant transpiration. The evaporation of soil water is estimated using exponential functions of the water depth and content in the soil (Neitsch et al., 2005), while transpiration is estimated by correcting the potential evapotranspiration for conditions of vapor pressure deficit and soil water content deficit (Neitsch et al., 2005). The Penman-Monteith method (Jensen et al., 1990) was used to estimate potential evapotranspiration in this study. Surface runoff was estimated using the curve number method (USDA-SCS, 1972) with a change in the retention parameter, which varies according to the soil's water content (Neitsch et al., 2005). Percolation was estimated using a combination of a storage propagation technique and a crevice flow model (Arnold et al., 1998). Lateral runoff was estimated simultaneously with percolation using a kinetic storage model (Sloan et al., 1983). Underground runoff was determined

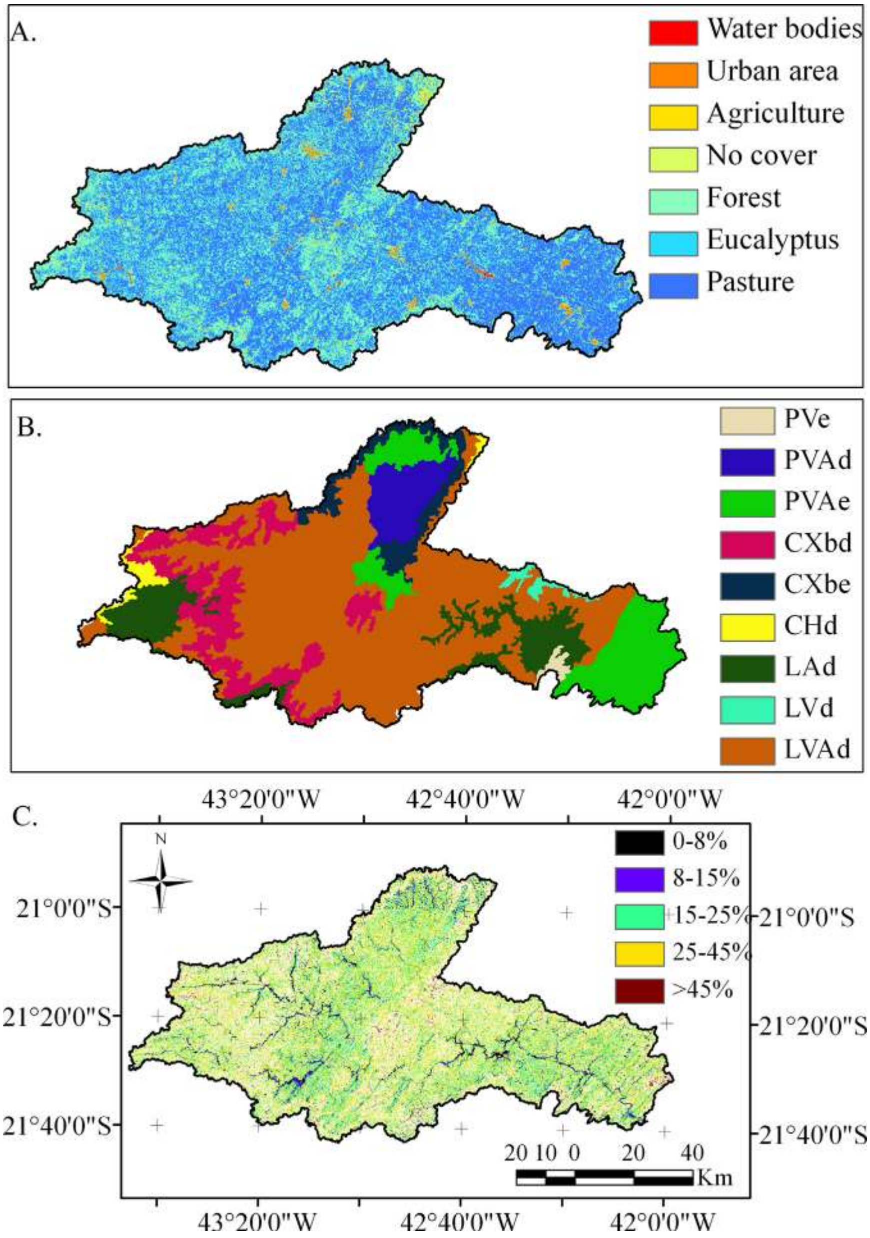

Fig. 3. Maps of soil uses (A), soil types (B), and terrain slope classes (C).

based on the hydraulic conductivity of the free aquifer, on the distance traveled by the runoff until the main canal, and the depth of the water table (Neitsch et al., 2005). The hydrological components were simulated for each HRU and then aggregated to the sub-basin.

3.1.2. Database required for the simulation

The database required for the SWAT hydrological simulation was made up of discretized information (climate, vegetation, soils, flow) provided by tables and spatial information (Digital Elevation Model – DEM, maps of soil types, occupation, and use). Next, the spatial discrete database required for the application of the model is presented, as well as the obtention method.

3.1.2.1. Hydrographically conditioned digital elevation model (HCDEM). The present study used a Hydrographically Conditioned Digital Elevation Model (HCDEM) (Fig. 1) because it better represents runoff generation in basins. The HCDEM was obtained from the DEM from ASTER images acquired from NASA (http://asterweb.jpl.nasa.gov/gdem.asp) with a 30 m spatial resolution, and from the mapped (vectorial) hydrography at a 1:50,000 scale obtained from the Brazilian Institute of

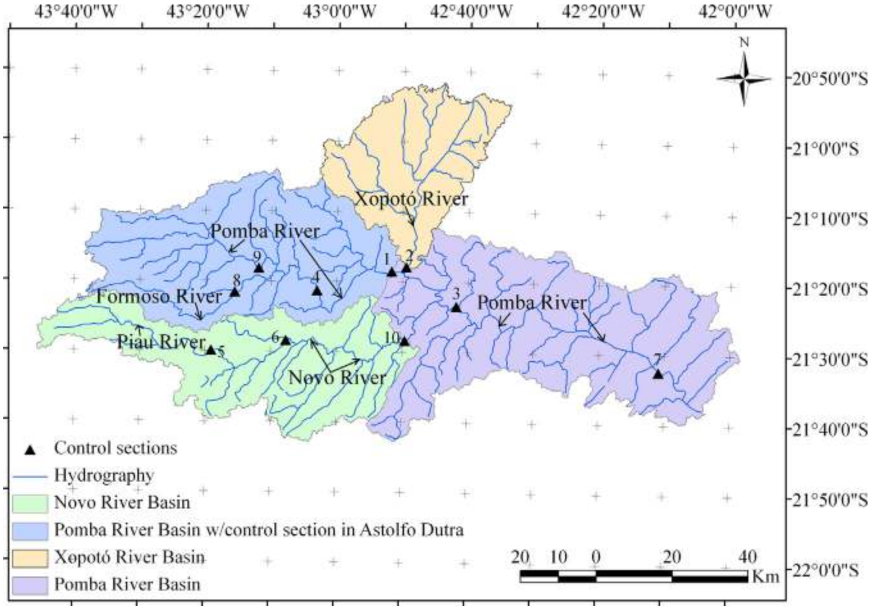

Fig. 4. Location of the streamflow gauging stations and of the sub-basins of the Pomba River with control section in Astolfo Dutra (used in temporal calibration and validation) and the Novo and Xopotó Rivers (used to validate the model in different sub-basins).

Geography and Statistics (IBGE). The DEM and the hydrography were pre-processed (elimination of double river banks and bifurcations and correction of errors in hydrography (vectorial) towards the river mouth). After hydrography and DEM pre-processing, they were input into the command Terrain Pre-Processing/DEM Manipulation/DEM/Reconditioning of the tool ArcHydro 9.3 to obtain the HCDEM.

3.1.2.2. Soil use and occupation map. The Pomba River Basin soil use and occupation map (Fig. 3A) was obtained from the classification of the images from the sensor Landsat TM+ of 2010 using the maximum likelihood supervised classification method. For that, 267 training samples were collected over the basin area, which considered seven classes of soil use obtained based on satellite images and field visits: pasture, native vegetation (Atlantic Forest), eucalyptus, agriculture, soil with no vegetation cover, urban area, and water bodies. Kappa coefficient, an indicator of sampling quality, was 80.5%, classified as excellent according to Congalton and Green (1998). To assess the quality of mapping and to correct any possible failures in the classification, the soil use map was met to the vegetation cover map of the Ecological and Economic Zoning of the state of Minas Gerais (ZEE MG) of 2009, which has information obtained in field inspections by a technical team.

3.1.2.3. Soil map. The Unit of Planning and Management of Hydrological Resources of the Pomba River and Muriaé Tributaries in Minas Gerais (UPGRH PS2) has a soil survey carried out by Schaefer et al. (2010) at a 1:500,000 scale, which was used in this study. The following soil classes are found in the basin: eutrophic Red Podzolic (PVe), dystrophic Red-Yellow Podzolic (PVAd), eutrophic Red-Yellow Podzolic (PVAe), dystrophic Tb Haplic Cambisol (CXbd), eutrophic Tb Haplic Cambisol (CXbe), dystrophic Humic Cambisol (CHd), dystrophic Red-Yellow Latosol (LVAd), dystrophic Red Latosol (LVd), and dystrophic Yellow Latosol (LAd) (Fig. 3B).

3.1.2.4. Hydroclimatic data. The rainfall database was made up of historical daily rainfall series from 14 rain gauging stations available in the Hydrological Information System (HIDROWEB) of the National Water Agency (ANA) (Fig. 2). The data to calculate evapotranspiration were obtained from daily maximum and minimum air temperature, relative humidity, wind velocity, and insolation (after transformation to solar radiation) from three meteorological stations of the National Institute of Meteorology (INMET) (Fig. 2). The database was organized in the period from January 1st, 1994 to December 31st, 2004 due the occurrence of a few gaps in the records, both from rain and other meteorological data sets. The few gaps were corrected by the weighted average of the values obtained in the neighboring stations.

The streamflow database came from ten streamflow gauging stations, and the Astolfo Dutra station was used to calibrate and validate the model in the temporal scale. The data of the other stations were used to validate the model calibrated in the spatial scale, with the Guarani, Ituerê, and Tabuleiro stations being used to validate the upstream portion of the calibration section, the Cataguases and Santo Antônio de Pádua stations used to validate the downstream portion of the calibration section, and the Usina Maurício, Rio Novo, Piau, and Xopotó stations used to validate the sub-basins other than the one used for calibration. The locations of the streamflow gauging stations are presented in Fig. 4. Table 1 shows key information on the streamflow gauging stations used.

Table 1
Main information on the streamflow gauging stations used in the study.

Streamflow gauging station	Code	Entity	Latitude (°)	Longitude (°)	River	Da (km^2)
1. Astolfo Dutra	58735000	ANA	−21.309	−42.860	Pomba	2350
2. Barra do Xopotó	58736000	ANA	−21.298	−42.823	Xopotó	1280
3. Cataguases	58770000	ANA	−21.390	−42.696	Pomba	5880
4. Guarani	58730001	ANA	−21.355	−43.049	Pomba	1650
5. Piau	58750000	ANA	−21.499	−43.318	Piau	490
6. Rio Novo	58755000	ANA	−21.474	−43.128	Novo	835
7. Santo Ant. de Pádua	58790000	ANA	−21.541	−42.180	Pomba	8210
8. Tabuleiro	58720000	ANA	−21.360	−43.258	Formoso	322
9. Usina Ituerê	58710000	ANA	−21.304	−43.198	Pomba	784
10. Usina Maurício	58765001	ANA	−21.473	−42.826	Novo	1770

Da—drainage area.

Table 2
Modified vegetation parameters from the model's database.

Vegetation cover	BLAI (Maximum leaf area index) ($m^2\ m^{-2}$)	GSi (Canopy stomatal conductance) ($m\ s^{-1}$)	OV_N (Manning's "n" for the surface) ($s\ m^{-1/3}$)
Native vegetation (Atlantic Forest)	7.5 (Almeida and Soares, 2003)	0.033 (Tonello and Teixeira Filho, 2012)	0.3 (Neitsch et al., 2005)
Eucalyptus	4.0 (Almeida and Soares, 2003)	0.01 (Almeida and Soares, 2003)	0.17 (Neitsch et al., 2005)
Pasture	3.0 (Viola et al., 2009)	0.010 (McWilliam et al., 1996)	0.23 (Gomes et al., 2008)
Agriculture	7.0 (Viola et al., 2009)	0.0095[a]	0.14 (Neitsch et al., 2005)

[a] Mean value obtained based on studies on agricultural crops.

3.1.2.5. Soil and vegetation data. The soil data of the Pomba River Basin were obtained from the Soil Exploratory Survey carried out by project Radambrasil at 1:1,000,000 scale (Radambrasil, 1983) relating to the profiles 13 (dystrophic Red-Yellow Latosol), 19 (dystrophic Yellow Latosol), 41 (dystrophic Tb Haplic Cambisol), 41 (extra) (dystrophic Tb Haplic Cambisol), 44 (extra) (dystrophic Humic Cambisol) and 51 (eutrophic Tb Haplic Cambisol). The data from these profiles were typed directly into the SWAT database and consisted of information on the physical-hydrological characteristics of the soils (number of layers, depth of the bottom limit of each layer from the surface, density, available water capacity, hydraulic conductivity of the saturated soil, and percentage of texture classes). As the characteristics of the soils used by model is in layers that is a function of the depth, were considered the average values of density, available water capacity, hydraulic conductivity of the saturated soil, and percentage of texture to each soil layer. Subsequently, the soil database was linked to soil use classes for the creation of model input files.

The basin's soils were classified as belonging to hydrological groups A and C, based on the study by Sartori et al. (2005). The hydraulic conductivity values of saturated soil required as inputs to the model were drawn from field experiments carried out by Moraes et al. (2003) and Zonta et al. (2010). In both studies, the authors used the constant head permeameter for determining the hydraulic conductivity values of saturated soil at different depths.

The vegetation data used were those from the model's database (defaut) with changes in maximum leaf area index (BLAI), canopy stomatal conductance (GSI) and Manning's "n" for the surface variables for the Native vegetation (Atlantic Forest), Eucalyptus, Pasture and Agriculture vegetation cover types, so as to better represent the Brazilian vegetation conditions, as shown in Table 2.

3.1.3. Model calibration and validation

Calibration was performed between 1996 and 1999 and comprised prolonged floods and droughts to allow the model to simulate the highest and lowest streamflow events. The years of 1994 and 1995 were used to warm up the model in order to eliminate the uncertainties existing in the beginning of modeling, particularly regarding the soil's water content (Viola et al., 2009; von Stackelberg et al., 2007; Zhang et al., 2007). The calibration was made for the average daily streamflow and was performed by trial and error by changing one parameter at a time and then analyzing the results. At every attempt, we analyzed the setting of minimum and maximum daily flow rates, the shape of the simulated hydrograph, the values obtained for the Nash-Sutcliffe coefficient (Eq. (1)), the logarithmic version of Nash-Sutcliffe coefficient (Eq. (2)) and bias percentage (Donigian et al., 1983; Liew et al., 2007) (Eq. (3)), trying to maximize the first and second and minimize the latter. The calibration process was finalized when the changes in parameters resulted in little or no change in the output results of the model. It should be noted, however, that this method was chosen for the model calibration with the goal of the keeping the mean physical of the calibration parameters due to the large number of hydrologic response units (3768) generated for the simulation of the basin.

$$C_{NS} = 1 - \frac{\sum_{i=1}^{n}(Q_{oi} - Q_{ei})^2}{\sum_{i=1}^{n}\left(Q_{oi} - \bar{Q}_o\right)^2} \tag{1}$$

$$(C_{NS})_{log} = 1 - \frac{\sum_{i=1}^{n}(\log(Q_{oi}) - \log(Q_{ei}))^2}{\sum_{i=1}^{n}\left(\log(Q_{oi}) - \log(\bar{Q}_o)\right)^2} \tag{2}$$

$$P_{BIAS} = \left(\frac{\sum_{i=1}^{n}Q_{ei} - \sum_{i=1}^{n}Q_{oi}}{\sum_{i=1}^{n}Q_{oi}}\right) \times 100 \tag{3}$$

where C_{NS}—Nash-Sutcliffe Coefficient; $(C_{NS})_{log}$—Nash-Sutcliffe coefficient of the streamflow logarithm; P_{BIAS}—difference between the estimated and observed streamflow values (%); Q_{oi}—streamflow observed on day i ($m^3\ s^{-1}$); Q_{ei} – streamflow estimated on day i ($m^3\ s^{-1}$); $\bar{Q}_o$ mean streamflow observed during the period ($m^3\ s^{-1}$); and n – number of streamflow days.

C_{NS} and $(C_{NS})_{log}$ indicate the goodness-of-fit of the simulated and observed data in the line 1:1 and can range from $-\infty$ to 1 (Zhang et al., 2007). The C_{NS} coefficient indicates the model's precision in simulating the flood streamflow and the $(C_{NS})_{log}$ indicates the precision in simulating the drought streamflow (Viola et al., 2009). In this evaluation, the classification suggested by Motovilov et al. (1999) was adopted, described as: $C_{NS} > 0.75$ (model is appropriate and good); $0.36 < C_{NS} < 0.75$ (model is satisfactory); and $C_{NS} < 0.36$ (model is unsatisfactory). The same criterion was adopted for $(C_{NS})_{log}$.

The P_{BIAS} coefficient is a measure of the tendency of the mean streamflows simulated by the model being higher or lower than the ones observed, indicating over or underestimation (Andrade et al., 2013a; Donigian et al., 1983; Liew et al., 2007). According to this criterion (Liew et al., 2007): $|P_{BIAS}| < 10\%$ (model is very good), $10\% < |P_{BIAS}| < 15\%$ (model is good); $15\% < |P_{BIAS}| < 25\%$ (model is satisfactory), and $|P_{BIAS}| \geq 25\%$ (model is unsatisfactory).

It is important to make it clear, that the water withdrawals of the basin were not considered due the network of information is quite scarce and with heterogeneous distribution over the basin. Probably the use of such data would not affect significantly the calibration.

SWAT was validated aiming at a greater applicability to the Pomba River Basin by carrying out the following tests proposed by Klemes (1986):

Split Sample Test: application of the previously calibrated model for a given period of time to another unknown period of time. In this test, SWAT calibrated between 1996 and 1999 was applied to the period of 2000–2004.

Proxy-Basin Test (different basins): application of the model calibrated for one basin to other basins with similar hydrologic characteristics. In this test, SWAT was calibrated for the Pomba River sub-basin with a control section in Astolfo Dutra and applied to the sub-basins of the Novo and Xopotó Rivers between 1996 and 2004, which have similar hydrologic characteristics (specific yield) to of the calibration (Atlas Digital das Águas de Minas, 2010).

Proxy-basin test (upstream and downstream from the calibration section): In this test, SWAT calibrated for the control section in Astolfo Dutra was applied to the sections upstream and downstream from this control section using the data from the Guarani, Ituerê, and Tabuleiro streamflow gauging stations (upstream) and the Cataguases and Santo Antônio de Pádua streamflow gauging stations (downstream) between 1996 and 2004.

Complementarily, the model performance in simulating the maximum, average and minimum annual daily streamflow values performed based on the paired *t*-test and linear regression analysis was evaluated.

4. Results and discussion

4.1. SWAT calibration and validation in the Pomba River sub-basin with a control section in Astolfo Dutra

After the analysis of the sensitivity of the SWAT parameters, which was performed using the "sensibility analysis" command from the "SWAT simulation" menu, it was verified that from the 21 parameters of the model, the seven most sensitive in decreasing order were SOL_K, APLHA_BF, ESCO, CN_2, CH_N_2, SOL_AWC, and SOL_Z. We chose to calibrate only these seven most sensitive parameters to facilitate the calibration process because this has been carried out by a trial and error method and in order to have a less complex model. Table 3 presents the description and values of these parameters after calibration.

Table 3
SWAT calibration and validation in the Pomba River sub-basin with a control section in Astolfo Dutra.

Parameter	Default	Description	Calibrated value
CN_2	35–92	Curve number, condition AMCII (dimensionless)	*0.7
SOL_AWC	0.15–0.34	Soil's available water capacity(mm mm^{-1})	*1.15
SOL_Z	150–1960	Soil layer depth (mm)	*0.85
SOL_K	5–75	Hydraulic conductivity of the saturated soil (mm h^{-1})	*0.12
ESCO	0.95	Soil water evaporation compensation factor (dimensionless)	0.3
ALPHA_BF	0.048	Base runoff recession coefficient (days)	0.004
CH_N_2	0.014	Manning coefficient for the main canal (s m$^{-1/3}$)	0.012

Multiplication sign showing that the default values of the parameters are multiplied by the number after "".

Table 4
Results of the precision statistics for the calibration and validation periods.

Step.	Precision statistics.		
	C_{NS}	$(C_{NS})_{log}$	P_{BIAS}
Calibration	0.76	0.79	4.6
Validation	0.76	0.78	5.1

C_{NS}—Nash-Sutcliffe efficiency coefficient; $(C_{NS})_{log}$—Nash-Sutcliffe efficiency coefficient of the streamflow logarithm; and P_{BIAS}—bias percentage.

Table 4 presents the results of the precision statistics employed to assess SWAT performance in simulating the streamflow of the Pomba River sub-basin with a control section in Astolfo Dutra during the calibration and validation periods.

The analysis of the results (Table 4) shows C_{NS} values of 0.76 both for calibration and validation and $(C_{NS})_{log}$ values of 0.79 and 0.78 for calibration and validation, respectively, which means that the model is appropriate and good for the simulation of maximum (C_{NS}) and minimum ($(C_{NS})_{log}$) streamflows, according to the classification suggested by Motovilov et al. (1999). Regarding the P_{BIAS}, it indicated slight deviations between the mean simulated and observed streamflows, showing overestimation of 4.6 and 5.1% in calibration and validation, respectively, which means the performance of the SWAT model in estimating the mean streamflows is very good according to the classification proposed by Liew et al. (2007).

Many studies with the SWAT related C_{NS} values ranged from 0.3 to 0.9, depending on the drainage area of basin, the time interval of the simulation and the available database. Kannan et al. (2007) obtained C_{NS} values of 0.61 and 0.59 in the calibration and validation of SWAT, respectively, for the simulation of daily streamflow for the basin in the 1.42 km^2 of drainage area in Bedfordshire, United Kingdom, using a time series of data of little more than one year to calibrate and simulate the model. Sexton et al. (2010) obtained C_{NS} values between 0.46 and 0.58 for the calibration and between 0.68 and 0.76 for the validation of the simulation of daily streamflow for a basin with a 50 km^2 drainage area located on the coastal plain of Maryland on the eastern shore of the Chesapeake Bay in the USA. Durães et al. (2011) obtained C_{NS} values of 0.79 for both the calibration and validation of SWAT for the simulation of daily streamflow of a basin with a 10,200 km^2 drainage area located in the state of Minas Gerais, Brazil, using six years of data available for calibration and five for validation. Andrade et al. (2013a) obtained C_{NS} values of 0.66 and 0.87 for the calibration and validation of SWAT, respectively, for the simulation of daily streamflow of a basin with a 32 km^2 drainage area located in the Alto Rio Grande region in the state of Minas Gerais, Brazil, based on an available database of two years for calibration and one years for validation. Pereira et al., 2014a obtained C_{NS} values of 0.65 and 0.70 in the calibration and validation of SWAT, respectively, for the simulation of daily streamflow in the Galo Creek Basin (drainage area of 943 km^2) in the state of Espírito Santo, Brazil, based on six years of data for calibration and three for validation. Machado et al. (2003) obtained C_{NS} value of 0.92 for the calibration of SWAT for the simulation of the monthly average streamflow of the basin, with a 59.7 km^2 drainage area, located in São Paulo, Brazil, using data available from two years. The authors did not realize the model validation. It is also worth highlighting that in all of these studies, the SWAT model was considered satisfactory and appropriate for the simulation of the basins.

Regarding the $(C_{NS})_{log}$ coefficient, no studies were found in which the $(C_{NS})_{log}$ was used to evaluate the SWAT despite its significance in evaluating the performance of the model for the simulation of the minimum streamflows. However, it is believed that $(C_{NS})_{log}$ presents a behavior similar to that observed for C_{NS} because it is the same coefficient, but $(C_{NS})_{log}$ is applied to the logarithmic data. The many P_{BIAS} studies with the SWAT have shown values ranging from −20 to 20%. Pereira et al. (2014a) obtained P_{BIAS} values from 7.2 and 14.1% for the calibration and validation of SWAT, respectively, for the simulated daily average streamflow of a basin with a 943 km^2 drainage area located in the State of Espírito Santo, Brazil, based on six years of data available for calibration and three for validation. Andrade et al. (2013a) obtained P_{BIAS} values from 4.3 and −1.6% for the calibration and validation of SWAT, respectively, for the simulation of daily average streamflow of a basin with a 32 km^2 drainage area located in region of the upper Rio Grande in the State of Minas Gerais, Brazil. Sexton et al. (2010) obtained P_{BIAS} values from −15.3 and 0.5% for the calibration and −11.9 and −19.8% for the validation of SWAT for the simulation of daily average streamflow of a basin with a 50 km^2 drainage area in the Chesapeake Bay, USA.

Based on the statistical results obtained and compared to the values observed in other studies, it can be inferred that SWAT will yield good results in estimating the maximum, average and minimum streamflows. However, other analyses are presented in more detail to verify the performance of the model.

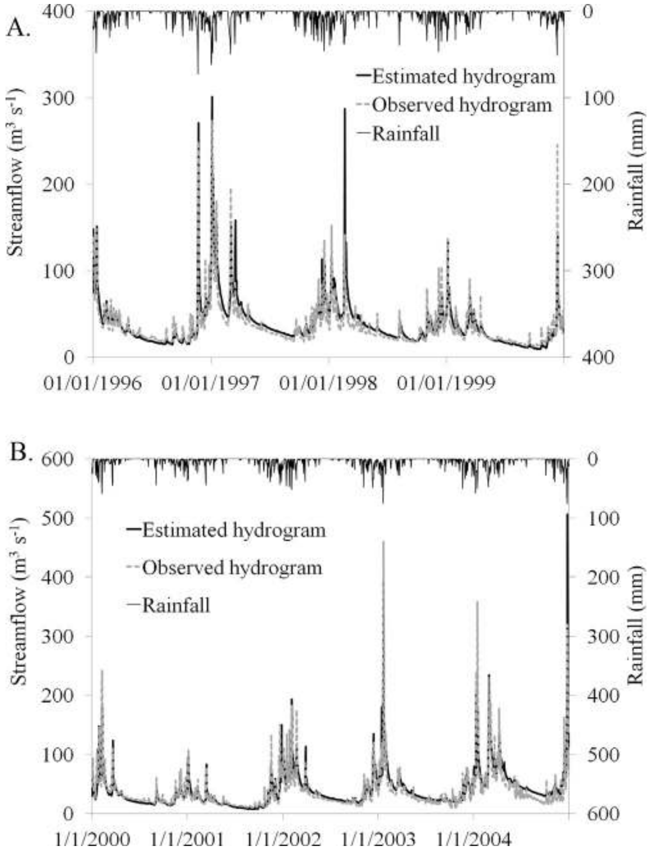

Fig. 5. Hydrograms (estimated and observed) and daily histograms obtained for the Pomba River sub-basin with a control section in Astolfo Dutra during the periods: (A) calibration and (B) validation.

The fits of the simulated hydrograms to the observed ones are presented in Fig. 5A and B. Overall, the streamflows simulated by the SWAT model fit the observed ones well, albeit with some difficulties in simulating some streamflow peaks both in the calibration (Fig. 5A) and validation (Fig. 5B) periods. This same difficulty was found by other authors, such as Viola et al. (2009), Pereira et al. (2014a), and von Stackelberg et al. (2007), and is related to the representation of the spatial and temporal rainfall distribution. The rainfall distribution in SWAT is conducted by associating the sub-basin with the nearest streamflow gauging station closest to its centroid, and because the sub-basin has only five rainfall gauging stations upstream from the control section in Astolfo Dutra, the spatial representativeness of some rainfall was compromised. Combined with the temporal rainfall variation, which is difficult to represent through a daily time step, this made the response of the SWAT model in simulating some peak streamflows difficult.

To better analyze the performance of SWAT in the simulation of daily streamflows, especially the extremes, the values observed and simulated by SWAT of the maximum, average and minimum annual daily streamflows with the corresponding scatter plots are shown in Fig. 6. This analysis is fundamental to the management of water resources in the basin, providing for hydrologic simulation a viable tool for predicting the peak flows used in the study of floods and of maximum and minimum streamflows and for various other purposes. It should be noted that for the maximum and minimum streamflow, analyses were carried out based on two values for each year because the model does not always simulate the largest or the lowest streamflow value on the day it occurred.

Fig. 6B, based on the angular coefficient, shows that the model tended to underestimate peak flows. This underestimation was greater in 2001 and 2004 (Fig. 6A), producing errors of 58 and 56%, respectively. The simulated peak flows in 2001 and 2004 were 62.8 and 158 $m^3 s^{-1}$, with observed values of 150.2 and 357.8 $m^3 s^{-1}$, respectively. However, overestimation was also observed, as in 1998 and 2001 (Fig. 6A), in which the model simulated values of 287 and 150 $m^3 s^{-1}$ compared to the observed values of 103.6 and 65 $m^3 s^{-1}$, producing errors of 177.1 and 130.9%, respectively. These errors are dimensionless and show the difficulty of the model in simulating some values of maximum streamflow due to the difficulty of spatial and temporal representations of rainfall, as mentioned previously. For example, at the end of 2004, there was a large concentration of rainfall, which totaled 232 mm in six days, and of these, 76 mm occurred the day before the event of maximum streamflow, making model estimates difficult. However, for most of the year, good streamflow values were simulated with fairly small estimation errors, ranging from 5.9% (2002) to 36.7% (2003).

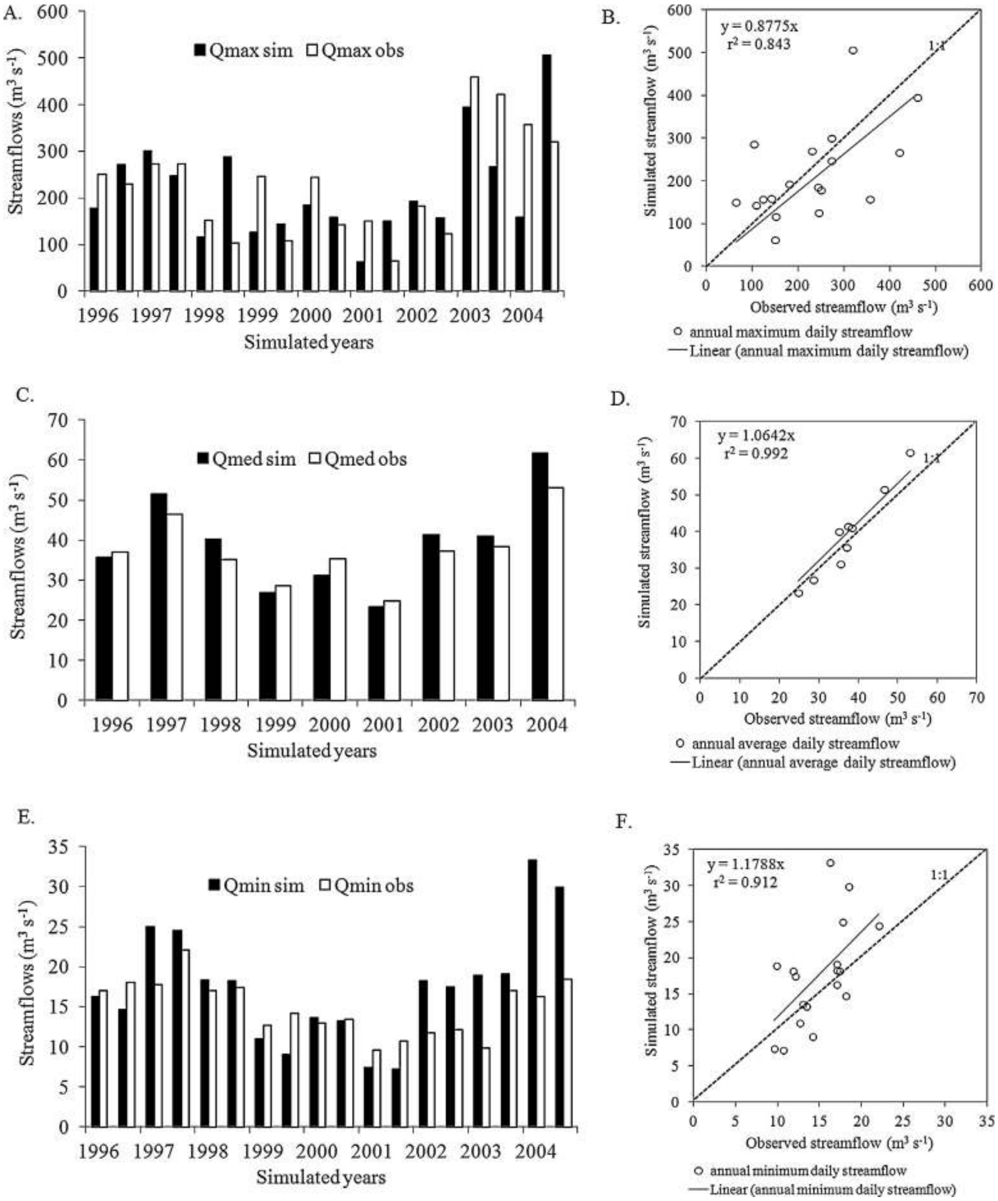

Fig. 6. Maximum, average and minimum annual daily streamflows observed and simulated for the Pomba River sub-basin with control section in Astolfo Dutra.

Analyzing the annual daily average streamflow (Fig. 6C), there is a major difference between the simulated and observed values in 2004, with an estimate error of 16%. Estimate errors ranged from 3.7 (1996) to 16% (2004). In average terms, in the period from 1996 to 2004 a value of 39.2 $m^3 s^{-1}$ was simulated for the observed value of 37.4 $m^3 s^{-1}$, resulting in an overestimate of 4.9%. Although the analysis has been made on the basis of nine years, this value is close to the long-term average streamflow obtained from the Atlas Digital das Águas de Minas (2010), which is 41.4 $m^3 s^{-1}$.

Analyzing Fig. 6E and F, the model's tendency to overestimate the annual daily minimum streamflows appears to be based on the angular coefficient. This overestimation was higher for 2004, when the values simulated by SWAT were 33.3 and 29.9 $m^3 s^{-1}$ and the observed were 16.2 and 18.4 $m^3 s^{-1}$, resulting in errors of 105 and 62%, respectively. It is interesting to note that in this year, the annual rain volume (1922 mm) was above the average for the period (1415 mm). This higher concentration of rain could explain the error raised by the model. However, there is a good simulation of the annual daily minimum streamflows, with errors ranging from 0.7 (2000) to 40% (1997). In the year 2000, the model simulated a value of 13.3 $m^3 s^{-1}$ compared to the observed value of 13.4 $m^3 s^{-1}$.

Table 5
Results of the regression analysis and paired *t*-test applied to the data of maximum, average and minimum annual daily streamflows observed and simulated by SWAT in the Pomba River sub-basin.

Streamflow	n	a	t_{cal}	t_{crit}	r^2
Annual daily maximum	18	0.8775	0.455	2.110	0.843
Annual daily average	8	1.0642	−1.498	2.262	0.992
Annual daily minimum	18	1.1788	−1.909	2.110	0.912

n—number of sample values; a—angular coefficient; tcalc. paired *t*-test, calculated value; tcrit—paired *t*-test, bi-caudal value; ns—not significant at the 5% level of significance.

Table 6
Components of the annual water balance, in mm, simulated by SWAT for the Pomba River sub-basin, with the exception of rainfall, which was input data.

Year	PT (mm)	E_{sup} (mm)	E_{lat} (mm)	E_{sub} (mm)	ET (mm)	ΔA (mm)
	Calibration					
1995	1291.6	10.1	132.4	64.9	917.2	108.6
1996	1497.2	25.3	209.1	147.4	971.1	30.5
1997	1432.3	36.1	210.2	293.2	992.3	−76.2
1998	1350.3	17.6	173.3	194.9	919.4	39.9
1999	1187.9	13.3	153.3	160.9	873.4	−17.6
Average	1351.9	20.5	175.6	172.3	934.7	17.0
	Validation					
2000	1405.8	22.5	191.1	174.1	939.5	26.2
2001	1255.2	14.6	147.2	109.3	925.0	2.6
2002	1372.4	17.4	200.3	210.0	959.0	−34.2
2003	1429.9	28.7	197.4	231.7	956.0	4.2
2004	1922.3	50.1	296.0	361.9	917.5	50.4
Average	1477.1	26.7	206.4	217.4	939.4	9.8

The graphical analysis should always be accompanied by statistics in regard to evaluating the performance of models (Willmott, 1982). Therefore, Table 5 shows the results of the regression analysis and paired *t*-test applied to the data of the maximum, average and minimum annual daily streamflows observed and simulated by SWAT.

Analyzing the SWAT performance with respect to the paired *t*-test at a 5% significance level, we note that the t_{cal} values were not significant for the maximum, average and minimum annual daily streamflows. We are able to say with 95% probability that on average, the difference between observed and simulated values by SWAT for the Pomba River sub-basin with a control section in Astolfo Dutra is void. Based on these results, one can say that, statistically, the SWAT can be applied for the estimation of maximum, average and minimum annual daily streamflows with potential use in hydrological studies and water management in the sub-basin. However, it should be noted that the model needs a better spatial and temporal representation of rainfall to properly simulate some maximum and minimum streamflows.

In Table 6, the results of the annual simulated water balance components for SWAT for the Pomba River sub-basin from 1995 to 2004 period are shown.

Analyzing the components of the water balance, in average terms, it appears that the sum of the surface and subsurface runoff totaled 196.1 and 233.1 mm during the period of calibration and validation, respectively, equivalent to 13.3 and 15.8% of output components of the water balance. Groundwater contributions were 12.7 and 14.7% in the calibration and validation steps, respectively, equivalent to 172.3 and 217.4 mm. The evapotranspiration represented substantial participation in the annual water balance of the sub-basin, which in average percentage terms was equivalent to 69.1 and 63.6% of the total volume precipitated during the calibration and validation periods, respectively. Regarding the water storage in the soil, annual average variations of 17.03 and 9.83 mm were simulated, equivalent to 1.3 and 0.7% of the total water balance, for the calibration and validation periods, respectively.

Pereira et al. (2010) performed the water balance in an Atlantic Forest area of a basin located in the region of the Mantiqueira Range, Brazil, on the basis of measurements made in the field. The authors found that evapotranspiration corresponded to 89%, percolation to 12.1% and storage to −1.1% of the water balance. These results are close to those simulated by SWAT, except for evapotranspiration, but it should be noted that the value obtained by the authors was for the Atlantic Forest, which has vegetation that consumes more water compared to different areas in the basin. It is worth noting, too, that the authors did not estimate the surface and subsurface runoff. Nevertheless, the results help to give physical support to the simulations of water balance components simulated by SWAT.

4.2. Proxy basin test: SWAT validation upstream and downstream from the calibration section

Table 7 presents the results of the precision statistics obtained by applying the SWAT model, calibrated in the control section in Astolfo Dutra, to the streamflow gauging stations located upstream (Guarani, Ituerê, and Tabuleiro) and downstream (Cataguases and Santo Antônio de Pádua).

Table 7
Statistical results obtained in the validation of the SWAT model in the control sections of Guarani, Ituerê, Tabuleiro, Cataguases, and Santo Antônio Pádua.

Streamflow gauging stations	Code	Precision statistics		
		C_{NS}	$(C_{NS})_{log}$	P_{BIAS}
Guarani (upstream)	58730001	0.62	0.67	10.5
Tabuleiro (upstream)	58720000	0.27	0.16	−27.8
Ituerê (upstream)	58710000	0.47	0.59	15.3
Cataguases (downstream)	58770000	0.81	0.76	11.7
Santo Antônio de Pádua (downstream)	58790000	0.76	0.75	8.3

C_{NS}—Nash-Sutcliffe efficiency coefficient; $(C_{NS})_{log}$—Nash-Sutcliffe efficiency coefficient of the streamflow logarithm; and P_{BIAS}—bias percentage.

The values obtained for the Nash-Sutcliffe coefficient (CNS) and its logarithmic version ($(C_{NS})_{log}$) ranged from 0.16 (Tabuleiro) to 0.81 (Cataguases), as shown in Table 6. In the control sections upstream from the section used in calibration, the SWAT model had a satisfactory performance in Guarani ($C_{NS} = 0.62$ and $(C_{NS})_{log} = 0.67$) and Ituerê ($C_{NS} = 0.47$ and $(C_{NS})_{log} = 0.59$), and a non-satisfactory performance in Tabuleiro ($C_{NS} = 0.27$ and $(C_{NS})_{log} = 0.16$), according to the classification proposed by Motovilov et al. (1999). Regarding the sections downstream from the calibration section, SWAT had appropriate and good performance with values for C_{NS} and $(C_{NS})_{log}$ of 0.81 and 0.76, respectively, (Cataguases) and 0.76 and 0.75, respectively (Santo Antônio de Pádua).

The differences between the mean calculated and observed streamflows, i.e., the bias (P_{BIAS}), ranged from −27.8% (Tablueiro station) to 15.3% (Ituerê station), which indicates greater underestimation in simulating the streamflows in Tabuleiro and overestimates the other sections. According to the classification proposed by Liew et al. (2007), the model had very good performance ($|P_{BIAS}| < 10\%$) in the section of Santo Antônio de Pádua, good ($10 < |P_{BIAS}| < 15\%$) in Guarani and Cataguases, satisfactory ($15\% < |P_{BIAS}| < 25\%$) in Iturê, and non-satisfactory ($|P_{BIAS}| \geq 25\%$) in Tabuleiro.

Based on the statistical results described above, the SWAT is expected to produce satisfactory simulations of daily streamflows in the sub-basins located upstream and downstream from the calibration section, except in sub-basin with the control section on Tabuleiro. The fit of the streamflows simulated by the SWAT model compared to the observed streamflows during the validation in sections upstream and downstream from the calibration section is presented in Figs. 7 and 8 for the period between January 1996 and December 2004, except in Santo Antônio de Pádua, in which the simulated period was from January 1996 to December 2001 due to the deactivation of the gauging station.

Overall, good fits can be seen for the streamflows simulated by the SWAT model to the streamflows observed in the gauging stations upstream (Fig. 7) and downstream (Fig. 8) from the calibration section, except for the section in Tabuleiro (Fig. 7C), in which the SWAT model simulated minimum streamflows close to zero, besides peak streamflows with a high-magnitude underestimation. The explanation for this is the lack of representativeness of rainfall, which is made by a single rainfall gauging station (Tabuleiro), and the drainage occurring in a few hours due to the steepness in the sub-basins head, which made simulating floods more difficult. According to Silva and Tucci (1998), the estimate errors of peak flow rates increase as the time of concentration of the basin decreases, which was observed in the study (Figs. 7 and 8), in which we can verify that the modeling results were better in the downstream sections of the calibration section, which features concentration times greater than those located upstream. Based on the results obtained, it should be noted that the transfer of calibrated parameters for smaller areas should be made with criteria mainly in mountainous basins, such as those in the study.

To better analyze the performance of SWAT in the simulation of daily streamflows in upstream and downstream sub-basins of the calibration section, the scatter plots of simulated and observed maximum, average and minimum daily annuals streamflows are shown in Figs. 9–11.

It is observed that the SWAT tends to overestimate the annual daily maximum streamflows in sections of Guarani (A), Ituerê (B) and Cataguases (D) and to underestimate them in sections of Tabuleiro (C) and Santo Antônio de Pádua (E) (Fig. 9). The model showed the same behavior observed in the calibration section, that is, it presented difficulties in simulating some peak flow rates (farthest points of the straight 1:1), providing errors in greater magnitude estimates in all sections in 1998. The simulated daily maximum streamflows by the model for this year were 293, 255, 38, 488 e 527 $m^3 s^{-1}$ in Guarani, Ituerê, Tabuleiro, Cataguases and Santo Antônio de Pádua, compared to those observed of 109.8, 81.5, 15.9, 177 and 232.2 $m^3 s^{-1}$, producing errors 167, 213, 139, 175.7 e 127%, respectively. However, good estimates of annual daily maximum streamflow were simulated by the model (closest points of the straight 1:1), except for in the Tabuleiro section (Fig. 9C).

Fig. 10 shows the annual daily average streamflows in all sections, except in Tabuleiro, based on the slope of the regression, which the SWAT tends to overestimate. The overestimation of greater magnitudes was observed in 2004 in the Ituerê section (farthest point of the straight 1:1), in which the model simulated a daily average streamflow of 26.9 $m^3 s^{-1}$ for the observed value of 18.3 $m^3 s^{-1}$, providing an estimation error of 47.6% (Fig. 10B). In the Tabuleiro section, the model adequately estimated the daily average streamflow only in the years 1997 and 1998, simulating values of 8.9 and 6.7 $m^3 s^{-1}$ compared to those observed of 8.6 and 6.8 $m^3 s^{-1}$, producing errors of 3.4 and 1.6%, respectively.

Based on angular coefficients from regressions, we observed that the SWAT tends to overestimate the annual daily minimum streamflows in the Guarani (A), Ituerê (B) and Cataguases (D) sections and underestimate them in Tabuleiro (C) and Santo Antônio de Pádua (E) (Fig. 11). The overestimates of greater magnitude were observed, generally, in 2004, in which

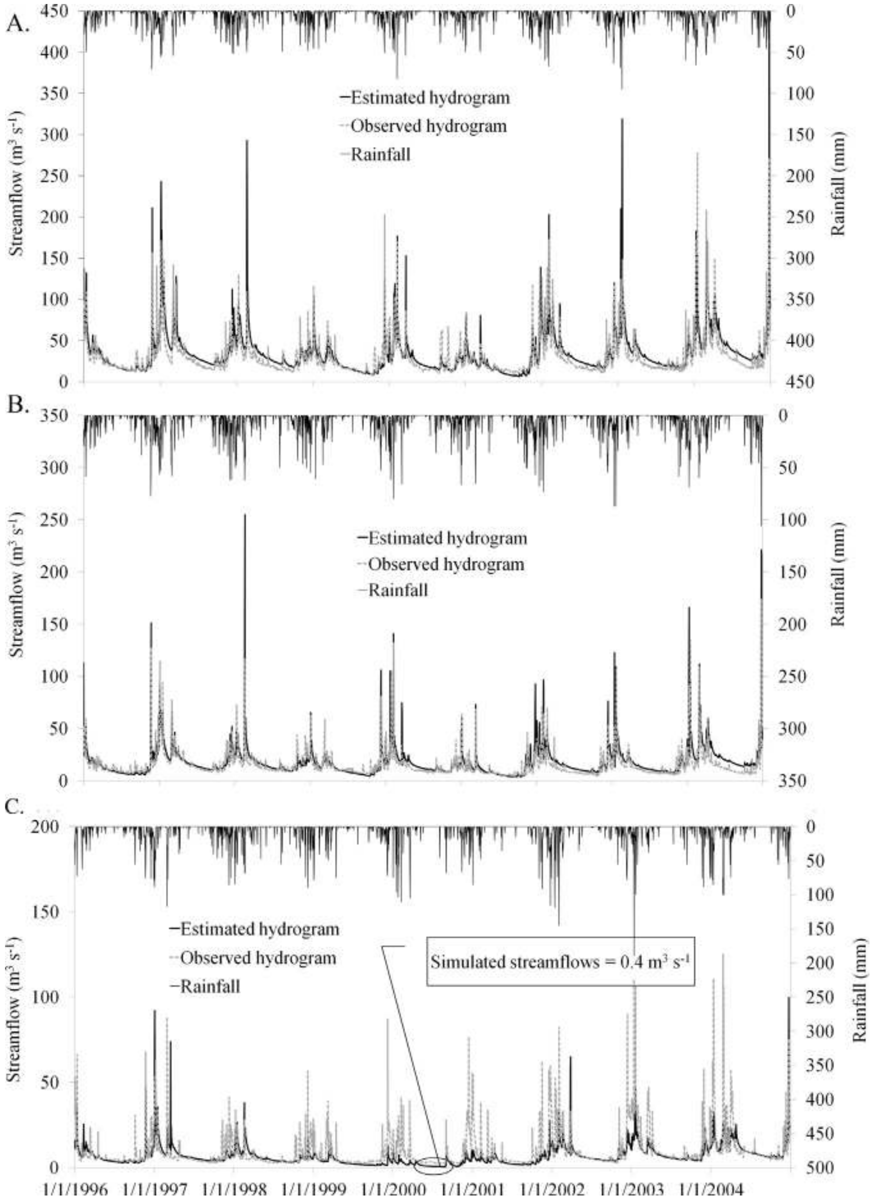

Fig. 7. Daily hydrograms (estimated and observed) and histograms obtained from the validation of the SWAT model upstream of the (A) Guarani, (B) Ituerê, and (C) Tabuleiro calibration sections.

the model simulated values of 26.2, 15.6 and 87.3 $m^3 s^{-1}$ compared with the annual observed minimums of 14.8, 6.1 and 32 $m^3 s^{-1}$ in Guarani, Ituerê e Cataguases, respectively, producing estimate errors of 77.5, 154.7, and 173.2%, respectively. The simulated annual daily minimums this year in these sections were 25.9, 13.6 and 76 $m^3 s^{-1}$, with observed values of 15.4, 7.0 and 40.5 $m^3 s^{-1}$, producing overestimates of 68.5, 94.3 and 87.9%, in Guarani, Ituerê and Cataguases, respectively. As a reminder, this year was atypical, with rainfall well above the annual average (Table 6), which led to these great overestimates of annual daily minimum streamflow by the model. In other years, the estimates were reasonably good, with errors ranging from 0 a 50% in Guarani and Cataguases and from 0 to 38% in Ituerê. In the Tabuleiro section (Fig. 11C), there were, in some years, good estimates of daily minimum streamflows (points near the straight 1:1), but overall, the model underestimated them with great magnitude, producing errors of 30–86%. In Santo Antônio de Pádua, the best estimates of annual daily minimum streamflows are based on the angular coefficient, whose errors ranged from 1 to 32.5%, except for 2001, when a value of 21.8 $m^3 s^{-1}$ was simulated, compared to an observed value of 8.54 $m^3 s^{-1}$, with an error of 155% (Fig. 11E).

Table 8 shows the results of the regression analysis and paired *t*-test applied to the maximum, average and minimum annual daily streamflows observed and simulated by SWAT for the sub-basins located upstream and downstream of the calibration section.

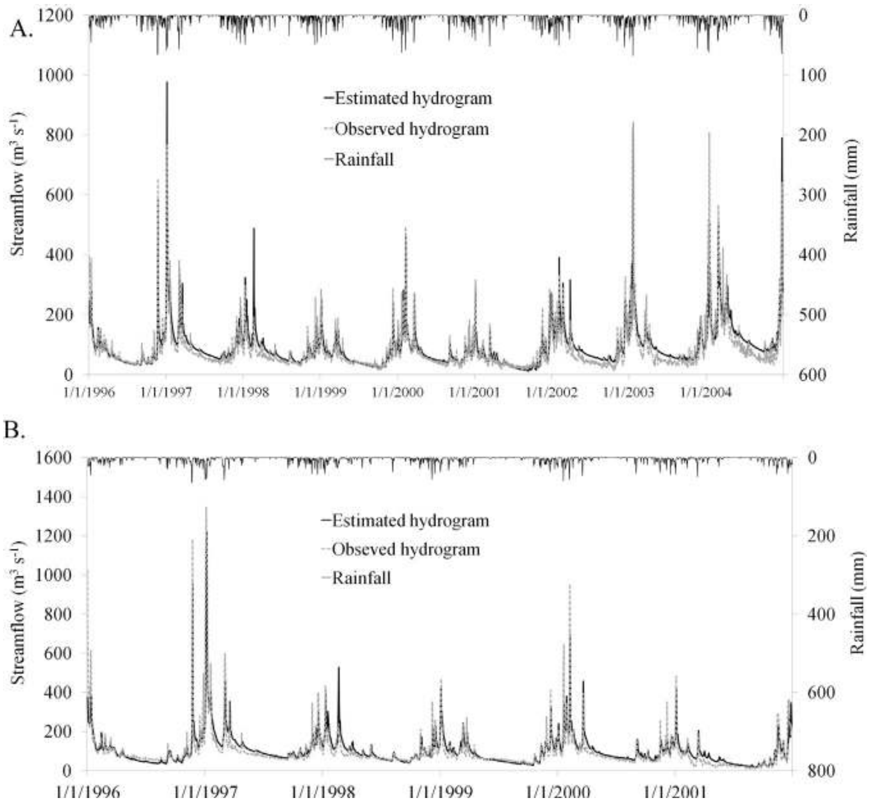

Fig. 8. Daily hydrograms (estimated and observed) and histograms obtained from the validation of the SWAT model downstream of the (A) Cataguases and (B) Santo Antônio de Pádua calibration sections.

Table 8
Results of regression analysis and paired *t*-test applied to data of the maximum, average and minimum annual daily streamflows observed and simulated by SWAT in the sub-basins located upstream and downstream of the calibration section.

Control section	Streamflow	n	a	t_{cal}	t_{crit}	r^2
Guarani	Annual daily maximum	18	1.1197	$-0.700^{(ns)}$	2.110	0.823
	Annual daily average	9	1.1138	$-2.297^{(ns)}$	2.306	0.990
	Annual daily minimum	18	1.3625	-3.568^{*}	2.110	0.938
Ituerê	Annual daily maximum	18	1.0992	$-1.159^{(ns)}$	2.110	0.814
	Annual daily average	9	1.1475	$-2.283^{(ns)}$	2.306	0.978
	Annual daily minimum	18	1.1526	$-1.739^{(ns)}$	2.110	0.879
Tabuleiro	Annual daily maximum	18	0.3865	3.306^{*}	2.110	0.449
	Annual daily average	9	0.7351	3.966^{*}	2.306	0.933
	Annual daily minimum	18	0.6815	$1.602^{(ns)}$	2.110	0.714
Cataguases	Annual daily maximum	18	1.0142	$-0.758^{(ns)}$	2.110	0.904
	Annual daily average	9	1.1246	-3.233^{*}	2.306	0.995
	Annual daily minimum	18	1.2521	$-1.977^{(ns)}$	2.110	0.857
Santo Antônio de Pádua	Annual daily maximum	18	0.8684	$1.162^{(ns)}$	2.110	0.934
	Annual daily average	6	1.0459	$-1.435^{(ns)}$	2.306	0.993
	Annual daily minimum	18	0.9851	$-0.291^{(ns)}$	2.110	0.952

n—number of sample values; a—angular coefficient; tcalc. paired *t*-test, calculated value; tcrit—paired *t*-test, bi-caudal value; ns—not significant at the 5% level of significance.

[*] Significant at the 5% level of significance.

Analyzing the SWAT performance with respect to the paired *t*-test at 5% significance (Table 8), the annual daily maximum streamflows the values of t_{cal} were not significant in any control sections, except in Tabuleiro, which allows us to state with 95% probability that, on average, the difference between observed and simulated values by SWAT for the sub-basins is void. Regarding the annual daily average streamflow, the estimates are not reliable for the Tabuleiro and Cataguases sections, where t_{cal} was significant, indicating that, statistically, the average of the estimated and observed values are different from zero. For annual daily minimum streamflows, the model is not reliable only in Guarani section, where the *t*-test showed

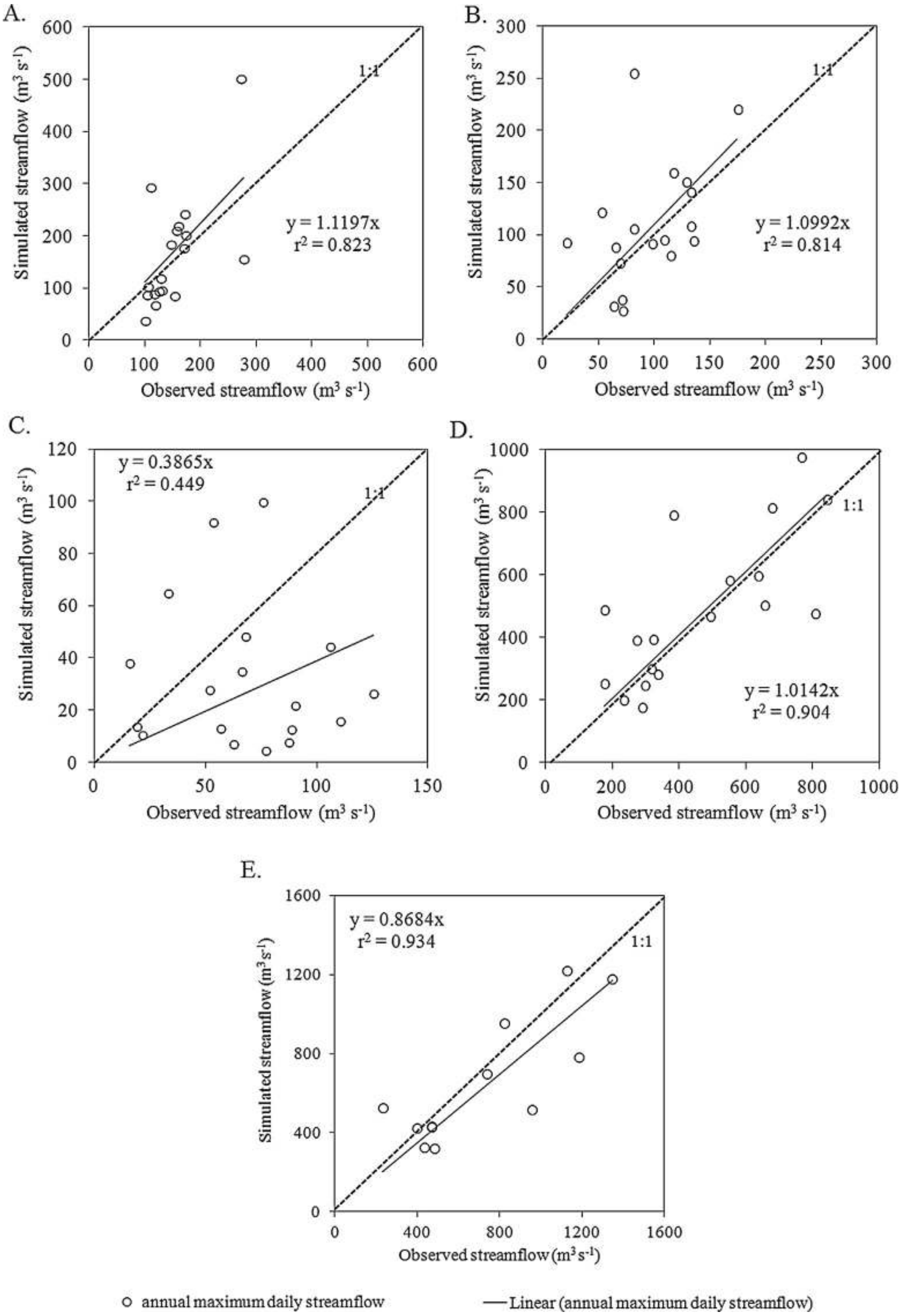

Fig. 9. Scatter plots of the annual daily maximum streamflow observed and simulated by SWAT in the sections located upstream (A) Guarani (B) Ituerê (C) Tabuleiro, and downstream (D) Cataguases (E) Santo Antônio de Pádua, of the calibration section.

significant differences at 5%. Based on these results, it can be stated statistically that SWAT can be applied for the estimation of maximum, average and minimum daily annual streamflows, except in the sections in which t_{cal} was significant.

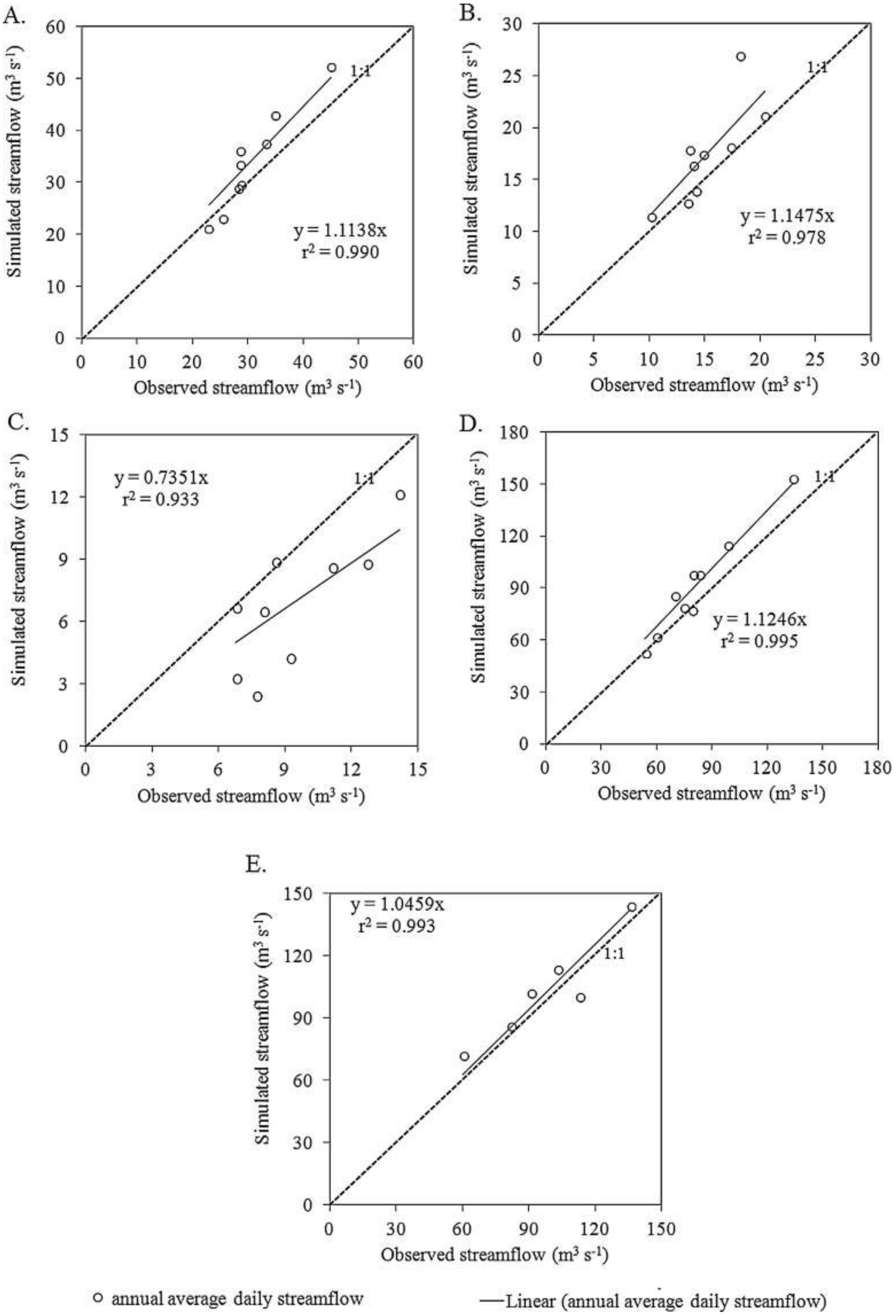

Fig. 10. Scatter plots of the annual daily average streamflow observed and simulated by SWAT in the sections located upstream (A) Guarani (B) Ituerê (C) Tabuleiro, and downstream (D) Cataguases (E) Santo Antônio de Pádua, of the calibration section.

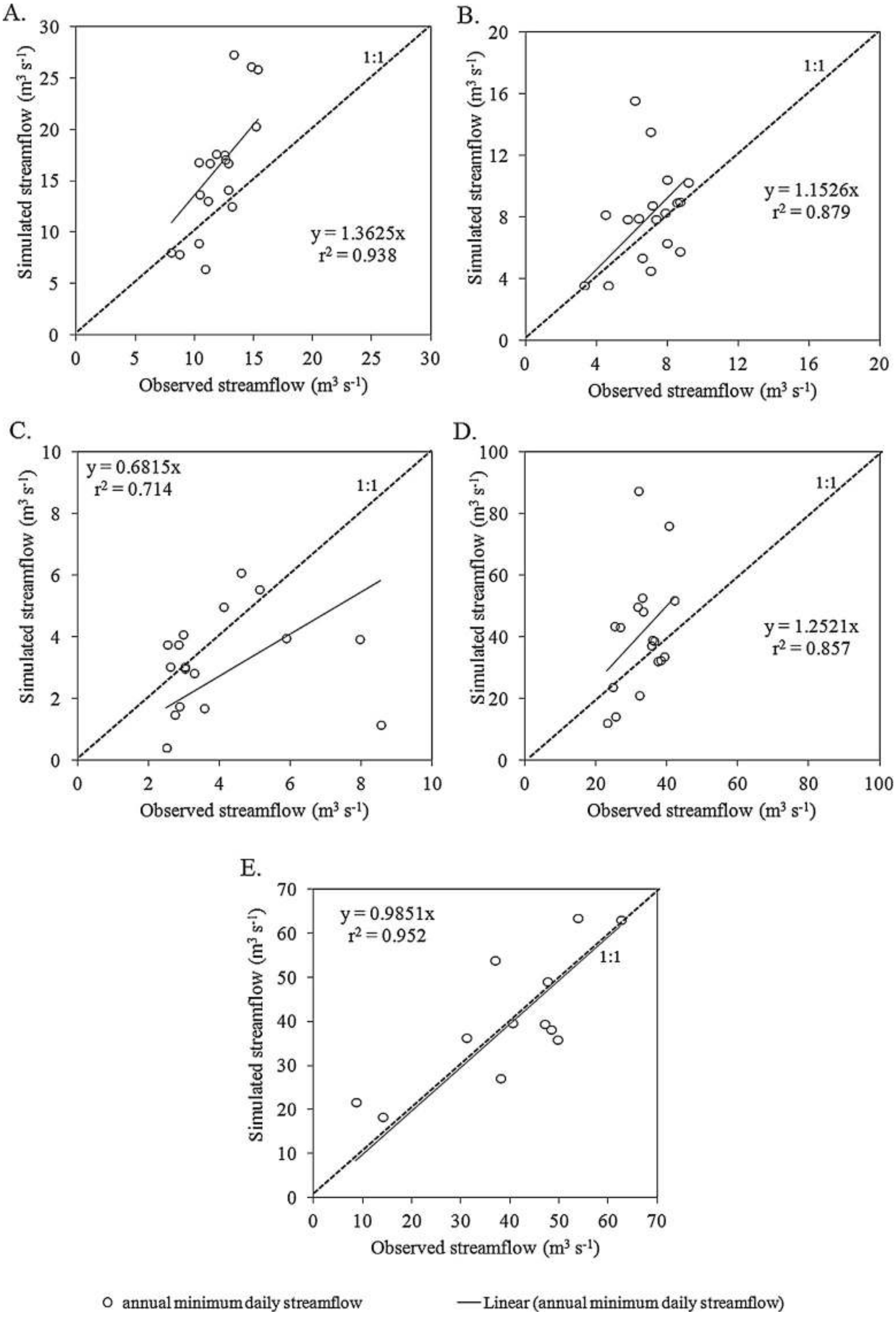

Fig. 11. Scatter plots of the annual daily minimum streamflow observed and simulated by SWAT in the sections located upstream (A) Guarani (B) Ituerê (C) Tabuleiro, and downstream (D) Cataguases (E) Santo Antônio de Pádua, of the calibration section.

4.3. Proxy basin test: validation of the SWAT model in different sub-basins

To carry out this test, we moved the model with the parameters calibrated in Astolfo Dutra to simulate daily streamflows in the sub-basins of the Novo and Xopotó Rivers, tributaries of Pomba River, between January 1996 and December 2004. These sub-basins are not part of the calibration sub-basin, as seen in Fig. 4, but have similar edaphoclimatic characteristics

Table 9
Statistical results of applying SWAT calibrated for the control section in Astolfo Dutra to the sub-basins of the Novo and Xopotó Rivers.

River	Station	Precision statistics		
		C_{NS}	$(C_{NS})_{log}$	P_{BIAS}
Novo	Usina Maurício	0.74	0.66	11
Novo	Rio Novo	0.54	0.53	6.2
Piau	Piau	0.46	−0.32	−8.6
Xopotó	Barra do Xopotó	0.36	0.13	45.1

C_{NS}—Nash-Sutcliffe efficiency coefficient; $(C_{NS})_{log}$—Nash-Sutcliffe efficiency coefficient of the streamflow logarithm; and P_{BIAS}—bias percentage.

and are hydrologically homogeneous to those used to calibrate the model with similar flow regimes, according to the Atlas Digital das Águas de Minas (2010). The land use, soils and relief information, necessary for the simulation of sub-basins, were extracted by SWAT using the land use maps (Fig. 3A), type of soil (3B) and slope (3C) related to the region of each sub-basin. The model evaluation results under this test are shown in Table 9.

An analysis of Table 9 shows the satisfactory performance of the SWAT model when applied to the sections of Usina Maurício and Rio Novo ($0.36 < C_{NSand}$ $(C_{NS})_{log} < 0.75$) and non-satisfactory performance ($(C_{NS})_{log} < 0.36$) when applied to the sections of Piau and Barra do Xopotó, according to the classification adopted and proposed by Motovilov et al. (1999). It is also observed that in the sections where performance was satisfactory, the mean simulated streamflows were overestimated compared to the observed streamflows, with P_{BIAS} values below 15% (good model) and 10% (very good model), according to the classification proposed by Liew et al. (2007). Moreover, using the SWAT model in the section of Barra do Xopotó yielded the greatest overestimations of the mean streamflows at approximately 45%, thus providing non-satisfactory ($P_{BIAS} > 0.25$) results (Liew et al., 2007).

The fit of the streamflows simulated by the SWAT model to the observed ones (period from 1996 to 2004) in the sections located in the sub-basin of the Novo and Xopotó Rivers can be seen in Figs. 12 and 13.

Overall, a good fit is found for the streamflows simulated by the SWAT model compared to those observed in the control sections of Usina Maurício (Fig. 12A) and Rio Novo (Fig. 12B), with some underestimates in the peak floods and overestimates in the recession of the hydrogram at Usina Maurício, as well as overestimates of some peaks and underestimates of the minimum streamflows in the recession period of the year 2001 at Rio Novo. The streamflows simulated for the section did not adjust well to those observed mainly between the years from January 1999 to December 2001, when we observe large underestimates of the flow rates and periods of recession with flow rates close to zero (Fig. 12C). The application of the SWAT in the Xopotó River sub-basin was also non-appropriate, as the statistics show and as verified by the poor fit of the simulated data compared to the observed (Fig. 13), with hydrogram overestimation in virtually all of the periods analyzed.

It is interesting to observe that the behavior of the SWAT when transferred to the Piau and Tabuleiro sections was similar and worse than the behavior for the section where it was calibrated. Both sections have the lowest drainage areas of the basin, below 500 km^2, have low rainfall representativeness (only a single rainfall gauging station) and steep terrain, characteristics that differentiate them from other sub-basins, particularly due to the lack of rainfall representativeness, which explains the poor efficiency in transferring the model's parameters to these sub-basins.

The analysis of the data measured (obtained from ANA) during the recession periods of the control section of Barra do Xopotó shows that the value of the recession constant is 0.009, which is higher than the value calibrated for Astolfo Dutra (0.004). Hence, the use of this value explains the overestimation of the recession streamflows in the section of Barra do Xopotó. Gonçalves et al. (2005), while working in the same basin as this study, obtained recession coefficient values in five of the ten sections used in this study that ranged from 0.00315 to 0.00393, values close to those calibrated and lower than those observed at Barra do Xopotó (0.009). This result suggests that the sub-basin's geological conditions are different from the calibration sub-basin, despite the Digital Atlas of Minas Gerais Water indicating that these areas are hydrologically homogeneous regarding their flow regimes. Regarding the overestimation of peak streamflows, the explanation lies in the fact that the sub-basin does not have any rainfall gauging station in its premises and the stations of Astolfo Dutra, Viçosa, and Fazenda Umbaúbas are used in the modeling. The latter two are located outside the basin's watersheds and are likely not representative of the rainfall in the area.

To better analyze the SWAT performance in the simulation of daily streamflows of the sub-basins of the Novo and Xopotó River, the results of the paired *t*-test applied to the data of the maximum, average and minimum annual daily streamflow simulated by the model and those observed are shown in Table 10.

In Table 10, with respect to the paired *t*-test at 5% significance level, it appears that for the annual daily maximum streamflow, the t_{cal} values were not significant in all sections, indicating that on average the difference between observed and simulated maximum streamflows by SWAT is void. Regarding the annual daily average streamflow, the estimates are not reliable for the Barra do Xopotó section, where the t_{cal} was significant, indicating that, statistically, the average of the simulated and observed values is nonzero. For the annual daily minimum streamflows, the model is not reliable in the Usina Maurício and Barra do Xopotó sections, where the *t*-test showed significant differences at a level of 5%. Interestingly, the SWAT, despite being suitable for the simulation of daily streamflows in the Usina Maurício section and unsuitable in the Piau section, based on the Nash-Suticliffe coefficient applied to the logarithm of the streamflow, was statistically inappropriate in the first and adequate the second for the simulation of annual daily minimum streamflows based on the paired *t*-test. The

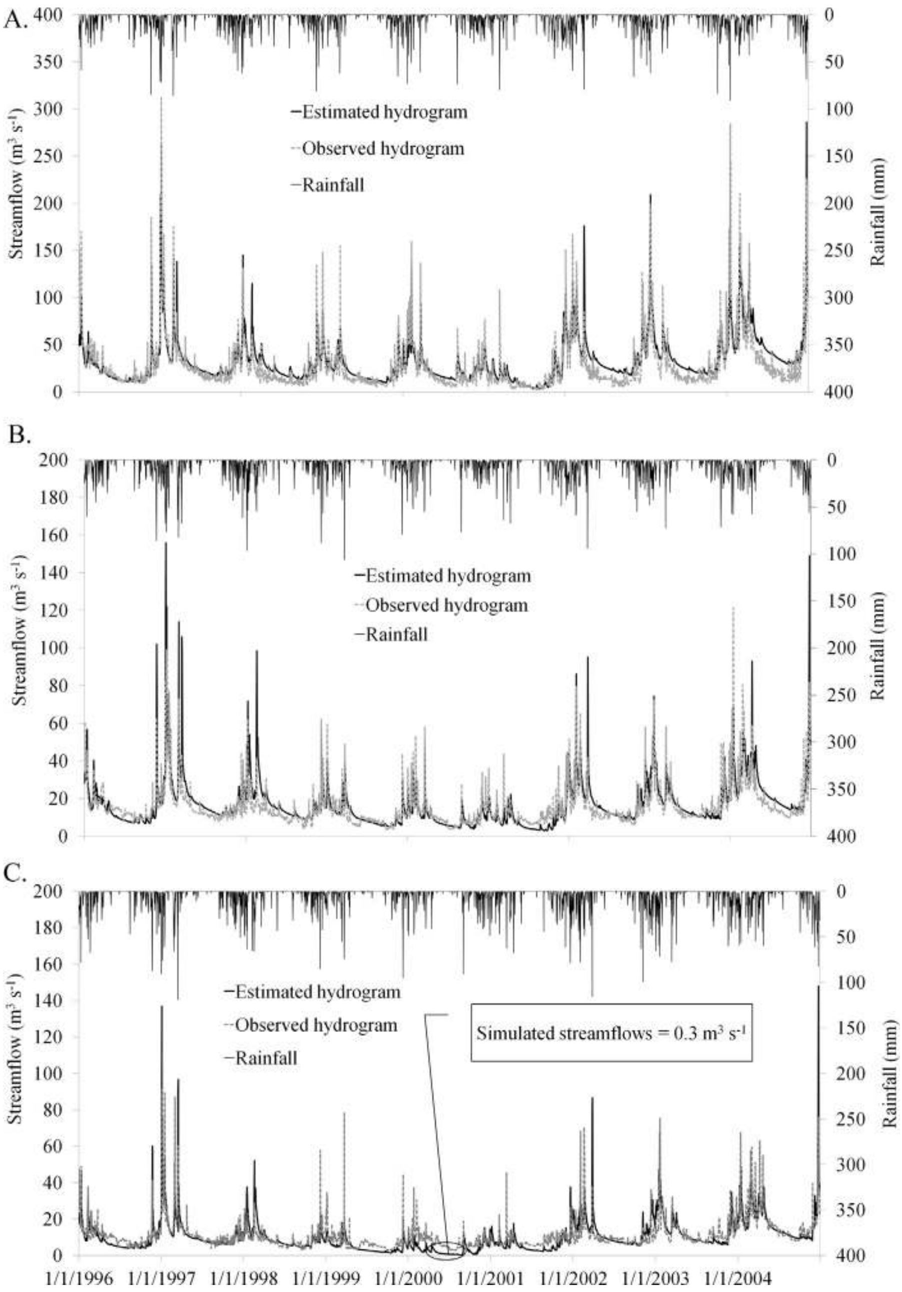

Fig. 12. Daily hydrograms (estimated and observed) and histograms obtained in the validation of the SWAT model in the streamflow gauging stations located in the sub-basins of the Novo River at (A) Usina Maurício, (B) Rio Novo, and (C) Piau.

scatter plot of maximum, average and minimum annual daily streamflows simulated by SWAT in relation to the observed values are shown in Figs. 14–16 .

Analyzing Fig. 14, based on the observed angular coefficients the SWAT tended to overestimate the annual maximum daily streamflows in the Rio Novo (Fig. 14B) and Barra do Xopotó (Fig. 14D) sections and underestimate them in the Usina Maurício (Fig. 14A) and Piau (Fig. 14C) sections. Although statistically the performance of the model was suitable for the simulation of the annual maximum daily streamflows based on paired *t*-test, it should be noted that at times it showed great magnitude estimation errors, possibly due to the lack of representativeness of precipitation, both spatial and temporal, which was verified in the model calibration section and in sections upstream and downstream of it. Estimation errors of −80 to 108% in 2001 and 2002 in the Usina Maurício section, respectively; −58 and 154% in Rio Novo in 2000 and 2002, respectively; 92, 246 and 277% in 2000, 2001 and 2002, respectively, in the Piau section; and of 111, 580 and 239% in Barra do Xopotó in 1996, 1998 and 1999, respectively, have been observed. According to Sexton et al. (2010), the spatial and

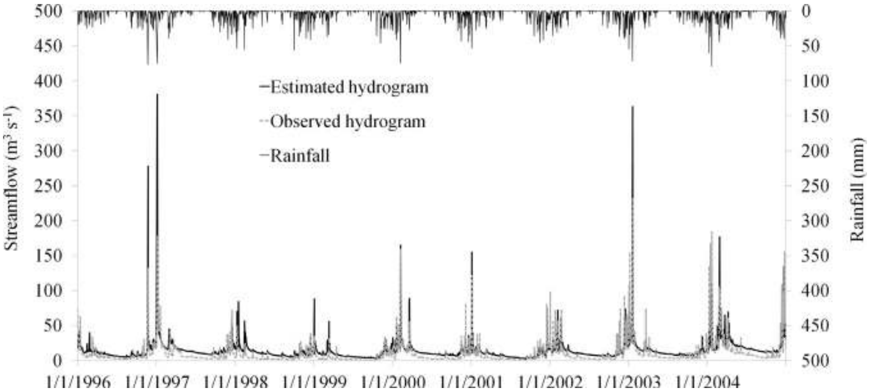

Fig. 13. Daily hydrograms (estimated and observed) and histograms obtained in the validation of the SWAT model at the control section of the sub-basin of the Xopotó River.

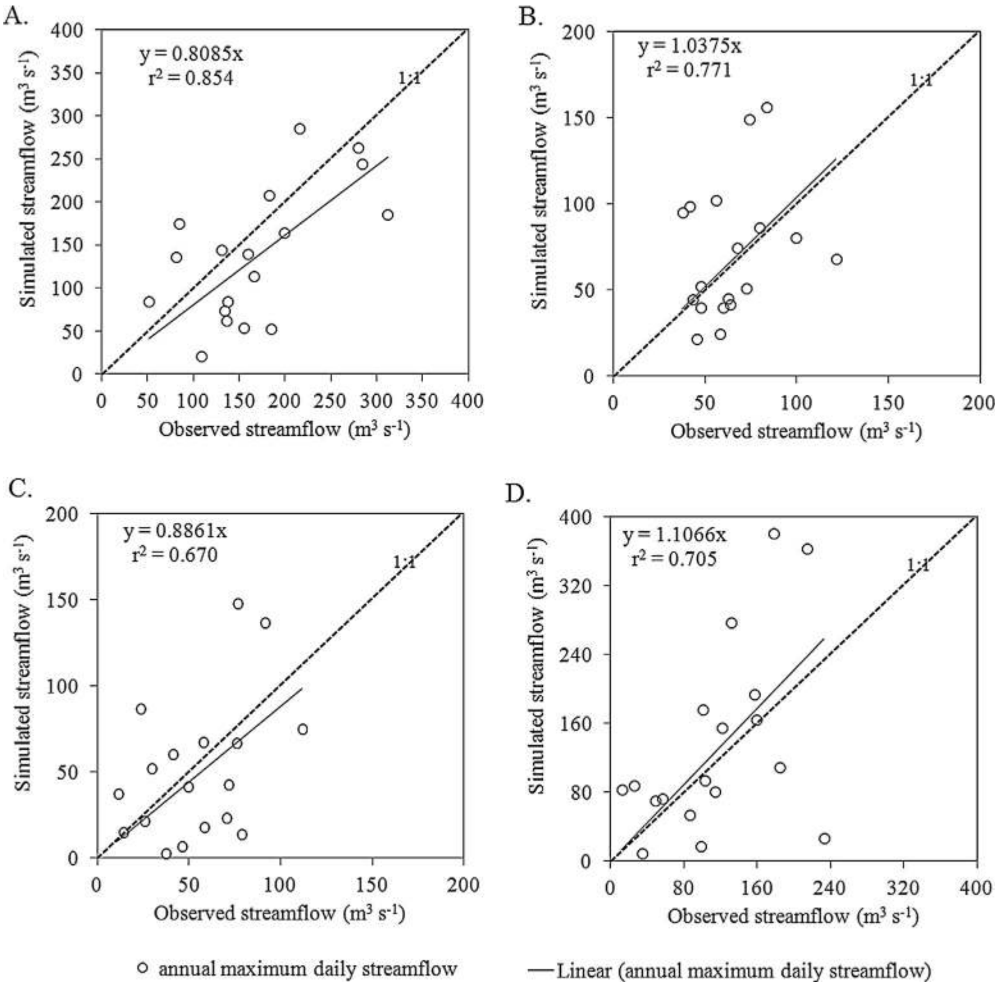

Fig. 14. Scatter plots of the annual maximum daily streamflows observed and simulated by SWAT in sections located in the sub-basins of the Novo River at (A) Usina Maurício, (B) Rio Novo, and (C) Piau, and of the Xopotó River in (D) Barra do Xopotó.

temporal variability of rainfall is a critical issue to be considered when applying hydrological models, including SWAT, and the estimation errors obtained in this study represent this well, as reported by the authors.

Regarding the annual daily average streamflow (Fig. 15), there is trend of overestimation by SWAT in the Usina Maurício (Fig. 15A), Rio Novo (Fig. 15B) and Barra do Xopotó sections (Fig. 15D) and of underestimation in Piau (Fig. 15C). In Barra do Xopotó, the model overestimated the daily average streamflow throughout the period of the simulation and with large

Table 10
Results of regression analysis and paired *t*-test applied to data on the maximum, average and minimum annual daily streamflows observed and simulated by SWAT in the sub-basins of the Novo and Xopotó Rivers.

Control section	Streamflow	n	a	t_{cal}	t_{crit}	r^2
Usina Maurício	Annual daily maximum	18	0.8085	$1.805^{(ns)}$	2.110	0.854
	Annual daily average	9	1.1167	$-1.968^{(ns)}$	2.306	0.984
	Annual daily minimum	18	1.7075	-4.935^{*}	2.110	0.863
Rio Novo	Annual daily maximum	18	1.0375	$-0.675^{(ns)}$	2.110	0.771
	Annual daily average	9	1.0827	$-0.980^{(ns)}$	2.306	0.976
	Annual daily minimum	18	1.0057	$-0.720^{(ns)}$	2.110	0.845
Piau	Annual daily maximum	18	0.8861	$0.285^{(ns)}$	2.110	0.670
	Annual daily average	9	0.9383	$1.435^{(ns)}$	2.306	0.968
	Annual daily minimum	18	0.6607	$1.791^{(ns)}$	2.110	0.761
Barra do Xopotó	Annual daily maximum	18	1.1066	$-0.907^{(ns)}$	2.110	0.705
	Annual daily average	9	1.3794	-8.105^{*}	2.306	0.974
	Annual daily minimum	18	2.153	-9.340^{*}	2.110	0.721

n—number of sample values; a—angular coefficient; tcalc. paired *t*-test, calculated value; tcrit—paired *t*-test, bi-caudal value; ns—not significant at the 5% level of significance.

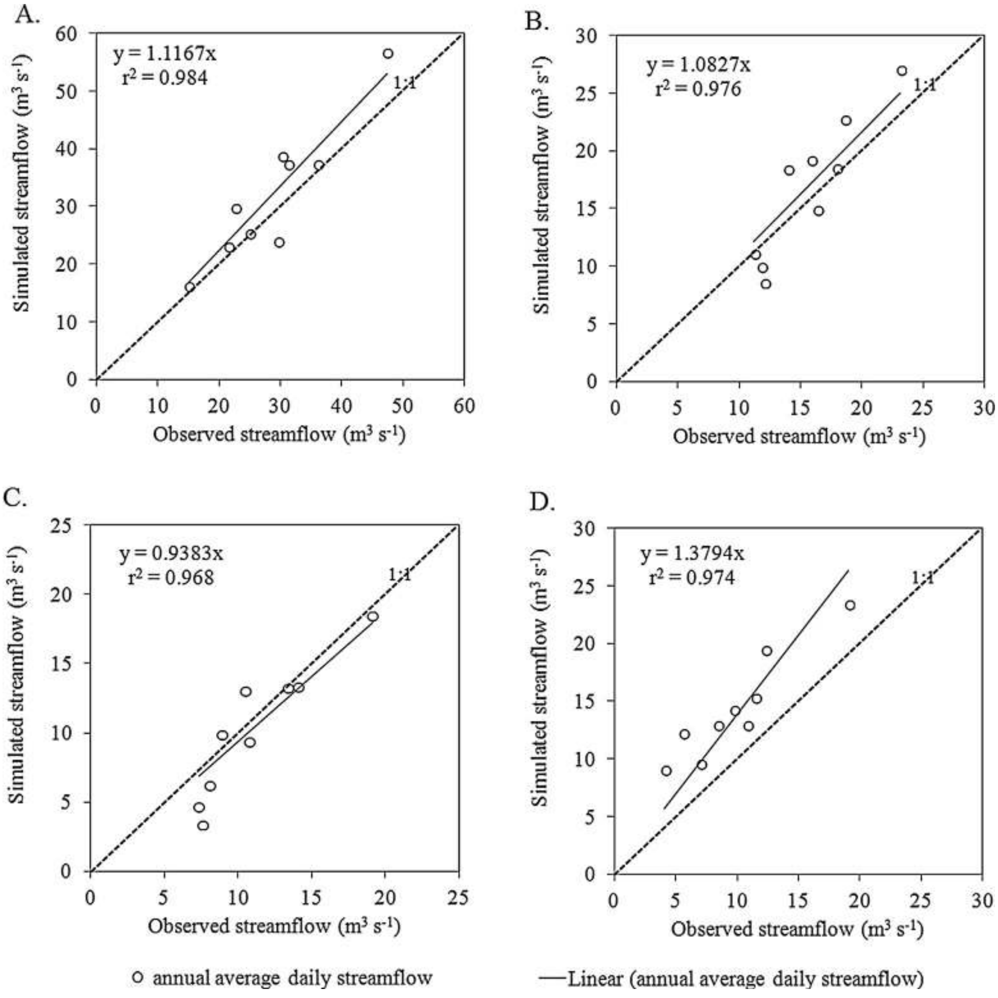

Fig. 15. Scatter plots of the annual daily average streamflow observed and simulated by SWAT in sections located in sub-basins of the Novo River at (A) Usina Maurício, (B) Rio Novo, (C) Piau, and of the Xopotó River at (D) Barra do Xopotó.

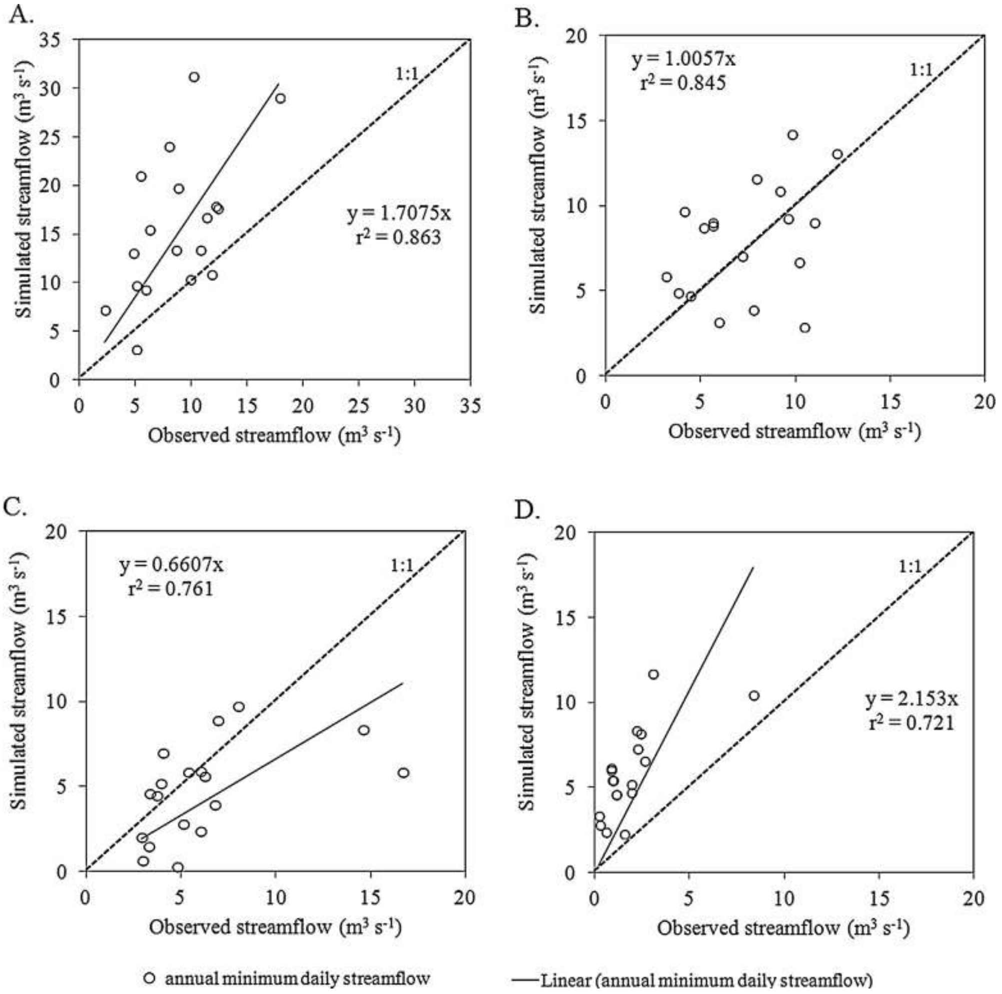

Fig. 16. Scatter plots of the annual daily minimum streamflow observed and simulated by SWAT in sections located in sub-basins of the Novo River at (A) Usina Mauricio, (B) Rio Novo (C) Piau, and of the Xopotó River at (D) Barra do Xopotó.

magnitude errors in the years 1998 (115%) and 1999 (119%). In other sections, the highest estimate errors were found in 1998 in Usina Maurício (30%) and Rio Novo (31%), and in 2000 in the Piau section (56%).

As regards the annual daily minimum streamflows (Fig. 16), based on the slope coefficients the simulation in the Usina Maurício (Fig. 16A) and Barra do Xopotó (Fig. 16D) sections were not adequate, as the *t*-test paired had already indicated. In the Usina Maurício section, estimates error of −37% (2001) to 290% (2002) occurred, and in Barra do Xopotó estimates error of 26% (2004) to 1620% (1999) were found. In the Rio Novo and Piau sections, the model has been statistically qualified for the simulation of annual daily minimum streamflows based on the paired *t*-test, though errors of estimation of greater magnitude were observed in 1998 and 1999 in Rio Novo and in 1997 and 2000 in Piau. In 1998 and 1999, the model estimated a value of 9.7 and 5.8 $m^3\ s^{-1}$ compared to those observed of 4.1 and 3.2 $m^3\ s^{-1}$, generating errors of −135 and 83%, respectively. In 1997 and 1998, the model estimated values 7.0 and 0.7 $m^3\ s^{-1}$ compared to those observed of 4.0 and 3.0 $m^3\ s^{-1}$, generating errors of 73 and −77%, respectively.

Based on the above results, the SWAT calibrated for the Pomba River sub-basin with a control section in Astolfo Dutra can be applied to the hydrological simulation of the Novo River sub-basin to estimate maximum, average and minimum streamflow in those locations where performance was adequate, thus contributing to the planning and management of water resources of the basin, although it is recognized that the model still needs improvement in the representation of rainfall for a more appropriate estimate of some extreme values. The model is not reliable to estimate the streamflow of the Xopotó River sub-basin because it showed unsatisfactory performance, requiring a specific calibration for this site.

5. Conclusions

1. The SWAT model, calibrated and validated for the Pomba River sub-basin, can be used for the hydrologic simulation of this area with good estimates of water balance components and of maximum, average and minimum annual daily streamflows, contributing to the planning and management of water resources in the basin.
2. The model can be applied in hydrologic simulations upstream and downstream of the calibration section with potential for the estimation of maximum, average and minimum annual daily streamflows, focusing on those sections in the performance that were statistically satisfactory.
3. The model can also be applied in the hydrologic simulation of the Novo River sub-basin in the study with maximum, average and minimum annual daily streamflows, looking at those sections in the performance that were statistically satisfactory.
4. The used of the model in the hydrologic simulation of the Xopotó River sub-basin is not recommended, necessary a new calibration is conducted in this local.
5. The model still needs improvement in its representativeness of rainfall so that it can consistently simulate extreme streamflow values, despite the obtained good results.

Conflict of interest

None.

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