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HYDROLOGICAL MODELING OF TRIBUTARIES OF CANTAREIRA SYSTEM, SOUTHEAST BRAZIL, WITH THE SWAT MODEL

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ABSTRACT: The lack of hydrological data in Brazil is the main limitation for structuring hydrological models, which are able to assist water resources management. Therefore, studies are needed to evaluate the performance of models without on-site calibration. Within this context, the aim of this study was to calibrate the SWAT hydrological model for the Camanducaia River Basin and to evaluate the performance of this calibration in a contiguous drainage basin, one of the Jaguarí River. For the calibration and validation steps, the SWAT-CUP program was utilized. Uncertainty analysis and calculation of efficiency indexes were carried out through the SUFI-2 algorithm. The SWAT adjustment in the Camanducaia River Basin obtained adequate results, with a Nash-Sutcliffe coefficient higher than 0.80 in the monthly time step and of 0.64 for the daily time step. With the parametrical transfer of this model to the Jaguarí River Basin, simulations were classified as very good in the monthly time step and acceptable for the daily time step. Based on these results, it can be concluded that the parametric transfer is a promising technique to model ungauged catchments, and can contribute towards water resources management in the river basins of the Mantiqueira Range region, as well as in other regions with shortage of hydrological monitoring.

KEYWORDS: calibration, model transfer, uncertainty analysis, water security.

INTRODUCTION

The Cantareira Supply System provides water for about 47% of the São Paulo Metropolitan Area. The main tributary of this system is the Jaguarí River, which is also one of the main tributaries to the Piracicaba River, an important water source for agricultural activities. Between 2013 and early 2015, the Southeastern region of Brazil underwent a severe drought (COELHO et al., 2015). During such period, the Jaguarí River discharge and the water level at dams from the Cantareira System reached the lowest values ever recorded. Water use concessions were temporarily suspended and farmers were asked to reduce water use for irrigation, which further emphasized the issue of water security and water management.

Hydrological modeling is one of the leading tools for water resource management, because it allows evaluating both the spatial and temporal distributions of hydrological phenomena. It also enables the simulation of possible effects of land use and climate changes.

The Soil and Water Assessment Tool (SWAT) (ARNOLD et al., 1998) is a time-continuous, semi-distributed, process-based hydrological model. It is developed for assessing the impact of management and climate on water supplies, sediment, and agricultural chemical yields in watersheds and larger river basins. SWAT has been widely studied and applied to a number of regions in the world with satisfactory results (BONUMÁ et al., 2014, 2015; PEREIRA et al., 2014; ZHANG et al., 2014; ABBASPOUR et al., 2015; BRESSIANI et al., 2015).

SWAT-CUP (ABBASPOUR et al., 2007) is a software developed for calibrating SWAT parameters and for performing an uncertainty analysis of the modeling results. SWAT has proved to be a promising tool regarding hydrological modeling, even in catchments with a poor availability of rainfall data (ASHRAF VAGHEFI et al., 2013; BONUMÁ et al., 2013, 2015; RODRIGUES et al., 2014; BRESSIANI et al., 2015; MONTEIRO et al., 2015).

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However, obtaining hydrometeorological data is still the greatest challenge regarding hydrological modeling in Brazil (BRESSIANI et al., 2015; MONTEIRO et al., 2015). Such difficulty increases the uncertainties involved in the modeling process, especially during the calibration and validation stages. Therefore, methods which evaluate the uncertainty and the sensitivity of modeling parameters are necessary (ZHANG et al., 2014).

In this sense, KLEMEŠ (1986) proposed a proxy basin test, in which model parameters of a given basin with poor input data availability are calibrated based on data from an analogous, well monitored, basin. This test allows a broader evaluation of modeling quality at ungauged catchments (HENRIKSEN et al., 2003; POHLERT et al., 2007; VIOLA, 2008; GAUTAM, 2012).

In such context the objectives of this study were to calibrate and validate the SWAT model in the Camanducaia River Basin; and also, to evaluate the model application in the Jaguarí River Basin, using the previously calibrated set of parameters. The hypothesis is that calibrated parameters can be transferred from neighboring basins, with analogous catchment area, and under the same geological and pedobioclimatic characteristics.

MATERIAL AND METHODS

Study Area

The study area comprehends two contiguous river basins situated in the south ridge of the Mantiqueira Range: the Camanducaia River Basin and the Jaguarí River Basin, which are situated between the geographic coordinates 22.60° S and 22.91° S of latitude and 45.85° W and 47.00° W of longitude (Figure 1a). The Köppen climatic classification for the basins is the Cfb (humid subtropical with temperate summer) (ALVARES et al., 2013). The native vegetation is seasonal semideciduous forest, inserted in the Atlantic Forest Biome. The current land use is predominantly grazing pasture (Figure 1b). The geology of the area is represented by the granite-gneiss and the main soil classes are Red-Yellow Latosols (LVA) and Red-Yellow Argisol (PVA) (Figure 1c).

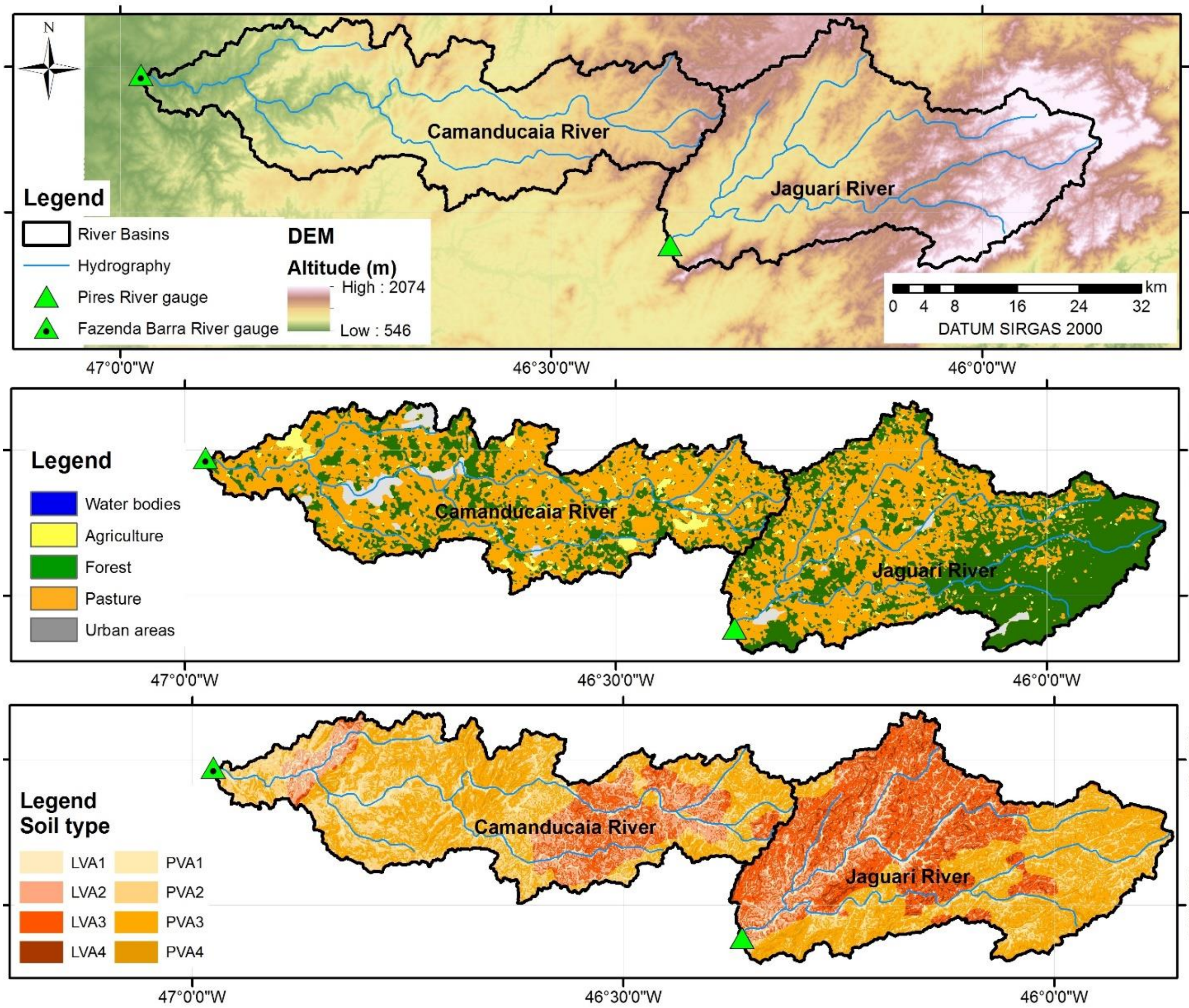

FIGURE 1. Localization of the studied basins, river gauges and DEM with 30 meters of spatial resolution (a). Land use map (b) and pedological map (c). LVA: Red-Yellow Latosol, PVA: Red-Yellow Argisol. Slopes degrees: 1: 0 to 8%; 2: 8 to 20%; 3: 20 to 45% and; 4: > 45%.

SWAT model setup

The hydrological simulation was developed with the ArcSWAT version 2012. In order to characterize the relief, satellite images of Shuttle Radar Topography Mission (SRTM) (FARR et al., 2007) with spatial resolution of 1 arc-seg (30 m) were utilized. The land use and soil cover were classified (Figure 1b) using Landsat imagery from September 5th 2004. The orthorectified images were made available by the Division of Imaging of National Institute for Space Research (DGI/INPE).

The SWAT model uses the concept of hydrological response units (HRU), which are obtained by separating homogeneous combinations of soil classes, land use and slope classes. In the present study, the slope classes adopted were of 0 to 10%, 10 to 20%, 20 to 45% and greater than 45%.

Input Data

Rainfall, river and weather stations with daily historical series for the period of 1971 to 1993 were selected (Figure 1). The name and code of the rain gauge stations provided by the National Water Agency (ANA) were: Amparo (2246023), Bairro do Analdino (2245084), Camanducaia (2246057), Cambuí (2246050), Fazenda da Barra (2246021), Fazenda Chapadão (2246020), Formiga (2246088), Joanópolis (2246090), Monte Alegre do Sul (2246022), Pedra Bela (2246095), Pedreira (2246028), Pinhalzinho (2246025), Ponte Nova (2246139), São Benedito (2245045), São

Bento do Sapucaí (2245011), São Francisco Xavier (2245050), Serra Negra (2246019), Socorro (2246017), Tuiuti (2246029) and Zé da Rosa (2245029).

The weather data consisted of temperature, relative humidity, wind speed and solar radiation, obtained from five weather stations: Caldas (83681), Campos de Jordão (83714), Guarulhos (83075), São Carlos (83726) and Sorocaba (83851). The information was provided by the Meteorological Database for Teaching and Research (BDMEP) of the National Weather Institute (INMET).

Also, daily and monthly discharge data of the river gauging stations Fazenda Barra (62628000), with a drainage area of 928 km^2 on the Camanducaia River, and Pires, (62590000) with a drainage area of 955 km^2 on the Jaguarí River, were utilized to calibrate and validate the models. The period from 1974 to 1983 was used in the calibration stage for the Camanducaia River Basin, whereas the period from 1984 to 1993 was used for validation. The period of 1971 to 1973 was utilized as a "*warm-up*" period, in which simulations are used to reduce the uncertainties related to initial conditions, such as initial soil water content, and thus the model does not display the output results to the period.

Calibration, validation and sensitivity and uncertainty analyses

For the processes of calibration, validation, sensitivity and uncertainty analysis, the SUFI-2 algorithm (ABBASPOUR et al., 2007) of the SWAT-CUP program was utilized. This algorithm enables the stochastic evaluation of the simulation through the P-factor and R-factor statistics, from the determination of the 95% prediction uncertainties (95PPU). The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of the simulation results, obtained through Latin hypercube sampling.

The P-factor represents the fraction of the measured data bracketed by the 95PPU band. The R-factor is the ratio of the average width of the 95PPU band and the standard deviation of the measured variable. Values of P-factor > 0.7 and R-factor < 1.5 are recommended (ABBASPOUR et al., 2015).

During model calibration, five iterations with 500 simulations each were performed. The calibrated parameters and their initial minimum and maximum values (range) were chosen according to expert knowledge, based on a bibliographical review (ARNOLD et al., 2012; LELIS et al., 2012; SHEN et al., 2012; ZHANG et al., 2014) (Table 1).

Parameter sensitivity was estimated automatically by SWAT-CUP with the Global Sensitivity Analysis (GSA) method. This technique enables the identification of the parameters of greatest sensitivity in the calibration process through the Student's t-test p-value. At each new iteration, the parameters which presented p-value < 0.05 in the previous iteration had their range reduced by half**,** with the central value of the range presumed equal to the fitted value in the previous iteration. This procedure was done with the objective of standardizing the calibration process.

SWAT-CUP also calculates efficiency indexes which compare observed to simulated data. In this study, the Nash-Sutcliffe efficiency index (NSE) (SCHAEFLI & GUPTA, 2007) and the percent bias index (PBIAS) were utilized. For PBIAS the following classification was used for the SWAT applications (VAN LIEW et al., 2007): |PBIAS| < 10%, very good; 10% < |PBIAS| < 15%, good; 15% < |PBIAS| < 25%, satisfactory; and |PBIAS| > 25%, inadequate. For NSE, the classification proposed by MORIASI et al. (2007) was utilized: NSE > 0.65, very good; 0.54 < NSE < 0.65, adequate; NSE > 0.5, satisfactory; and NSE < 0.5, unsatisfactory.

TABLE 1. List of SWAT’s parameters that were fitted and their initial range values.

Parameters	Description	Initial range
*v__ESCO.hru	Soil evaporation compensation coefficient	0.5 to 0.95
**r__CN2.mgt	Moisture constition II curve number	-0.1 to 0.1
*v__ALPHA_BF.gw	Baseflow recession constant (days)	0 to 0.174
***a__GW_DELAY.gw	Delay time for aquifer recharge (days)	-30 to 60
***a__GWQMN.gw	Threshold water level in shallow aquifer for base flow (mmH_2O)	-1000 to 1000
*v__CANMX.hru	Maximum amount of water that can be trapped in the canopy when it is fully developed (mmH_2O)	0 to 30
*v__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	0 to 10
*v__CH_N2.rte	Manning's "n" value for the main channel	-0.01 to 0.2
*v__EPCO.bsn	Plant uptake compensation factor	0.01 to 1
*v__GW_REVAP.gw	Groundwater "revap" coefficient	0.02 to 0.2
***a__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mmH_2O)	-1000 to 1000
**r__SOL_AWC().sol	Available water capacity ($mmH_2O\ mm_{soil}^{-1}$)	-0.05 to 0.05
**r__SOL_K().sol	Saturated hydraulic conductivity ($mm\ h^{-1}$)	-0.1 to 0.1
*v__SURLAG.bsn	Surface runoff lag time (days)	0.01 to 24
*v__CH_N1.sub	Manning's "n" value for the tributary channels	0.01 to 0.2
*v__CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium ($mm\ h^{-1}$)	0 to 5
*v__SLSOIL.hru	Slope length for lateral flow (m)	0 to 150
*v__LAT_TTIME.hru	Lateral flow travel time (days)	0 to 150
**r__HRU_SLP.hru	Average slope steepness ($m\ m^{-1}$)	-0.25 to 0.25
**r__SLSUBBSN.hru	Average slope length (m)	-0.25 to 0.25

*v – value, the initial value is replaced by the value of the calibrated parameter; **r – relative, the value points out the percent increment to be applied to the initial value; ***a – absolute, the value is summed to the initial value of the parameter. For further details, refer to the SWAT-CUP manual (http://swat.tamu.edu/media/114860/usermanual_swatcup.pdf).

In order to simplify the presentation of the results, the hydrograms and the PBIAS and NSE statistics were calculated for the best-fitted hydrogram simulation. The calibrated, best-fitted, parameter values were also used for model validation, in order to obtain the NSE and PBIAS indexes.

Proxy basin test

The proxy basin test is a validation method for hydrological models (KLEMEŠ, 1986). The test is developed for situations in which model parameters are calibrated for a basin and then applied to another contiguous basin, presupposing that the hydrological conditions of two basins are stationary. For its application, the two monitored basins must have similar geological and pedobioclimatic characteristics.

In this study, in order to perform the proxy basin test, we calibrated the SWAT parameters in the Camanducaia River Basin and applied them to the Jaguarí River Basin. The 95PPU, the P-factor and R-factor evaluation indexes, as well as the NSE and PBIAS, were generated using SWAT-CUP, according to the previously discussed methodology.

RESULTS AND DISCUSSION

The uncertainty analysis results and the precision statistics of model calibration and validation for the Camanducaia River Basin are presented in Table 2.

TABLE 2. Statistical indexes used to evaluate the modeling performance: monthly and daily time steps for the calibration and validation periods in the Camanducaia River Basin.

Index	Montlhy time step		Daily time step	
	Calibration	Validation	Calibration	Validation
P-factor	0.80	0.87	0.79	0.71
R-factor	0.80	0.84	0.78	0.69
NSE	0.85	0.88	0.73	0.64
PBIAS	-10.9	-1.1	-7.3	-1.8

The monthly and daily simulations results were classified as very good according to the NSE (MORIASI et al., 2007) and PBIAS (VAN LIEW et al., 2007), except for the monthly time step during the calibration period, in which the PBIAS was greater than |10%|. The P-factor values for the monthly and daily time steps were above 0.7 during the calibration period, which indicates that the model results are adequate.

It is interesting to notice that the NSE and P-factor values of the monthly simulation were higher for the validation period than in the calibration period. Such results indicate a good model performance, demonstrated by its capacity to simulate average monthly discharge values. Moreover, the low PBIAS values observed in monthly and daily time steps of the validation period indicate that the prediction error is low. The hydrograms presented in Figure 2 reinforce the good results of the precision statistics, with adequate representation of the maximum events and the recession periods.

In the daily time step, the simulated data is less accurate, which is expected, given that in a larger time period analysis the hydrological processes tend to be more stable. In this sense, greater accuracy from hydrological models forecasts are expected at monthly and annual time steps (POHLERT et al., 2007). The results from this study displayed an overestimation of extreme events at the daily time step, as in February 1983, March 1988 and January 1990.

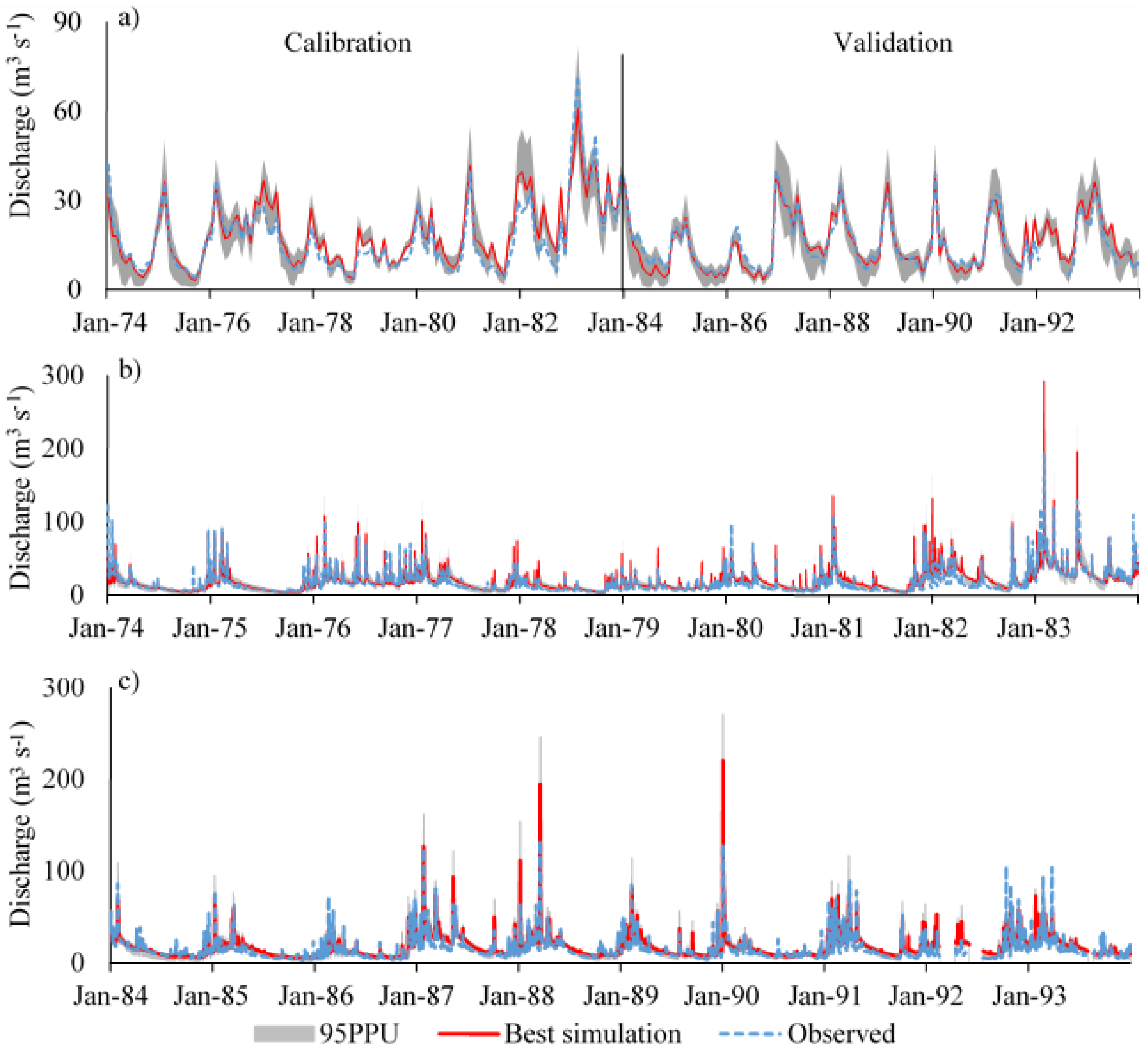

FIGURE 2. Comparison between simulated and observed discharges, monthly (a) and daily time steps, for calibration (b) and validation (c) periods in the Camanducaia River Basin. Region 95PPU represents the 95% prediction uncertainty calculated.

The overestimation of extreme events can be mainly associated with the uncertainties from the CN2 parameter, which is used by the curve number method to estimate the direct surface runoff. Furthermore, soil water storage capacity (parameter SOL_AWC), soil water evaporation compensation coefficient (ESCO parameter), and surface water runoff delay coefficient (SURLAG parameter) are sensitive parameters for estimating surface runoff and may help to explain such overestimation. Due to the high sensitivity of these parameters, their initial range was narrowed in order to reduce the uncertainty associated to the parameter estimation (Table 3).

Table 3 presents the final range for the SWAT parameters in the calibration process, as well as their best-fitted value (i.e. the parameter values which yielded the highest NSE).

TABLE 3. Results of the parameter calibration in the monthly and daily time steps for the Camanducaia River Basin.

Parameter	Montlhy time step			Daily time step		
	Best simulation	Final Range		Best simulation	Final Range	
	Fitted value	Below limit	Upper limit	Fitted value	Below limit	Upper limit
v__ESCO.hru	0.518	0.5	0.567	0.519	0.5	0.668
r__CN2.mgt	-0.0915	-0.1	-0.0342	-0.0752	-0.1	-0.0327
v__ALPHA_BF.gw	0.00596	0.0	0.0283	0.143	0.0868	0.261
a__GW_DELAY.gw	-18.985	-30	24.80	25.563	-18.80	60
a__GWQMN.gw	-86.270	-498.704	663.082	389.509	-59.58	889.865
v__CANMX.hru	19.985	6.323	30	23.244	11.79	30
v__CH_K2.rte	5.406	4.810	8	3.438	0	3.807
v__CH_N2.rte	0.199	0.144	0.2	0.134	0.118	0.2
v__EPCO.bsn	0.260	0.01	1	0.060	0.01	1
v__GW_REVAP.gw	0.196	0.160	0.2	0.194	0.172	0.2
a__REVAPMN.gw	633.774	-414	1000	-167.442	-1000	598
r__SOL_AWC().sol	0.0493	0.0224	0.05	-0.0311	-0.05	0.0181
r__SOL_K().sol	-0.0814	-0.1	0.1	0.0166	-0.1	0.1
v__SURLAG.bsn	15.433	3.651	24	12.461	0.01	24
v__CH_N1.sub	-	-	-	0.174	0.160	0.196
v__CH_K1.sub	-	-	-	1.435	0	5
v__SLSOIL.hru	-	-	-	10.896	0	47.168
v__LAT_TTIME.hru	-	-	-	110.951	61.899	149.649
r__HRU_SLP.hru	-	-	-	-0.0223	-0.164	0.25
r__SLSUBBSN.hru	-	-	-	-0.236	-0.25	0.25

The parameter values obtained from the calibration of SWAT in the Camanducaia River Basin (Table 3) were then used for the proxy basin test in the Jaguarí River Basin.

Proxy basin test

The parametric transfer enabled the evaluation of the SWAT model using the proxy basin test. Figure 3 presents the hydrograms generated by the SWAT results in the Jaguarí River Basin, using the calibrated input parameters from the Camanducaia River Basin. The statistical indexes of modeling efficiency are displayed in Table 4.

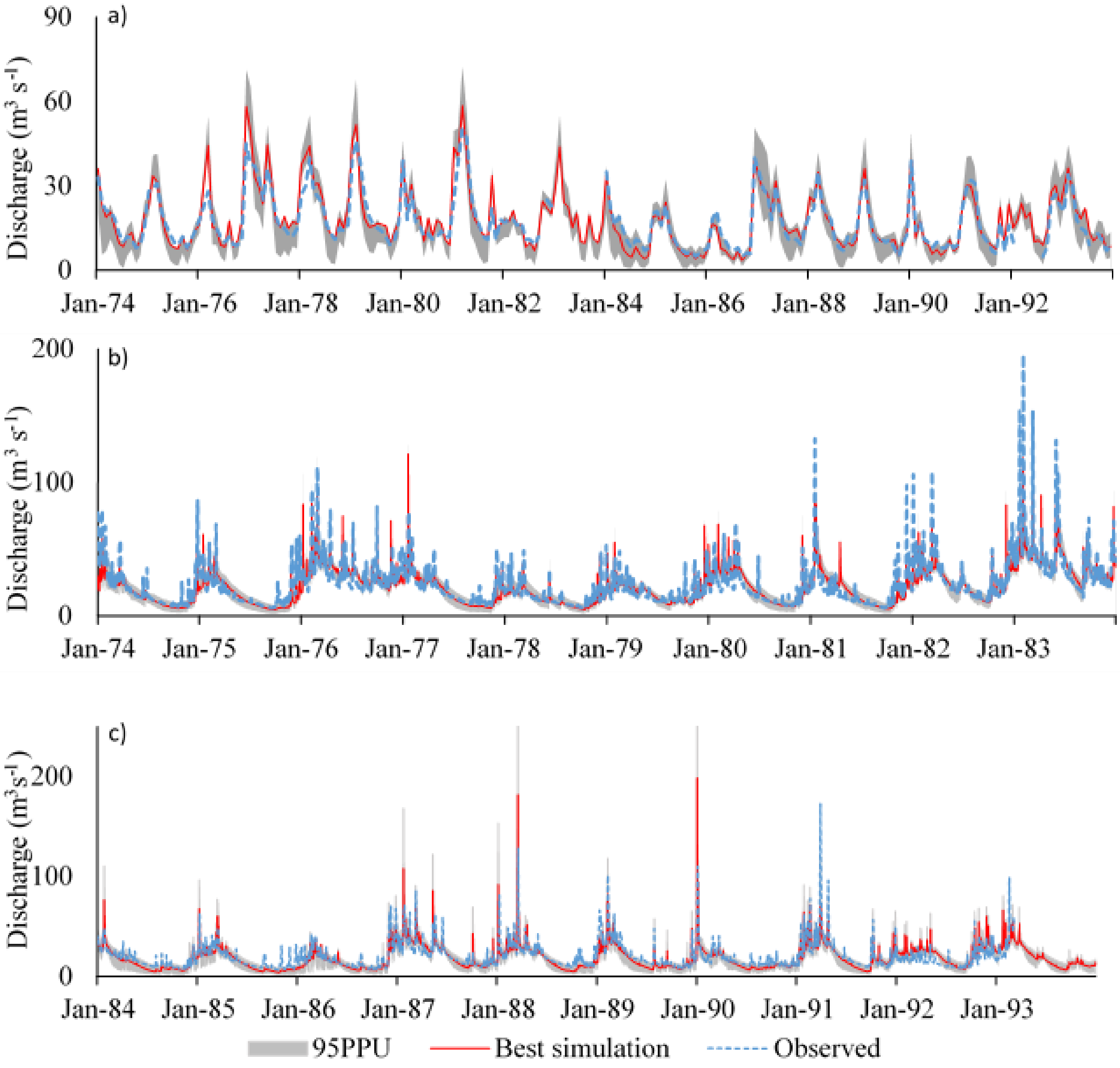

FIGURE 3. Proxy basin test: results of the monthly (a) and daily simulation in the Jaguarí River Basin, from 1974 to 1983 (b) and from 1984 to 1993 (c).

TABLE 4. Proxy basin test: statistical indexes obtained from the monthly and daily time steps in the Jaguarí River Basin.

Index	Montlhy time step		Daily time step	
	1974-1983	1984-1993	1974-1983	1984-1993
P-factor	0.72	0.78	0.81	0.69
R-factor	0.68	0.73	0.71	0.66
NSE	0.81	0.71	0.65	0.59
PBIAS	4.10	-3.50	7.90	-0.70

Figure 3 displays a good match between the simulated and observed discharges values. The efficiency indexes (Table 4) point in the same direction, with a good balance between the R-factor and P-factor, i.e. the 95PPU range was sufficiently narrow and enveloped much of the observed data. In addition, the NSE value classifies the simulation as very good in the monthly time step and good for the daily time step (MORIASI et al., 2007).

The proxy basin validation method indicated a good performance for the SWAT model in the Jaguarí River Basin, considering that the model parameters were only calibrated in the

Camanducaia River Basin, using observed data comprised from 1974 to 1983. However, it is important to highlight that in the daily time step, during the 1984-1993 periods, the P-factor value was below the recommended by the SWAT-CUP developers. Nevertheless, the NSE and PBIAS values were classified as very good for the monthly time step (NSE> 0.65 and |PBIAS| <10%) and adequate in the daily time step (0.54 <NSE <0.65 and |PBIAS| <10%) (MORIASI et al., 2007). These results suggest that the parametric transfer employed in this study is a viable technique for calibrating the SWAT parameters and ungauged catchments.

Satisfactory results with the proxy test basin were also reported in other studies. VIOLA (2008) applied the hydrological model LASH calibrated to the Rio Grande River, MG, in an adjacent basin, that of the Aiuruoca River, located in the Southeast region of Brazil, obtaining NSE of 0.76. COLLISCHONN et al. (2007) applied the distributed model MGB-IPH, calibrated to the Taquari-Antas River Basin, RS, in the Uruguay River Basin, with the NSE ranging from 0.62 to 0.84.

In Germany, POHLERT et al. (2007) calibrated SWAT to a basin in the mountainous region of Hesse and applied the same parameterization in sub-basins upstream, obtaining good results in most cases, with NSE between 0.76 and 0.51. Only a headwater sub-basin, with distinct geology from the rest of the basin obtained unsatisfactory results (NSE = 0.14). Moreover, GAUTAM (2012) obtained satisfactory results at monthly time steps (NSE = 0.73) and unsatisfactory ones for the daily time step with the proxy basin test in two small-sized basins in Canada. In Denmark, HENRIKSEN et al. (2003) evaluated different hydrological models and used the proxy basin test to evaluate the simulations, obtaining satisfactory results when the climatic, pedologic and land use conditions of the basins were similar. These authors concluded that the geographic parametric transfer is a promising method to obtain consistent hydrological simulations at ungauged basins.

It should be highlighted that an important feature of the present study was the uncertainty analysis associated with the proxy basin test, which allowed a broader evaluation of the modeling quality. The results for the monthly and daily times steps were satisfactory in calibration, validation and uncertainty analysis (P-factor > 0.70) and in relation to the efficiency index (NSE > 0.5).

The results obtained in this study suggest that the SWAT model may provide useful information for water resource management in the Cantareira System and other watercourses in the Mantiqueira Range region. Model applications include the evaluation of different land use scenarios, which allows for a more adequate soil and water conservation planning. Moreover, the accurate estimations of minimum discharges using parametric transfer presented in this study can provide useful reference values for water concessions at ungauged basins. Also, the hydrological simulation at climate changing scenarios can assist the decision-making for public policy developers in cases of extreme events of drought or flood.

CONCLUSIONS

The SWAT modeling results in the Camanducaia River Basin presented in this study are qualified as adequate for hydrological simulations, as indicated by the efficiency indexes and the uncertainty analysis for the calibration and validation steps.

The SWAT parametric transfer from the Camanducaia River Basin to the Jaguarí River Basin increases the modeling degree of uncertainty (decrease of P-factor), but, keeps the efficiency indexes in the range classified as very good in the monthly time step and adequate in the daily time step.

The geographical parametric transfer is a promising technique to model ungauged catchments, where the lack or shortage of hydrological data precludes the direct model calibration. However, such methodology requires data from well monitored catchments, with similar drainage area, geological and pedobioclimatic conditions. The parametric transfer can contribute towards water resources management in the river basins of the Mantiqueira Range region, as well as in other regions with shortage of hydrological monitoring.

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