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Comparative hydrology: relationships among physical characteristics, hydrological behavior, and results of the SWAT model in different regions of Brazil

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ABSTRACT

Comparative hydrology studies, either by the similarities or the differences in the obtained data and results, represent an important tool for advancing knowledge of cause-effect relationships between the physical characteristics of the basins and their hydrological behavior. The objective of this study was to present a comparative analysis of measured and simulated characteristics of experimental and representative basins in different regions of Brazil. The SWAT model was used. Four catchments were evaluated: Alto Ipanema, located in the Caatinga biome, with semi-arid climate; Tapacurá, in the transition zone between the Caatinga and Atlantic Forest biomes, with hot and humid tropical climate; and Lago Descoberto and Alto Jardim, both in the Cerrado biome and with tropical altitude climate. The catchments were compared with respect to their physical characteristics (climate, soil, altitude, and land use). Using sensitivity analysis, it was found which of the SWAT model parameters best explain the hydrological behavior of the study regions. Considering its characteristics, the parameters values obtained in each catchment after model calibration were analyzed and compared, indicating the possibility of using these values as reference for their regions. The results indicate a clear relationship between the physical characteristics of watersheds, their respective hydrological behavior, and the values of two SWAT model parameters, CN2 and SOL_K. For other parameters, the relationship between the obtained values do not reflected adequately the characteristics of the catchment, indicating a need for improvement in the physical basis of the calibrated model.

Key-words: Experimental basins; representative basins; model parametrization.

Hidrologia comparativa: relações entre características físicas, comportamento hidrológico e resultados do modelo SWAT em diferentes regiões do Brasil

RESUMO

Estudos de hidrologia comparativa, seja pelas similaridades ou diferenças nos dados e resultados obtidos, representam importante ferramenta para o avanço no conhecimento das relações causa-efeito entre as características físicas das bacias e seus respectivos comportamentos hidrológicos. O objetivo deste estudo é apresentar uma análise comparativa de características medidas e simuladas em bacias experimentais e representativas de diferentes regiões do Brasil, utilizando o modelo SWAT. Foram avaliadas quatro bacias, sendo a do Alto Ipanema no bioma Caatinga, com clima semiárido, a do Tapacurá, em zona de transição entre os biomas Caatinga e Mata Atlântica, com clima tropical quente e úmido, e as bacias do Lago Descoberto e do Alto Jardim no bioma Cerrado, ambas com clima tropical de altitude. As bacias foram comparadas em relação às suas características de clima, solos, relevo e uso do solo. Por meio da análise de sensibilidade, verificou-se quais parâmetros do modelo SWAT melhor explicam o comportamento hidrológico das regiões de estudo. Considerando suas características, foram analisados e comparados os valores dos parâmetros obtidos em cada bacia após o processo de calibração do modelo, buscando indicativos da possibilidade de uso desses valores como referência para as respectivas regiões. Os resultados indicam uma clara relação entre as características físicas das

bacias hidrográficas, os seus respectivos comportamentos hidrológicos e os valores dos parâmetros CN2 e SOL_K do modelo SWAT. Para os demais parâmetros, a relação entre os valores obtidos não refletiram adequadamente as características das bacias, indicando a necessidade de melhoria na base física do modelo calibrado.

Palavras-chave: Bacias experimentais; bacias representativas; parametrização de modelos.

Introduction

Monitoring and modeling studies in experimental and representative basins can be useful for developing knowledge on hydrological processes and tools to support integrated water resources management.

Considering the impracticality involved on monitoring all the catchments with required hydrological data, the use of experimental and representative basins is presented as an important tool for generating knowledge on hydrological behavior of different regions. Detailed data obtained from these catchments also enable the evaluation of the applicability of different hydrological models as well as the parameterization of these models according to regional peculiarities.

Studies in catchments of regions with different physical characteristics and use can support one subdivision of the hydrology area known as "comparative hydrology". In these studies, either by the similarities or the differences in the data and the obtained results, it is possible to advance, for example, the knowledge of cause-effect relationships between the physical characteristics of the basins and their hydrological behavior (Falkenmark & Chapman, 1989).

This technique has been applied in many regions around the world. Atkinson et al. (2002) compared the hydrological behavior of four small basins located in New Zealand and found that the streamflow generation in the drier areas tends to be more sensitive to soil characteristics than in wetter areas. Similarly, analyzing the water balance of 11 basins in semi-arid regions of Australia, Farmer et al. (2003) found that the soil water storage and drainage characteristics are factors that govern the runoff generation in drier areas, being less important in more humid regions. Samuel et al. (2008) also used "comparative hydrology" to evaluate the interactions between climate variability and environmental factors that control water balance in three regions of Australia, verifying the importance of depth and physical

characteristics of the soils in the streamflow generation. In a modeling study, van Werkhoven et al. (2008) found a significant variation in the parameters that govern the hydrological behavior of basins in dry and humid regions. Araújo & Piedra (2009) compared a catchment located in the semi-arid region of northeastern Brazil with another one in Cuba, located in a humid tropical region, identifying significant differences in hydrological processes and water availability in these basins with similar areas. Gaál et al. (2012), using "comparative hydrology", studied the climatic and physical factors that control the flood events in 396 Austrian basins concluding that catchment area is not the most important control on the flood timescales, and climate is very important due to storm type and antecedent soil moisture, and geology is very important due to soil characteristics.

Brazil is a country of continental dimensions and has a broad range of environments. The country is divided into six major biomes: Amazon, Cerrado (Brazilian savanna), Atlantic Forest, Caatinga, Pantanal, and Pampa. The REHIDRO Project, funded by the Brazilian Government (MCT/FINEP/CT-Hidro) and integrating the National Network of Experimental and Representative Basins, is responsible for hydrological studies in basins from Caatinga, Cerrado, and a transition zone between Caatinga and Atlantic Forest. In climatological and physical terms, these biomes have very distinct characteristics that may reflect directly on the hydrological behavior of basins inserted in their areas.

Thus, the objective of this study is to present a comparative analysis of measured and simulated characteristics of four experimental and representative basins located in three different regions of Brazil: Caatinga, Cerrado, and a transition zone between Caatinga and Atlantic Forest biomes.

Material and Methods

Study areas

The study was conducted with data from four experimental and representative basins located in different biomes of Brazil (Figure 1).

Figure 1. Location of the experimental and representative basins used in the study in relation to Brazilian biomes.

Alto Ipanema Representative Basin

Located in the State of Pernambuco (PE), inserted in the Caatinga biome, in a region known as Agreste, the Alto Ipanema Representative Basin (Figure 1) has an area of 194.82 km² among coordinates 8°34'17" e 8°18'11" S, and 37°1'35" e 36°47'20" W. Within its area, an experimental basin with 14 km² (Mimoso) has also been studied.

The basin presents a narrow alluvial valley limited by slopes of crystalline basement, with relatively shallow soils. The basin is inserted in a semi-arid region with annual precipitation, in average, about 700 mm. Several investigations considering groundwater recharge patterns and spatiotemporal variability of groundwater levels and salinity have been developed in the aforementioned valley (Andrade et al., 2012; Fontes Júnior et al., 2012; Andrade et al., 2014).

Hydrological monitoring of the basin is carried out using 10 automatic rainfall gauges, an agrometeorological station, a fluvimetric station, three piezometric wells with automatic water level monitoring, weighing and drainage lysimeters, and evaporation pans.

Soil moisture has been regularly monitored at the experimental basin adopting a capacitance probe, at 20 different locations, in areas with caatinga and pasture.

In the region is practiced small-scale agriculture, using irrigation with groundwater through sprinklers and micro-sprinklers systems, but, in general, without a proper water management.

Montenegro & Ragab (2010) discusses the hydrological behavior of the representative catchment, applying hydrological distributed model to simulate discharges and soil moisture.

Tapacurá Representative Basin

The Tapacurá catchment is one of the main sub-catchments responsible for the water supply of Recife Metropolitan zone, in Pernambuco state, Brazil. The Tapacurá catchment covers an area of about 470 km², and is located in the transition region between Caatinga and Atlantic Forest biomes, among coordinates 7°58'0" and 8°13'0" S, and 35°5'0" and 35°30'0" W (Figure 1).

The relief of this catchment is constituted by high hills, deep valleys, large plateaus and gullies. The rainfall is characterized by an annual precipitation ranging from 800 to 1,800 mm with the rainy season between March and August (Silva et al., 2010). Rainfall is higher in the east portion of the basin, closer to the coast, in the Atlantic Forest biome zone, and is usually not well distributed over the year. Dry and wet periods often alternate rapidly, resulting in a highly erratic and unpredictable river flow regime. Rapid surface flows dominate the hydrographs (Montenegro & Regab, 2012; Santos et al., 2013). The climate is tropical, hot and humid.

Daily precipitation data were collected from six rainfall gauges distributed within the study area. Daily wind speed, relative humidity, as well as maximum, minimum and mean air temperature data were collected at one climatological station.

The current land use of the catchment is (Santos et al., 2014): agriculture (39% of the total area), livestock (39%), sugarcane (11%), rain forest (6%), urban areas (2%), water (2%), and caatinga vegetation (1%).

Lago Descoberto Representative Basin (DF)

Lago Descoberto (Descoberto Lake) is responsible for approximately 65% of the amount of water used for public supply of the Federal District (DF) population. The Lago Descoberto basin, located among the coordinates 15°47'30" and 15°35'0" S, and 47°10'30" and 48°2'30" W, has 452 km², being 30% of its area inserted in Goiás State (GO), and 70% in the Federal District (DF).

The average annual rainfall varies between 1,200 and 1,800 mm, however, approximately 80% of this occurring from October to April (Ferrigo, 2014). Thus, the other months are usually very dry. The

average temperature ranges from 19° to 23°C. The relative humidity varies according to the rainfall regime, reaching levels below 15% in the dry season. According to the Köppen classification, the climate of the region is Aw, tropical climate with winter dry season, typical from savanna regions.

The relief of the basin is slightly hilly, and more than 70% of the area is covered with deep, well-structured and well drained Oxisols. Cambisols occupy 14% of the entire basin and usually are associated with the most rugged areas (Reatto et al., 2003).

In relation to land use, beyond the protected areas created to preserve the quantity and quality of water for public supply, the basin is used for agricultural activities, with emphasis on horticulture and livestock on small farms. Due to the rapid increase of the population of the Federal District, some farms of this basin are under urbanization process.

In the area of the basin and its surroundings there are six rainfall gauge stations. The basin has eight fluviometric stations operated by the local sanitation company (CAESB).

Within the Lago Descoberto Representative Basin, an experimental basin of 16 km² (Capão Comprido) has also been studied.

Alto Jardim Experimental Basin (DF)

Located in the eastern part of the Federal District, among latitudes 15°43'00" and 15°51'00" S and longitudes 47°33'00" and 47°38'39" W, the Alto Jardim Experimental Basin, as well as the Lago Descoberto Representative Basin, is in a central part of the continuous Cerrado region (Figure 1). The basin has a total drainage area of 104.86 km² divided into two main catchments, the Estanislau (49.71 km²) and the Jardim (55.15 km²).

The climate is typical of the Cerrado region, with two well defined seasons: rainy summer and dry winter. Following the Köppen classification, the climate is tropical with dry winter (Aw).

Regarding the soils, 76.4% of its area is covered by Oxisols, and 16.7% of Cambisols (Lima, 2010), with similar characteristics of those from the Lago Descoberto Basin.

Concerning the land use, this basin is inside the main agricultural region of the Federal District. The main activities developed in the basin are: grain crops (soy, beans, corn, and sorghum), cotton, citrus, coffee, cassava and vegetables; in addition to poultry and livestock. Castro (2013) found that about 80% of the area of the basin is used for agricultural purposes, with only 20% of the area is still maintained with natural vegetation.

Since 2004 the basin is being monitored systematically using the following structure: 3 fluviometric stations, where they are also collected suspended sediment concentration and water quality parameters; 3 rainfall gauge stations; 56 piezometric wells; and a climatological station.

SWAT Model

The SWAT (Soil and Water Assessment Tool) is a hydrological model developed by the US Department of Agriculture (USDA/ARS) to predict the impact of land use change on streamflow, sediment yield and nutrient flow in complex watersheds (Neitsch et al., 2005). It is a model that aims the physical representation of various steps of the water cycle in an integrated way; it is computationally efficient; and capable to perform continuous simulations for long time periods (Neitsch et al., 2005; Gassman et al., 2007).

The fact of being a model with great application potential, non-commercial and open source has made the use of SWAT spread all over the world. In Brazil, since 1999, the number of SWAT users and applications has been increasing rapidly in the various regions (Garbossa et al., 2011). The first studies with SWAT in Brazil were performed in areas of the Atlantic Forest and only after 2005 they began in basins of the Caatinga biome (Garbossa et al., 2011). In the case of the Cerrado biome, the first works were published in 2010 (Silva, 2010), however, since that, several studies using the SWAT model were performed (Ferrigo et al., 2011; Minoti et al., 2011; Salles & Chaves, 2011; Strauch et al., 2012; Strauch et al., 2013; Castro, 2013; Ferrigo, 2014).

In this context, under the REHIDRO Project, which is part of the National Network of Experimental and Representative Basins, it was decided to use the SWAT model as an integration tool for the hydrological studies that are being carried out in different regions of Brazil.

Comparative studies

Initially, the studied basins were compared with regard to their climate, soil, topography and land use characteristics.

Based on measured data and considering the water balance (rainfall, baseflow, surface runoff, streamflow, and evapotranspiration), the hydrological behavior of the studied basins was evaluated and compared. At this stage, for the analyzed period, in annual terms, the variation of the amount of water stored in the soil was considered equal to zero.

Sensitivity analyses were performed in order to obtain optimized SWAT model parameters that best explain the hydrological behavior of the study regions. In these cases, the model was evaluated for streamflow generation.

Considering the physical and hydrological characteristics of the studied basins, the parameters values obtained in each of them after the SWAT model calibration were analyzed and compared in order to verify if the obtained values have some physical meaning and if they can be considered as reference for their respective regions.

Results and Discussion

Table 1 shows some physical characteristics of the four experimental and representative basins used in this study.

Table 1. Comparison of some physical characteristics of the studied basins.

Basin	Area (km ²)	Biome	Clima	Avg. T (°C)	Avg. RH (%)	Altitude (m)	Avg. Soil Depth ¹ (m)	Ksat ² (cm.h ⁻¹)	Agricultural area (%)
Alto Ipanema	195	Caatinga	Semiárido	23.0	70.0	600 - 1120	1.46	7.84	26.4
Tapacurá	470	Caatinga / Atlantic Forest	Tropical, hot and dry	27.0	70.0	40 - 645	2.00	31.8	89.0
Lago Descoberto	452	Cerrado	Tropical with a dry winter	20.8	67.0	1000 - 1300	11.0	93.2	22.0
Alto Jardim	105	Cerrado	Tropical with a dry winter	21.9	69.2	900 - 1175	8.0	89.9	80.0

1: Depth defined by the average groundwater level or the presence of an impermeable soil layer.

2: Defined by the average saturated hydraulic conductivity of the topsoil.

As shown in Table 1, the average temperature in Caatinga is higher than those found in the Cerrado basins. Altitude variations are also higher in the studied basins of the Caatinga than those of the Cerrado. When comparing Alto Ipanema and Tapacurá basins, in terms of altitude variations, the range is similar but it is important to notice that their areas are different. In relation to the soil depth and hydraulic conductivity at saturation (Ksat), the values obtained in the Cerrado basins are much higher than the ones observed in Caatinga, confirming the premise that, in general, the Cerrado soils are very deep and well drained. It can be noticed that all the basins are essentially used for agricultural purposes, with emphasis on Tapacurá and Alto Jardim basins, one in Caatinga/Atlantic Forest, and another in the Cerrado, both with more than 80% of their areas under agricultural use.

The data presented in Table 1 reflect environmental characteristics which can directly influence the hydrological behavior of the catchment. Temperature and relative humidity values, for example, can respond for the higher evapotranspiration in the Caatinga basins in comparison with the Cerrado ones. The highest changes in altitude in Alto Ipanema and Tapacurá basins indicates a more rugged terrain, which can lead to greater variability of environments, interfere in rainfall and other climate variables, and increase surface runoff generation, in detriment of water infiltration in the soil. The low saturated hydraulic conductivity and soil depth observed in the Caatinga can also lead to reduced infiltration and increased runoff in these regions in comparison with the Cerrado basins. The intense agricultural use in the studied basins can also interfere in the hydrological behavior, not just by suppressing the pristine vegetation, but also by the use of irrigation in these regions, decreasing streamflow and increasing actual evapotranspiration.

It is worth noting that the rainfall regime in these different regions is also quite heterogeneous, as shown in Figure 2.

Figure 2. Average monthly precipitation in the study basins.

As shown in Figure 2, only the data of the basins Lago Descoberto and Alto Jardim, both in the Federal District, inserted in the Cerrado biome, with only 60 kilometers between them, have some similarity. The data indicate a significant difference between the rainfall amount and regime in the basins of the different Brazilian biomes: Semi-arid, Semi-arid / Atlantic Forest, and Cerrado.

Table 2 presents the results of the water balance observed in the experimental and representative basins of the REHIDRO Project. As shown in Table 2, the average annual precipitation in the basin of the Caatinga (semi-arid climate), is lower than the values observed in the basins of the Cerrado biome (tropical climate), and in the basin located in the transition zone between Caatinga and Atlantic Forest biomes (tropical climate). However, it is important to mention that, despite having the average annual rainfall equivalent to the ones observed in the Cerrado basins, the Tapacurá basin, located in the transition between two biomes with such distinctive features, has a great variability of the average rainfall in its area, from 800 to 1,800 mm.yr⁻¹. The percentage of precipitation that returns to the atmosphere through evapotranspiration in the region of Caatinga proved to be slightly higher than that values observed in the Cerrado basins, however, it is worth noting that the reference evapotranspiration in semiarid region, certainly, is much higher than in the tropical areas. The lower water availability in Caatinga can explain the similarity on the percentage of actual evapotranspiration observed in such different regions.

In relation to the streamflow, it is remarkable that even presenting similar percentages of the annual precipitation in their regions, about 30%, in the Alto Ipanema basin (Caatinga), surface runoff represents 14% of this amount, while in the basins of Cerrado this value is lower than 5%. It is evident that baseflow

controls the streamflow in the Cerrado basins, what make the rivers of this region perennial. In the case of the rivers of Caatinga region, most of them are intermittent.

Table 2. Representation of the water balance in the experimental and representative basins of the REHIDRO Project.

Catchment	Biome	Area (km ²)	Rainfall (R) (mm.yr ⁻¹)	Runoff (%R)	Baseflow (%R)	Streamflow (%R)	Evapotranspiration (%R)
Alto Ipanema	Caatinga	195	738	14.00	12.00	26.00	74.00
Tapacurá	Caatinga / Atlantic Forest	470	1,210	-	-	27.36	72.64
Lago Descoberto	Cerrado	452	1,440	4.29	42.71	47.00	53.00
Alto Jardim	Cerrado	105	1,100	2.94	27.10	30.04	69.96

Note: Annual variation in water storage in the soil was considered as zero.

In Table 3, the five SWAT parameters defined as the most relevant for modeling the streamflow in the

studied basins, obtained by sensitivity analysis, are presented.

Table 3. Parameters identified as the most important for streamflow simulation using SWAT model in experimental and representative basins of the REHIDRO Project.

Catchment	Bioma	Area (km ²)	1°	2°	3°	4°	5°
Alto Ipanema	Caatinga	195	ALPHA_BF	CN2	SURLAG	GWQMN	SHALLST
Tapacurá	Caatinga / Atlantic Forest	470	ALPHA_BF	GWQMN	GW_REVAP	REVAPMN	RCHRG_DP
Lago Descoberto	Cerrado	452	SOL_K	CN2	SOL_AWC	SHALLST	ANION_EXC
Alto Jardim	Cerrado	105	SURLAG	ALPHA_BF	CN2	GWQMN	SOL_K

As shown in Table 3, the parameters ALPHA_BF, CN2 and GWQMN appear as the most important in three of the four studied basins, while SOL_K, SURLAG and SHALLST parameters appear in two of them. This demonstrates that the results of the sensitivity analysis are likely to be more dependent on the model itself, or the modeling process, than on the physical characteristics and the hydrological behavior of the basins. The only parameter that appears as important in the Cerrado (Lago Descoberto and Alto Jardim basins) and is not listed for the basins of Tapacurá and Alto Ipanema is the SOL_K, what can be

explained, in part, by the higher hydraulic conductivity and depth of the Cerrado's soils (Table 1).

Noteworthy is the fact that SOL_K, ALPHA_BF, GWQMN and SHALLST parameters are related to the water flow in the soil, being related mainly to the baseflow generation, while CN2 and SURLAG are mainly related to the surface runoff generation and its occurrence behavior in the basin.

Table 4 shows the parameters values obtained by SWAT model calibration for the streamflow simulation in the experimental and representative basins of the REHIDRO Project.

Table 4. Values of the parameters obtained by SWAT model calibration process for the streamflow simulation in the experimental and representative basins of the REHIDRO Project.

Parâmetro	Unidade	Alto Ipanema	Tapacurá	Lago Descoberto	Alto Jardim
CN2	dimensionless	81.89	-	38.36	51.40
SOL_K	mm.h ⁻¹	25.00	-	914.00	1350.00
SOL_AWC	mm.mm ⁻¹	0.3860	-	0.0980	-
SURLAG	days	15.497	1.000	-	0.0100
ALPHA_BF	days	0.2450	0.3000	0.2885	0.1000
GWQMN	mm	885.0	2.5	1068.6	0.0000
SHALLST	mm	2490.00	-	2926.22	-

As shown in Table 4, the CN2 value was higher in the Alto Ipanema Basin (Caatinga) than in Lago Descoberto and Alto Jardim basins (Cerrado), which was expected due to the higher permeability and depth of Cerrado's soils, as well as the milder relief observed in this region (Table 1). The difference between the CN values in the Cerrado basins can be explained, at least in part, due to the fact that the drainage area of Lake Discovered basin is four times greater than that of the Alto Jardim Basin, increasing infiltration opportunity in the basin before rainwater reaches the stream.

In relation to SOL_K, the calibrated values also reflect the characteristics of the different regions, being higher in the Cerrado basins (Table 1).

For other parameters, the relationship between the obtained values and the characteristics of the basins is not so clear, reflecting limitations of the calibrated models in relation to their physical basis. These limitations may be caused by problems in the representation of the physical characteristics of the basins by means of the input data, the initial and the variation limits for each model parameter, or even due to the conceptual model represented by SWAT that may need some adjustments and adaptations for use in the studied regions. Strauch (2014), for example, identified that, when simulating evapotranspiration, SWAT model consider the existence of a dormant period of natural vegetation during the winter, which does not occur in general with the Cerrado's native vegetation, generating an underestimation of this process in the basins of this region.

Conclusions

- The results indicate a clear relationship between the physical characteristics of the studied river basins, their respective hydrological behavior, and the values of certain parameters of the SWAT model after calibration, the CN2 and the SOL_K, respectively;
- For CN2 and SOL_K, the values of these parameters obtained after the calibration process can be considered as a reference for other basins of the respective regions with similar physical characteristics, at least as an initial value. For other parameters, the

relationship between the obtained values and the characteristics of the basins is not so clear, reflecting limitations of the calibrated model in relation to its physical basis;

- The comparison among the sensitivity analysis results indicates that the setting of parameters with greater ability to change SWAT streamflow simulations is more dependent on the model itself, or on the modeling processes, than on the physical characteristics and the hydrological behavior of the studied basins. The only exception was the SOL_K parameter, which appeared among the most important in the Cerrado basins, but not in the other studied areas (Caatinga, and Caatinga/Atlantic Forest basins);
- In the SWAT application for streamflow simulation in the four studied basins, ALPHA_BF, CN2 and GWQMN appeared as the most important parameters in three of these cases, while SOL_K, SURLAG and SHALLST appeared in two of them.

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