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Hydrological simulation with SWAT and VIC Models in the Verde River Watershed, Minas Gerais

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ABSTRACT

Successful streamflow forecasts depend on an adequate performance evaluation of the hydrological model. In this study, the hydrological responses were compared using two hydrological models, physic-based and semi-distributed, Soil and Water Assessment Tool (SWAT) and Variable Infiltration Capacity (VIC), using input data from the Verde River Watershed, located in the Minas Gerais state in southern Brazil. This is a study of one of the most important headwater watershed regions of Brazil (Mantiqueira Range). Both models were suitable for streamflow simulation, with values of R^2 (determination coefficient) and NSE (Nash-Sutcliffe) higher than 0.8, NSELog higher than 0.35 (Nash–Sutcliffe Efficiency of the logarithmic values of discharge) and P_{BIAS} (percentage deviation) less than 25%. The integration of SWAT and VIC models can be useful in different water-resource assessment studies. Therefore, based upon this study further investigations should be conducted using various hydrological models and climate, land-use and land-cover changes scenarios in the region.

Keywords: hydrological modeling, performance evaluation, streamflow forecasts, SWAT model, VIC model.

Simulação hidrológica com os modelos SWAT e VIC na bacia hidrográfica do rio Verde, Minas Gerais

RESUMO

Previsões de vazão bem-sucedidas dependem de uma adequada avaliação de desempenho do modelo hidrológico. Neste estudo, as respostas hidrológicas foram comparadas usando dois modelos hidrológicos, físico-baseados e semi-distribuidos, Water Assessment Tool (SWAT) e Variable Infiltration Capacity (VIC), utilizando dados de entrada da bacia hidrográfica do rio

Verde, localizada ao sul do estado de Minas Gerais, Brasil. Este é um estudo de uma das mais importantes regiões hidrográficas de cabeceiras do Brasil (Serra da Mantiqueira). Ambos os modelos foram adequados para simulação da vazão, sendo os valores de R^2 (coeficiente de determinação) e de NSE (Nash-Sutcliffe) superiores a 0,8, NSELog superiores a 0.35 (Eficiência Nash–Sutcliffe do logarítimico dos valores de vazão) e P_{BIAS} (desvio percentual) menor que 25%. A integração da avaliação de desempenho dos modelos SWAT e VIC pode ser útil em diferentes estudos de avaliação dos recursos hídricos. Portanto, a partir deste estudo mais investigações devem ser conduzidas usando vários modelos hidrológicos e cenários de mudanças climáticas e de uso e cobertura da terra, na região.

Palavras-chave: avaliação de desempenho, modelagem hidrológica, modelo SWAT, modelo VIC previsões de vazão.

1. INTRODUCTION

Hydrological models have been increasingly used because they help understand the impact of future changes in water balance associated with climate and land-use changes (Alvarenga *et al.*, 2018; Louzada and Ribeiro, 2019). Physically based and distributed models typically include a detailed representation of the physical processes in each grid cell of the Digital Elevation Model or in the hydrological response units. Thus, the performance of these models depends on an adequate specification of several parameters, which are often collected in water-resource monitoring programs. More complex parameters to be quantified must be refined during the calibration phase of a model (Du *et al.*, 2014). The available data in a simulation should represent the input variables and parameter distributions of the hydrological model to recommend the use of more complex distributed models (Santos *et al.*, 2018).

The performance of a model can vary with hydrological variables and conditions assessed, such as droughts or floods. Therefore, the greater complexity of a hydrological model cannot guarantee improvements in its performance. Physically based and distributed models can be useful for detailed surface overland flow assessments and water balance studies. To assess the impacts of climate change, a simple conceptual model can also be appropriate (Singh and Marcy, 2017; Orth *et al.*, 2015).

The choice of a particular model should be made based on the desired application, availability of basic data in the area, number of parameters required and description level of the hydrological processes. Each hydrological model presents its assumptions, limits and potentialities. The use of distributed and semi-distributed physical hydrological models is based on the argument that this type of model best represents the physical processes within a watershed, considering the spatial variability of the physical and climatic parameters (Orth *et al.*, 2015).

Different studies have been carried out with the aim of comparing different hydrological model performances (Orth *et al.*, 2015; Singh and Marcy, 2017; Santos *et al.*, 2018). This is the first research in the Verde River Watershed, located in the Minas Gerais state, in which a hydrological model will be calibrated in the mesoscale (SWAT), and this model will generate results to be compared with a developed and applied model for the macroscale (VIC) which will be later validated at the mesoscale (Verde River Watershed). Thus, this study will provide important results in terms of hydrological responses modeling for future research of climate and land-cover changes in the Verde River Watershed to assist in the appropriate water management policies to local communities. In this context, this research evaluated Variable Infiltration Capacity (VIC) and Soil and Water Assessment Tool (SWAT) model performances in predicting streamflow in the Verde River Watershed.

2. MATERIAL AND METHODS

2.1. Description of the study area

The Verde River Watershed has a drainage area of 4100 km^2 (Figure 1) and is part of the Rio Grande Watershed, which in turn is part of the Paraná River Watershed, one of the main hydrographic regions in Brazil in terms of water availability and hydropower production. The Verde River Watershed is located in the south of Minas Gerais state, southeastern Brazil (Minas Gerais-MG, Espírito Santo-ES, São Paulo-SP and Rio de Janeiro-RJ states), and is inserted in the Atlantic Forest biome, with springs in the Serra da Mantiqueira. The Atlantic Forest is one of the most important forest biomes in terms of biodiversity in Brazil.

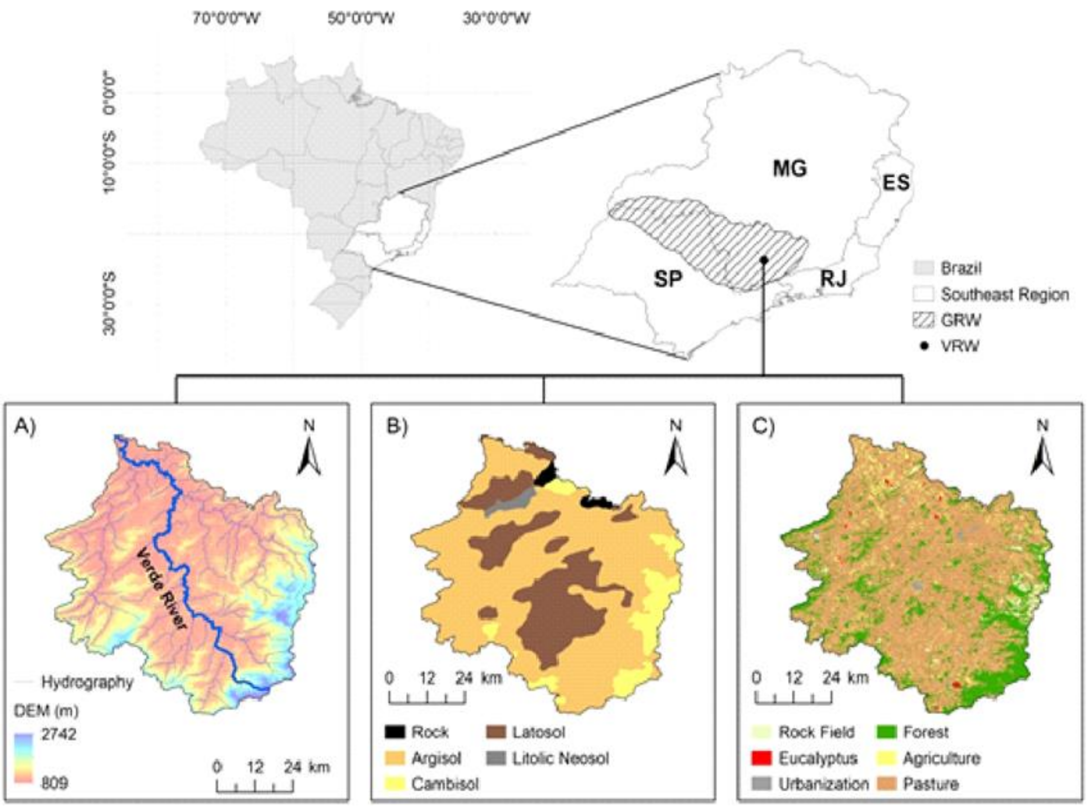

Figure 1. Geographical location of the Verde River Watershed (VRW) in Grande River Watershed (GRW), Brazil's southeast region; Digital Elevation Model (DEM) and hydrography (A), soil class (B), and vegetation (C) maps.

According to the Köppen classification, the watershed climate is mostly Cwb, or subtropical highland climate (south and southwest), and Cwa, or humid subtropical climate, can occur in a smaller part of the basin (north and northeast). The average annual rainfall is 1500 mm and the average annual temperature is 18°C with the dry winter season (Mello *et al.*, 2012). Data from the Digital Elevation Model (DEM) indicate that the topography is bumpy, with a maximum and minimum elevation of 2742 m and 809 m. Soil classes predominate in the higher parts are Argisol (65.3%), Latosol (23.3%) and Cambisol (8.9%), followed by Rock (1.3%) and Fluvic Neosol (1.2%) found in the lower parts (watershed lowlands). Land use is diverse and well distributed in the watershed, consisting of pasture (69.2%), native forest (21.3%), rock field (1.7%), eucalyptus (0.2%), agriculture (7%) and urbanization (0.6%).

2.2. Soil and Water Assessment Tool (SWAT)

SWAT is a large-scale hydrological model, physically based and semi-distributed in space; that is, it divides the watershed into sub-basins connected by a stream network. Each sub-basin is delimited in hydrological response units consisting of unique combinations of land use, slope and soil type (Arnold *et al.*, 1998). This technique was developed to predict the impact of land-use and management practices on water, sediment and agricultural chemicals generated in large, complex watersheds with different soil types, land use and management conditions over long periods of time (Neitsch *et al.*, 2011). SWAT simulations are based on water balance and are performed through hydrological routines that calculate water cycle components such as surface and subsurface flows, evapotranspiration, infiltration, percolation and soil moisture for each hydrological response unit. A more detailed description of the SWAT model can be found in Arnold *et al.* (1998) and Neitsch *et al.* (2011). In this study we used the SWAT2012 version of the model (SWAT, 2012).

2.3. Variable Infiltration Capacity (VIC)

The Variable Infiltration Capacity (VIC) model is a physical and semi-distributed model that describes the drainage area in homogeneous grid cells, where water and energy balances are calculated at each time step (Liang *et al.*, 1994; 1996). This model has been widely used for applications that include a variety of research areas, such as: construction of hydrological datasets, water balance, forecasting, coupled climate modeling and climate change impact assessment (Liang *et al.*, 1994; Zhai and Tao, 2017). The main characteristic of the VIC model is the variable infiltration curve, which represents the statistical distribution of the maximum soil water storage capacity in each cell of the model, determining the maximum rate of water infiltration and runoff for each vegetation cover of the cell, according to soil moisture. The flow-routing model is due to the module Route. The module calculates at each grid cell the time of concentration, which is the time for the entire surface runoff to leave each cell after the precipitation stops. As the flow enters river channels, the daily flood routing is determined by the continuity equation, as the piecewise water budget through the channel (Lohmann *et al.*, 1998).

2.4. Input data and calibration scheme

The VIC was manually calibrated using spatial resolution of 0.01° (~ 1 km) with a total of 3728 grid cells covering the entire Verde River Watershed. SWAT was calibrated using the Sequential Uncertainty Fitting Algorithm (SUFI2) implemented in SWAT CUP by Abbaspour *et al.* (2007). The spatial resolution of 30 m was used with a total of 57 sub-basins with 1503 hydrologic response units covering the entire study area. To simulate the hydrological cycle, these models require data on weather forcing, vegetation cover, soil physical characteristics and drainage network information in each basin cell (VIC) or in each hydrologic response unit (SWAT).

Information from the ASTER sensor, with spatial resolution of 30 m, was used to obtain the Hydrologically Consistent Digital Elevation Model. LANDSAT 8 sensor images with spatial resolution of 30 m were used to obtain the land-use map by means of supervised and object oriented classification techniques. The mapping of soil classes was derived from the soil map of Minas Gerais, produced by the State Environmental Foundation.

Meteorological data for the region were obtained from meteorological stations of the Instituto Nacional de Meteorologia (INMET, 2019). Data from the stations used in the models are available for the locations of São Lourenço, Lavras and Machado (Minas Gerais state). Daily weather observations will be used to force hydrological models during their assessment. In these models, historical series on the daily scale of maximum and minimum temperatures, relative humidity, solar radiation, wind speed and precipitation are required.

Hydrological models are run for 1990–2005 period, with 1993-1999 being the calibration period and 2000-2005 the validation period, both with daily data. The first 3 years were used as warm-up. In the performance-testing process of each model the simulated streamflow adherence with the observed streamflow (Fluviometric station from Três Corações- code 61510000) was verified. The observed streamflow series was obtained from the National Water Agency (ANA, 2019). Monthly streamflow data allow calibration and model validation by comparing simulated and observed streamflows. In the refinement of the calibration and validation of the models statistical indices were calculated. The indices observed were: Nash-Sutcliffe Efficiency (NSE), Nash–Sutcliffe Efficiency of the logarithmic values of discharge (NSELog), coefficient of determination (R^2) and percentage bias (PBIAS).

The NSE and NSELog efficiency quantifies the residual variance relative to the data variation, indicating how much the simulated data compared to the observed one fits in a 1:1 line, and its value ranges from $-\infty$ to 1, with 1 being its optimal value; values between 0.35 to 0.50 and 0.5 to 0.7 indicate medium and good hydrological model performance. The coefficient of determination describes the proportion of variance of observed data explained by the model; values above 0.50 are considered acceptable. P_{BIAS} measures the average tendency of simulated data to be larger or smaller than the observed data; Results are considered satisfactory if P_{BIAS} <25% (Moriasi *et al.*, 2007; Safeeq and Fares, 2012).

2.5. Models parameterization

The calibration of the SWAT model was done by adjusting 14 parameters that represent the surface and subsurface flow processes. These parameters are: soil evaporation compensation coefficient (ESCO); initial SCS runoff curve number for moisture condition II (CN2); the baseflow recession constant (ALPHA_BF), Groundwater delay time (GW_DELAY); threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN); maximum canopy storage (CANMX); effective hydraulic conductivity in main channel (CH_K2), Manning's "n" value for the main channel (CH_N2); plant uptake compensation factor (EPCO);groundwater "revap" coefficient (GW_REVAP); threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (REVAPMN); soil available water capacity (SOL_AWC); saturated hydraulic conductivity (SOL_K) and surface runoff lag coefficient (SURLAG).

The calibration of the VIC model was done by adjusting the parameters described: i) infiltration parameter (b_infilt) describes the amount of available infiltration capacity as a function of relative saturated gridcell area. A higher value of b_infilt gives lower infiltration and yields higher surface runoff; ii) thickness of the third soil layer (depth_3), interfering in the transpiration (depending on root depth) and baseflow. Where thick layers of soil have slower runoff responses (predominance of baseflow) and high evapotranspiration, however, the result is high moisture retention and high baseflow in dry periods; iii) maximum baseflow that can occur from the lowest soil layer (Ds); and iv) fraction of the maximum soil moisture (Ws). A higher value of Ws will raise the water content required for rapidly increasing, non-linear baseflow, which will tend to delay runoff peaks. In addition to the calibration of the VIC model, the parameters of the surface-flow propagation model (Route) were also refined (kinematic wave speed (C) and diffusivity (D)).

3. RESULTS AND DISCUSSION

Tables 1 and 2 list the calibrated parameters using the SWAT and VIC models during water balance simulations for the Verde River Watershed. After the calibration phase, the models were validated by replacing the initial parameters by those obtained in the calibration phase. The parameters used for calibration are those that present the highest sensitivity according to the literature (Oliveira *et al.*, 2018; Gao *et al.*, 2010; Arnold *et al.*, 1998; Liang *et al.*, 1994; 1996).

Table 1. Calibrated parameters of the SWAT model during water-balance simulations for the Rio Verde Watershed.

Parameters	Unit	Amplitude	Calibrated value
SWAT model			
Soil evaporation compensation coefficient - v__ESCO.bsn	-	0.7 a 0.95	0.78342
Initial SCS runoff curve number for moisture condition II - r__CN2.mgt	-	-0.1 a 0.1	-0.0982
Baseflow recession constant - v__ALPHA_BF.gw	days	0.005 a 0.009	0.005172
Threshold depth of water in the shallow aquifer required for return flow to occur a__GW_DELAY.gw	days	-30 a 60	-18.75
Threshold depth of water in the shallow aquifer required for return flow to occur- a__GWQMN.gw	mm	-1000 a 1000	-906
Maximum canopy storage - a__CANMX.hru	mm	0 a 30	2.25
Effective hydraulic conductivity in main channel - v__CH_ K2.rte	mm h^{-1}	0 a 10	6.09
Manning's "n" value for the main channel - v__CH_N2.rte	-	-0.01 a 0.2	0.12083
Plant uptake compensation factor - v__EPCO.bsn	-	0.01 a 1	0.43471
Groundwater "revap" coefficient - v__GW_REVAP.gw	-	0.02 a 0.2	0.1469
Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur - a__REVAPMN.gw	mm	-1000 a 1000	-674
Soil available water capacity - r__SOL_AWC().sol	mm H_2O /mm soil	-0.05 a 0.05	-0.0135
Saturated hydraulic conductivity - r__SOL_K().sol	mm h^{-1}	-0.1 a 0.1	-0.0462
Surface runoff lag coefficient - v__SURLAG.bsn	days	0.01 a 24	8.43049

Table 2. Calibrated parameters of the VIC model during water-balance simulations.

Parameters	Unit	Amplitude	Calibrated value
VIC model			
Infiltration parameter- b_infilt	-	0.001 – 0.400	0.35
Fraction of maximum base-flow velocity - Ds	-	0.001 – 0.999	0.01
Third layer thickness - Depth_03	m	0 – 200%	100%
Fraction of maximum soil moisture content - Ws	-	0.001 – 0.999	0.05
Route model			
Flow Propagation Speed - C	m s^{-1}	0.5 – 3.0	0.5
Flow diffusivity - D	m^2 s^{-1}	200 – 4000	2200

The statistical indices NSE, NSELog, R^2 and P_{BIAS}, resulting from the comparison between the observed and simulated monthly streamflows by the SWAT and VIC models, are in the Table 3. According to the statistical indices, a good performance of both hydrological models were obtained. R^2 values higher than 0.50 indicate the ability of the models to explain most of the variation in the observed data. NSE values from 0.814 to 0.861 for monthly outputs during the calibration and validation periods, respectively, suggest that the models are appropriate to simulate the monthly streamflow of the Rio Verde Watershed. NSELog values higher than 0.35

indicate medium and acceptable model performance. The P_{BIAS} value ranges from -8.29% to 13.88%, indicating satisfactory SWAT and VIC performance. In general, by comparison, the effect of observed and simulated values adjusting was better for the SWAT model when compared to the VIC model.

Table 3. Statistical indices resulting from the comparison between VIC and SWAT models for monthly average streamflows.

Statistical indices	Calibration		Validation	
	SWAT	**VIC**	**SWAT**	**VIC**
Monthly average streamflow				
NSE	0.861	0.858	0.814	0.829
NSELog	0.840	0.543	0.782	0.421
R^2	0.873	0.920	0.843	0.925
P_{BIAS}	0.45	14.81	-8.29	13.88

Figure 2 shows the average monthly hydrographs for the SWAT and VIC in the calibration and validation periods. The comparison of simulated and observed streamflow in both cases shows reasonable agreement for both calibration and validation periods. In general, it can also be seen that monthly simulations estimate peak flow and recession period satisfactorily. The average streamflows observed in the Rio Verde Watershed are 80.15 and 75.09 $m^3 s^{-1}$ in the calibration and validation, respectively. The simulated average streamflows were overestimated by 0.45 and 14.81% during the whole calibration period; in the validation, underestimated and overestimated values were simulated by -8.29 and 13.88%, using the SWAT and VIC models.

Differences in the results of the simulated streamflow by the SWAT and VIC models indicate the need to evaluate the uncertainties of hydrological simulations obtained from different models in climate and land-use change research. As in this study, Singh and Marcy (2017) and Orth *et al.* (2015) also highlighted that for more realistic studies, the performance evaluation of various hydrological models may reduce uncertainties due to the different structures and complexity of the different hydrological models chosen.

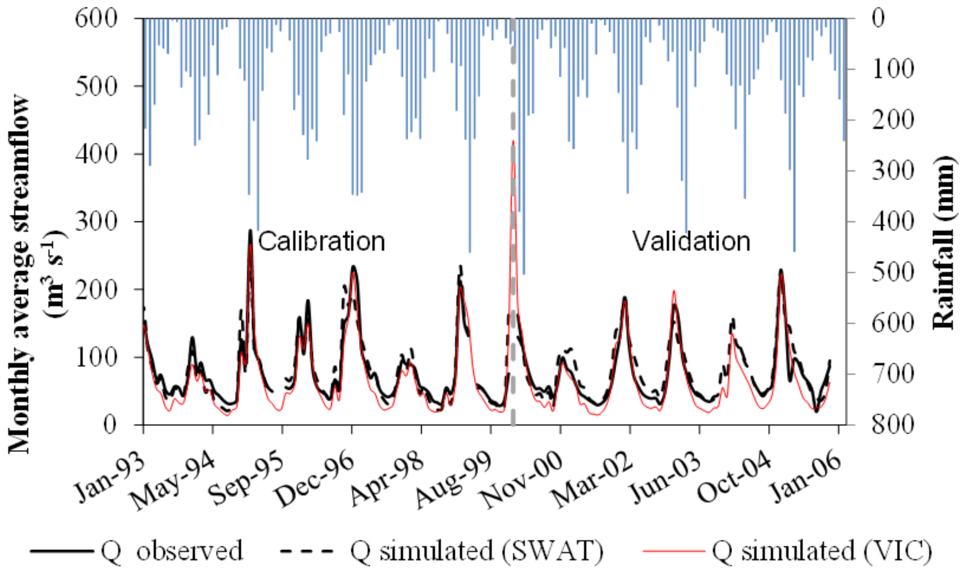

Figure 2. Simulated and observed streamflows (Q) during the calibration and validation periods of the SWAT and VIC models.

In addition to performance analysis of hydrological models (Figure 2), the estimated annual evapotranspiration (ET) for both models was verified to ensure a reasonable set of final parameters. In this research, the average annual evapotranspiration values simulated by the SWAT and VIC models were 981 and 863 mm, corresponding to 65.7 and 57.9% of the rainfall. Viola *et al.* (2013) also showed good performance of the LASH model compared to its evapotranspiration module. The average annual evapotranspiration was similar to the value obtained based on the vertical water balance, with a deviation of <4% for the Rio Verde Watershed.

In Table 4, it is possible to observe that the monthly trend of simulated ET can be positively related to rainfall - R (mm) seasonality. In both models, the simulated ET was higher from November to March and the lowest values were from April to October, in the rainy and dry seasons, respectively. These results are in agreement with the climatic and hydrological variability of this study region according to Viola *et al.* (2013) and Oliveira *et al.* (2018).

Table 4. Average monthly evapotranspiration (ET) estimated by the SWAT and VIC models and observed average monthly rainfall (R).

Month	ET (mm)		R (mm)
	VIC	SWAT	
January	134.36	97.60	298.33
February	117.98	92.22	215.14
March	112.93	95.75	156.72
April	85.73	73.55	57.15
May	53.16	50.34	64.20
June	37.27	32.75	25.68
July	34.21	29.39	20.35
August	27.77	40.36	17.87
September	45.29	57.91	75.38
October	86.39	84.14	112.32
November	111.92	98.22	176.60
December	133.98	110.91	287.58

4. CONCLUSIONS

The SWAT and VIC, semi-distributed hydrological models, can be very useful tools in the prediction of streamflow in the mesoscale. During the simulation period, the NSE and NSELog presented values that ranged from 0.861 to 0.814 and 0.421 to 0.840, ensuring reasonably simulated streamflow. Evapotranspiration presented values that ranged from 57.9 to 65.7% of the rainfall. These percentages show reasonable performance of the VIC and SWAT for estimating evapotranspiration and, consequently, its capability of simulating streamflow in the Verde River Watershed.

These results suggest that SWAT and VIC can be useful for simulations focusing on the long-term trend. Therefore, if the interest of the research is to evaluate the impacts of different scenarios on the water balance components, the semi-distributed hydrological models are recommended for hydrological studies and uncertainty evaluations of different hydrological model simulations in the Verde River Watershed.

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