Research, Society and Development, v. 9, n. 5, e100953262, 2020
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Modelagem hidrológica de bacias hidrográficas tropicais sob baixa disponibilidade de dados

Hydrological modelling of tropical watersheds under low data availability

Modelado hidrológico de cuencas tropicales bajo baja disponibilidad de datos

Recebido: 27/03/2020 | Revisado: 28/03/2020 | Aceito: 29/03/2020 | Publicado: 30/03/2020

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Resumo

A modelagem hidrológica é uma ferfamenta importante para o planejamento e manejo dos recursos hídricos. Todavia, a falta de dados de entrada, especialmente daqueles relacionados ao solo e clima, frequentemente dificultam a aplicação de modelos hidrológicos nas bacias da Mata Atlântica brasileira. O objetivo deste estudo foi analisar a aplicação do modelo VIC sob

condições de baixa disponibilidade de dados para simular vazões diárias de duas bacias (Jucu e Santa Maria da Vitória). Os resultados mostraram desempenho satisfatório apenas para a bacia de Santa Maria da Vitória. Todavia, devido às limitações e formas simplificadas de estimar os dados de entrada faltantes, a aplicação do VIC sob baixa disponibilidade de dados ainda pode ser considerada como promissora para o entendimento do regime hidrológico destas bacias.
Palavras-chave: Modelo VIC; Vazão; Chuva.

Abstract
Hydrologic simulation is an important tool for the planning and management of water resources. However, the lack of input data, particularly soil and climate data, frequently complicates the application of hydrological models in Brazilian Atlantic Rainforest basins. The purpose of this study was to analyse the application of the VIC model, under the condition of low data availability, to predict the daily streamflow of two basins (Jucu and Santa Maria da Vitória). The results showed satisfactory statistical indexes only for the Santa Maria da Vitória basin. Due to data limitations and the simplified forms used to estimate these missing data, the model proved promising for understanding the hydrologic regime of these basins.
Keywords: VIC model; Streamflow; Rainfall.

Resumen
La modelización hidrológica es una herramienta importante para la planificación y gestión de los recursos hídricos. Sin embargo, la falta de datos de entrada, especialmente los relacionados con el suelo y el clima, a menudo dificultan la aplicación de modelos hidrológicos en las cuencas del bosque atlántico brasileño. El propósito de este estudio fue analizar la aplicación del modelo VIC, bajo la condición de baja disponibilidad de datos, para predecir el flujo diario de dos cuencas (Jucu y Santa Maria da Vitória).. Los resultados mostraron un desempeño satisfactorio solo para la cuenca de Santa Maria da Vitória. Sin embargo, debido a las limitaciones y las formas simplificadas de estimar los datos de entrada faltantes, la aplicación de VIC con poca disponibilidad de datos aún puede considerarse prometedora para comprender el régimen hidrológico de estas cuencas.
Palabras clave: Modelo VIC; Caudal; Lluvia.

1. Introduction

Achieving sustainability of water resources is difficult because many conflicting factors must be balanced due to the complexities of the watersheds (Zhang, Li, Huang, & Liu, 2014). In this context, knowledge of the hydrologic behaviour of the watersheds is a key factor. Hydrological simulation is an important tool for planning and managing water resources. Simulations can be used to estimate water availability, streamflow forecasting and the hydrologic response of watersheds to changes in the land use. The assessment of variations in water resource quality and quantity is one of the most relevant applications of hydrological models (D. dos R. Pereira, Almeida, Martinez, & Rosa, 2014) and converts computational models into essential tools for watershed planning and management.

Several hydrological models have been developed and applied to simulate the major water balance components at the basin scale. One notable model is the Variable Infiltration Capacity (VIC) model (Liang, Lettenmaier, Wood, & Burges, 1994). VIC is characterized as a semi-distributed, grid-based, macroscale hydrological model designed to simulate both the water and the energy budgets of large areas. This model is distinguished from other hydrology models by its sub-grid parameterization of the topography, soil, and vegetation data. The VIC model has been recommended by the World Bank as an aid to the institution's decision-making in the implementation of regional development projects due to the satisfactory results the model achieves for large river basins (Jaw, Li, Hsu, Sorooshian, & Driouech, 2015; Tang & Dennis, 2014; Tesemma, Wei, Peel, & Western, 2015; Xie et al., 2007).

Recently, after a consistent calibration (Wallner, Haberlandt, & Dietrich, 2013), some hydrological models developed for major basins were applied to smaller watersheds. These applications resulted in promising performances (Cuartas et al., 2012; Pinto, Silva, Beskow, Mello, & Coelho, 2013) and necessitated more studies as these models generally required less input data than lower scale hydrological models.

In Brazil, the use of water from basins frequently occurs without adequate planning, which leads to water scarcity scenarios. Therefore, decision support tools are needed to augment Brazilian watershed management activities. Thus, professionals involved in water resource management face the need to develop, improve and apply tools for solving water quantity and quality problems, including hydrological models (Bressiani et al., 2015).

The Atlantic Forest was once one of the largest rainforests in the Americas, originally covering approximately 150 million ha, in highly heterogeneous environmental conditions. This present-day Atlantic Forest fragmentation has led to a large proportion of the forest's vast biodiversity being threatened to extinction (M. C. Ribeiro, Metzger, Martensen, Ponzoni, & Hirota, 2009). Deforestation and a population increase is causing the Atlantic Forest basins to face threats of water scarcity. In many basins, a concern has been raised over the freshwater shortage as a consequence of lateralization, unplanned land occupation, population and economic growth, increasing demands and rising conflicts aggravated by pollution, all of which limit the potential uses of water (Marques, Costa, Mayorga, & Pinheiro, 2004). The Jucu basin and the Santa Maria da Vitória basin, located within the original area of the Atlantic Forest, are the only water sources supplying Vitória's metropolitan region with approximately 1.8 million inhabitants. The hydrological modelling of these basins is important to provide improved watershed management that could increase the water availability associated with the Atlantic Forest reconstitution. However, like many of the basins surrounding these two, a significant lack of data (climatic, soil properties, geological, and environmental) exists, which can preclude the application of some hydrological models.

The purpose of this study was to analyse the application of the VIC model, under the condition of low data availability, to predict the daily streamflow of the Jucu and Santa Maria da Vitória basins.

2. Methods

The present research is methodologically classified as a case study of a quantitative nature. The research developed in a natural environment, where the researcher is the main instrument for the analysis of the collected descriptive data. In addition to this, another characteristic of this study is that it is a laboratory research, since the analysis employed, which involved the elaboration of cartographic products and the execution of computational modeling, was all carried out in a computational environment, that is, the research was controlled (A. S. Pereira, Shitsuka, Parreira, & Shitsuka, 2018).

2.1. Area under studies

The areas under studies are the Santa Maria da Vitória river basin and the Jucu river basin are located in Espírito Santo State, Brazil (Figure 1). The topography varies from flat near the outlet (altitude equal to 0 m) to mountainous at the basin heads (1,300 and 1,800 m in altitude). The original land cover was the Brazilian Atlantic Rainforest, which is a typical tropical rainforest and a biodiversity hotspot due to its high species richness and high level of

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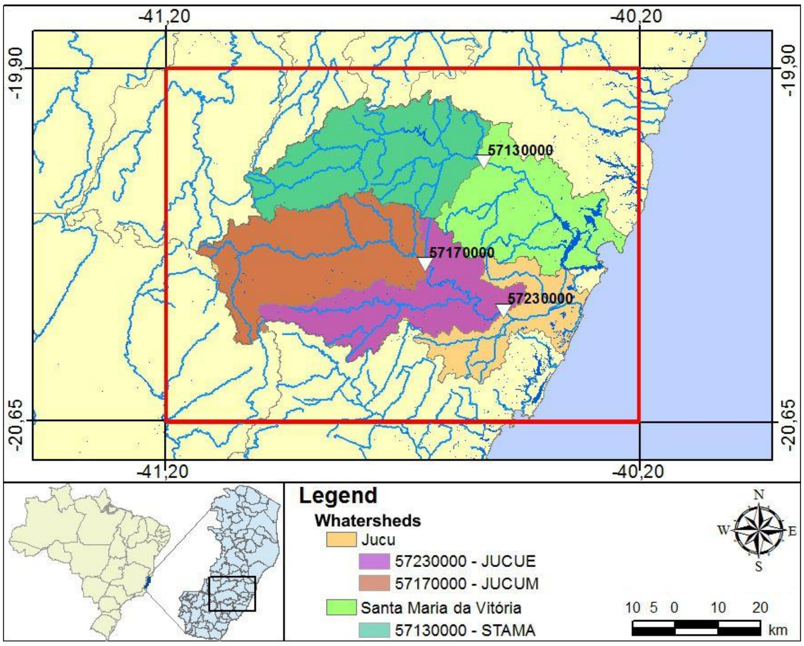
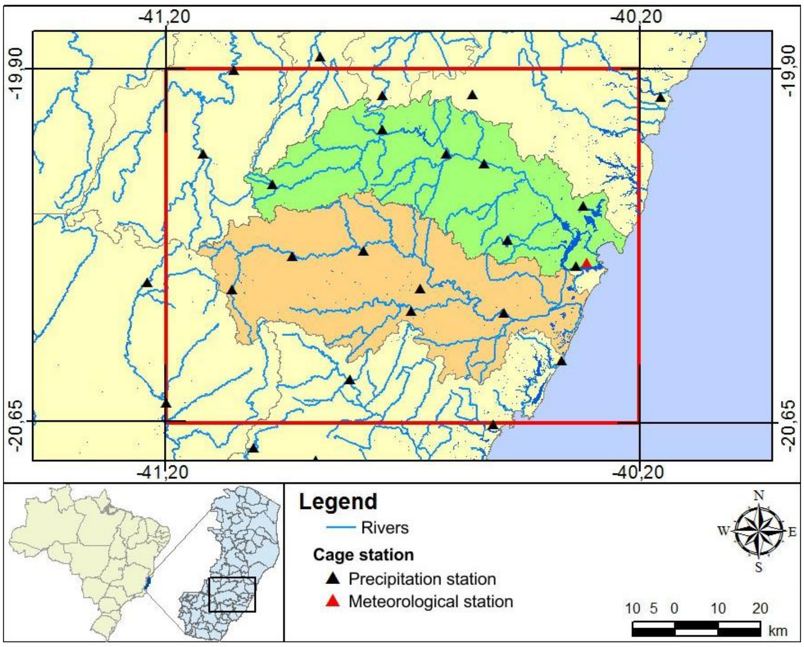
species endemism (Scarano, 2002). The local climate includes Aw (tropical with dry winter) and Am (tropical with monsoon), according to the Köppen classification (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013).

Figure 1. Maps from the Santa Maria da Vitória basin and the Jucu basin depicting (a) the stream gauge stations and (b) the rain gauge and the meteorological stations used in this paper.



(a)



(b)

Source: elaborated by the authors.

In the Figure 1 the reader can observe the spatial location of the basins, with areas of 1,800 km^2 (Jucu) and 2,148 km^2 (Santa Maria da Vitória).

The main input of the VIC model includes a digital terrain elevation model (DEM), a hydrologic and meteorological dataset, a soil dataset and a vegetation dataset. The DEM used in this study was obtained from an SRTM mission (radar satellite imagery) and had a resolution of 90 m per pixel.

Table 1 presents information about three stream gauge stations from which the hydrologic dataset were used. Information of the stations presented at Table 1 includes the daily observed discharges (1992 to 2001), acquired from the Agência Nacional de Águas (ANA) (the Brazilian Water Agency), and defines three sub-basins: Santa Maria da Vitória (STAMA), Jucu-Braço Norte (JUCUM) and Jucu (JUCUE). The meteorological dataset includes the daily precipitation, the maximum and minimum temperatures, and the wind speed, which are the primary meteorological variables that drive VIC. These meteorological data were collected daily from 1992 to 2001 at 28 rain gauge stations (only rainfall data) from ANA and only one meteorological station (all the data) from Instituto Nacional de Meteorologia (INMET) (the Brazilian Meteorological Institute), which characterizes a scarcity of data, particularly meteorological data. Figure 1b shows the spatial distribution of the stations.

Table 1. Description of the stream gauge stations used in this paper.

Code number	Sub-basin	Latitude	Longitude	Contributing area (km^2)
57130000	Santa Maria da Vitória (STAMA)	-20.100º	-40.528º	929
57170000	Jucu-Braço Norte (JUCUM)	-20.316º	-40.652º	980
57230000	Jucu (JUCUE)	-20.415º	-40.485º	1690

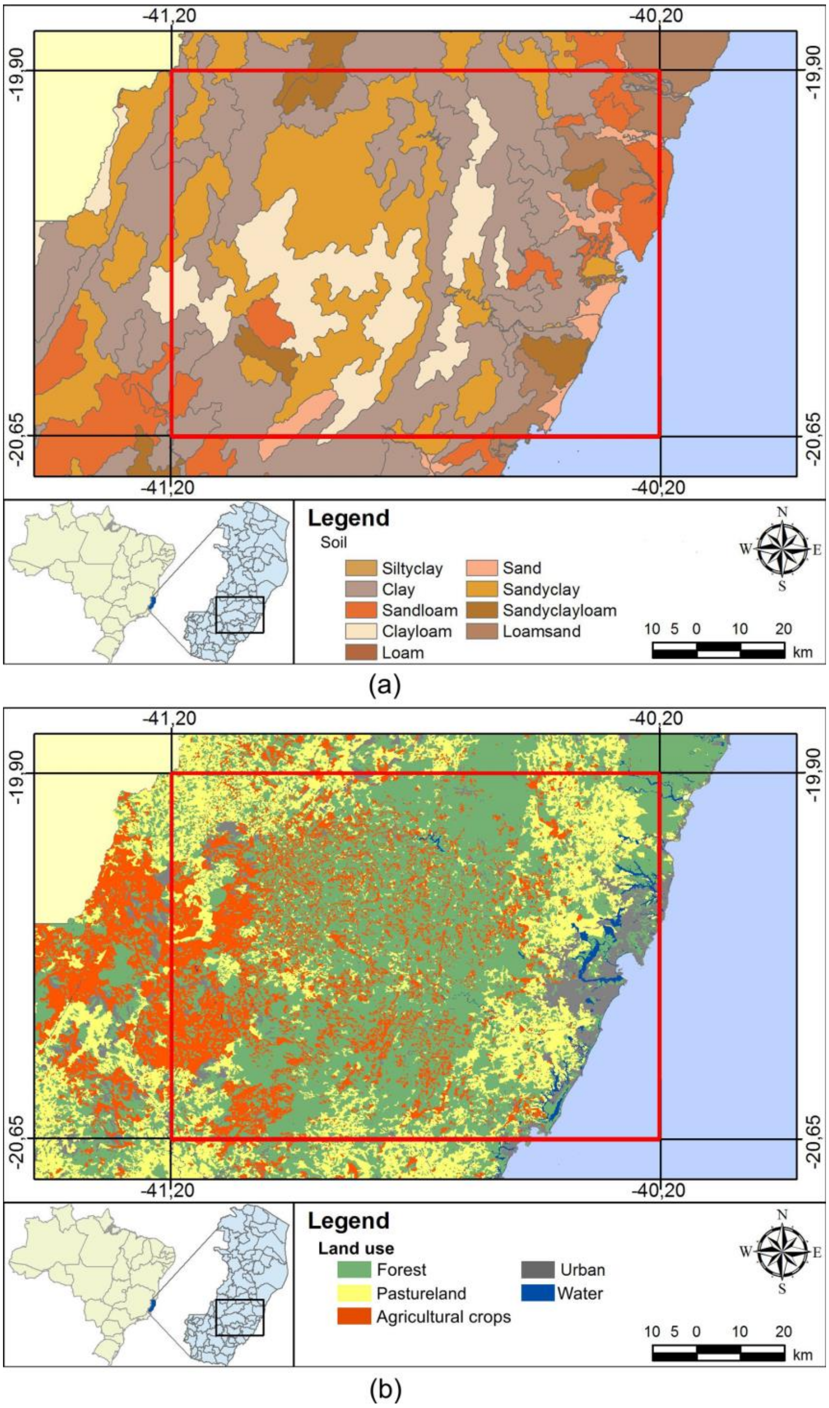
Source: elaborated by the authors.

The estimated soil parameters are divided into two categories (Xie et al., 2007). For the first category, the soil parameters required by the VIC model for each soil layer are the saturated hydraulic conductivity, the porosity, the field capacity, the wilting point, and the exponent of the unsaturated hydraulic conductivity curve. However, the only available data from these basin soils were the soil class, the texture (Figure 2a) and the depth (GEOBASES, 2012). Therefore, the soil parameters values were estimated from the US Department of Agriculture (USDA) soil texture classes, which are based on literature descriptions (Rawls, Ahuja, Brakensiek, & Shirmohammadi, 1993). These parameters were estimated for the three soil layers considered in the VIC application. The depths were determined to be 0.3 m to the first soil layer and 1.0 m to the second soil layer. The depth of the third soil layer was calibrated, as described later.

The second category of soil parameters is subject to calibration: the infiltration parameter (b_inf); the three soil-layer thicknesses (depth); and the three parameters in the base flow scheme, including the maximum velocity of base flow (Dsmax), the fraction of maximum base flow (Ds), and the fraction of maximum soil moisture content of the third layer (Ws) at which a nonlinear base flow response is initiated. All these parameters were calibrated due to the difficulty in determining average soil properties over a large area and because soil depths are not well known over large areas (Xie et al., 2007).

The identification of land cover was determined from aerial photographs using remote sensing photo-interpretation techniques (GEOBASES, 2012). Five different classes were considered: forests, agricultural crops, pastureland, urban and water (Figure 2b).

Figure 2. Maps of the basins: (a) textural classes of the soil and (b) land cover and land use.



Source: elaborated by the authors.

In the Figure 2, the reads can observe the spatial distribution of soil types and the spatial distribution of land uses over Jucu and Santa Mara da Vitória basins.

Table 2 presents the correspondence of land uses classes to their corresponding land uses in Land Data Assimilation Systems (LDAS) (Rodell et al., 2004).

Table 2. Land cover and land use determined within the basins and their corresponding classes in Land Data Assimilation Systems (LDAS).

Number	Land cover and land use	Corresponding LDS class
1	Forest	Evergreen Needle Leaf Forest
2	Pastureland	Grassland
3	Agricultural crops	Cropland
4	Urban	Urban and Built-up
5	Water	Water

Source: elaborated by the authors.

The readers can observe in Table 2 that the correspondence was made due to the lack of data for all vegetation parameters required by VIC. Finally, vegetation-related parameters, such as architectural resistance, minimum stomatal resistance, leaf-area index, albedo, roughness length, zero-plane displacement, and fraction of root depth of each soil layer, for each vegetation class were estimated based on LDAS data (Rodell et al., 2004).

The runoff and subterranean flow simulated by VIC are routed from each model grid cell to one of eight neighbouring cells, according to the estimated local flow direction. The Lohmann et al. (1996) routing model was the use to simulate discharge along a stream network. The routing model uses a triangular unit hydrograph and linearized St Venant's equations to route the streamflow separately from each individual grid cell to the basin outlet through the channel network. To execute the routing model, the following parameters were necessary: a diffusivity equal to 800 m^2 s^{-1}; a streamflow velocity equal to 1.5 m s^{-1}; and a pixel size equal to each of VIC's tested spatial resolutions (as described later).

2.2. Calibration and validation of the VIC model

To calibrate and validate the model, VIC was executed at a daily time step for the period of 1992–2001. This period was partitioned into one period of 1992–1996, used for model parameter estimation (calibration), and another period of 1997–2001, used for model verification (validation). In the calibration phase, the first two years were used to establish the VIC model. Table 3 presents the soil parameters that were calibrated.

Table 3. The soil parameter calibration values for the basins analysed by the VIC model.

Parameter	Values			
b_inf (dimensionless)	0.001	0.134	0.267	0.4
Ds (dimensionless)	0.001	0.334	0.667	1
Dsmax (mm day^{-1})	0.001	10	20	30
Ws (dimensionless)	0.001	0.334	0.667	1
Depth (m)	0.001	0.667	1.34	2

Source: elaborated by the authors.

As can be seen in Figure 3, the following soil parameters were calibrated: Ds, Dsmax, Ws, b_inf and the depth of the third soil layer.

Due the lack of data, inherent of the present study, the values of these parameters were obtained from these suggested by Gao et al. (2010). All combinations of the different calibration values for each parameter were tested, resulting in a total of 1,024 parameter combinations. The calibration was performed for each of the three sub-basins separately, using the daily flow recorded at each stream gauge.

VIC commonly has been applied using spatial resolutions between 0.125º and 2º, whereas new applications use a refined resolution of 0.0625º. With these spatial resolutions, VIC is designed for watershed scales greater than 500 km2 (Beckers, Smerdon, & Wilson, 2009). This size is compatible with the dimensions of the three sub-basins analysed in this paper (980, 1690 and 929 km²). The entire calibration phase was conducted using only one standard spatial resolution: 0.0625º.

Subsequently, in the validation phase, ten different spatial resolutions were tested. The purpose of these tests was to verify under what spatial resolution VIC would perform better. The spatial resolutions tested were 0.0833º, 0.0625º, 0.0500º, 0.0333º, 0.0250º, 0.0200º, 0.0167º, 0.0133º, 0.0125º and 0.0083º, corresponding to pixels of 9.2 km, 6.9 km, 5.5 km, 3.7 km, 2.8 km, 2.2 km, 1.8 km, 1.5 km, 1.4 km and 0.9 km, respectively. Generally, spatial resolutions lower than the tested values do not allow for the execution of the ROUTE model, whereas higher values do not represent the environmental characteristics of the basins, due the great pixel size.

Statistical indexes were used to compare the simulated and observed outlet streamflow hydrographs to evaluate the ability of VIC to reproduce the continuous daily streamflows at each sub-basin. The following statistical indexes were used for the calibration and validation phases: the Nash–Sutcliffe efficiency coefficient (NS); the logarithm NS (NSlog) and the relationship between the observed and simulated streamflow depths (ΔV), represented by

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equations 1, 2 and 3, respectively.

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

$$NS_{log} = 1 - \frac{\sum_{i=1}^{n}(\ln S_i - \ln O_i)^2}{\sum_{i=1}^{n}(\ln O_i - \ln \overline{O})^2} \quad (2)$$

$$\Delta V = \frac{\sum_{i=1}^{n}(S_i) - \sum_{i=1}^{n}(O_i)}{\sum_{i=1}^{n}(O_i)}.100 \quad (3)$$

where: S is the VIC daily simulated streamflow (m^3 s^{-1}); O is the daily observed streamflow (m^3 s^{-1}); and $\overline{O}$ is the daily observed average streamflow (m^3 s^{-1}).

2.3. Simulation of land use changes

Following VIC's calibration and validation, three scenarios of land use alteration were simulated. All scenarios consisted of increasing the Atlantic Rainforest cover representing Espirito Santo State project of increasing on forest cover, as follows:

- The application of a government project known as "Ecological Corridors" (Bergher et al., 2015), which consists of linking native forest fragments (CM1) .
- The increase of 20% of the forest cover (CM2).
- The increase of 50% of the forest cover (CM3).

3. Results and Discussion

Among the 1,024 combinations of calibration parameters tested, Table 4 presents the ten best performing combinations for each sub-basin or stream gauge station.

Table 4. The combinations of calibration parameters used in the calibration phase that resulted in the best performance of VIC for the Santa Maria da Vitória (STAMA), Jucu Braço Norte (JUCUM) and Jucu (JUCUE) watersheds.

Station	Combination	b_inf (dimensionless)	Ds (dimensionless)	Ds_max (mm day^{-1})	Ws (dimensionless)	Depth (m)	NS	NS_{log}	ΔV
STAMA	607	0.267	0.334	10	1	1.34	0.24	-2.68	-42%
	603	0.267	0.334	10	0.667	1.34	0.23	-3.23	-41%
	606	0.267	0.334	10	1	0.667	0.23	-3.80	-41%
	671	0.267	0.667	10	1	1.34	0.23	-3.77	-41%
	623	0.267	0.334	20	1	1.34	0.23	-3.78	-41%
	602	0.267	0.334	10	0.667	0.667	0.23	-4.81	-41%
	604	0.267	0.334	10	0.667	2	0.23	-2.81	-42%
	624	0.267	0.334	20	1	2	0.23	-3.16	-42%
	672	0.267	0.667	10	1	2	0.23	-3.16	-42%
	608	0.267	0.334	10	1	2	0.23	-2.51	-44%
JUCUM	351	0.134	0.334	10	1	2	-0.45	-5.59	-48%
	348	0.134	0.334	10	0.667	2	-0.44	-5.87	-46%
	347	0.134	0.334	10	1	1.34	-0.43	-5.51	-45%
	352	0.134	0.667	10	1	2	-0.46	-6.46	-44%
	416	0.134	0.334	20	1	2	-0.46	-6.46	-44%
	368	0.134	0.334	10	0.667	1.34	-0.45	-6.46	-44%
	350	0.134	0.334	10	1	0.667	-0.48	-7.69	-44%
	415	0.134	0.667	10	1	1.34	-0.49	-7.58	-43%
	367	0.134	0.334	20	1	1.34	-0.49	-7.58	-43%
	276	0.134	0.001	10	0.001	2	-0.51	-7.89	-43%
JUCUE	351	0.134	0.334	10	1	1.34	-0.28	-4.30	-57%
	347	0.134	0.334	10	0.667	1.34	-0.28	-4.50	-56%
	348	0.134	0.334	10	0.667	2	-0.27	-4.18	-56%
	352	0.134	0.334	10	1	2	-0.29	-4.89	-56%
	368	0.134	0.334	20	1	2	-0.29	-4.89	-56%
	350	0.134	0.334	10	1	0.667	-0.28	-4.82	-55%
	367	0.134	0.334	20	1	1.34	-0.29	-5.61	-56%
	276	0.134	0.001	10	0.001	2	-0.31	-5.85	-55%
	344	0.134	0.334	10	0.334	2	-0.30	-5.57	-55%
	412	0.134	0.667	10	0.667	2	-0.30	-5.57	-55%

Source: elaborated by the authors.

As the reads can see at Table 4, the four best combinations for STAMA were 607, 603, 606 and 671. However, for JUCUM and JUCUE the four best combinations were the same values (351, 348, 347 and 352) because one sub-basin (JUCUM) is located inside the other (JUCUE).

All five parameter calibration values were similar to those determined in a previous VIC calibration study (Xie et al., 2007). Negative values of NS_{log} illustrate that none of the combinations was able to provide a good representation of the lower streamflow. By analysing ΔV values, we observed that the best combinations resulted in an underestimation of the streamflow depth between 40 and 50%. Positive values of NS were determined only for STAMA; however the values are too low (NS < 0,36), indicating an unsatisfactory performance (Motovilov, Gottschalk, Engeland, & Rodhe, 1999).

An alternative solution to obtain better calibration results includes a multi-site calibration (simultaneous calibration at two or more sites) (Fischer et al., 2013). However, the lack of data from these watersheds precluded this type of calibration.

Similar to the presented results, other studies (Victoria, 2010; Zhu & Lettenmaier, 2007) have determined low values for the NS index, including negative values, for VIC's calibration period. In Mexico, Zhu & Lettenmaier (2007) found NS lower than 0.3 in four of the 14 watersheds that they studied. They found no specific reason for the unsatisfactory performance of VIC but suspected errors in the rainfall input data and a deficiency of the parameter input values. Victoria (2010), studying basins in the Brazilian Amazon, found negative NS values in two of the five modelled watersheds. According to him, the underestimates of rainfall were responsible for the low performance. However, the researcher concluded that with the exception of errors in the magnitude of the simulated streamflow, the hydrologic response of the watersheds to the rainfall was satisfactory. Therefore, the VIC model could simulate different streamflows in response to different rainfall events due to the errors of the magnitude of the streamflow events. This occurred in the present paper, as shown later in Figure 3.

The low values of NS in the calibration phase and in the validation phase (described later) can be explained by the following reasons:

- Only one meteorological station dataset was considered in simulating the entire basin's evapotranspiration (ET).
- The two basins have very specific regional characteristics that cannot be modelled by VIC, a global model with a low spatial resolution: the high spatial variability of terrain slopes, the spatial distribution of vegetation and the fact that VIC assumes only one value for the infiltration rate for large surface areas.
- VIC models only natural streamflow and does not consider the flow regularization due to the existence of hydraulic structures, such as dams, unless this information is specifically inserted. However, the lack of data inherent to the studied basins did not allow for the insertion of this information because the existing dams are too little compared to the pixel size in VIC.

- The values of the input soil and vegetation parameters are related to the global soil and vegetation parameters and are not specific to the basin characteristics. However, this lack of information is inherent in the objective of this study.

During the validation phase, no combination presented positive values of NS for the JUCUM and JUCUE stations. Therefore, Table 5 shows the statistical indexes for the combinations with the best performances in the validation period for the STAMA station.

Table 5. The combinations of calibrated parameters that resulted in the best performance of VIC for the validation phase at the Santa Maria da Vitória station for all the analysed spatial resolutions.

Comb.	Station	Spatial resolution									
		0.0833º	**0.0625º**	**0.0500º**	**0.0333º**	**0.0250º**	**0.0200º**	**0.0167º**	**0.0133º**	**0.0125º**	**0.0083º**
347	NS	0.41	0.05	0.40	0.39	0.40	0.36	0.24	0.17	0.08	-0.06
	NS_{log}	-0.10	-3.14	-0.76	-0.18	-0.20	-0.12	-0.05	-0.03	-0.02	0.02
	ΔV	-8%	-72%	-38%	-7%	-12%	-8%	5%	8%	13%	20%
348	NS	0.43	0.03	0.26	0.41	0.37	0.37	0.28	0.22	0.14	0.02
	NS_{log}	0.17	-2.47	-1.25	0.12	-0.45	-0.33	0.20	0.21	0.20	0.21
	ΔV	-10%	-72%	-53%	-8%	-32%	-29%	4%	6%	12%	14%
351	NS	0.42	0.03	0.37	0.40	0.41	0.37	0.27	0.21	0.14	0.02
	NS_{log}	0.14	-2.67	-0.43	0.08	0.07	0.12	0.19	0.19	0.20	0.21
	ΔV	-12%	-73%	-41%	-11%	-16%	-12%	1%	4%	9%	14%
352	NS	0.33	0.10	0.41	0.30	0.34	0.29	0.10	0.01	-0.10	-0.23
	NS_{log}	-0.21	-3.41	-0.92	-0.29	-0.31	-0.24	-0.14	-0.12	-0.10	-0.04
	ΔV	-6%	-71%	-37%	-5%	-10%	-6%	8%	11%	16%	22%
603	NS	0.32	0.11	0.43	0.29	0.33	0.27	0.06	-0.02	-0.15	-0.29
	NS_{log}	-0.51	-4.00	-1.34	-0.64	-0.65	-0.57	-0.47	-0.43	-0.40	-0.31
	ΔV	-4%	-70%	-35%	-2%	-7%	-3%	11%	14%	19%	26%
606	NS	0.29	0.12	0.43	0.26	0.31	0.25	0.02	-0.07	-0.21	-0.35
	NS_{log}	-0.86	-4.78	-1.83	-1.02	-1.03	-0.92	-0.79	-0.74	-0.69	-0.55
	ΔV	-4%	-70%	-35%	-2%	-8%	-4%	10%	13%	19%	25%
607	NS	0.33	0.10	0.41	0.30	0.34	0.29	0.10	0.01	-0.10	-0.23
	NS_{log}	-0.21	-3.41	-0.92	-0.29	-0.31	-0.24	-0.14	-0.12	-0.10	-0.04
	ΔV	-0.06	-0.71	-0.37	-0.05	-0.10	-0.06	0.08	0.11	0.16	0.22
671	NS	0.30	0.13	0.43	0.27	0.32	0.26	0.03	-0.06	-0.20	-0.35
	NS_{log}	-0.79	-4.54	-1.70	-0.94	-0.95	-0.85	-0.74	-0.69	-0.65	-0.52
	ΔV	-6%	-71%	-37%	-5%	-10%	-6%	8%	11%	16%	22%

Source: elaborated by the authors.

The results presented in Table 5 show that a spatial resolution equal to 0.0625º presented the worst statistical indexes, considering all the combinations tested. The values are worse than those presented in the calibration phase with the same spatial resolution. Using only one spatial resolution in the calibration phase proved to be inadequate for the basins under analysis. Providing different calibrations for the different spatial resolutions would be better for more accurately representing the specific soil and surface characteristics. However, the calibration of only one spatial resolution reduces the computational processing time.

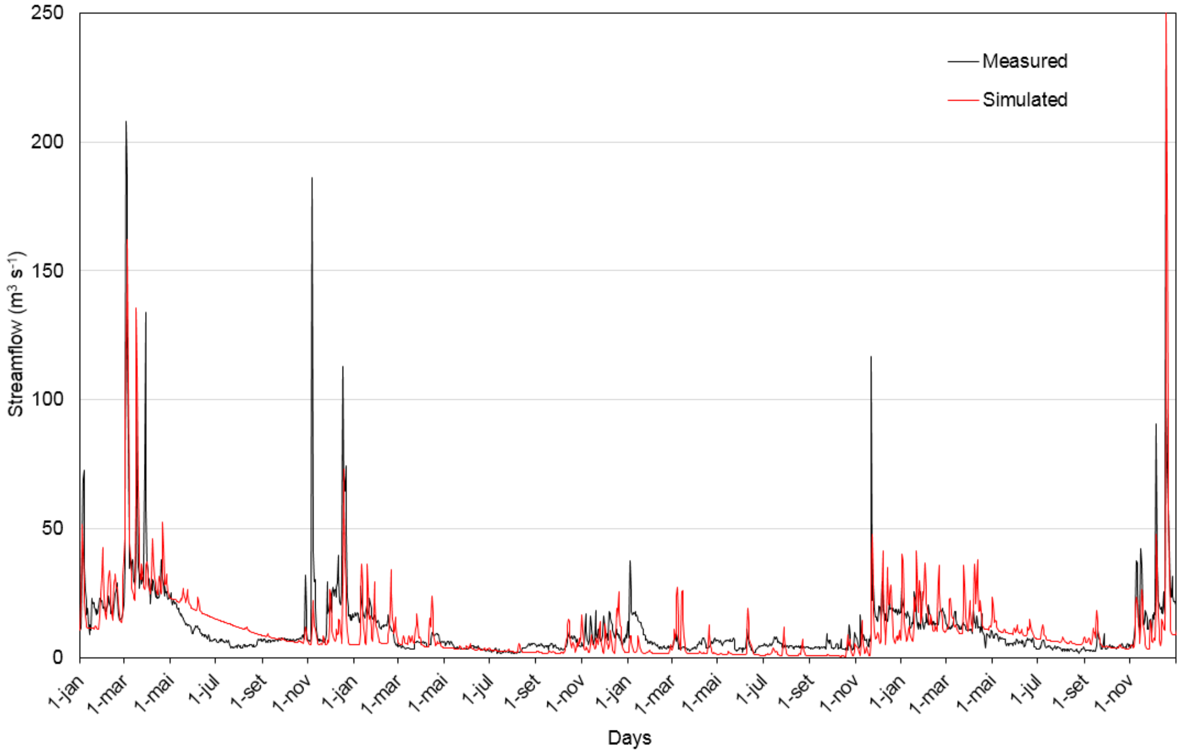
The results worsened when approaching a better spatial resolution (i.e., a smaller pixel size). To improve the resolution, new types and spatial distributions of the soil and land use area were inserted, resulting in VIC not accomplishing new specificities of the basins. Therefore, a new calibration of these resolutions must be conducted to provide a better simulation of the watershed hydrological behaviour, as suggested by Bressiani et al. (2015), analysing the application of another hydrological model (SWAT) under the same data conditions. One of the primary problems of applying global simulation models to smaller watersheds is the reduction in the spatial resolution, which results in an incomplete representation of the hydrological processes and the alteration of the magnitude of the simulated streamflow. Building the input files, with regards to the choice of spatial resolution, should be considered as the primary goal. Depending on the size of the basin, the results may not be satisfactory because, in addition to the error regarding the size of the area in the flow results, the simulations of land use and cover change may be affected by not covering all the areas belonging to a particular basin.

Combinations 348 and 351 provided the best results of all the tested spatial resolutions. Both combinations were not among the best ten combinations determined for the calibration phase (Table 4) for STAMA. This shows that the best input parameter calibration values will not necessarily be the best for validation, necessitating the verification of many combinations among the best ones. An interesting result was found: the transfer of the calibration parameters from JUCUM and JUCUE to STAMA generated good results, compared to the opposite (parameters transferred from STAMA to JUCUM and JUCUE). This illustrates that the application calibrated parameter established for other watersheds may not always be representative of other sites or of the larger region (Groenendijk et al., 2011).

The best results when aggregating the spatial resolution and the input parameter combination, shown on Table 5, was 0.0833º (spatial resolution) and 348 (input parameter combination), with NS equal to 0.43, greater than the minimum considered to be satisfactory (Van Liew, Veith, Bosch, & Arnold, 2007; Motovilov et al., 1999).

The observed and simulated hydrographs for STAMA are shown in Figure 3.

Figure 3. The hydrograph of the STAMA station, containing the simulated (best combinations of input parameters and spatial resolution) and observed streamflows during the validation period.

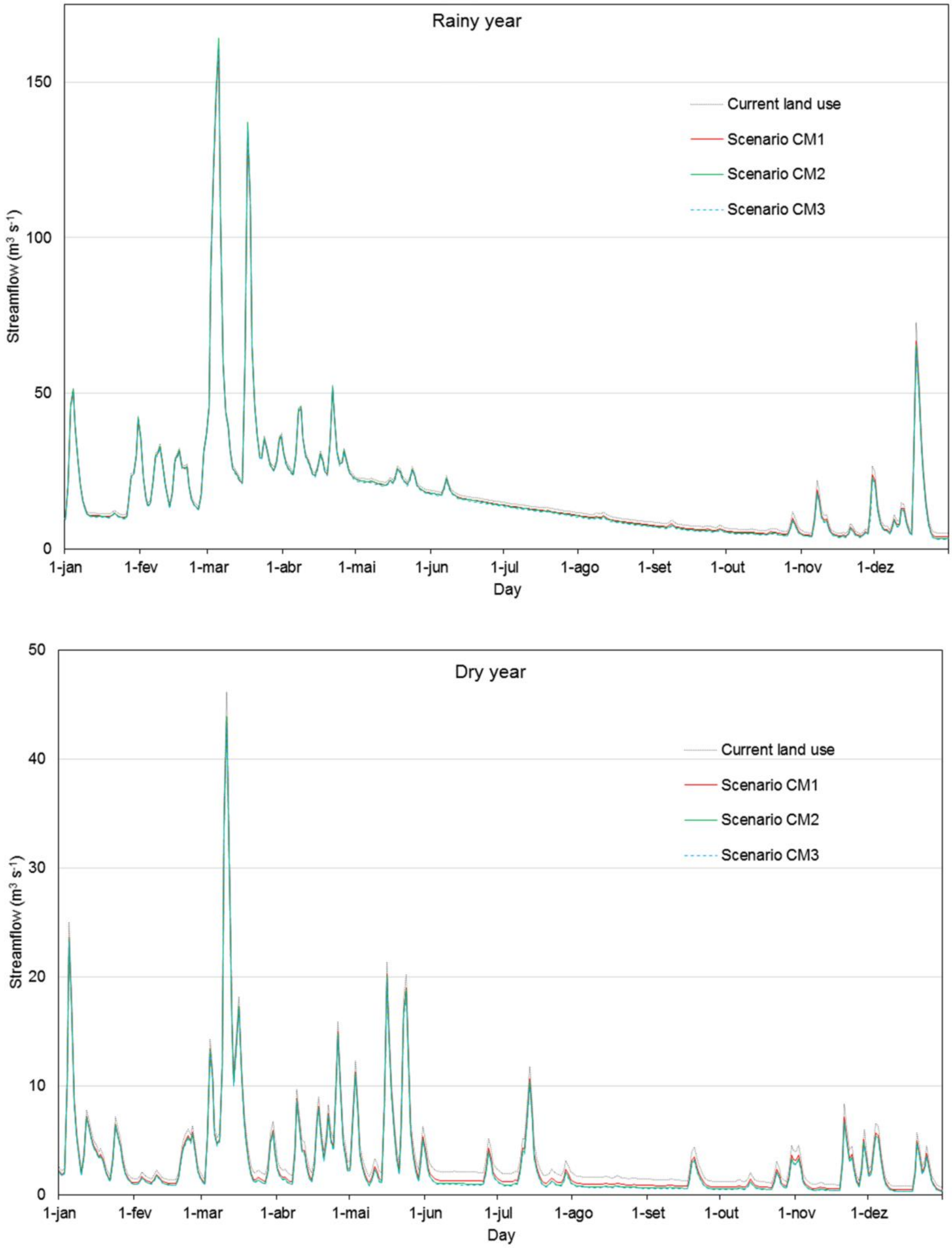


Source: elaborated by the authors.

As shown in the Figure 3, the simulated hydrograph behaviour exhibited a good response, although deficiencies in the magnitude of the events existed, particularly for higher streamflow values. The tendency to underestimate streamflows is evident, particularly for the low flow periods, which is due to an overestimation of ET. ET overestimation occurs because all the meteorological data were obtained from Vitória's weather station. This station is located near the coast at the outlet of the basins, where the wind speed, air temperature, and ET are higher (Castro, Pezzopane, Cecílio, Pezzopane, & Xavier, 2010; C. A. D. Ribeiro et al., 2011). However, due to the lack of data, this was the only meteorological information available. (Authors. Before you insert Figure 3 in text it's necessary to call that figure).

The scenarios for land cover and land use changes for STAMA were simulated using the best set that aggregated the spatial resolution and the input parameter combination for the validation (0.0833º on spatial resolution and combination of input parameters combination number 348). The hydrographs are shown in Figure 4.

Figure 4. Hydrographs simulated by VIC for standard land use and forest cover increasing scenarios for the STAMA station: (a) all streamflow values and (b) streamflow values lower than 30 $m^3\ s^{-1}$.



Source: elaborated by the authors.

The reader can observe in the Figure 4 that the streamflow decreased for the scenarios with an increase in forest cover area. The greater the increase in forest cover, the higher the reduction of streamflow. The reduction of annual average streamflow was approximately 8.5% for CM1 (Ecological Corridors); 10.4% for CM2 (an increase of 20% of forest cover) and 12.8% for CM3 (an increase of 50% of forest cover). The surface runoff was reduced by approximately 3.3%, 3.1% and 5.2% for scenarios CM1, CM2 and CM3, respectively.

Similar results, with measured data showing the reduction of streamflow in response to the increase in forest cover, have been previously obtained. This result was also found on nearby basins (Eugênio, Santos, Dalfi, & Moreira, 2013; D. dos R. Pereira et al., 2014), other basins with tropical forest cover (Beskow, Norton, & Mello, 2013; Jobbágy, Baldi, & Nosetto, 2012; Locatelli & Vignola, 2009) and basins with alternate forest cover (Andréassian, 2004; Farley, Jobbágy, & Jackson, 2005).

The impacts of forest cover on streamflow, to a greater or lesser degree, depend on several factors, such as: the basin area, the soil use that is being replaced for forest cover, the amount of surface that is being altered, the soil type and properties, the water table depth, the spatial distribution of land cover on the basin, basin climatic and meteorological conditions, the topography and other basin morphometric characteristics (Bleby, Colquhoun, & Adams, 2012; Farley et al., 2005; Ferraz, Lima, & Rodrigues, 2013; Salemi et al., 2012, 2013; Williams et al., 2012).

Regarding the water cycle, forest cover has a positive impact on increasing water infiltration and decreasing runoff and soil erosion, which is associated with an increased groundwater recharge and subsurface flow. However, increasing forest cover is also associated with higher ET and rainfall interception by the canopy. The ultimate impact of forests on streamflow depends on the balance between the positive impact of increased infiltration with the negative effects of increased ET and interception. If the increase in infiltration is greater than the rise of ET, streamflow generally will increase. If the increase in ET is higher than the increase in infiltration, the effect on the streamflow will be a reduction.

Due to the physical, geological, geographical, climatic and biological complexities of the watershed, the actual impact of land use and land cover change can vary greatly between different river basins. Therefore, the impacts on the streamflow simulated in STAMA may not be the same as other basins in the same region, which reinforces the important role of hydrological modelling for predicting the effects of changes for each particular basin.

Final Considerations

Hydrological models are fundamental water resource management tools. The VIC model is more suitable for applications on a global scale. Therefore, as demonstrated in this paper, a limitation exists in the application of the model in small basins due to the necessity to improve the spatial resolution of the area under analysis.

The results obtained during the process of calibration and validation indicate that VIC's performance was satisfactory in only one basin. These results likely were influenced by the adopted type of calibration, in addition to the lack of information that leads to the simplification of the input parameterization process.

Despite the limitations observed, the VIC model has potential for use in basins similar to Jucu and Santa Maria da Vitoria as the calibration could be performed with more available input data. The existence of more climatic data is essential for a better representation of the wide distribution of ET and a better performance of VIC on streamflow simulation.

The simulation of the scenarios where an increase of forest cover occurred along the basin showed the tendency of the average streamflow and runoff to decrease in STAMA.

Both for the VIC model and for future projects with hydrological modeling, obtaining more accurate information on the base data (soil, vegetation, climate) is of paramount importance for a good result in the hydrological simulation process and, consequently, in the management water resources. In general, the main base data found for Brazil, have certain problems in relation to quality, comprehensiveness and availability. These characteristics of the Brazilian data make the research time-consuming, limited and with a high level of reservations. With this, it is necessary to start a survey of the basic data, together with their quality, before starting to work with the model.

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) - Finance Code 001; and, Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

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