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Special Edition

Performance evaluation of HEC-HMS hydrological model applied to the Tibagi river watershed in the State of Paraná – Brazil

Avaliação de desempenho do modelo hidrológico HEC-HMS aplicado à bacia do rio Tibagi no Estado do Paraná – Brasil

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ABSTRACT

The present work performs statistical evaluations of the HEC-HMS hydrological model for the six sub-basins that form the Tibagi River watershed, located in the central-eastern region of the state of Paraná, Brazil. The physical characterization of the study area is developed by techniques of geographic information systems. The effective rainfall is estimated using the SCS curve number method, the baseflow is determined by a recession curve method, and hydrographs are simulated using the SCS unity hydrograph method. The simulated hydrographs are compared with measured outflow data of the six sub-basins for a selected period of 2017. The performance of the models is assessed using a validation criterion based on RSR, NSE e PBIAS statistical indexes. After input parameters calibration, the comparisons of the hydrographs show excellent agreement with measure data according to the classification adopted in the work. The simulated peak flows range from 3.3 to 8.6% when compared to the observed peak flows, indicating that the model can assist in the prediction of maximum discharges.

Keywords: GIS; HEC-HMS; Hydrologic modeling; Tibagi river watershed

RESUMO

Este trabalho avaliou a performance do modelo hidrológico HEC-HMS aplicado às seis sub-bacias que formam a Bacia Hidrográfica do Rio Tibagi, localizada na região centro-oriental do estado do Paraná, Brasil. A caracterização física da área de estudo foi realizada por técnicas de sistemas de informações geográficas (SIG). A chuva efetiva foi estimada usando o método *SCS Curve Number*, o escoamento de base foi determinado pelo método da curva de recessão e a transformação da precipitação efetiva em vazão foi realizada pelo método do Hidrograma Unitário SCS. Os hidrogramas simulados foram comparados com os hidrogramas observados nos exutórios das seis sub-bacias para um período selecionado no ano de 2017. O desempenho dos modelos foi avaliado mediante o uso de um critério de performance baseado nos índices estatísticos RSR, NSE e PBIAS. Após a calibração dos parâmetros de entrada das simulações, as comparações entre os hidrogramas foram caracterizadas como sendo “muito boas”, de acordo com a classificação de performance estabelecida. As vazões de pico simuladas variaram entre 3,3 e 8,6% em relação as vazões de pico observadas, indicando que o modelo possui potencial para auxiliar na previsão de vazões máximas.

Palavras-chave: SIG; HEC-HMS; Modelagem hidrológica; Bacia do rio Tibagi

1 INTRODUCTION

Hydrological modeling consists of procedures employed for simulation of hydrological variables of interest with several objectives, such as contributing to the understanding of hydrological processes, estimating variables that are not available in the field, and predicting scenarios for water resources management (MORAES *et al*., 2003). One of the most practical ways to perform hydrological simulations is by the use of computational models, which are primarily developed through geographic information systems (GIS), for later use in specific computational tools in order to obtain the hydrological variables of interest (KLEMES, 1986, MOREIRA, 2013).

Among the hydrological models that use data from a GIS, the Hydrologic Modeling System of the Hydrologic Engineering Center (HEC-HMS) is one of the most applied worldwide. HEC-HMS is an open-source computer program, developed by the US Army Corps of Engineers, that calculates series of flows using mathematical models that simulate the discharge-precipitation process in dendritic watersheds. The objective of the program is the generation of synthetic hydrographs that can help in decision making and in a better understanding of the hydrological processes of the watershed (USACE, 2000).

In Brazil, HEC-HMS has been used in several studies to perform simulations and create hydrological scenarios (DE SOUZA, 2017, RESENDE *et al*., 2017, MOREIRA, 2013). Resende *et al*. (2017) studied the optimization of the storage volume of the

Três Marias Hydroelectric Power Plant (HPP) in times of water scarcity. The objective was to establish minimum water levels in the Jaíba Irrigation District (DIJ), located downstream from this HPP. Through simulations in the HEC-HMS, outflow propagation from four incremental watersheds were performed to the city of Mocambinho, enabling the determination of the flow and minimum water levels that would reach DIJ. The study concluded that the minimum incoming flow of the Três Marias HPP could be reduced from 420 m³/s to 80 m³/s, so that the water storage in the reservoir was preserved and the supply in the city was assured.

Recent studies have also used HEC-HMS to model flood scenarios. Moreira (2013) simulated runoff caused by rainfall with various return periods, in the Granjeiro River Hydrographic Basin (BHG), located in the municipality of Crato, state of Ceará. The author implemented the HEC-HMS model based on the current land occupation scenario and also for increase and reduction scenarios of land occupation. The results showed that with a 15% increase in occupation in BHG, the probability of flooding in the Granjeiro River would double, and with a 15% reduction in the population, the possibility of flooding in the river would be reduced by half.

In general, most studies available in the literature demonstrate that the HEC-HMS hydrological model can help in the management of water resources and in the planning of actions, especially in extreme events such as floods and droughts, enabling the preservation of water resources and minimizing the impacts of these events over the environment.

In the specific case of the state of Paraná, which in 1890 had 249,491 inhabitants and in 2010 contained 10,444,526 (IBGE, 2010), it was observed an accentuated reduction of forest areas from 16.76 million hectares in 1890 to 0, 87 million hectares in 1990 (GUBERT FILHO, 1998). One of the most affected regions was the Second Planalto Paranaense region, which from 1920 onwards went through a process of extinction of forest areas due to the implementation of extensive agriculture (GUBERT FILHO, 2010). As a result of deforestation, the region became more susceptible to flooding during periods of extreme rainfall, so that hydrological studies in the region were necessary and pertinent.

The Tibagi River watershed (BHRT) is located over this affected region. BHRT has a water demand for public supply of 4.96 m³/s, and industrial water demand of 6.52 m³/s and an agricultural water demand of 0.105 m³/s, totaling a demand of 16.55 m³/s (ÁguasParaná, 2013). In addition, this watershed contains four relevant HPP with approximately 376 MW (COPEL, 2019).

Considering the importance of BHRT for the affected region, in terms of housing water supply, as well as for the local economy, industries and agriculture, this paper aims to: (a) develop a hydrological modeling study for BHRT, considering a selected period of the year 2017 and (b) perform a complete statistical analysis to quantify the performance of the results obtained by the HEC-HMS model, when compared with flow data measured in the BHRT.

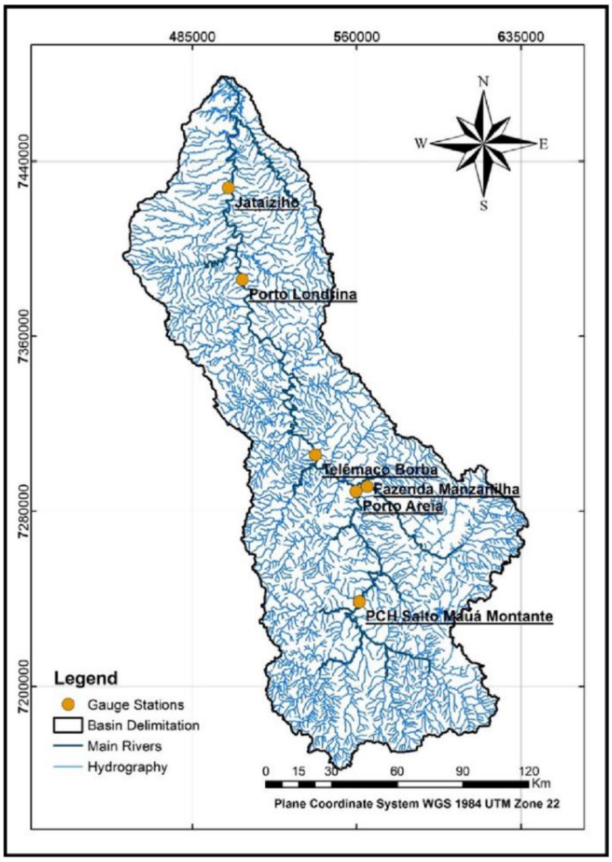
The remainder of this manuscript is organized as follows: section Materials and Methods describes the characteristics of the study area, the type of soil and discharge station maps, the hydrograph simulation methods, the calibration parameters and the performance analysis criteria. Section Results and Discussions describes and discusses the obtained results and presents the performance of the HEC-HMS model for each sub-basin separately. Section Conclusions presents the conclusions and recommendations for future work.

2 MATERIALS AND METHODS

BHRT is located in the central-eastern region of the state of Paraná, between the geographic coordinates 22º 47' 22'' and 25º 36' 25'' of south latitude, and 49º 36' 00" and 51º 27' 36'' of west longitude. BHRT is one of the largest watersheds in the state, presenting an area of 24,937.4 km², equivalent to 13% of Paraná state area. Tibagi River begins in the municipality of Palmeira at 1,150 m of altitude, flowing into the Paranapanema River 550 km away to the north at 300 m of altitude (ÁGUASPARANÁ, 2009, DE FRANÇA, 2002)

In the present study, BHRT is divided into six sub-basins: PCH Salto Mauá Montante, Fazenda Manzanilha, Porto de Areia, Telêmaco Borba, Porto Londrina and Jataizinho. Each of them presents outlet discharge and precipitation monitoring stations with data available from the website of the Agência Nacional de Águas (ANA). The BHRT map with the location of the monitoring stations of each sub-basin is shown in Figure 1.

Figure 1 – Map of Tibagi River watershed (BHRT). Location of rainfall and discharge monitoring stations in the sub-basins



Source: Authors, 2021

To characterize the BHRT regarding the types of soil, as well as the soil use and occupation, maps of land use and occupation and soil types of the State of Paraná are used in shapefile format. These maps are retrieved from the online library of the Instituto de Terras, Cartografia e Geologia do Paraná (ITCG). The ITCG land use and occupation map are based on data from the Instituto Paranaense de Desenvolvimento Econômico e Social for the year of 2002.

The maps with information on land type, use and occupation are processed using GIS techniques, allowing to obtain curve number (CN) values for the BHRT region. CN is a constant that varies from 1 to 100 and attempts to represent the soil cover conditions, its permeability and infiltration capacity. Average CN values are adopted for each sub-basin as input in the HEC-HMS computational program.

Digital Elevation Models (DEM) are employed to obtain the average slopes of the sub-basins, the drainage network and the flow directions. The adopted DEMs are provided by the Instituto Nacional de Pesquisas Espaciais (INPE), having arc resolution of 1 s and 30 m. Precipitation data used as input in the simulations are obtained from the six selected monitoring stations (ANA, 2019). The precipitations are considered uniformly distributed on the sub-basins. Table 1 illustrates the codes and names of the monitoring stations, the average values of CN and slopes, and the sub-basin areas used in the simulations.

The HEC-HMS simulations are performed from June 1 to 20, 2017, period selected due to the availability of consistent data at all precipitation and discharge monitoring stations. Hourly precipitation data are used as input parameters in the simulations of the Fazenda Manzanilha, Telêmaco Borba and Jataizinho sub-basins. The simulations for the other sub-basins, SHP Salto Mauá Montante, Porto de Areia and Porto Londrina, use 15 minutes input precipitation data.

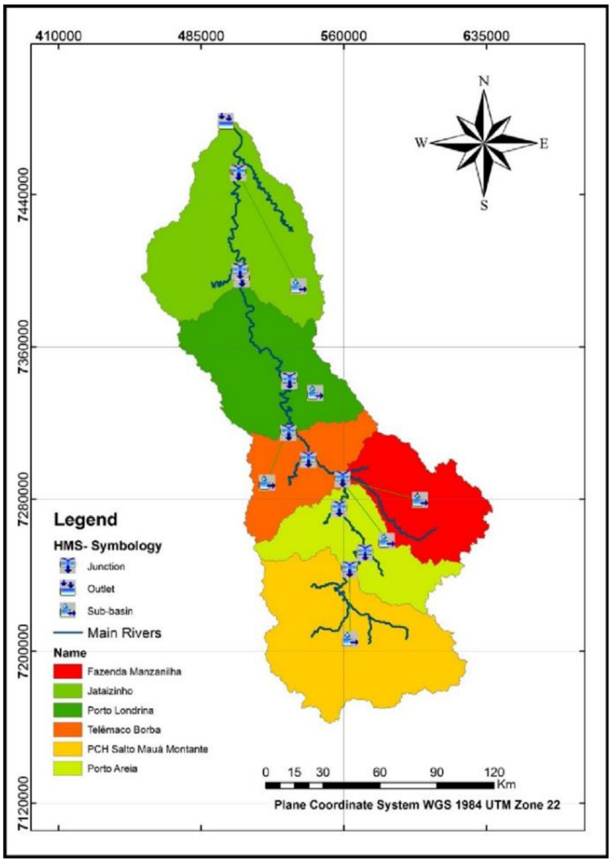
The hydrographs resulting from the simulations are obtained at the junctions between the sub-basins, in the regions close to the monitoring stations. It should be noted that the simulated hydrograph at a given junction is the result of the sum of the flow caused by precipitation over the sub-basin and the outflow from the sub-basins located upstream. Figure 2 illustrates the computational domain used by HEC-HMS simulations, showing the position of the sub-basins, the main river paths and the positions of the junctions in which the hydrographs were simulated.

Table 1 – Codes and names of monitoring stations (ANA, 2019), average CN, average slope and sub-basin areas used in the simulations

Precipitation monitoring station (ANA)	Discharge monitoring station (ANA)	Sub-basin names	Average CN	Average Slope (%)	Sub-basin area (km²)
2350000	64507000	Jataizinho	75.0	2.48	6,009.1
2350066	64501000	Porto Londrina	85.0	5.52	4,456.3
2450061	64482000	Telêmaco Borba	65.5	7.80	2,508.3
2450073	64480995	F. Manzanilha	79.0	11.48	3,048.2
2450072	64464995	Porto de Areia	76.2	15.45	2,975.1
2450076	64446999	PCH Salto Mauá	63.0	21.16	5,945.3

Source: Authors, 2021

Figure 2 – Computational domain in the HEC-HMS symbology, showing the location of the sub-basins, the main river paths and the junctions where the hydrographs are simulated



Source: Authors, 2021

2.1 Hydrograph simulation methods

Simulations in HEC-HMS are performed using the unit hydrograph method, based on the SCS unit hydrograph model SCS-UH (CHOW *et al*., 1988). SCS-UH is an empirical model designed for flood simulation, being one of the most widespread in the world due to the use of a reduced number of parameters that are related to the watershed physical characteristics (TUCCI, 2005). This model was developed through observations of average unit hydrographs, measured in a large number of the United States watersheds (CHOW *et al*., 1988). SCS-UH assumes a linear shape unit hydrograph, such that 37.5% of the total flow occurs before the hydrograph peak given by:

$$Q_p = \frac{2{,}08 \cdot A}{\frac{t_r}{2} + t_p} \tag{1}$$

where Q_p is the peak flow in m^3/s, A is the drainage area in km^2, t_r is the precipitation time in hours and t_p is the peak time in hours.

The peak time is given as a function of the concentration time which can be calculated according to several empirical equations available in the literature. The present work uses the equations suggested by Chow *et al*. (1988) and later analyzed by Silveira (2005) to calculate the peak and concentration times:

$$t_p = 0{,}6 \cdot t_c \tag{2}$$

$$t_c = 0{,}057 \cdot \left(\frac{1000}{CN} - 9\right)^{0{,}7} \cdot L^{0{,}8} \cdot Y^{-0{,}5} \tag{3}$$

where t_p is the peak time in hours, t_c is the concentration time in hours, CN is the curve number; L is the length of the main channel in kilometers and Y s the average slope of the basin in m/m.

The effective rainfall adopted in the SCS-UH model is estimated by the SCS curve number method (TUCCI, 2005). This method uses as input parameters precipitation, soil moisture data, land type and land use data. In this method, the surface runoff volume per unit area of the basin is determined according to (USACE, 2000):

$$V = \frac{(P - I_a)^2}{P + S - I_a} \quad \text{when } P > I_a \tag{4}$$

$$V = 0 \quad \text{when } P \leq I_a \tag{5}$$

where V is the runoff volume per unit area of the basin in mm, P is the precipitation in mm, I_a is the initial losses due to infiltration and S is the soil water storage capacity in mm.

The initial losses, I_a, are estimated for average conditions to be 20% of the soil's storage capacity, S. The soil storage capacity is calculated as (USACE, 2000):

$$S = \frac{25400}{CN} - 254 \tag{6}$$

where CN is the curve number ranging from 1 to 100. The CN represents the soil cover conditions, its permeability and infiltration capacity. The higher the CN, the lower the infiltration and storage capacity of the soil. In the study watershed there is a great diversity of soil and land occupation, so the final CN values used in the simulations are obtained by the average of the CN weighted by the areas of the sub-basins.

The base flow is estimated using the recession curve method according to Chow *et al*. (1988):

$$Q_t = Q_0 K^t \tag{7}$$

where Q_t is the base flow for a given time in m^3/s, Q_0 is the flow at the beginning of the recession in m^3/s and K is a recession constant.

2.2 Calibration of input parameters

The input data required by the HEC-HMS simulations are precipitation data series for the selected period, average CN, estimated initial losses due to infiltration, peak time of the unit hydrograph and baseflow values. These variables are used as input for each sub-basin in preliminary simulations.

HEC-HMS input parameters are calibrated by comparing hydrographs of preliminary simulations with hydrographs measured at the monitoring stations. Calibration is a process of input parameters adjustment, in order to obtain simulated hydrographs as close as possible to those measured in the field. This process is fundamental to improve the performance of final simulations.

An automatic calibration of the HEC-HMS is used in the present work, based on the Peak-Weighted Root Mean Square Error (PWRMSE) function (POURNAMDARI & KAMALI, 2016). The PWRMSE function calculates the square root of the quadratic difference between observed and simulated flows, associating weights to these operations according to:

$$PWRMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Q_i^{obs} - Q_i\ \right)^2 \cdot \left(\frac{Q_i^{obs} - Q_{med}}{2Q_{med}}\right)}{N}} \tag{8}$$

where Q_i^{obs} is the observed discharge and Q_i is the simulated discharge at time i, Q_{med} is the average discharge observed in the period and N is the size of sample data. This index is used to perform automatic calibration of the HEC-HMS, which seeks to adjust the set of input parameters (average CN, initial losses, unit hydrograph peak time and baseflow rate) in order to minimize the value of the PWRMSE function. Once the input parameters are adjusted, new simulations are performed and so-called calibrated simulations.

2.3 Evaluation of simulations performance

For evaluation of simulations performance, three indexes are adopted to measure the accuracy of the simulated hydrographs when compared to the hydrographs measured at the monitoring stations. The first used index is the RSR. This statistical index, typically used for evaluation of hydrological models, consists of the ratio between the root mean square error (RMSE) and the standard deviation of the observed data (DEVP) (SINGH *et al*., 2005):

$$RSR = \frac{RMSE}{DEVP} = \frac{\sqrt{\sum_{i=1}^{N}\left(Q_i^{obs} - Q_i\ \right)^2}}{\sqrt{\sum_{i=1}^{N}\left(Q_i^{obs} - Q_{med}\right)^2}} \tag{9}$$

where Q_i^{obs} is the observed discharge and Q_i is the simulated discharge at time i, Q_{med} is the average discharge monitored in the period and N is the size of sample data.

The second index adopted to the hydrological model performance analysis is the NSE (Nash-Sutcliffe). This statistical index presents the variance of the observed data series in the denominator, such that outputs values are limited between -∞ and 1, the unit value being indicative of a perfect agreement between simulation results and observed data. The NSE index is given by:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_i^{obs} - Q_i\ \right)^2}{\sum_{i=1}^{N}\left(Q_i^{obs} - Q_{med}\right)^2} \tag{10}$$

where Q_i^{obs} is the observed discharge and Q_i is the simulated discharge at time i, Q_{med} is the average discharge monitored in the period and N is the size of sample data.

The third index is the percentage of bias, PBIAS. This statistical index measures the tendency of simulated results to be larger or smaller than observed data. The optimal value of PBIAS is zero, and values close to zero refer to a good precision simulation (GUPTA *et al*., 1999). The PBIAS index is written as follows:

$$PBIAS = \frac{\sum_{i=1}^{N}\left(Q_i\ - Q_i^{obs}\right)\cdot 100}{\sum_{i=1}^{N} Q_i^{obs}} \tag{11}$$

where Q_i^{obs} is the observed discharge and Q_i is the simulated discharge at time I and N is the size of sample data.

RSR, NSE and PBIAS indexes are used in the evaluation of simulations performance, following the criteria established by Moriasi *et al*. (2007), which determines precision levels for the simulations according to the values obtained from these three indexes. The accuracy levels, or also called degrees of performance, are classified into unsatisfactory, satisfactory, good, and excellent.

Table 2 shows the degree of performance classification adopted in the present work, which is determined by combination of RSR, NSE and PBIAS values.

Table 2 – Degrees of hydrological model performance based on combination of RSR, NSE and PBIAS indexes values

Degree of performance	**RSR**	**NSE**	**PBIAS**
Excellent	0.0 ≤ RSR ≤ 0.5	0.75 < NSE ≤ 1.0	PBIAS ≤ ±10
Good	0.5 < RSR ≤ 0.6	0.65 < NSE ≤ 0.75	±10 ≤PBIAS ≤ ±15
Satisfactory	0.6 < RSR ≤ 0.7	0.5 < NSE ≤ 0.65	±15 ≤PBIAS ≤ ±25
Unsatisfactory	RSR > 0.7	NSE ≤ 0.5	PBIAS ≥ ±25

Source: Moriasi *et al*., 2007

3 RESULTS AND DISCUSSIONS

The parameters used as input in the simulations are the precipitation time series, the peak time, t_p, the CN and I_α coefficients, the initial baseflow, Q_0, the recession factor, K, and the peak ratio. Initial values of these parameters are adopted for the simulations called preliminary. Subsequently, based on the hydrographs resulting from the preliminary simulations, the calibration function PWRMSE is used to obtain calibrated input parameters. The calibrated parameters are adopted as input for simulations called calibrated simulations. Table 3 shows the input parameters used in the preliminary and calibrated simulations.

The performance of the simulations is calculated for each sub-basin and shown in terms of the criteria established by Table 2. Firstly, the results are described and discussed for each sub-basin separately. Afterwards, a summary of the simulation results is presented.

Table 3 – Input parameters used in the preliminary and calibrated simulations

Sub-basin	Parameters	SCS curve number		Unit hydrograph	Base flow		
		CN	I_α (mm)	$t_p(h)$	Q_0 (m^3/s)	K	Peak ratio
PCH Salto Mauá	Preliminary	63.00	20.00	200.00	167.69	0.93	0.99
	Calibrated	49.42	7.51	188.90	240.91	0.93	0.99
Fazenda Manzanilha	Preliminary	79.00	15.00	5.83	100.00	0.91	0.90
	Calibrated	54.27	0.00	4.30	100.00	0.90	0.78
Porto de Areia	Preliminary	76.20	14.00	21.70	300.00	0.92	0.70
	Calibrated	71.18	16.00	20.60	300.00	0.93	0.61
Telêmaco Borba	Preliminary	65.50	22.50	23.40	200.00	0.81	0.80
	Calibrated	75.91	11.77	24.00	200.00	0.82	0.69
Porto Londrina	Preliminary	85.00	10.00	15.00	600.00	0.40	0.90
	Calibrated	97.26	8.18	10.90	575.04	0.49	0.86
Jataizinho	Preliminary	75.00	15.00	16.70	500.00	0.80	0.80
	Calibrated	38.14	9.75	18.90	335.80	0.07	0.05

Source: Authors, 2021

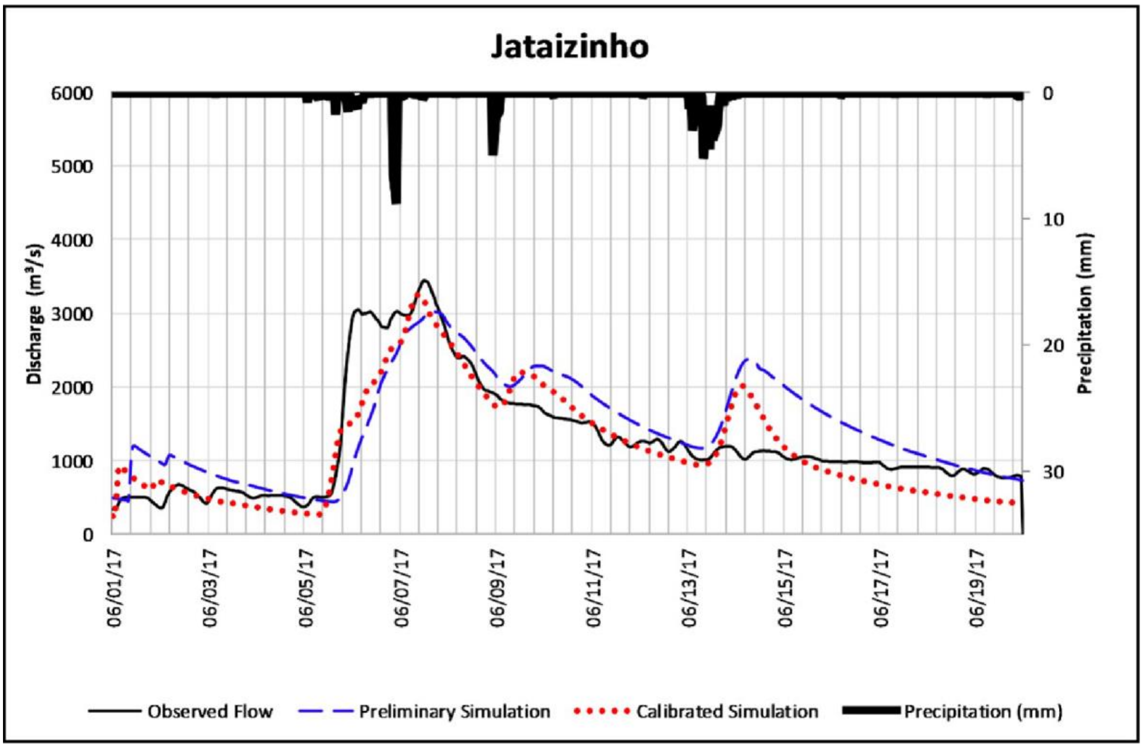
3.1 Jataizinho sub-basin

The results obtained for Jataizinho sub-basin are illustrated in Figure 3 in terms of preliminary and calibrated simulated hydrographs and observed hydrographs. It is observed that the accumulated precipitation is 77 mm during the simulation period. The observed peak flow is 3,455 m³/s, whereas the preliminary simulation peak flow is 3,029.2 m³/s, leading to a difference of 14.1%. The peak flow of the calibrated simulation reached 3,251.4 m³/s, being 5.9% lower than the observed peak flow.

This improvement of the results is associated with the input parameters calibration process. Among all parameters, the major changes are implemented on the CN, reduced from 75 to 38.14, and on the initial baseflow, reduced from 500 to 335.8 m³/s.

It can be noticed that the calibrated simulation follows the overall behavior of the observed flow data. The NSE, PBIAS and RSR indexes values are 0.79, 7.42% and 0.45, respectively, for the calibrated simulation. Therefore, the performance of the calibrated simulation is considered excellent according to the classification criteria established by Table 2. The inconsistencies of the simulated hydrograph observed from 13 to 15-jun-2017 can be related to the fact that Jataizinho monitoring station is located downstream from Maua hydroelectric power plant. As a consequence, the hydrograph can be affected by the control of plant's operation outflow.

Figure 3 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the Jataizinho sub-basin, during the period of June 1st to 20th, 2017

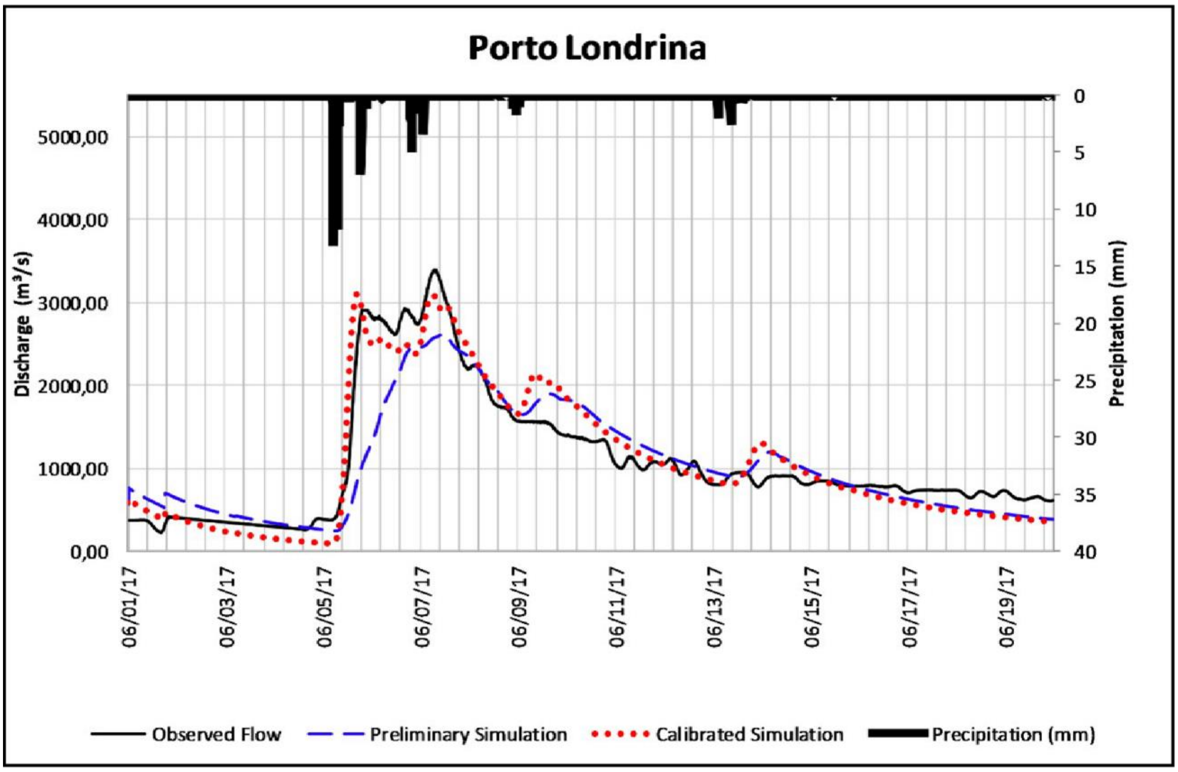


Source: Authors, 2021

3.2 Porto Londrina sub-basin

Figure 4 shows preliminary and calibrated simulated hydrographs and observed hydrographs for the Porto Londrina sub-basin. The average daily precipitation is shown in the upper horizontal axis. The total rainfall over the sub-basin for the period is 103.8 mm. The peak flow obtained from the preliminary simulation is 2,614.44 m³/s, 23.1% lower than 3,399.8 m³/s from the observed peak flow. The peak flow of the calibrated simulation is equal to 3,107.9 m³/s, being 8.6% lower than the observed peak flow. The performance indexes for the calibrated simulation indicates that the simulation presents excellent agreement with observed data, according to the criteria of Table 2. The resulting values are 0.90 for the NSE index, -1.22% for the PBIAS index and 0.32 for the RSR index.

Figure 4 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the Porto Londrina sub-basin, during the period of June 1st to 20th, 2017



Source: Authors, 2021

It can be noticed that the hydrograph of the calibrated simulation presents a behavior very similar to the observed data. The most sensitive input parameters changes performed on the calibration process are the CN coefficient, changed from 85 to 97.26, the hydrograph peak time, changed from 15 to 10.9 h and on the baseflow from 600 to 574.04 m^3/s.

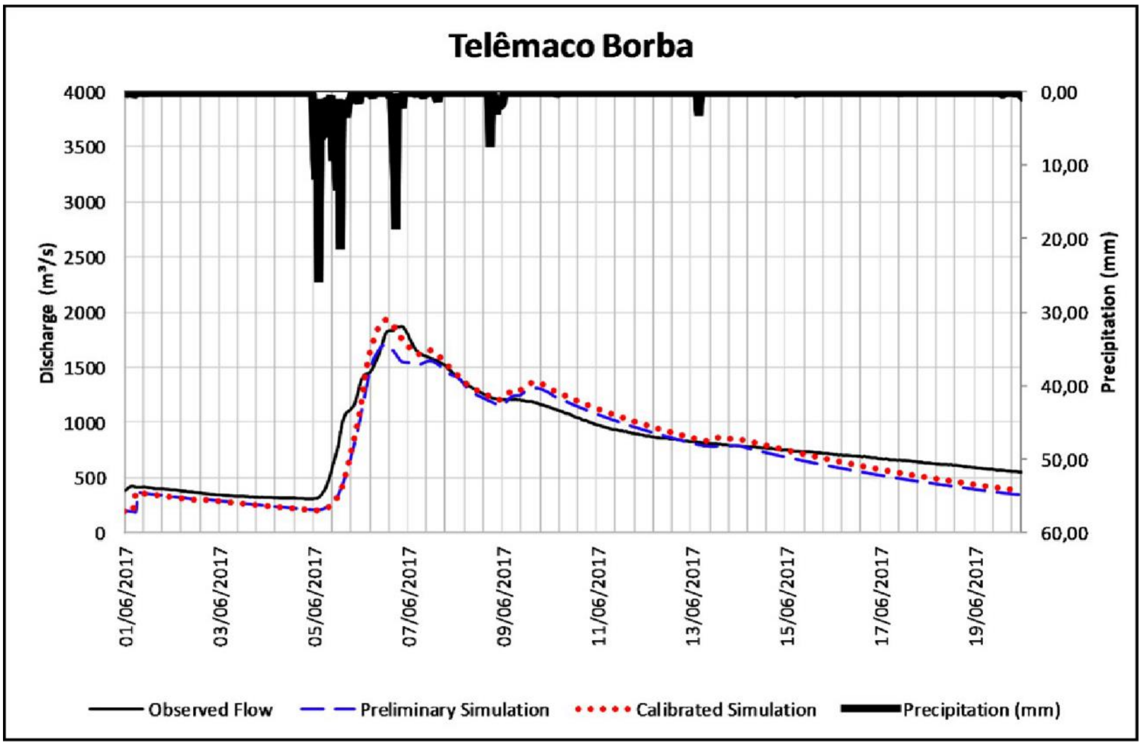
3.3 Telêmaco Borba sub-basin

Figure 5 presents preliminary and calibrated simulated hydrographs and observed hydrographs for the Telêmaco Borba sub-basin. The average daily rainfall for the simulation period is shown on the upper horizontal axis.

The accumulated precipitation on the sub-basin is 181.5 mm for the simulated period. The observed peak flow reaches 1,807.7 m^3/s, whereas the preliminary simulated peak flow is 1,712.5 m^3/s, 5% lower than the observed peak flow. The calibration process produces an increase of the peak flow to 1,901.2 m^3/s, so the difference between observed and calibrated peaks reaches 6.3%. NSE, PBIAS and RSR indexes for the calibrated simulation are 0.90, -3.03% and 0.32, respectively. According to the criteria of Table 2, the performance degree of calibrated simulation is classified as excellent for this sub-basin.

It should be noted that the preliminary simulation shows good agreement with the observed hydrograph, even before the calibration process. For this reason, calibration leads to small changes on the input parameters, being the most expressive to the CN coefficient, which changes from 65.5 to 75.91, and to the initial losses, changing from 22.5 to 11.77 mm. Even though the absolute peak flow difference increases after calibration process, it is noted an improvement on the overall distribution of the simulated hydrograph when compared with the observed data, especially during maximum discharges between 6 and 7-jun-2017.

Figure 5 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the Telêmaco Borba sub-basin, during the period of June 1st to 20th, 2017



Source: Authors, 2021

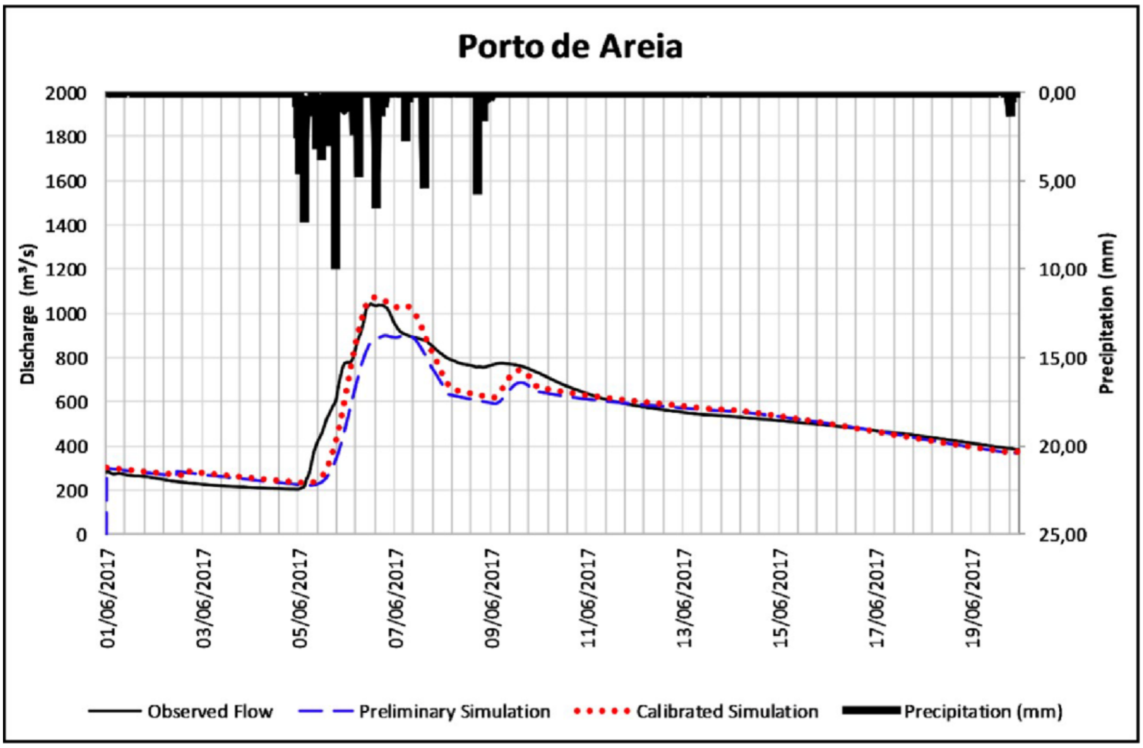
3.4 Porto de Areia sub-basin

Figure 6 shows the results of the preliminary and calibrated hydrographs for the Porto de Areia sub-basin. These hydrographs are compared with the observed hydrograph for the simulation period. Average daily precipitation is shown on the upper horizontal axis.

For the simulation period, total rainfall over this sub-basin is 148.4 mm. The observed peak flow is 1,041.1 m³/s, whereas preliminary simulated peak flow is 903.1 m³/s (difference of 13.3%). After calibration of the input parameters, the simulated peak flow is 1,075.1 m³/s (difference of 3.3%). The performance indexes are 0.92 for NSE, -4.39% for PBIAS and 0.28 for RSR, indicating that the calibrated simulation shows excellent agreement with measured data, according to the classification of Table 2.

Similar to what happens in the Telêmaco Borba sub-basin, the preliminary simulation of Porto de Areia shows good agreement with the observed hydrograph. Calibration caused small changes in the input parameters, the most expressive being the CN coefficient, which changes from 76.20 to 71.18. An improvement in the temporal distribution of the simulated hydrograph is also observed, mainly in the regions of maximum flow.

Figure 6 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the Porto de Areia sub-basin, during the period of June 1st to 20th, 2017



Source: Authors, 2021

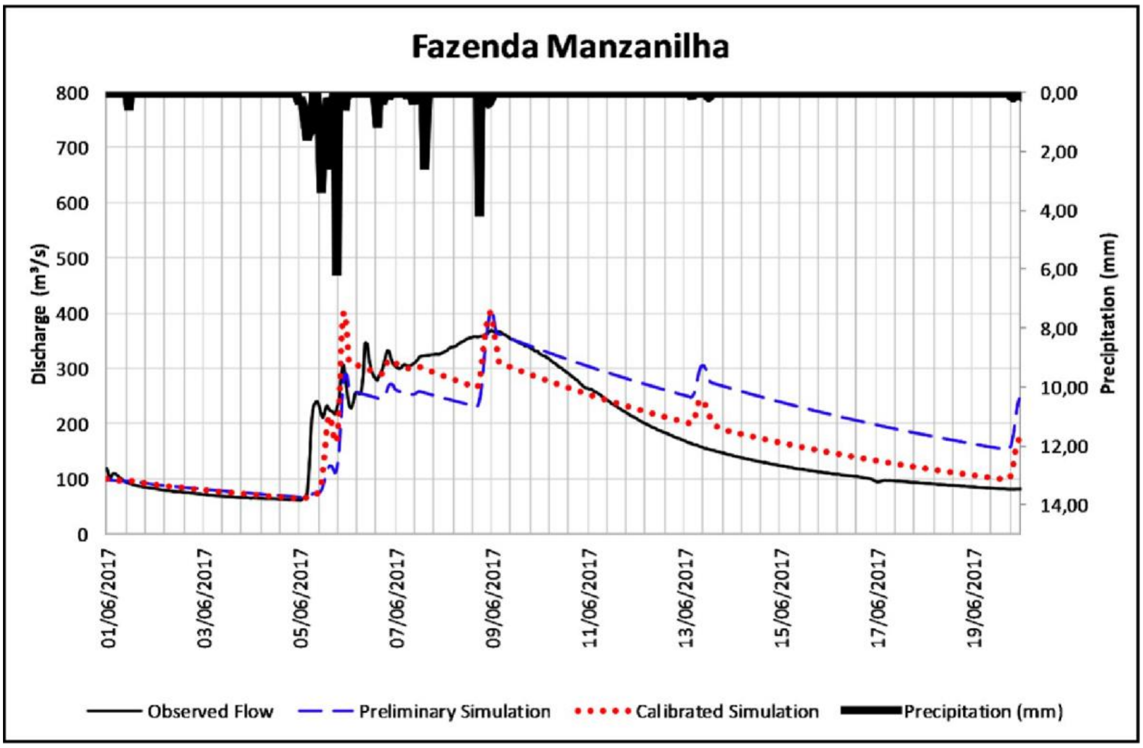
3.5 Fazenda Manzanilha sub-basin

Figure 7 shows simulated preliminary and calibrated hydrographs, compared with the hydrograph observed at Fazenda Manzanilha. The accumulated precipitation for the simulation period is 39.2 mm. The observed peak flow is 370.6 m³/s, whereas preliminary simulated peak flow reaches 406 m³/s, 9.5% higher than observed value. The peak flow of the calibrated simulation reaches 402.6 m³/s, 8.6% higher than the observed peak flow.

It can be noted that both simulated preliminary and calibrated hydrographs present peaks that do not correspond exactly with the temporal distribution of the measured data. In addition, the preliminary simulation performance indexes demonstrate unsatisfactory model performance.

The calibration process strongly modifies two input parameters: the CN coefficient, which changes from 79 to 54.27, and the initial losses, which changes from 15 to 0 mm. Once these modifications are performed, the obtained NSE, PBIAS and RSR indexes are 0.85, 4.25% and 0.39, respectively. As a result, the calibration simulation indicates excellent agreement with observed data, according to the classification of Table 2.

Figure 7 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the Fazenda Manzanilha sub-basin, during the period of June 1st to 20th, 2017



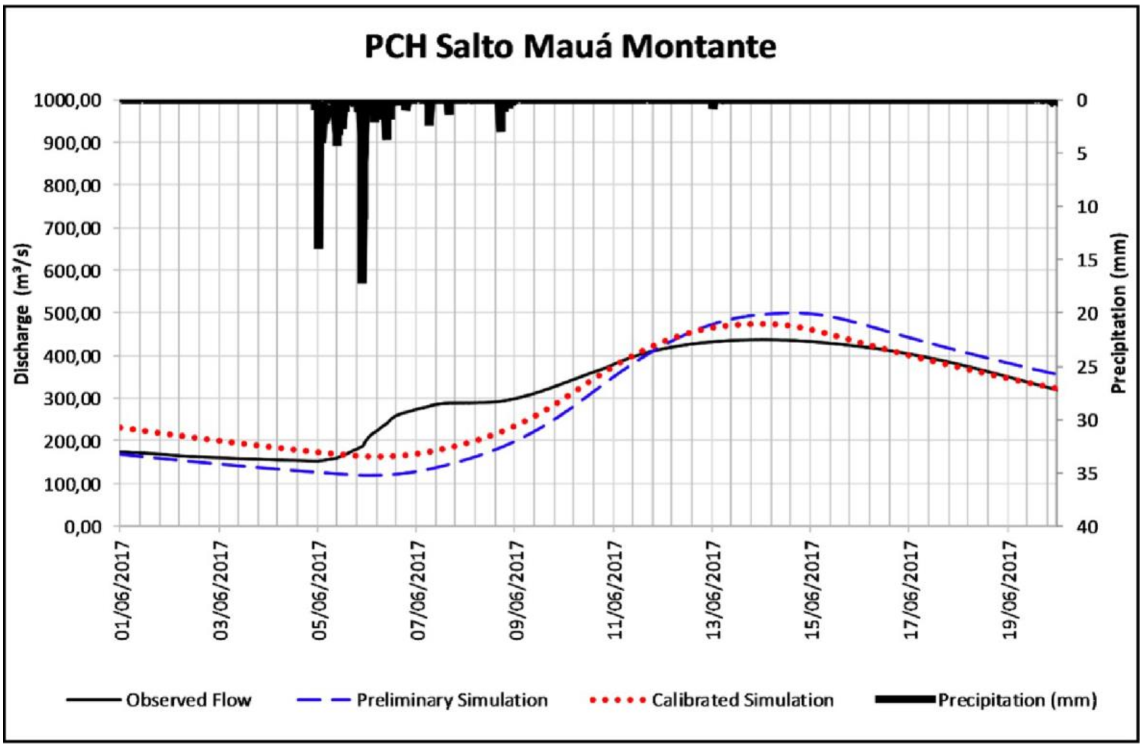
Source: Authors, 2021

3.6 PCH Salto Mauá Montante sub-basin

Figure 8 shows the results of the simulated preliminary and calibrated hydrographs, compared with the hydrograph observed at the Salto Mauá Montante station. Average daily precipitation is shown on the upper horizontal axis.

Total precipitation during this period is 167.4 mm. The peak flow of the preliminary simulation is 13.7% higher than the observed flow. After calibration, this difference reduces to 7.8%. The NSE, PBIAS and RSR indexes values are 0.81, -1.65% and 0.43, respectively, indicating that the calibrated simulation presented excellent agreement with observed data. After the calibration process, input parameters that underwent major modifications are the CN coefficient and initial losses values, ranging from 63 to 49.42 and from 20 to 7.51 mm, respectively.

Figure 8 – Observed hydrograph, preliminary and calibrated simulated hydrographs and daily precipitation for the PCH Salto Mauá Montante sub-basin, during the period of June 1st to 20th, 2017



Source: Authors, 2021

3.7 Summary of simulations performance evaluation

Table 4 presents observed and calibrated simulations peak flows, and the percentage differences between these values. A summary of the performance indexes obtained by the calibrated simulations is illustrated, as well as the final evaluation of the performance degree obtained by the simulations for in each sub-basin.

The final evaluation of the performance degree of HEC-HMS simulations is calculated considering the average of the NSE, PBIAS and RSR statistical indexes, shown in Table 2. It can be observed that all six sub-basin simulations achieve final degrees of performance considered excellent. It can also be noted that the calibration process acts by adjusting the peak flows of the simulated hydrographs for all sub-basins. Minimum differences of 3.3% and maximum differences of 8.6% are obtained between simulated calibrated and observed peak flows, considering the results for all six sub-basins.

Although the final performance evaluation provides excellent agreement between simulation results and measured data, it is possible to notice that the simulated results are not perfectly adjusted when the temporal discharge distribution is concerned. The main differences on the hydrograph's comparisons are observed in the occurrence of abrupt flow variations, usually associated with heavy and localized rainfalls.

Some of these discrepancies may be associated with the hypothesis of uniformly distributed precipitation on the sub-basins, used as input condition in the simulations. The precipitation data used as inputs were obtained at the monitoring stations located in the outlets of each sub-basin. Another source of discrepancy may be associated with the land use and occupation maps used in the simulations, which may be out of date, as they were produced in 2006. The physical and land use characteristics are represented by an average value of the CN coefficient, which is the most sensitive input simulation parameter, being adjusted on all HEC-HMS calibration processes.

Table 4 – Summary of the calibrated simulations performance evaluation

Sub-basin	**Observed Peak flow (m^3/s)**	**Calibrated simulated peak flow (m^3/s)**	**Diff. (%)**	**Calibrated simulations performance indexes**			**Final evaluation**
				NSE	**PBIAS**	**RSR**	
PCH Salto Mauá	439.0	473.5	7.8	0.81	-1.65%	0.43	Excellent
Fazenda Manzanilha	370.6	402.6	8.6	0.85	4.25%	0.39	Excellent
Porto de Areia	1,041.1	1,075.1	3.3	0.92	-4.39%	0.28	Excellent
Telêmaco Borba	1,807.7	1,901.2	6.3	0.90	-3.03%	0.32	Excellent
Porto Londrina	3,399.8	3,107.9	8.6	0.90	-1.22%	0.32	Excellent
Jataizinho	3,455.0	3,251.4	5.9	0.79	7.42%	0.45	Excellent

Source: Authors, 2021

4 CONCLUSIONS

The present work analyzed the performance of HEC-HMS hydrological modeling for the six sub-basins that form the Tibagi River watershed, located in the central-eastern region of the state of Paraná, Brazil. The main objective was to evaluate degrees of performances of the hydrological simulations, based on a statistical criterion established for comparisons of simulated results with flow data measured in the sub-basins outlets.

The obtained results of the calibrated simulations followed the overall behavior of the observed hydrographs. Statistical indexes showed that the comparisons were considered excellent, according to the classification suggested by the study. Furthermore, the calibrated simulated peak flows ranged from 3.3 to

8.6% when compared to the observed peak flows, indicating that the HEC-HMS simulations is suitable to be used to predict peak discharges.

Despite the good level of agreement observed between calibrated simulations and the measured data, it was not possible to conclude that the rainfall-runoff relationship was unequivocally determined, since the simulations were only performed for a short period of time, when consistent field data was available. In this context, it is recommended for future works that other simulations be performed for different periods of time, preferably in different hydrological periods, in order to corroborate the calibrated values of the input parameters and to perform further model validation.

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