v. 3, n. 17, 2023

Journal of
Engineering
Research

HYDROLOGICAL MODELING FOR SIMULATION OF EXTREME FLOW EVENTS IN THE RIVER BASINS OF THE TUBARÃO, SANTA CATARINA

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Abstract: The simulation of hydrological processes in watersheds has been used as a tool in the management of water resources, due to the possibility of predicting the fluvial regime. This study develops hydrological behavior on a regional scale that integrates rainfall, flow, land type and use, digital terrain model and a model hydrological analysis (HEC-HMS). The study aims to generate project flows to support flood coping procedures and contribute to territorial management. The study area is the basin of Rocinha and Bonito rivers, which form the Tubarão river located in the south of Santa Catarina. This is a region subject to frequent occurrences of floods due to the geomorphology of the basin being embedded in the escarpments of Serra Geral. The HEC-HMS hydrological model was used applying rainfall-runoff that converts excess precipitation into surface runoff, based on the design hydrographs derived from the hydrological model. Using hydrological data, a hydrological model was developed, generating flows for return periods (T2, T10, T25, T50 and T100) of Rocinha and Bonito river basin and the drainage area of the fluviometric station of Orleans Montante. The results achieved point to design flows for the basin of the rivers Rocinha and Bonito from 73 m^3/s (T2) to 202.8 m^3/s (T100), while for the area of fluviometric station Orleans Amount of 462 m^3/s (T2) to 1297.9 m^3/s (T100).
Keywords: hydrograph, design flows, hydrological modeling.

INTRODUCTION

Understanding hydrological processes is fundamental in environmental studies, in the management of water resources and in hydraulic works projects (Knebl et al., 2005; Lastra et al., 2008; Filho et al., 2012). The time that water remains in different parts of the hydrosphere influences several factors, including water availability, the occurrence of floods and the dynamics of nutrients and pollutants in water bodies (Filho et al., 2012).

Viola et al. (2009) point out that among the most common ways of evaluating the hydrological behavior of watersheds is the development and application of models physically based on mapping techniques, combining other hydrological models, such as CN-SCS (Easton et al., 2008; Notter et al., 2007; Stackelberg et al., 2007), ARNO (Collischonn et al., 2007) and HEC-HMS (USACE-HEC, 2022; Fiegembaun et al., 2022).

Hydrological models have been widely used in recent years for flood risk mapping, real-time flood forecasting, flood-related engineering, and water resource planning (Moraes, 2003; Vaze et al., 2013). These models consist of a system of equations and procedures composed of variables and parameters that describe the hydrological processes in the basin and have been used in environmental studies for various purposes (Silva, 2007). They are important analysis tools, as they allow a better understanding of hydrological processes, analyze the performance of management practices, as well as analyze risks and benefits arising from different types of land use (Spruill et al., 2000).

Hydrological models allow simulating floods, which are among the most devastating environmental disasters, frequently occurring in different regions of the world (Arduino et al., 2005; Teng et al., 2017). As the severity and frequency of floods increase, there is growing concern to decrease related deaths and associated economic losses (Sarhadi et al., 2012). Among the main hydrological-hydraulic factors that favor the occurrence of floods, we mention the relief, type and intensity of rain, vegetation cover, drainage capacity, geology, river morphology, channel extension and floodplain (Monte et al, 2016).

Identification of prone areas can be one of the main solutions in mitigating flood events, helping authorities in planning strategies to mitigate damage to extreme events (Sarhadi et al., 2012). For the identification of areas susceptible to flooding, it is necessary to develop models that allow estimating hydrological and hydraulic variables.

For effective flood management in an urban area, the estimation of hydrograph times (such as peak time, concentration time, recession time), peak discharge and surface runoff volume are important elements to be considered (Fiegenbaum et al, 2022). In this regard, hydrological modeling is a tool that has been applied to estimate the hydrological response of the watershed due to precipitation (Halwatura and Najjim, 2013).

The HEC-HMS (Hydrological Engineering Center - Hydrologic Modeling System) model has been widely used in hydrological engineering analysis to simulate rainfall-runoff (Collischonn and Dornelles, 2013; Fiegenbaum et al., 2022), and may represent the hydrological behavior of the hydrographic basin, forecasting flows, areas of flooding, among others. The model generates hydrographs and information regarding runoff volume, peak flow and hydrograph times.

Therefore, this study proposed the development of a hydrological modeling using the HEC-HMS model to determine the design flows in the Rocinha and Bonito river basins, which form the Tubarão river, members of the Tubarão river basin, southern Brazil, with a view to contribute to the territorial management of these spaces.

MATERIALS AND METHODS

STUDY AREA

The Tubarão river watershed (BHRT) belongs to the South Atlantic Hydrographic Region, has an area of 4,735 km2 and covers the total or partial area of 22 municipalities located in the south of the State of Santa Catarina, Brazil. It has its main sources in the plateaus of Serra Geral (SDE, 2017).

For the simulation of the hydrological model, a study area was defined that comprises the basins of the Rocinha and Bonito rivers, which form the Tubarão river (Figure 1). This area has 90.91 km², with a perimeter of 60.15 km and watercourse length of 47.91 km.

The climate regime in the Tubarão river basin region is classified, according to the Köeppen climate classification, as Cfa type (temperate mesothermal, humid, without dry season and with hot summer). The average annual rainfall in the south of Santa Catarina ranges from 1,220 to 1,660 mm, with a probability of 50% (1300 to 1400 mm) on the southern coast of the state (Coan et al., 2014), and presenting the annual total of days of rain between 98 and 150 days (Back, 2009).

DESCRIPTION OF THE HYDROLOGICAL MODEL

The hydrological model used was the HEC-HMS (version 4.9) of the US Army Corps of Engineers (USACE-HEC, 2022). This model allows simulations of the transformation processes of rain into flow in dendritic watersheds, allowing the analysis of parameters such as runoff volume, peak flow and runoff time.

The input data in the model considered the hydrometeorological variables (precipitation and flow), the digital terrain model (MDT) and the type and use of the soil.

Daily rainfall data (consistent) were obtained from four rainfall stations, three belonging to the Hydrological Network (RH) of the National Water and Sanitation Agency (ANA) available in the Hydrological Information System (HidroWeb) (ANA, 2022) and one station of the National Institute of Meteorology (INMET). And the flow data were obtained from a fluviometric station belonging to ANA's RH. Table 1 gathers the

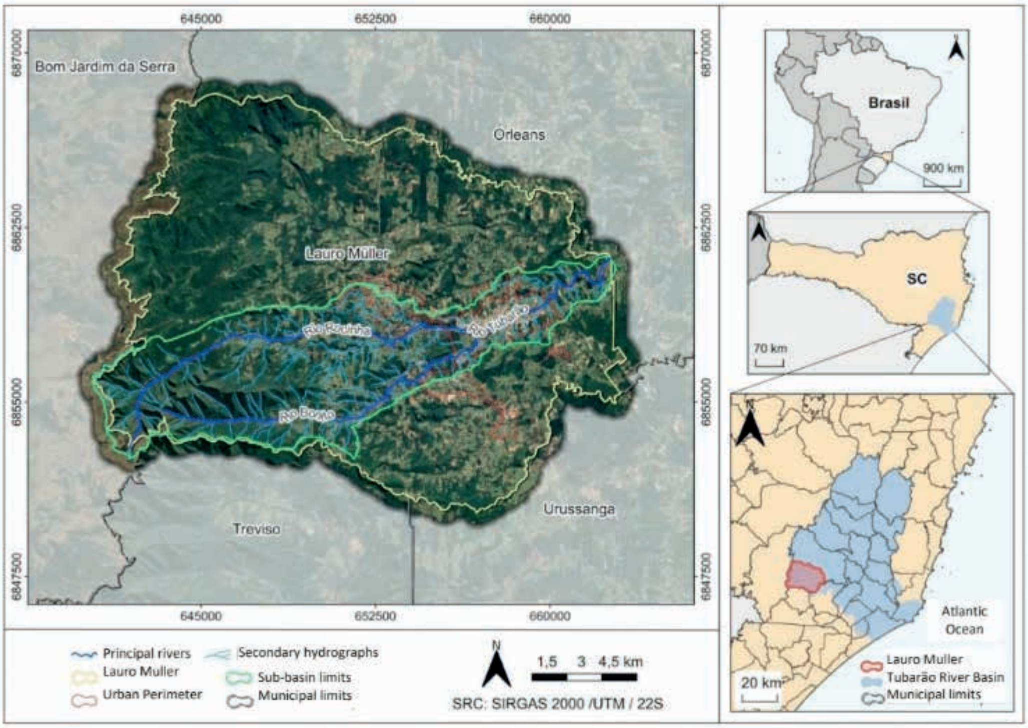


Figure 1. Spatial location of Rocinha and Bonito river basins, which form the Tubarão river.

Station data	Rainfall or Fluviometric Station				
	Orleans - Amount	**Bom Jardim da Serra**	**Urussanga**	**serrinha**	**Orleans - Amount**
Code	2849001	2849009	2849011	2849029	84249998
Type	rainfall	rainfall	rainfall	rainfall	Fluviometric
County	Orleans	Bom Jardim da Serra	Urussanga	Sideropolis	Orleans
Latitude	-28.3589	-28.3397	-28.5322	-28.6122	-28.3586
Longitude	-49,295	-49.6214	-49.315	-49.5511	-49,295
Altitude (m)	90	1,200	48	-	100
Initial Year	May/39	Oct./69	Jun./48	Dec./86	mar./83
Final year	Feb./22	Feb./22	Dec./94	Feb./22	Feb./22
Responsible	A-N-A	A-N-A	INMET	A-N-A	A-N-A
Operator	Epagri-SC	CPRM	INMET	Epagri-SC	Epagri-SC

Table 1 - Stations used to obtain rainfall and flow series.

Stage of the hydrological cycle	Applied method
Infiltration	initial and constant
Transformation of rain into flow	SCS Unit Hydrograph
base flow	Recession
flow propagation	Munkingum-Cunge

Table 2 - Methods applied to simulate the hydrological cycle.

basic information of the pluviometric and fluviometric stations used in the hydrological calculations.

The MDT used was the ALOS-PALSAR, with a spatial resolution of 12.5 meters available on the Data Search Vertex portal, in order to delimit the sub-basins in the study area. Land use was verified in satellite images available on the Google Earth platform, while soil type was obtained from EMBRAPA (2004). These parameters served as a basis for determining the conditions of infiltration and initial losses.

The study area was subdivided into sub-basins considering characteristics of hydrological similarity. Methods were determined to represent each of the stages of the hydrological cycle (Table 2).

The concentration time of the basins was determined using the Kirpich equation (Equation 1).

Tc = 57 equation 1 $\left(\frac{L^3}{\Delta h}\right)$

Where:

Tc: concentration time (minutes).

L: length of the main watercourse (km).

Δh: difference in altitude along the thalweg of the watercourse (m).

With the time of concentration of the basin of the Rocinha and Tubarão rivers, the maximum precipitated depths for the duration found were obtained using the HidroChuSC software (BACK, 2013), referring to the Orleans Montante station. The distribution of hyetogram intervals was carried out considering the second quartile of the Huff Method and intervals of 6 to 6 hours.

As the study area encompasses the basin of the Rocinha and Bonito rivers is extensive, a precipitation reduction factor per area (FRA) was applied, according to Equation 2 (BRAZIL, 2005).

FRA = equation 2 $\frac{y}{y+log^2\left(\frac{A}{5}\right)}$

Where:

FRA: area precipitation reduction factor by basin.

A: basin area (km²).

y: empirical function that can be estimated by (Equation 3):

y = 35. log (0.7d + 1) equation 3

Where: duration of precipitation in hours.

The calibration of the hydrological model was performed considering three precipitation events that occurred in the study region. The first event was used to calibrate the model and the other two for validation. The historical series of the fluviometric station (84249998) Orleans Montante was used to compare the hydrographs generated from the hydrological model with the observed flow data. To perform the comparison, the root mean squared error normalized by the observation standard deviation (RSR) (Equation 4), the Bias (Equation 5) and the Nash-Sutcliffe Coefficient (NS) (Equation 6) were used as verification metrics. These metrics are used in order to verify the quality of hydrological simulations and their values are automatically generated when running the model in HEC-HMS.

RSR = equation 4 $\frac{RMSE}{\sigma}\sqrt{\frac{\Sigma(Q_{obs}-Q_{calc})^2}{\Sigma(Q_{obs}-\bar{Q}_{obs})^2}}$

Bias = equation 5 $100\cdot\frac{\Sigma Q_{obs}-\Sigma Q_{calc}}{\Sigma Q_{obs}}$

NS = equation 6 $1-\frac{\Sigma[Q_{calc}(t)-Q_{obs}(t)]^2}{\Sigma[Q_{obs}(t)-\bar{Q}_{obs}(t)]^2}$

Where:

Qobs: Flow observed in the time interval t (m³/s).

Qcalc: Flow calculated in the time interval t (m³/s);

Q̄obs: Average of observed flows (m³/s).

Figure 2 shows the sequence used to prepare and calibrate the hydrological model.

RESULTS AND DISCUSSIONS

The calibration and model validation results are shown in Table 3. The NS and RSR values performed very well both for calibration and for the periods chosen for validating the hydrological model. Bias performed very well for calibration and validation periods 2, in addition to satisfactory performance for validation period 1.

Figure 3 shows the observed and simulated hydrographs for each of the events. It is verified that the simulations represent the observed peaks appropriately, corroborating the model's performance metrics. The values found with the calibration and validation tests allow us to say that they are adequate.

The hydrological model built and calibrated for the study basin was integrated with the observed, predicted and simulated data, providing the generation of flows in the sub-basins inserted in the study area. The developed hydrological model allows performing hydrodynamic simulations identifying regions susceptible to the occurrence of floods.

The simulated flows shown in Figure 4A correspond to the drainage area of the Orleans Montante fluviometric station, while in Figure 4B, the simulated flows for the drainage area of the basin of the rivers Rocinha and Bonito, which form the Tubarão river.

Hydrographs were generated for different return periods (2, 10, 25, 50 and 100 years respectively denoted by T2, T10, T25, T50 and T100), and the flow peaks were reached for the time of 30 hours. At the Orleans Montante fluviometric station (Figure 4A), the peak discharge calculated with T2 is 462 m^3/s, reaching 1,297.9 m^3/s for T100 years, while in the area of the Rocinha and Bonito river basins (Figure 4B), the peak flow ranged from 73 m^3/s (T2), reaching 202.8 m^3/s (T100).

The design rains observed at the Orleans Montante fluviometric station are very intense and, being homogeneously distributed throughout the basin, resulted in high flows. Normally, rainfall is not homogeneously distributed throughout the basin, as can be seen from the data from the surrounding rainfall gauges used in this study. Therefore, the simulated flow would hardly be observed in a natural condition. Another situation that is observed is that the design rain has a greater accumulation of volume around its peak. In this aspect, as it is a considerably long rain, this concentration in a short interval creates a high flow response in the basin. Finally, the flow measurements available at the Orleans Montante fluviometric station are daily and, therefore, may not capture the flow peak during extreme events.

The increase in the frequency of extreme events in the last three decades in the Tubarão river basin has caused great damage to the population and requires the study and development of methodologies that allow the analysis of floods and their prediction. Using the HEC-HMS model, based on measured or predicted rainfall-flow data, it is possible to carry out flow propagation in the main rivers of the hydrographic basin.

The rainfall-runoff model obtained from the HEC-HMS indicates that the parameterization of the model is capable of representing the hydrological processes in the basin under study of the Rocinha and Bonito rivers and, thus, providing the flow values necessary for the representation of the boundary conditions of the river. hydrodynamic model.

The characteristics of the study basin, with a high slope and subject to orographic, convective and frontal rainfall, require the use of a rainfall-runoff model, as only the propagation of water present in the channels is not enough. Because the formation of the flood takes place very quickly and the rainfall-runoff modeling grants a gain in advance in the forecast.

Journal of Engineering Research ISSN 2764-1317 DOI 10.22533/at.ed.31731723310510

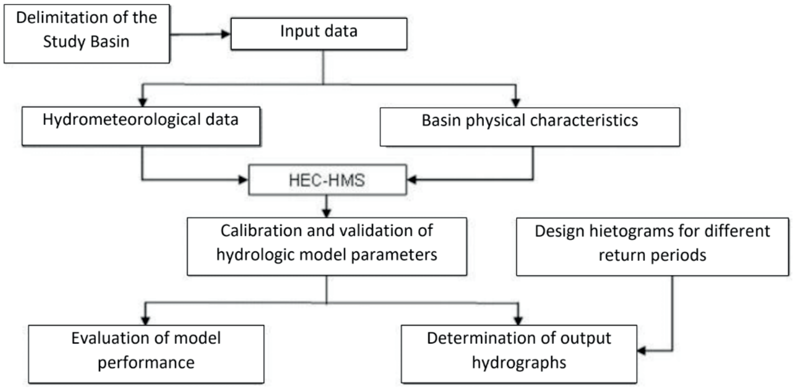
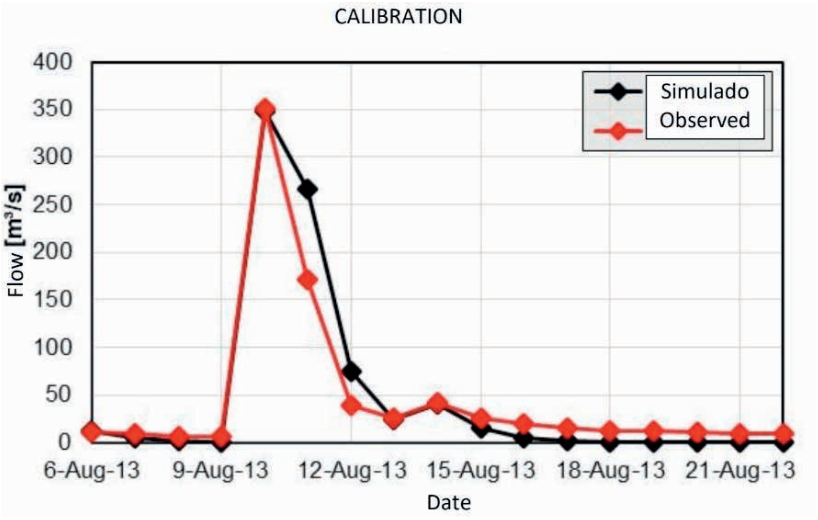
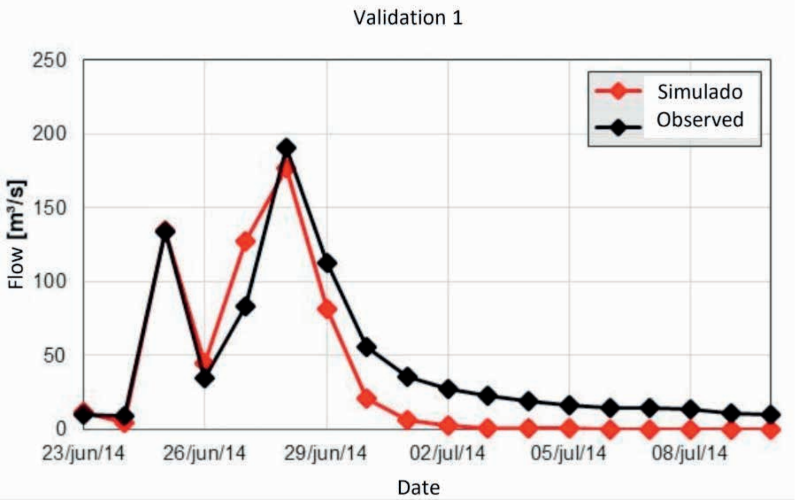


Figure 2. Flowchart of the hydrological model elaboration and calibration steps.

Event	RSR	NS	Bias (%)
Calibration	0.3	0.907	2.26
Validation 1	0.4	0.827	-24.96
Validation 2	0.5	0.793	-2.78

Table 3 - Hydrological model calibration and validation data.





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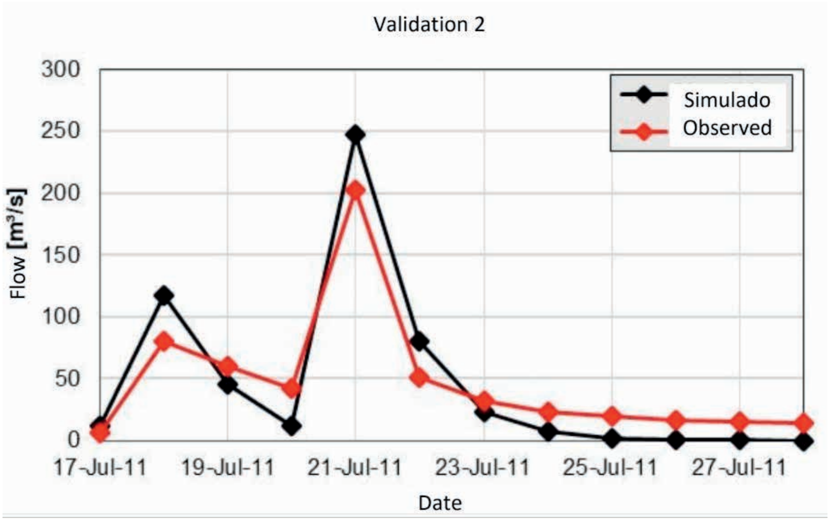

Figure 3. Hydrographs of observed and simulated calibration and validation events.

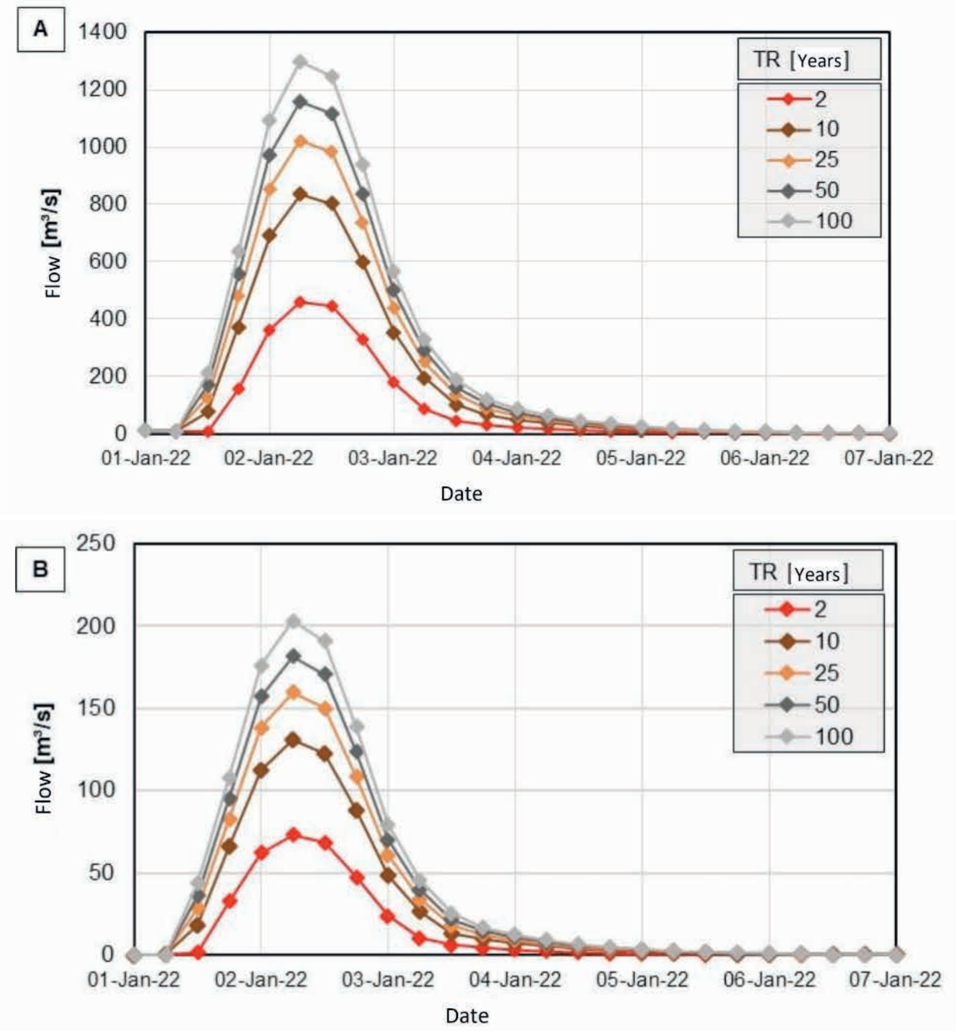

Figure 4. Project hydrographs, being (A) project area of the Orleans Montante fluviometric station and (B) project area of the Rocinha and Bonito river basins.

CONCLUSIONS

- In the calibration and validation of the hydrological model, the strategy that best responded to the characteristics of the basin under study was tested. We tried to calibrate the HEC-HMS model using three precipitation events that occurred in the region. The values found with the calibration and validation tests allow us to say that the hydrological model is adequate to the context of the basin and the information and input data used in the model.

- The HEC-HMS hydrological model allowed generating hydrographs with peak flows in different return periods, being reliable to perform hydrodynamic simulations and contribute to the identification of areas susceptible to flooding in the study region.

- The simulated project hydrographs can be applied in the management of water resources, allowing the government to reduce the risk of flooding and flooding, as well as in planning the use and occupation of the soil in the study basin.

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