Australian Journal of Basic and Applied Sciences

2021 June; 15(6): pages 1-14
https://doi.org/10.22587/ajbas.2021.15.6.1

ORIGINAL ARTICLE
AENSI PUBLICATIONS

HEC-HMS model application in event-oriented hydrological modeling

[1]Víctor Luís Padilha, [2]Francisco Henrique de Oliveira, [3]David Proverbs

[1]PhD Student, MSc., Territorial Planning and Socio-environmental Development Graduate Program, Santa Catarina State University – UDESC. 2007, Av. Madre Benvenuta, Florianópolis-SC, Brazil
[2]Associate Professor, PhD, Territorial Planning and Socio-environmental Development Graduate Program, Santa Catarina State University – UDESC. 2007, Av. Madre Benvenuta, Itacorubi, Florianópolis-SC, Brazil
[3]Associate Dean, PhD, Faculty of Computing, Engineering and Built Environment, Birmingham City University, University House 15 Bartholomew Row, B5 5JU, Birmingham, England

Correspondence Author: Víctor Luís Padilha. PhD Student, MSc., Territorial Planning and Socio-environmental Development Graduate Program, Santa Catarina State University – UDESC. 2007, Av. Madre Benvenuta, Florianópolis-SC, Brazil
E-mail address: victor.engambiente@gmail.com

Received date: 12 March 2021, Accepted date: 22 June 2021

Cite as: V.L. Padilha., F. He. de Oliveira., D. Proverbs., 2021. HEC-HMS model application in event-oriented hydrological modeling. Australian Journal of Basic and Applied Sciences, 15(6): 1-14. DOI: 10.22587/ajbas.2021.15.6.1.

ABSTRACT

Environmental disasters by flood have occurred frequently in different regions of the world. Based on that, the aim of this study is to provide technical support for knowledge of the application of HEC-HMS model in event-oriented hydrological modeling. The support with the hydrological models to the water resources management and planning tools have been chosen in order to demonstrate how components that influence in environmental disasters have been incorporated in modelling. Widely used by many hydrologists around the world, the HEC-HMS is an essential tool for understanding watershed hydrological behavior in event-oriented modelling. The applying methods were appropriate for event-oriented modelling since they cause huge impacts along the year in several cities and need focused studies on their behavior. In this context, the city of Lages, state of Santa Catarina, in Brazil, recorded extreme flood events in recent years. Therefore, this paper employed three different events (2005, 2008 and 2011) to calibrate and test the HEC-HMS 4.2 model to Caveiras Montante 1 watershed composed by 7 sub-catchments. The new findings were to be able to improve the assessment on the events severity for the urban sub-catchments Ponte Grande and Carahá, which do not have monitoring. In terms of contribution to applied hydrology, there is great emphasis in the model outputs, which provides an overview of HEC-HMS modelling approaches. Finally, all the events reached excellent NSE index and respective residual volumes in the optimization processes to calibrate the events. It means the hydrological behavior of the conceptual system of sub-catchments during the event-oriented modelling can confirm the use of the regionalized outputs for the urban ungauged sub-catchments of interest Ponte Grande and Carahá. The experimental use of the regionalized outputs may work, for example, in hydraulic modelling for the same flood events in future research.

Keywords: events, severity, urban sub-catchments, floods, HEC-HMS

INTRODUCTION

Many flood occurrences with significant environmental damages have grown considerably in Brazil. As the severity and frequency of flood events have dramatically increased, there is a growing global concern about the need to decrease flood-related fatalities and associated economic losses, considering available databases (EM-DAT, 2015). According to urban master plans, Brazilian cities usually do not consider the impact of urbanization on drainage flow. As a result, the impervious areas associated with upstream development transfer their effects downstream, increasing flood (Sarhadi et al., 2012). Usually, the city engineering departments do not have the hydrologic support to cope with this problem. Engineering works such as channels are not projected considering the possible downstream impacts, where built-up areas face the consequences during flood events and their peaks of discharge. Furthermore, flood damage affects the monetary issues directly to infrastructure system, as housing and industry.

Flood is a geographic phenomenon that occur in time and space, whose problems tend to be difficult to solve because they involve variables of the spatial domain, technical and scientific domain, organizational and administrative domain, social domain and, finally, temporal domain (Decina and Brandão, 2016). Therefore, for effective flood management in an urban area, estimation of flood hydrograph, flood peak, time to flood peak and flood plain delineation are critical (Cirilo et al., 2020; Siqueira et al., 2019). Therefore, hydrological modeling is a commonly used tool to estimate the watershed's hydrological response due to precipitation, varying significantly in time and space (Felix and Paz, 2016).

This analysis used the Hydrologic Modelling System (HMS), developed by the U.S. Army Corps of Engineers (USACE). The HEC-HMS, a successor to the HEC-1 model from the USACE Hydrologic Engineering Center, which is widely used in hydrologic engineering analysis for simulating rainfall-runoff (Steinmetz et al., 2019; Fleischmann et al., 2019; Wang et al., 2016; Cabral et al., 2017), being able to represent the watershed's hydrological behavior in a flood event. The HEC-HMS model provides the structural elements (sub-basins, reaches, reservoirs, junctions, diversions, sources and sinks) to build the basin model and a set of hydrologic methods for computations in each element, which has a unique combination of process representations and parameter definitions (Zi-jun Hu, 2017).

The city of Lages, selected to be the focus of this work, and the main economic center of the mountainous region of Santa Catarina in Brazil, registered several flood events, as in the years 1997, 2005, 2008, 2011, 2013, 2015 and 2017, which demands research to improve the flood risk management as practised in the European Union and the United States. In all these cases, there were significant social losses in Lage's urban territory representing an area of approximately 125km², and most of it within the Ponte Grande and Carahá watersheds, sub-catchments of the Caveiras watershed. Therefore, based in official maps with the delimitation of flood areas by the city hall, the sample events applied for this study analysis were 2005, 2008 and 2011 to estimate the volumes and peak of discharges that have a delineated floodplain. The state structure was created to monitor data nowadays, although there is no scientific knowledge of these events for this region in the literature. The understanding of hydrological data such as the runoff volume and peak discharge during the studied events represents a detailed overview of the flood mechanisms. Consequently, the expectation is to provide technical support for knowledge of the application of HEC-HMS model in event-oriented hydrological modeling.

1.1 Introduction – Case Study

The study area involves the Caveiras Montante 1 watershed, which has its outlet located in the Ponte Velha discharge gauge station, which CELESC (Santa Catarina Electrical Center Stations) monitors (Fig. 1).

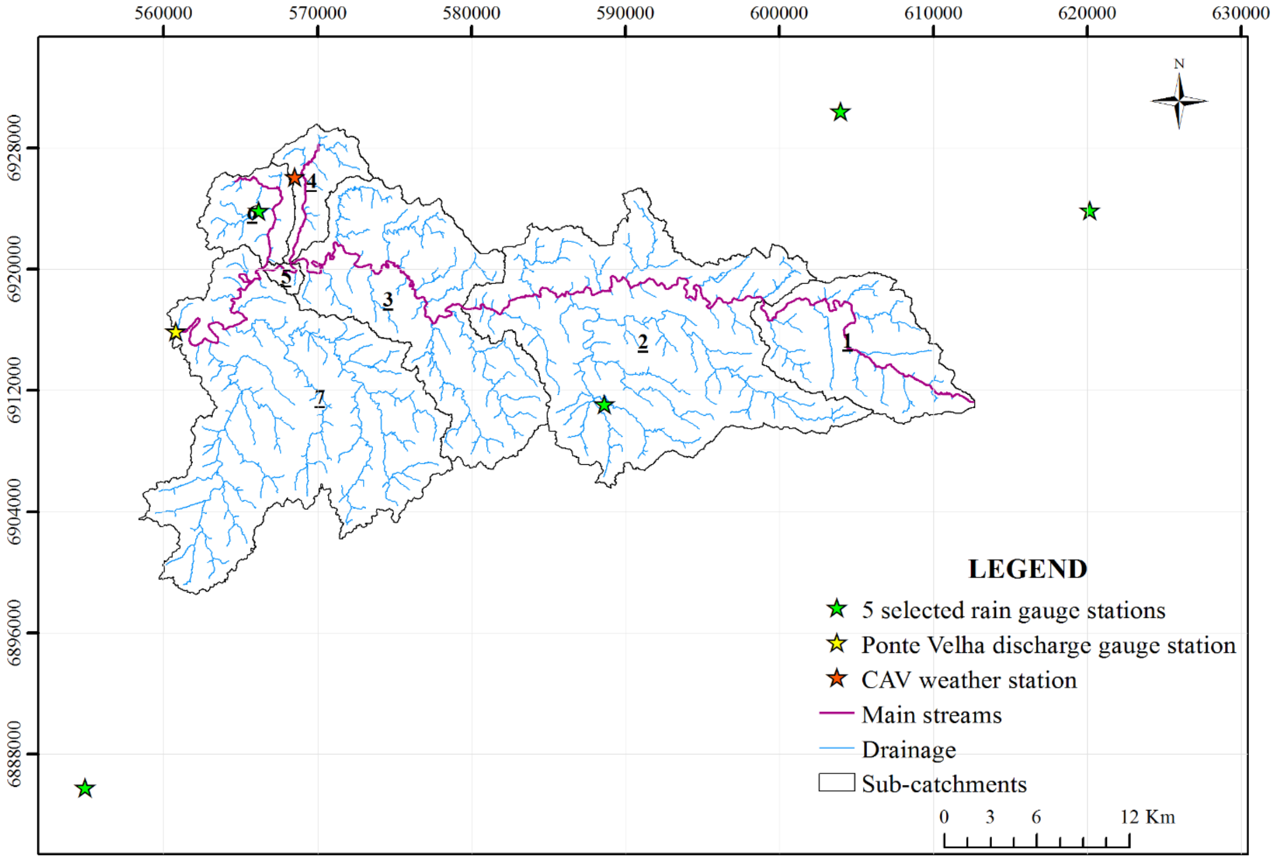

Fig. 1: Caveiras Montante 1 watershed, its sub-catchments, the weather, discharge and five rain gauge stations.

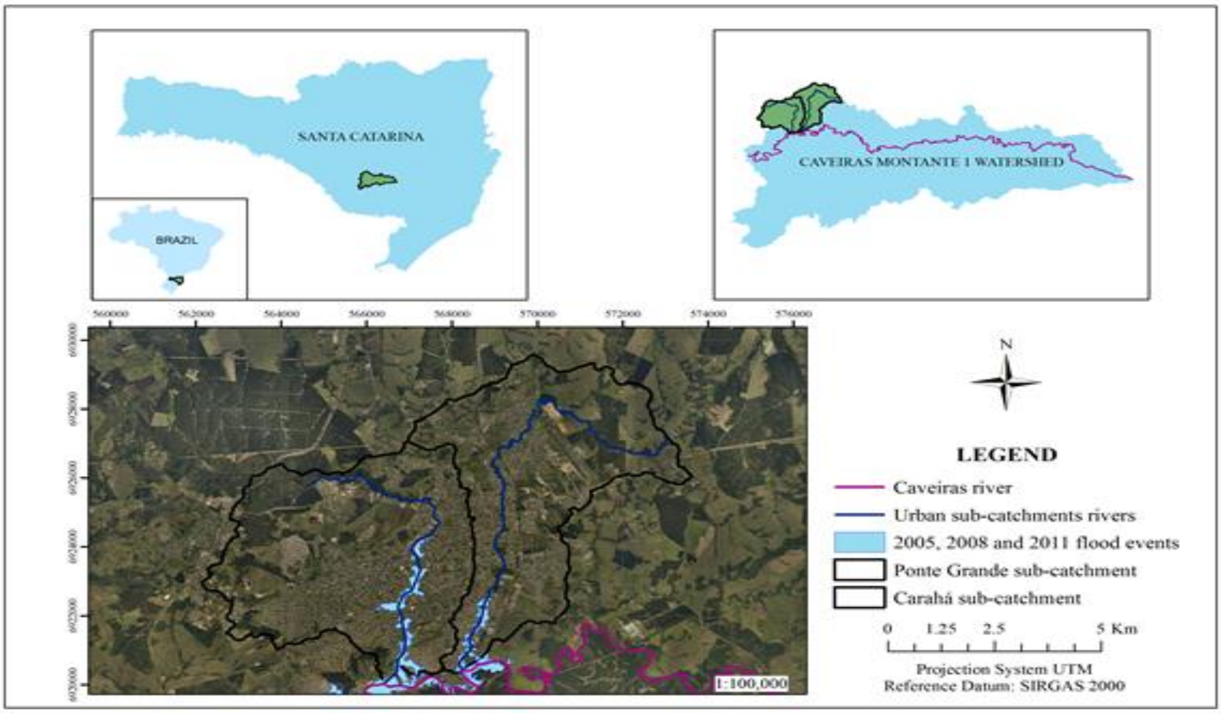

Fig 2: Location of the two urban sub-catchments and 2005, 2008 and 2011 flood events delineation in Lages (SC).

In Fig. 1 it is shown the sub-catchments used in hydrological modeling and the discharge and rain gauge highlighted. The sub-catchments 1-6 are essential in the hydrological modelling for the flood system analysis, since they include the urban sub-catchments Ponte Grande and Carahá (Fig. 2) and the rural sub-catchments 1, 2 and 3, which capture the rainfall upstream of the urban area, whose runoff is conducted through the Caveiras River. It is possible to observe the potential influence of the Caveiras River reach and the two other sub-catchment outlets to be analyzed within the flood risk area. The urban sub-catchments Ponte Grande and Carahá are the size of 27.15 km2 and 30.16 km2, respectively. In Fig. 2, the floodplain areas of 2005, 2008 and 2011 events demonstrate how severe the events were. Table 1 synthesizes the conceptual sub-catchments.

Table 1: Identification of Caveiras Montante 1 conceptual system of sub-catchments in HEC-HMS.

Order	Conceptual sub-catchments
1	Caveiras Montante 2
2	UDESC Painel
3	Caveiras Lages
4	Ponte Grande
5	Entre Rios
6	Carahá
7	Ponte Velha

2. MATERIALS AND METHODS

Sufficient Regarding the study events, their characterization considers their severity and spatial distribution. The scale of event severity follows its return period. The sampling range covers events of low (2011), medium (2008) and high severity (2005). The three selected events are representative samples of the extreme events that usually generate floods in Lages. The spatial distribution of these events also represents a sample of the spatial distribution of extreme events.

There are a set of rain gauge stations located around the city of Lages. The accumulated rainfall have their values established through the Thiessen polygons method that measures the weight of each of the five rain gauge stations for each of the sub-catchments in the Caveiras Montante 1 watershed (Bocaina do Sul, Lages, Coxilha Rica, Painel and Vila Canoas). After the Thiessen polygon weighting, the accumulated rainfall obtained for the urban sub-catchments (Ponte Grande and Carahá) is only from the Lages rain gauge station, monitored by INMET (National Meteorology Institute) and operated by EPAGRI/CIRAM (Santa Catarina hydrometeorology and environmental resources information center).

It was observed discharge at the Ponte Velha discharge gauge station, which characterizes the watershed response to the whole system of sub-catchments and enables the discharge regionalization for the ungauged urban sub-catchments. The detailed characterization of the observed rainfall events occurred by developing two methods, based on the duration time presented by the pluviograph installed with the CAV Weather Station, in the UDESC (Santa Catarina State University) campus. The reason for the choice of this station is the rainfall heights recorded in intervals of 10 minutes, being able to get events with duration time lower than 24 hours, a limitation for the other rain gauge stations.

First, an IDF (intensity-duration-frequency) curve was updated and published for the city of Lages recorded from a 10-years observation during 2000-2009, in CAV Weather Station, according to Cardoso et al. (2014). The IDF equation developed for events until 18 hours of a duration time, matching with the 2008 event (Table 2), follows below:

$$i = 2050Tr^{0.20}(t+30)^{-0.89} \qquad (1)$$

In which i is the rainfall intensity, Tr is the return period, and t is the rainfall duration.

The second method, for the 2005 and 2011 events with durations longer than 24 hours (Table 2), happened with the statistical analysis of intense rainfall probability and returned period in Lages rain gauge station by Gumbel distribution, in each available observation from 1987 to 2015, the maximum 48 hours height for each selected year.

Based on it, the systematic procedure was an annual maximum series set in descending order, calculating the statistical elements of the sample as the mean and standard deviation to generate Gumbel's reduced variable. The expected theoretical probability (P_i), according to Gumbel, follows through the equation:

$$P_i = 1 - e^{-e^{-y_i}} \qquad (2)$$

In which P_i was the expected probability, e was the basis of Nepierian logarithm and y_i was the Gumbel's reduced variable. The calculated return period (Tr_i) is in the following equation:

$$Tr_i = \frac{1}{P_i} \qquad (3)$$

This way, allowed the determination of the expected 48 hours return periods according to the maximum rainfall heights. The collected data from rain gauge stations and approximated values of the return periods calculated from each method are in Table 2. The use of both methods could normalize the severity of the selected events by considering the correct event duration time.

Table 2: Collected data from the selected flood events.

Year event/Accumulated Rainfall (mm)	Duration (h)	Mean Intensity (mm h^{-1})	Return Period (years)
2005 (183.6)	32	5.74	384
2008 (104)	4.5	23.11	29
2011 (123.6)	35	3.53	22

The spatial distribution of 2005, 2008 and 2011 events is set according to the accumulated rainfall in each sub-catchment (Fig. 3 to 5), obtaining distributed, concentrated, and distributed rainfall. The 2005 event was the best distributed in the area of the sub-catchments 1 to 6.

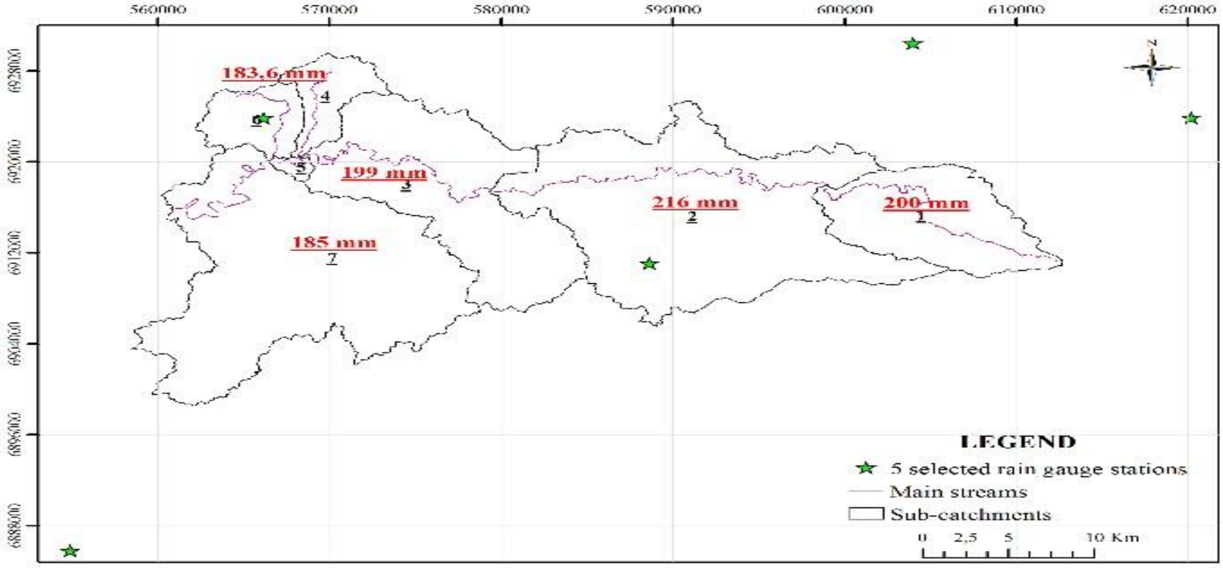

Fig. 3: Rainfall spatial distribution in 2005 event

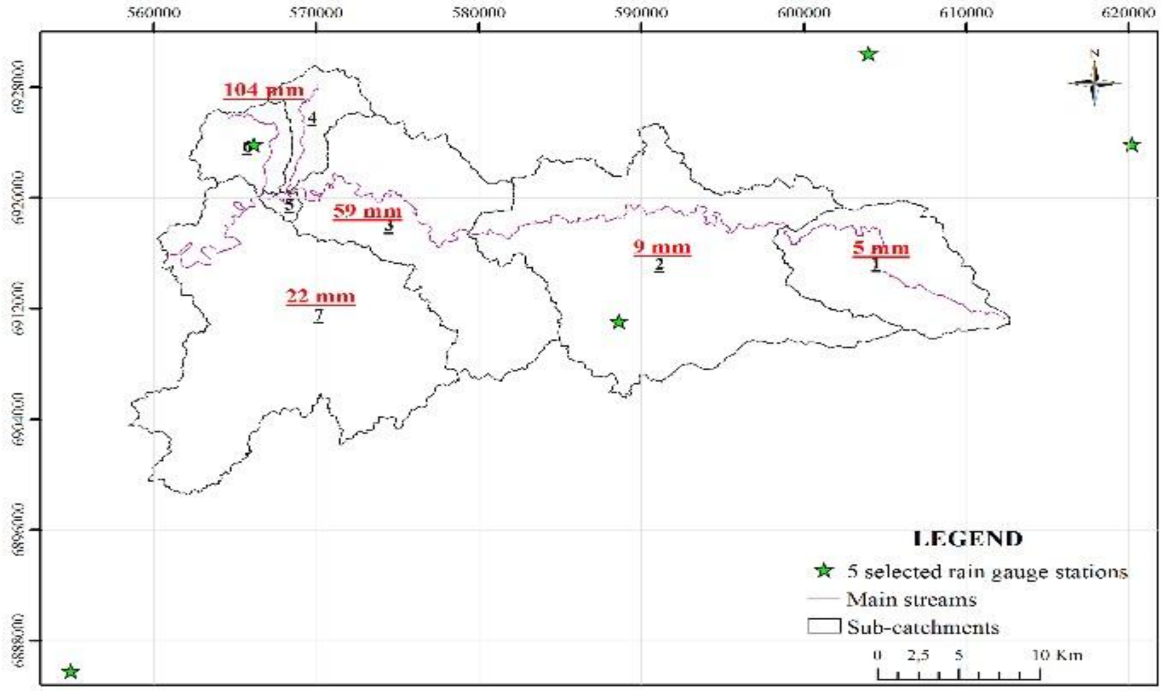

Fig. 4: Rainfall spatial distribution in 2008 event

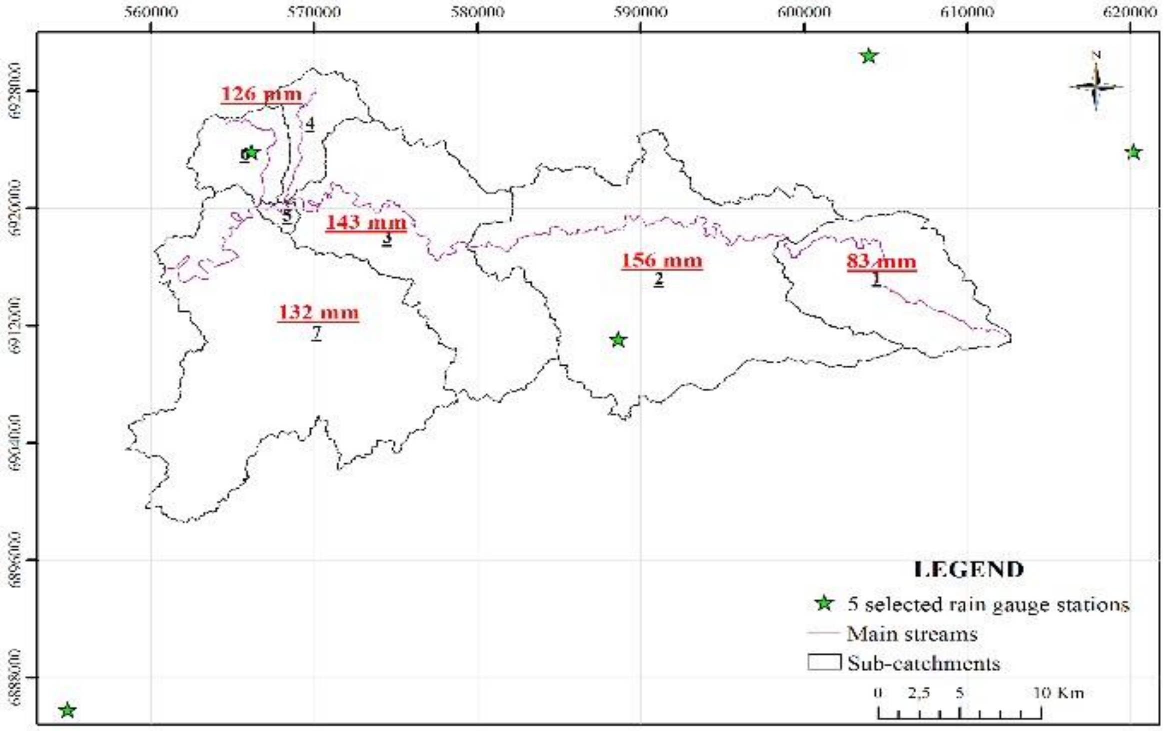

Fig. 5: Rainfall spatial distribution in 2011 event

2.1 Hydrological Model HEC-HMS:

The HEC-HMS (Hydrological Engineering Center – Hydrologic Modeling System) model is a discrete, concentrated, empirical/conceptual and deterministic mathematical model (U.S. Army Corps of Engineers, 2000) and is available on the World Wide Web. The version used in this study is the HEC-HMS 4.2. To simulate the rainfall-runoff process in watersheds, was developed the HEC-HMS (U.S. Army Corps of Engineers, 2000). The model generates hydrographs and information regarding the runoff volume, peak discharge and runoff time based on the simulations of the hydrological processes. It also has as an advantage the use of few parameters in the calibration and the adoption of combinations of several methods to represent the hydrological processes. The HEC-HMS model, usually with a daily time step as in this paper, have widely predicted floods in different regions of the world (Colossi and Tucci, 2020) through the Soil Moisture Accounting Model (SMA) loss model, available in the software package. The function of the SMA loss method is to implement storage to represent the dynamics of water movement above and in the soil (Lima et al., 2019).

Recent works have presented several applications using HEC-HMS. Wang et al. (2016) employed to simulate runoff in the semi-arid region of northwestern China, specifically the Hailiutu watershed. The results pointed out that, due to data unavailability on hydraulic engineering, the model faced challenges in simulating runoff properly for continuous simulation. Cabral et al. (2017) presented an analysis of uncertainties and errors of the SCS-CN model of the HEC-HMS module, for hydrological events using observed and RADAR-estimated precipitation data of the São Miguel River Basin in the State of Alagoas. This methodology had satisfactory results for this basin being a useful tool for the prediction of flooding in other watersheds. Fleischmann et al. (2019) applied HEC-HMS in the Itajaí-Açu river basin to compare a Continuous Simulation Model (CSM) method with 730 different simulations of an Event-Based method (EBM) one, considering different basin antecedent conditions and design hyetographs (10- and 50-years), having the results indicated that the EBM method leads to a large range of design discharges depending on the antecedent condition. Steinmetz et al. (2019) aimed to assess the influence of lumped and semi-distributed modeling on the applicability of Soil Conservation Service Unit Hydrograph (SCS UH) and Clark's Instantaneous Unit Hydrograph (CIUH) for estimation of flood hydrographs, through HEC-HMS. The main conclusions were the best performance of CIUH under the semi-distributed approach and being able to effectively estimate the direct surface runoff hydrographs even for long duration rainfall events. At the same time, SCS UH presented more accurate hydrographs for lumped modeling. This showed how HEC-HMS is suitable for understanding this kind of study.

The conceptual structure of HEC-HMS for the Caveiras Montante 1 watershed has its system delineation (Fig. 6). Similarly, the two urban sub-catchments in which flooding occurs, Ponte Grande and Carahá, are part of this system with their elements hydrologically connected.

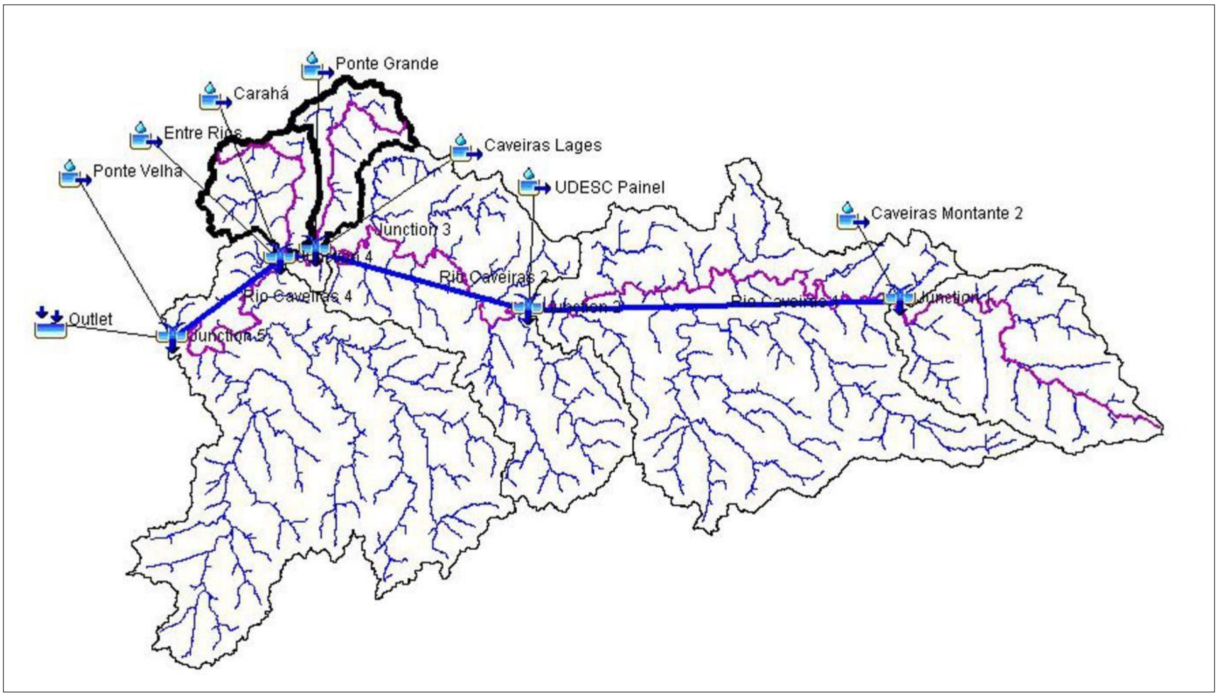

Fig. 6: Caveiras Montante 1 watershed, its sub-catchments, main rivers and the elements hydrologically connected in HEC-HMS model.

In addition, the model can work with two types of approaches to simulate the hydrological processes along with the time steps: continuous simulation and event-oriented simulation. The first needs the use of large historical series, which continuously accounts for volume variations in the hydrological cycle and ensures a better capacity of water balance determination (U.S. Army Corps of Engineers, 1994). However, it requires more information from the study catchments and becomes essential in water demand studies. The second occurs in this study when applied to three different events.

The event-oriented calibrations and tests performed in the HEC-HMS model, based on the observed time series in the Ponte Velha discharge station, have its location in the final outlet of the Caveiras Montante 1 watershed. Then, the two urban sub-catchments, without data monitoring, can have regionalized discharge for the events that caused floods.

In the search for data, all the parameters estimated by proper literature, orthophotos or satellite images, sub-catchments physical characteristics and measurements in the field were first determined. After this, they were performing the optimization to improve the representation of the simulated hydrographs with confidence. It depends on the technical capacity of the HEC-HMS calculations and on how well the hydrologist performs the model calibration.

The model calculation has its chosen methods defined according to the availability of data for the parameters. For example, the loss method was the National Resources Conservation Service Curve Number (NRCS-CN, former SCS-CN), for rainfall-runoff transformation, the method was the NRCS Unit Hydrograph (former SCS Unit Hydrograph), for baseflow was chosen the recession baseflow, and for routing the chosen method was the Muskingum-Cunge. The specific parameters for all chosen methods are set to each sub-catchment or reach of the river, which is part of the system. Besides its importance, this paper does not focus on it yet because of its emphasis on model outputs.

The model calibration aims to compare the simulated with the observed hydrograph, reaching a simulation as close as possible to reality. Therefore, the adopted test periods were the own calibrated events, seeking to discuss the differences between the selected events. Furthermore, the discussion of the runoff volumes, the peaks of discharge, the rising and falling limbs, and the hydrograph times will help evaluate the mechanisms that generate the flood.

The Nash-Sutcliffe Efficiency index – NSE (Nash and Sutcliffe, 1970) evaluates the model's performance. The higher is the index (from -∞ to 1), the better is the quality of the model representation or the agreement between the simulated and the observed data. All the statistical analysis correlates are implicit in HEC-HMS.

$$NSE = 1 - \frac{\sum_i (Q_{obs} - Q_{sim})^2}{\sum_i (Q_{obs} - \bar{Q}_{obs})^2} \qquad (4)$$

Q_{obs} is the average discharge of the daily-observed time series comprising the entire simulation period, Q_{obs} is the daily-observed discharge at a given time step, and Q_{sim} is the daily-simulated discharge.

Some authors indicated the influence of NSE index toward extreme high discharges, as in watersheds with higher dynamics. It suggests that is due to normalization in the variance of the observed data. Therefore, the use of NSE index to assess the quality of model representation in extreme isolated events appears to be adequate to the scope of this study. The chosen output for model representation analysis was the peak of discharge and residual volume in the Ponte Velha discharge gauge station. The residual volume represents the difference between the observed and the simulated volume resulted from runoff in the calibration processes. The quality of the model representation of the regionalized discharges in the Ponte Grande and Carahá sub-catchment outlets depends on the quality of the discharge representation in the control discharge gauge station (Ponte Velha).

3. RESULTS AND DISCUSSIONS:

3.1 Calibration processes

Table 3 presents the NSE index and the absolute residual volume from calibrated events and test periods processes in the Ponte Velha discharge gauge station. In bold, it shows the events used to guide the calibration, which means they have the best results.

Table 3: NSE index for calibration and test periods in the Ponte Velha discharge gauge station.

Calibrated events	**Nash-Sutcliffe (NSE)**		
	Test periods		
	2005	**2008**	**2011**
2005	0.965	0.025	0.258
2008	0.131	0.906	0.411
2011	0.594	0.625	0.725

Table 4: Residual volume for calibration and test periods in the Ponte Velha discharge gauge station.

Calibrated events	**Residual volume (m^3)**		
	Test periods		
	2005	**2008**	**2011**
2005	-8.95×10^5	-9.01×10^6	7.43×10^7
2008	1.90×10^8	100.00	2.55×10^7
2011	1.10×10^8	-3.72×10^6	900.00

The hydrographs in figures 7, 8 and 9 represent observed (dotted) and simulated (line) hydrographs in Ponte Velha discharge gauge station for 2005, 2008 and 2011 events.

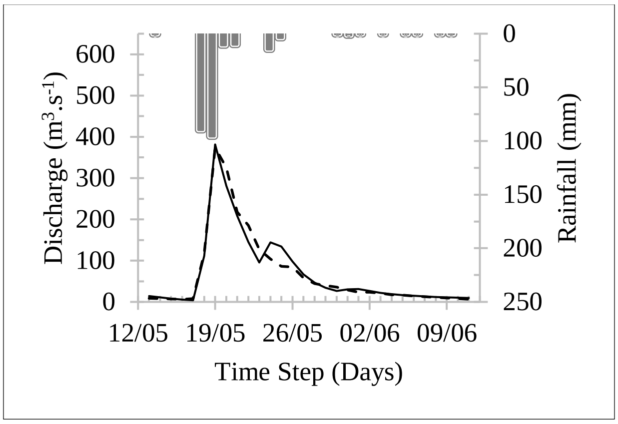

Fig. 7: Observed and simulated hydrographs in Ponte Velha discharge gauge station for 2005 event

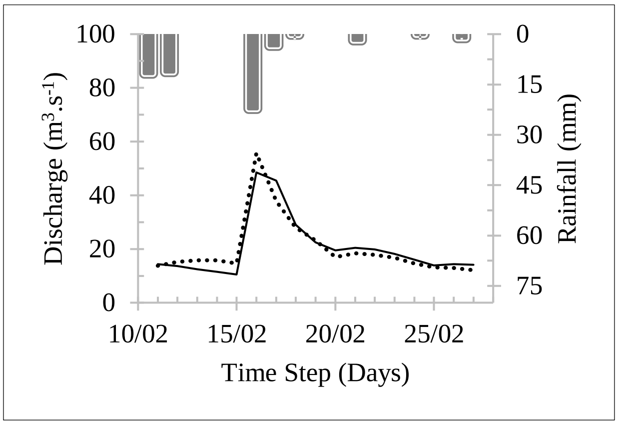

Fig. 8: Observed and simulated hydrographs in Ponte Velha discharge gauge station for 2008 event

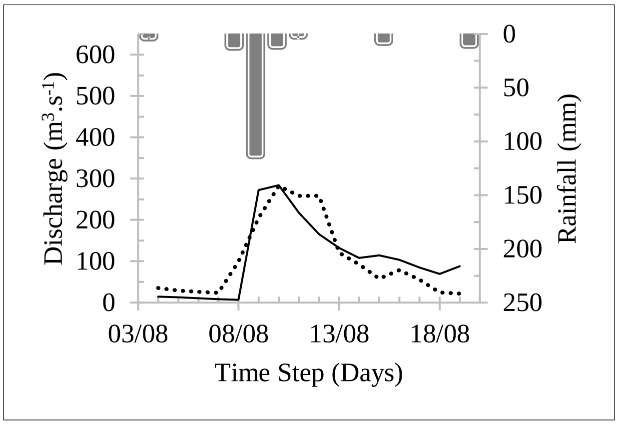

Fig. 9: Observed and simulated hydrographs in Ponte Velha discharge gauge station for 2011 event

The results produced through the HEC-HMS model, characterized in Table 5 and Table 6, brings information regarding the peak discharges and runoff volume based on simulations of the hydrological processes before and after the optimizations.

Table 5: Runoff volumes: observed, before and after optimization in Ponte Velha discharge gauge station.

Event	**Runoff Volume (m^3)**		
	Optimization		**Observed**
	Before	**After**	
2005	3.71 x 10^8	1.74 x 10^8	1.75 x 10^8
2008	3.28 x 10^7	2.85 x 10^7	2.85 x 10^7
2011	1.74 x 10^8	1.42 x 10^8	1.42 x 10^8

Table 6: Peak discharges: observed, before and after optimization in Ponte Velha discharge gauge station.

Event	Peak Discharges (m^3/s)		
	Optimization		Observed
	Before	After	
2005	509.6	381.6	373.6
2008	38.2	48.5	55.7
2011	283.8	284.1	282.5

The behavior of the simulated runoff volumes that have passed through the watershed after the optimization could, in all of the cases, practically match the observed volumes in each studied event. However, regarding peak of discharge, during optimization, it resulted in different behaviors for each event.

In the 2005 event, there was an overestimated peak of discharge before and after the optimization due to the event's severity, which means there is a need to reach the observed peak of discharge to get relevant changes in the hydrological processes of the watershed.

n the 2008 event, the simulated peak discharge of the Caveiras River was underestimated before optimization due to the concentrated rainfall in the urban sub-catchments. Therefore, it could not be considered until the watershed parameters were optimized to get near the observed peak of discharge of the Caveiras River. Finally, in the 2011 event, before the parameters optimization, the model had already simulated a peak of release near to the one observed afterwards. After the optimization, there was a small decrease in such values due to the preference to approximate the runoff volumes to represent the hydrological processes properly.

3.2 Analysis of 2005 event-oriented modelling

With all the information available, the event with the highest degree of severity is 2005, which reaches volumes and a discharge peak much superior to the other events, validating the highest return period of 384 years.

In the event of 05/18/2005 and 05/19/2005, according to Table 2, there is an accumulated rainfall of 183.6 mm for 32 consecutive hours, having an average intensity concerning the other two events and, with this, obtaining the longest return period. As shown in Figure 3, the spatial distribution of rainfall is widely distributed in the study event, leading to an increase in the outlets of all sub-catchments upstream of the Ponte Grande and Carahá sub-catchments. In addition, the long duration of the event, exceeding the time of concentration in this point of the Caveiras River indicates that the system formed by sub-catchments 1 to 6 (Table 1) is the main responsible for the severity of the 2005 event.

The NSE of 0.965 indicates a good representation in the HEC-HMS model. However, the Ponte Velha discharge gauge station's accumulated contribution reached the highest peak of discharge compared to the other events (381.6 $m^3.s\text{-}1$). Therefore, the simulated hydrograph (Fig. 7) accurately represented the rising limb, peak, and final part of the recession limb. Only in the initial part of the recession limb, it was not possible to follow the observed hydrograph in the same way.

This issue is a possible spatial distribution more concentrated of the rainfall in the days immediately after the event in the sub-catchments. Therefore, the model considered them distributed and, in the event, responsible for the peak itself, accusing a slight rise along the recession limb that is not consistent with reality. The result is in Table 4, which indicates the worst residual volume compared to the other events' simulation, even when analyzing the calibrated event.

3.3 Analysis of 2008 event-oriented modelling

In the event of 02/16/2008, according to Table 2, there is an accumulated rainfall of 104 mm. However, with the shortest duration, 4 hours and 30 minutes, and with the highest mean intensity compared to the other two events, obtaining a medium return period of 29 years. As shown in Figure 4, the spatial distribution of rainfall in the 2008 event was predominantly concentrated in the urban sub-catchments, contributing to its characteristic flood areas in the Carahá sub-catchment. In fact, regarding to spatial distribution, this event is different compared to 2005 and 2011 events. The NSE indexes in Table 3 indicate the great hydrological difference between 2005 and 2008, for example, when analyzing the low values when calibrated in 2005 and tested in 2008, or vice versa. It confirms the hypotheses of not applying the model for prediction when adopted the event-oriented hydrological modelling.

It is also perceptible that the discharge of the Caveiras River does not have a proportional peak as the ones found for the other events (Fig. 8). When analyzing the hydrograph, a low peak of discharge can be observed compared to the other events, and the HEC-HMS model could represent it satisfactorily. However, underestimating this index in relation to the observed data reaching a peak of discharge of 48.5 m^3/s and consequent NSE index of 0.906.

In general, the simulated hydrograph had an approximate representation of the rising limb and peak that may be explained with the more concentrated spatial distribution of the event in the urban sub-catchments, which means that, makes it difficult to simulate the minor peak of the Caveiras River in such a severe event. There has been a better representation of the reality in the recession limb, and it was possible to follow the hydrograph observed in smaller discharges. Table 4 shows the best residual volume compared to the simulation of the other events due to the optimization process and the minor scale from the event.

3.4 Analysis of 2011 event-oriented modelling

In the event of 08/08/2011 and 08/09/2011, according to Table 2, there is an accumulated rainfall of 123.6 mm for the longest duration, of 35 consecutive hours, however, with the lowest average intensity compared to the other two events and obtaining the shortest return period of 22 years.

Regarding the severity of the event, this event was the lowest compared to the others based on the return period. The spatial distribution of rainfall in 2011 (Fig. 5) was distributed, which caused an increase in the outlets of all the sub-catchments upstream of the Ponte Grande and Carahá sub-catchments reaching the peak of discharge simultaneously with the Caveiras river, as for the 2005 event. In Figure 9, this accumulated contribution can be verified in the Ponte Velha discharge gauge station, even though the HECHMS model achieved a lower NSE index than the others, of 0.725. With the satisfactory representation of the peak of discharge of 284.1 m^3/s, the values of NSE for the tests in 2005 and 2008 are 0.594 and 0.625, respectively, both acceptable values.

When analyzing the simulated hydrograph, the rising and recession times' inadequate representation appears when confronting the observed event. In addition, the dislocation of the rising limb, peak and recession limb in the presented hydrograph are perceptible, confirming that what guarantees the regular value of calibrated NSE is the good reach of the peak of discharge and optimum residual volume (Table 4).

The peculiarity of the 2011 event in improperly representing hydrograph times is related to the possible use of observed data with divergences in the rating curve of the discharge gauge station. Therefore, it could cause the visible difference between observed and simulated hydrographs, even after the optimization. Furthermore, the presence of discharges near the peak during the days after the event, in the observed hydrograph, is related to the spatial distribution of rainfall, which is a second factor to consider. This means that, while the model considered it distributed in the days immediately after the event responsible for the peak, the rainfall was concentrated at the Ponte Velha discharge gauge station.

3.5 Hydrological response of urban sub-catchments

The optimization procedure for the calibration of the parameters, both automatic and manual, as well as the hypotheses of backwater influence from the Caveiras River in the urban sub-catchments flood events, were not considered in this study due to the greater emphasis that the results from the HEC-HMS model output bring to the simulation of hydrological processes in a flood system, and how downstream sub-catchments can regionalize data to upstream sub-catchments. As a result, hydrographs generated for the urban sub-catchments of interest follows for each of the events:

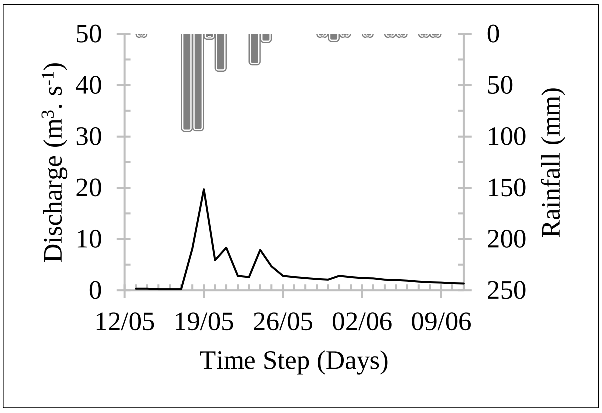

Fig. 10: Observed hyetograph and simulated hydrograph in Ponte Grande sub-catchment for 2005

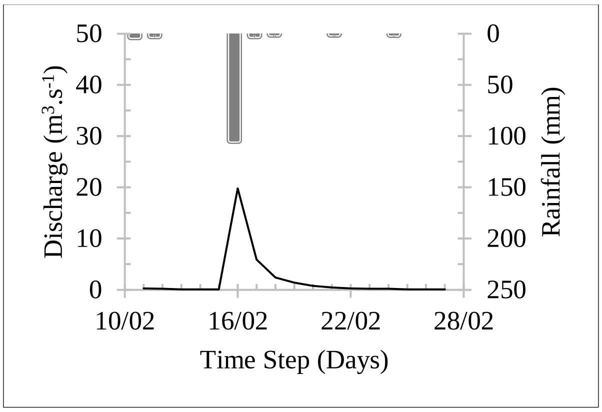

Fig. 11: Observed hyetograph and simulated hydrograph in Ponte Grande sub-catchment for 2008

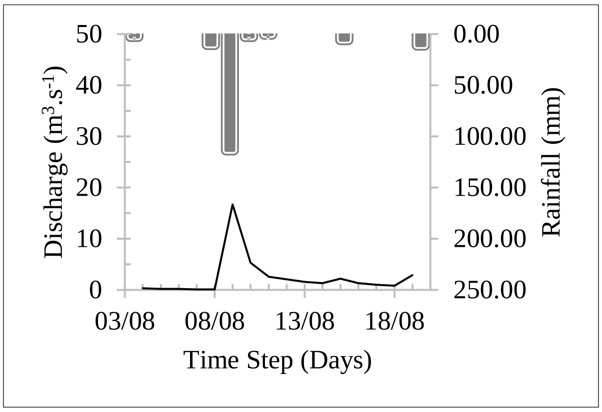

Fig. 12: Observed hyetograph and simulated hydrograph in Ponte Grande sub-catchment for 2011

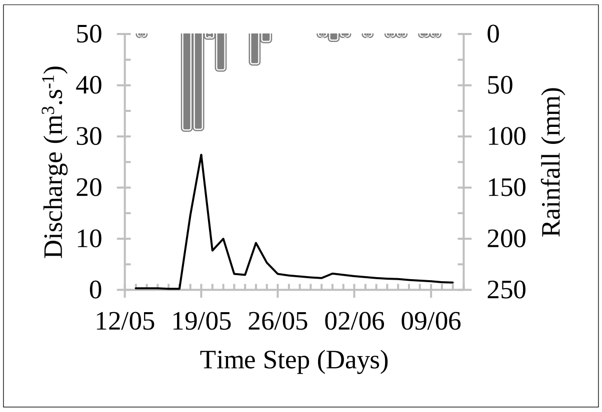

Fig. 13: Observed hyetograph and simulated hydrograph in Carahá sub-catchment for 2005

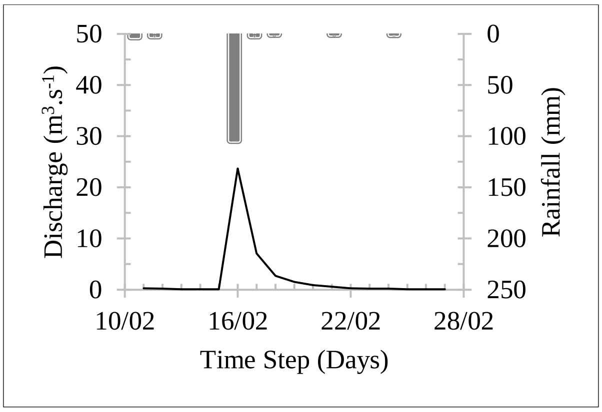

Fig. 14: Observed hyetograph and simulated hydrograph in Carahá sub-catchment for 2008

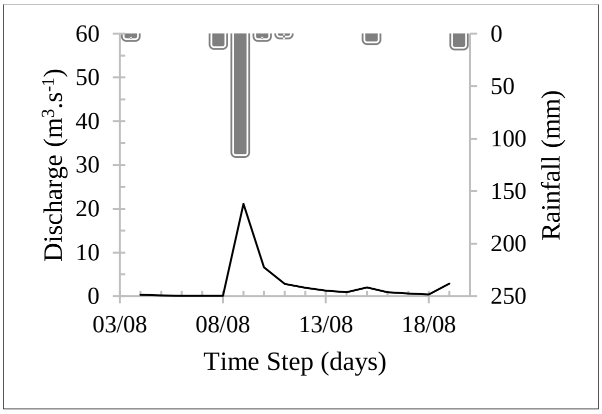

Fig. 15: Observed hyetograph and simulated hydrograph in Carahá sub-catchment for 2011

Based on the analysis of the presented hydrographs, Table 7 shows a synthesis of the results calculated with the HEC-HMS model, highlighting the volume and the peak of discharge for each event and indicating the hydrological behavior of these sub-catchments during the events.

Table 7: Total volume and peak discharge produced by Ponte Grande and Carahá sub-catchments during the events of 2005, 2008 and 2011.

Variable	**HEC-HMS Output**		
	Peak event date	**Ponte Grande**	**Carahá**
Volume (m^3)	05/19/2005	2.94 x 10^6	4.25 x 10^6
	02/16/2008	2.30 x 10^6	2.75 x 10^6
	08/09/2011	1.93 x 10^6	2.45 x 10^6
Peak Discharge (m^3.s^{-1})	05/19/2005	19.7	26.4
	02/16/2008	19.8	23.7
	08/09/2011	16.7	21.1

Regarding the volume of water in the urban sub-catchments, which has not been lost in any way after the rainfall and has become runoff, it occurs according to the event severity for both urban sub-catchments.

About the peaks, in the Ponte Grande sub-catchment, they do not follow the severity scale since it is output more sensitive with the specific watershed parameters optimization. Different adjustments make the peaks not behaving according to the event severity in each calibrated event. Unlike the Ponte Grande sub-catchment, the Carahá sub-catchment follows the same growth pattern as the volume, which means the development of the event severity due to its higher level of impervious surface expressed in the optimized parameters. Analyzing the generated volumes and peaks of discharge, it is possible to observe that the more severe the event is, the greater the amount of water drained in the urban sub-catchments and possibly the greater the risk of flood since the channel is not capable of carrying these peaks of discharge.

In Carahá sub-catchment, the output values are much higher than that found in the Ponte Grande sub-catchment, it occurs because of the greater area and higher level of the impervious surface due to the superior urban occupation. As a result, each event indicated a specific analyzed situation related to its characterization and the hydrological response in floods in Lages.

4. CONCLUSION

The flood maps of 2005, 2008 and 2011, and the precipitation series of the rain gauge stations used, point to specific flood situations associated with factors such as the spatial distribution of rainfall, its intensities, durations and return period. In this way, the range of such factors severity reflects in the outputs, creating specific scenarios in the floodplain. Therefore, the events confronted with the IDF equation for Lages and Gumbel distribution could properly classify the event's severity when observing most of the generated outputs for the Caveiras Montante 1 and urban sub-catchments with the hydrological responses from downstream, in the hydrographs outlet, to upstream.

Finally, all the events reached excellent NSE index and respective residual volumes in the optimization processes to calibrate the events. It means the hydrological behavior of the conceptual system of sub-catchments during the event-oriented modelling can confirm the regionalized outputs for the urban ungauged sub-catchments of interest Ponte Grande and Carahá. Therefore, the practical use of the regionalized outputs may work in future research, such as hydraulic modelling for the same flood events.

Monitoring variables such as rainfall and discharge for the application of hydrological modelling techniques and, mainly, hydraulic modeling in the sub-catchments is recommended in order to complement and make use of the outputs in the future.

Furthermore, studying the entire conceptual system of sub-catchments and considering a hypothesis about the possible backwater from the Caveiras River into the urban sub-catchments. Moreover, instead of studying only two hydrographs, all seven sub-catchment hydrographs may be discussed to improve knowledge of the system's hydrological behavior. In addition, the discussion presented here represents a way to combine scientific support with previous information for water resources management, increasing prevention and mitigation of impacts through hydrological modeling. It also revealed the Caveiras Montante 1 hydrological behavior in extreme situations, having great relevance for future studies on the delimitation of flood risk areas.

ACKNOWLEDGEMENT

The work could not be possible without the Santa Catarina State University (UDESC) for the essential support in elaborating work. In addition, the acknowledgements to the institutions that have provided the data for the development of the work, such as the ANA (National Water Agency), CELESC (Santa Catarina Electrical Center Stations), EPAGRI/CIRAM (Santa Catarina hydrometeorology and environmental resources information center) and INMET (National Meteorology Institute).

Funding Information:

This work was supported by CAPES (Coordination of Improvement of Undergraduate Level), the Santa Catarina Federal University (UFSC) and the Graduate Program in Environmental Engineering for the academic master's degree.

Conflict of Interest:

Authors declare no conflict of interest

Software/data availability:

Name of software: HEC-HMS 4.2
Developer: US Army Corps of Engineers (USACE) – Hydrologic Engineering Center (HEC)
Mailing Address: Department of The Army Corps of Engineers - Institute for Water Resources - Hydrologic Engineering Center. 609 Second Street. Davis, CA 95616-4687.
Telephone: (+1) 530 756-1104 / Fax: (+1) 530 756-8250
E-mail: hec.hms@usace.army.mil
Year first available: May, 1981 (HEC-1)
Hardware minimum requirements: CPU Speed - 1.6 GHz; Memory/RAM - 1 GB; Hard Drive Space – 20x the terrain data or 1GB.
Software minimum requirements: Operating System - Windows XP; Microsoft .NET Framework Version 2.
Availability and cost: Approved for public release; distribution is unlimited.

REFERENCES

Cabral SL, Sakuragi J, Silveira CS. Incertezas e erros na estimativa de vazões usando modelagem hidrológica e precipitação por RADAR. Revista Ambiente & Água 2017; 12(1):57-70. https://dx.doi.org/10.4136/ambi-agua.1924

Cardoso CO, Bertol I, Soccol OJ, Sampaio CA de P. Generation of Intensity Duration Frequency Curves and Intensity Temporal Variability Pattern of Intense Rainfall for Lages/SC. Braz. Arch. of Biol. and Technol. 2014; 57(2):274-283. http://dx.doi.org/10.1590/S1516-89132013005000014

Cirilo JA, Verçosa LF de M, Gomes MM de A, Feitoza MB, Ferraz G De F, Silva B de M. Development and application of a rainfall-runoff model for semi-arid regions. RBRH. 2020; 25:e15. Epub 27 April, 2020. https://doi.org/10.1590/2318-0331.252020190106

Colossi BR, Tucci CEM. Ensemble long-term soil moisture forecast using hydrological modeling. RBRH, Porto Alegre. 2020; 25:e28. Epub 07 August, 2020. https://doi.org/10.1590/2318-0331.252020190036

Decina TGT, Brandão JLB. Análise de desempenho de medidas estruturais e não estruturais de controle de inundações em uma bacia urbana. Eng. Sanit. Ambient., Rio de Janeiro. 2017; 21(1):207-217. https://doi.org/10.1590/S1413-4152201600100116134

EM-DAT – Emergency Disasters Database. Centre for research on the epidemiology of disasters. (2015). Belgium: CRED, 2015. Available from: http://www.emdat.be

Felix VS, Paz AR. Hydrological processes representation in a semiarid catchment located in Paraiba state with distributed hydrological modelling. RBRH. 2016; 21(3):556-569. https://dx.doi.org/10.1590/2318-0331.011616009

Fleischmann AS, Collischonn W, Paiva RCD. Estimating design hydrographs at the basin scale: from event-based to continuous hydrological simulation. RBRH, Porto Alegre. 2019; 24:e4. Epub 18 February, 2019. https://doi.org/10.1590/2318-0331.241920180109

Lima FN, Fernandes W, Nascimento N. Joint calibration of a hydrological model and rating curve parameters for simulation of flash flood in urban areas. RBRH, Porto Alegre. 2019; 24:e24. Epub 13 May, 2019. https://doi.org/10.1590/2318-0331.241920180066

Nash JE, Sutcliffe JV. River flow forecasting through conceptual models part I - a discussion of principles. J. Hydrol. 1970; 10:282-290. http://dx.doi.org/10.1016/0022-1694(70)90255-6

Sarhadi A, Soltani S, Modarres R. Probabilistic flood inundation mapping of ungauged rivers: Linking GIS techniques and frequency analysis. J. of Hydrol. 2012, 458-459, 68-86. http://dx.doi.org/10.1016/j.jhydrol.2012.06.039

Siqueira RC, Moura PM, Silva, das G TF. Methodology for the construction of an urban flood hazard chart. *RBRH*, Porto Alegre. 2019; 24:e23. Epub 27 June, 2019.http://dx.doi.org/10.1590/2318-0331.241920180125

Steinmetz AA, Beskow S, Terra F da S, Nunes MCM, Vargas MM, Horn JFC. Spatial discretization influence on flood modeling using unit hydrograph theory. RBRH. 2019; 24:e16. Epub 04 April, 2019. https://dx.doi.org/10.1590/2318-0331.241920180143

U.S. Army Corps of Engineers. Flood-runoff analysis, Engineer Manual - EM 1110-2-1417. Office of Chief of Engineers, Washington, DC 1994.

U.S. Army Corps of Engineers. Hydrologic Modeling System (HEC-HMS): Technical Reference Manual. Institute for Water Resources, Hydrologic Engineering Center, Davis 2000.

Wang M, Zhang L, Baddoo TD. Hydrological Modeling in a Semi-Arid Region Using HEC-HMS. Journal of Water Resource and Hydraulic Engineering. 2016; 5(3):105-115. http://dx.doi.org/10.5963/JWRHE0503004

Zi-jun H, Ling-ling W, Hong-wu T, Xiao-ming Q. Prediction of the future flood severity in plain river network region based on numerical model: A case study, Journal of Hydrodynamics, Ser. B. 2017; 29(4):586-595. ISSN 1001-6058, https://doi.org/10.1016/S1001-6058(16)60771-0.