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Hydrological Modeling of the Cambamba Watershed in Angola Using the HEC-HMS Model

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Abstract: When evaluating the impact of climate change on water resources in river basins it is crucial to accurately estimate the availability of water and such can be attained through hydrological modeling of the basin. The studies of the Hydrological Modeling System (HEC-HMS) for the Cambamba River Basin in Angola has been calibrated and validated for the prediction of its hydrologic response. Due to the complexity of Hydrologic models, a good calibration of the model should be established, therefore, improving its skills and effectiveness. A combination of both the energy budget and a physically-based rainfall-runoff model, which are used for the estimation of lake evaporation, were applied in the lake water balance model. Soil storage, as well as groundwater storage coefficient, are essential parameters for estimating the simulated streamflow. For an adequate performance evaluation of the model which entails the simulation of the streamflow on Cambamba watershed and quantification of water availability, The Nash-Sutcliffe model efficiency criterion; root mean square error; percentage error in volume PEV; and percentage error in peak PEP, were implemented. Model performance is improved by using semiannual parameter sets that consider the change in hydrological conditions, as evaluated in this study.

Key words: HEC-HMS, watershed, rainfall-runoff, flood hazards

1. Introduction

The precipitation, as well as the intensity and frequency of extreme hydrological events, would affect streamflow and flood hazards. Therefore, affects all aspects of water resources worldwide. Poor drainage conditions detrimentally impact both human and animal life when the precipitation levels are too high causing flooding thus, destroying the infrastructure as well as animal habitat; In African countries, such events are certain to happen due to the lack of flood forecasts and management of emergency systems. Major parts of Africa have been subjected to extreme changeability in precipitation leading to recurring flood events [1-4]. Concerning the installation of rainfall monitoring stations in Angola, the oldest was installed in Luanda-the capital city by João Capelo in 1857; Years after, beyond 1940, an outstanding procedure for the creation of a structured rainfall monitoring network was implemented therefore in late 1940s it reached 145 stations in 1960s it reached 371 stations. In 1974, 465 stations exceeded five years of record completeness, but, unfortunately, the Angolan civil war elapsed a year after, ruining all the efforts made thus minimizing the operation to only 18 stations that were located in the main cities. Along the coast, there is an outstanding variety of the maximum average of daily precipitation expanding from the Namib Desert in the south to Cabinda in the north of Angola In the city of Moxico-Cameia (interior south), precipitation of 360.0 mm/day was recorded in November 1953. On the southwestern coast of Namibe, Porto Alexandre, and Baia dos Tigres, the three monitoring stations that

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coexisted there were in vain as they merely registered a millimeter of precipitation over one year [5].

Misuse of water resources to sort extreme precipitation events result in flooding and thus, for adequate functioning of the hydraulic structure, safety, and economy in Luanda city, the most effective procedure to amend such events is to implement hydrological designs which aim at the estimation of maximum or minimum average floods that impacts the structure; Therefore, the estimation should be very accurate for the project to excel. In the design, operation of water resource and planning projects, the estimation of design stream-flows is considered one of the crucial components. There is an urge to gather information on the frequencies as well as the streamflows of Luanda for the hydraulic structures namely: flood plain zoning, economic evaluation of flood protection projects, lastly both road and urban drainage systems.

According to Mkilima (2018) [6], the estimation of peak flows on small and medium-sized plains is generally, a common application as they are needed for designing conservation works, etc. Plenty of methods are available for the estimation of streamflow, but, only three methods are widely used, namely: the rational method, and the Hydrologic Modelling System (HEC-HMS), developed by the Hydrologic Engineering Center, USA [7].

2. Cambamba River Basin Case Study

The Cambamba river (62.898 km long), originated from Zango III highlands (9°3’8.96’’N, 13°27’7.79’’E, elevation 193 m), extending over 506.5 km^2, with average annual rainfall in the watershed of 1400 mm. The information regarding Operational hydrologic models in use by the main National Water Resources Institute (INRH) is still unknown.

Visual surveys were used to identify and map variables like intermittent watercourses, urban open spaces, and tree-lined streets. To merge unlike variables into a spatial framework, the software packages used were ArcGIS 10.3 (ESRI) and QGIS 2.16, as presented in Fig. 1.

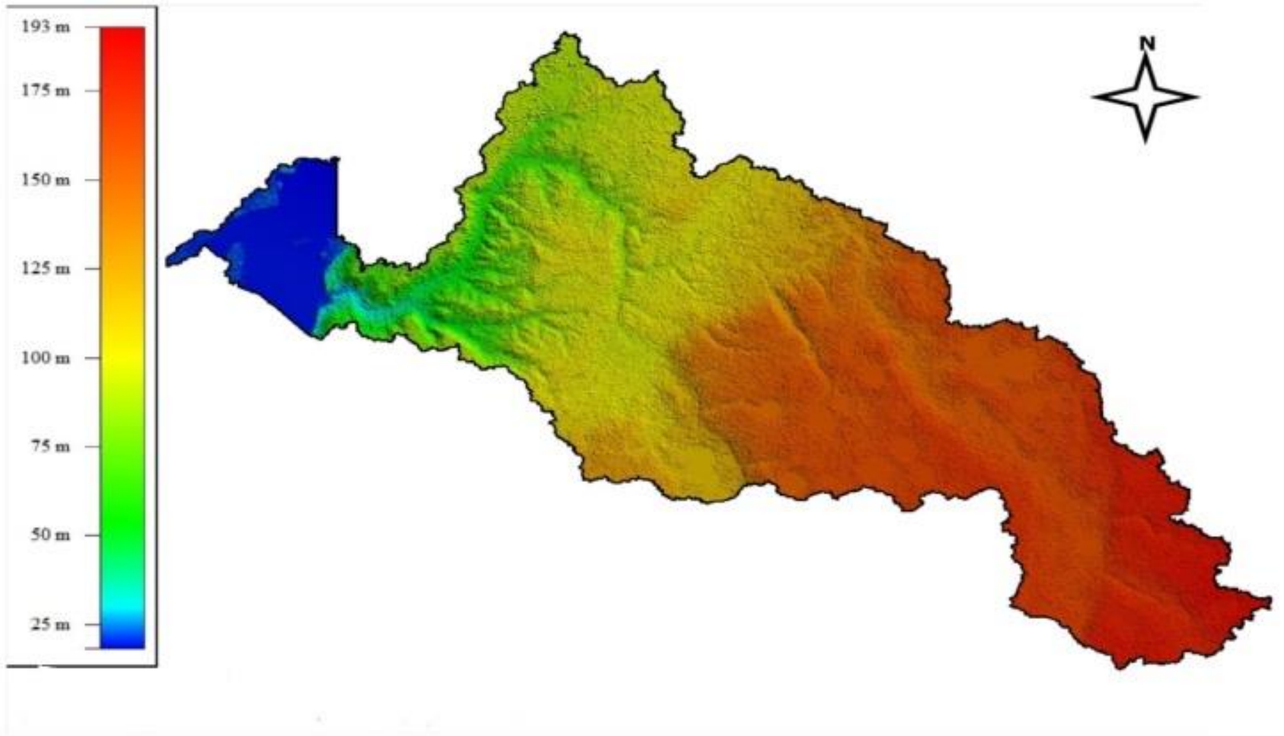

Fig. 1 Hypsometric map of Cambamba Watershed.

Using INAMET (National Institute of Meteorology and Geophysics) the Cambamba watershed survey was attained, thus entailing, rainfall data and gridded (1 × 1 degree) daily mean temperature data for the study period of 2004-2007, daily discharge data for 2004-2007 and plenty other pertinent data for the study were gathered from INRH. The present crossing of the Cambamba River in Rua da Vala, Angola-Luanda, an area known as "Wet Bridge", is named regarding the fact that it is constantly subjected to overtopping due to extreme rainfall. Overtopping has had tremendous consequences due to high traffic on that road, leading to traffic jams, affecting people, and vehicles as well as washing other goods away. Rua da Vala is an urban street highly densely located on the Benfica district after the left margin of the Cambamba River. Therefore the relocation of the street should be over the street illustrated below thus the new bridge facilitates and establishes a safe crossing of the river, even in a centenary flood scenario (COBA, 2015), as presented in Fig. 2.

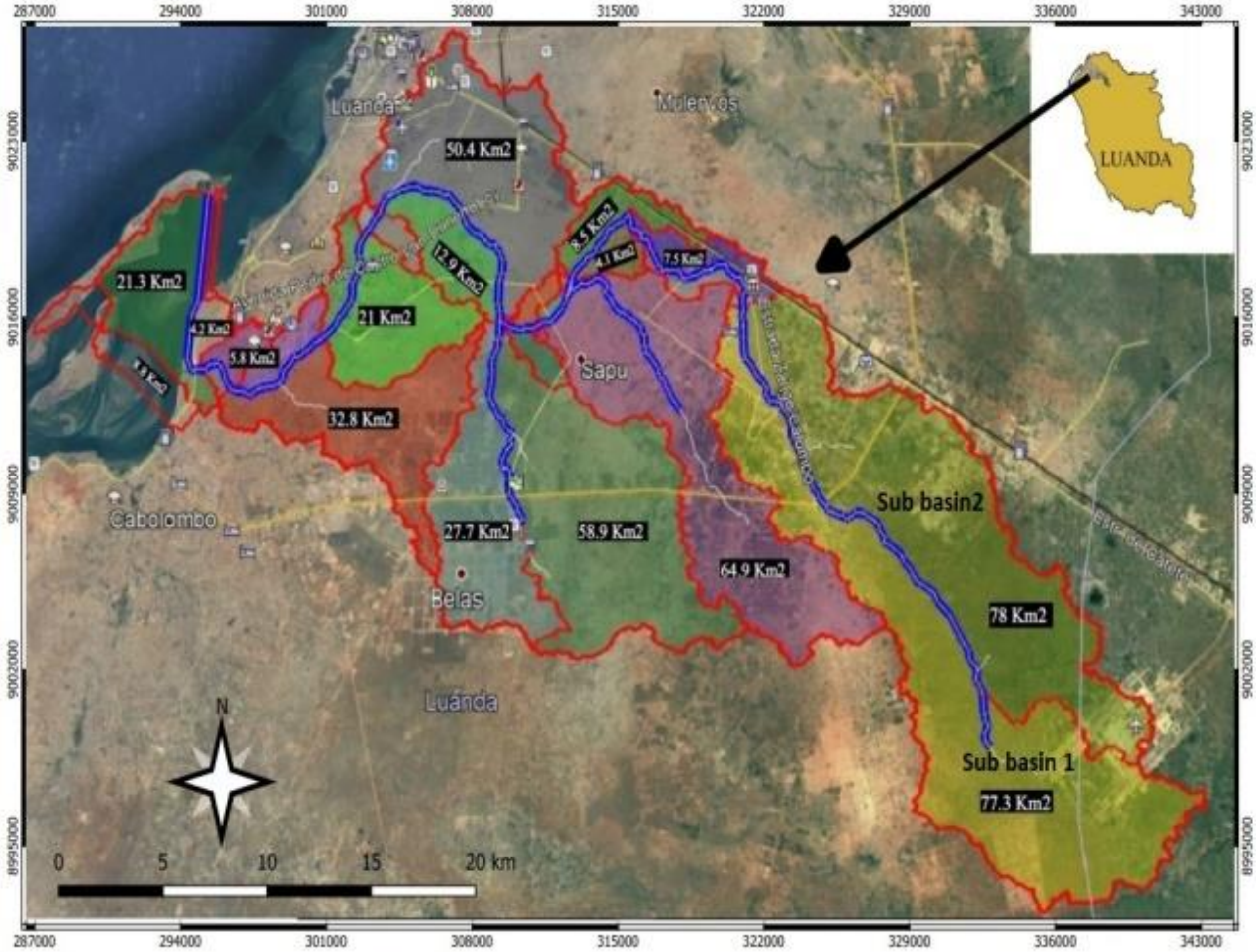

Fig. 2 Cambamba River watershed and respective sub-watersheds.

3. Material and Methods

3.1 HEC-HMS Model

The rainfall-runoff processes of Cambamba watershed systems are simulated by the HEC-HMS (Hydrologic Engineering Centre-Hydrologic Modelling System) model specifically through the Digital Elevation Model (DEM) of the studied regions with a Soil Moisture Accounting (SMA) algorithm. Over an endured period, the soil moisture balance is taken into account thus becoming convenient for the simulation of daily, monthly as well as a seasonal streamflow. Direct (surface flow) and indirect (interflow and groundwater flow) runoff [8] is accurately noted by the SMA algorithm. The requisites needed by the model entail, soil condition, daily rainfall, and alternate hydro-meteorological data as illustrated in Fig. 3 and Fig. 4 respectively.

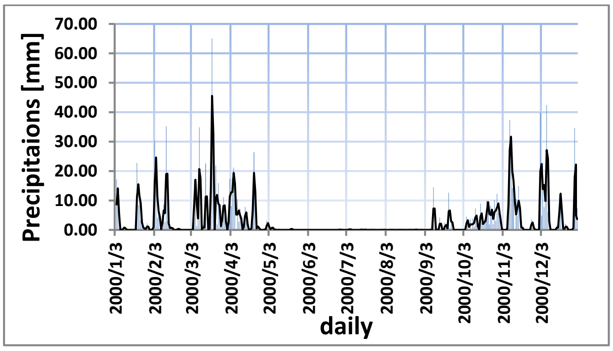

Fig. 3 Rainfall data of Cambamba station.

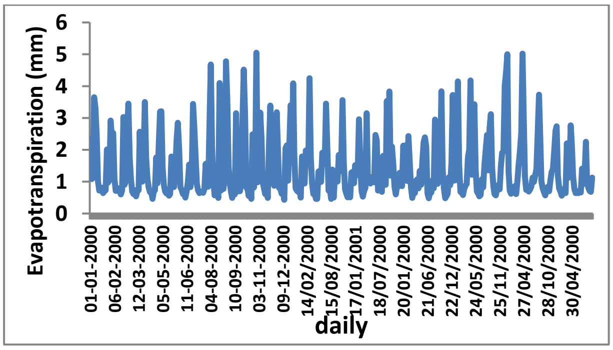

Fig. 4 Evapotranspiration data of the Cambamba station.

The HMS SMA algorithm represents a watershed with five different storage layers, canopy – Soil profile, groundwater storage, interception, surface depression, involving twelve parameters, surface-depression. The analysis has been performed for both sub-basins (1 and 2, respectively) in the Monsoon season with input parameters as follows: 3.2 and 2.3 mm for canopy storage, 12.7 and 12.8 mm for Surface storage, 2.0 and 6.3 mm/hr for.

Max rate of infiltration, 12 and 20% for impervious, 15.5 and 12.8 mm for Soil storage, 140.8 and 106.5 mm for Tension storage, 0.3 and 0.4 mm/hr for Soil percolation, 121 and 26 mm for Groundwater 1 storage, 0.3 and 0.3 mm/hr for Groundwater 1 percolation, 77.4 and 110 hr for Groundwater 1 coefficient, 176 and 57 mm Groundwater 2 storage, 0.3 and 0.2 mm/hr for Groundwater 2 percolation, 300 and 202 hr for Groundwater 2 coefficient.

A computation of runoff depth was established by using the SMA method in this study. The Snyder's unit hydrograph method used to compute both the Clark unit hydrograph technique with the peak and time to the peak was adopted to compute streamflow systems; the base flow was modelled by the linear reservoir method; For the generation of discharge hydrograph at the downstream point in the channel, there was the implementation of the Muskingum method of the channel routing.

2.2 HEC-HMS Project Set-Up

Considering both the topography and surface characteristics of the location being modelled (e.g., length of the reach) the HEC-HMS software was used for the conversion of rainfall data into the direct flow. In the runoff computation, the software reckons the routing, loss, and flow transformation. After checking the data, the HEC-HMS model emerged with the creation of plenty of parameters in the Cambamba Basin with meteorological model files. The requisites for running the HEC-HMS models are listed below in Table 1.

Table 1 The Hydrological Catchment Model Parameters for Cambamba case study.

No.	Model	Method	Parameters required units
1	Loss Rate Parameter	SCS Curve Number	Initial abstraction (mm) Curve Number and
2	Runoff transform	SCS Unit Hydrograph	Impervious area (%) Lag time (min)
3	Routing Methods Constants	Muskingum	Travel time (K) and dimensionless weight (X)

2.3 Model Evaluation

Sensitive analysis, calibration, and validation are part of the procedure of model evaluation; for an exact prediction of discharges, a precise estimation in determining prominent parameters was performed by the sensitivity analysis on computed discharges of the model. Thus, firstly, the input values (the database file) of the model was used to ensure its workability, evaluated by the methods shown above in Table 1 and base output was gathered; Secondly, to maintain the others constant and the model working, each input parameter within an assigned range was varied; lastly, an analysis was carried out to determine the change of outlet values according to the base output thus it is part of the sensitivity. For an improvement of the agreement between both the observed and simulated data, a calibration of the model for the recognized sensitive parameters was performed. Once more, the automatic calibration procedure in HEC-HMS exploits repetitious methods to lessen an objective function, like the sum of absolute residuals, and peak-weighted root mean square error, amongst others (HEC 2000). For this study a combination of both manual and automated calibration methods were used; the criteria adopted in this study for model assessment are as follows:

- Percentage Error in simulated Volume (PEV) – Eq. (1);
- Percentage Error in simulated Peak (PEP) – Eq. (2); and Net Difference of observed and simulated Time to Peak (NDTP) – Eq. (3).

$$PEV = \frac{(V_{po}l_o + V_{po}l_c)}{(V_{po}l_o)} \times 100 \tag{1}$$

$$PEP = \frac{(Q_{po} - Q_{pc})}{(Q_{po})} \times 100 \tag{2}$$

$$NDTP = \frac{(T_{po}T_{pc} - T_{pc})}{T_{po}} \times 100 \tag{3}$$

The variable $V_{po}l_o$ stands for the observed runoff volume (m^3), $V_{po}l_c$ is the computed runoff volume (m^3); Q_{po} is the observed peak discharge (m^3/s); Q_{pc} is the computed peak discharge (m^3/s); T_{po} is the time to peak of observed discharge (h), and T_{pc} is the time to peak of computed discharge (h). PEV measures the difference in contrast between simulated and observed volume of streamflow. The PEP, and the NDTP values measure the average absolute time lag and the percent deviation between the simulated and observed peak flows, respectively. The prediction of the overall performance of the model was assessed using the Nash-Sutcliffe model efficiency (EFF , Eq. (4)) criterion (Nash and Sutcliffe, 1970), recommended by the ASCE Task Committee (1993) where Q is the observed discharge (m^3/s).

$$EFF = \frac{\sum_{i=1}^{n}(Q_{0i} - Q_0)^2 - \sum_{i=1}^{n}(Q_{0i} - Q_{ci})^2}{\sum_{i=1}^{n}(Q_{0i} - Q_0)^2} \tag{4}$$

The variation of the EFF values is from 0 to 1, where 1 indicates an excellent fit of data. Regarding regular practice, simulation results are considered to be satisfactory for values of EFF greater than or equal to 0.75, while for values of EFF between 0.75 and 0.36 the simulation results are pondered adequate [9]. To verify the mentioned criteria, the sub-basins that appear in Figs. 5 and 6 were studied, showing their respective DEM.

4. Results and Discussions

4.1 Calibration and Validation Analysis

The model was calibrated for 2 (two) selected sub-basins for the full years of 1999 and 2000. The data sets for January to March were chosen for calibration because the weather conditions in those months were worse than in other months. The groundwater storage depths and storage coefficients, as obtained from streamflow recession analysis. Both the simulated and observed hydrographs exhibit nearly similar trends and shapes. Despite that, the peak discharge of the observed hydrograph is smaller than the simulated ones. In this study, the results of the Cambamba model show an acceptable fit between the simulated values and observation.

Validation was performed for 2 (two) selected sub-basins for both the years 2004 and 2007. The wettest months were from January to March and the datasets were chosen for validation. The results of the Cambamba model showed an acceptable fit between simulated and observed values.

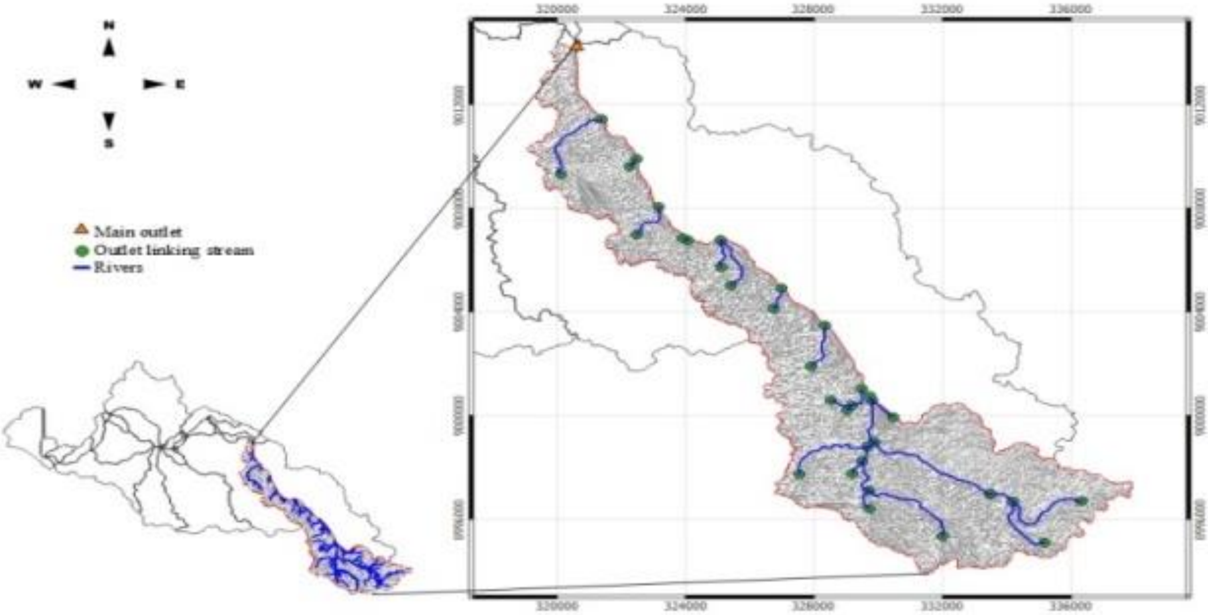

Fig. 5 Digital Elevation Model of Cambamba sub-basin 1.

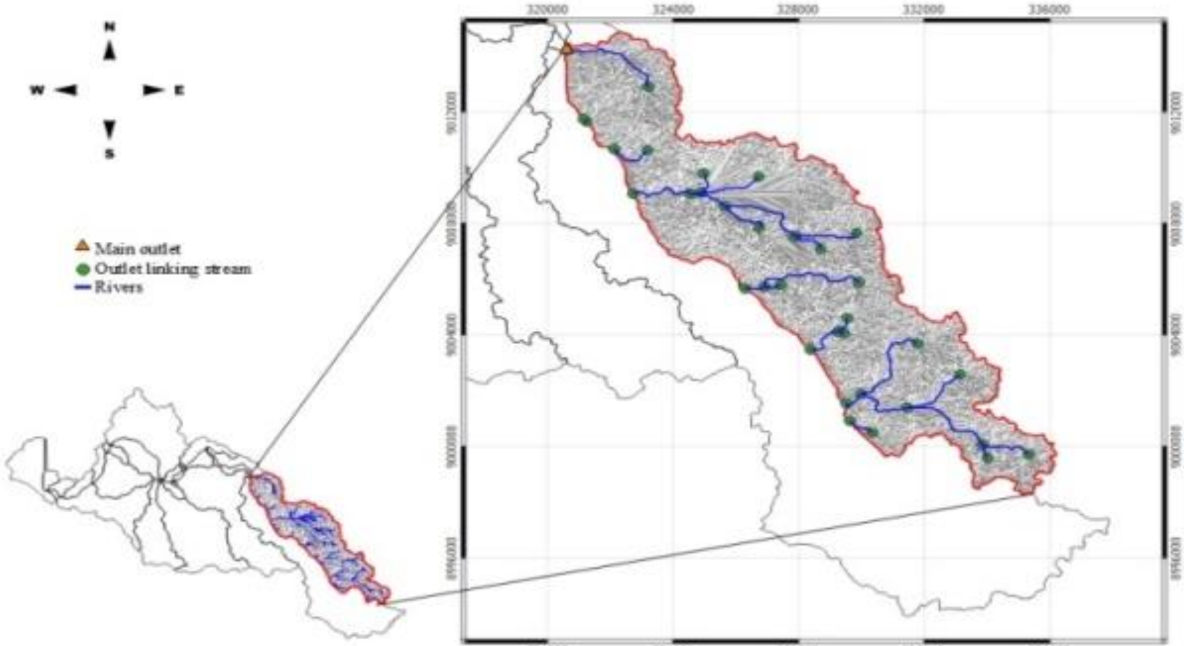

Fig. 6 Digital Elevation Model of the Cambamba sub-basin 2.

As presented, from Fig. 7 to Fig. 10 a time-series comparison of simulated and observed streamflows is illustrated for the sub-basins for the validation period of January to March 2000. The R^2 values for the calibration period in sub-basin 1 are 0.82 for the calibration and 0.82 for the validation periods.

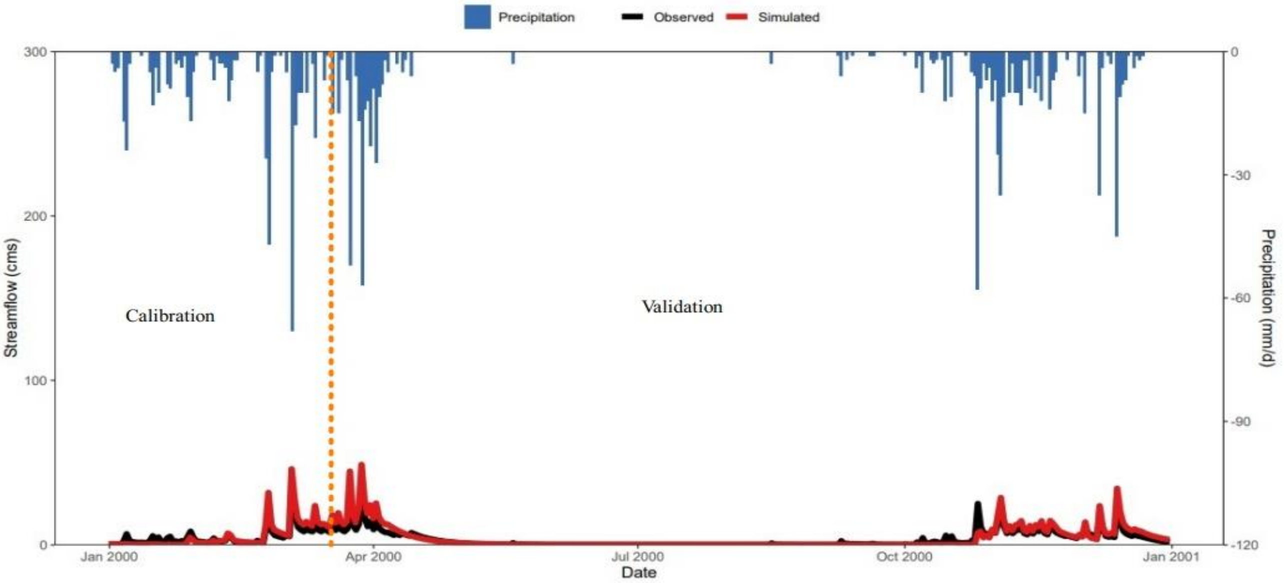

Fig. 7 Calibration and validation periods of sub-basin 1.

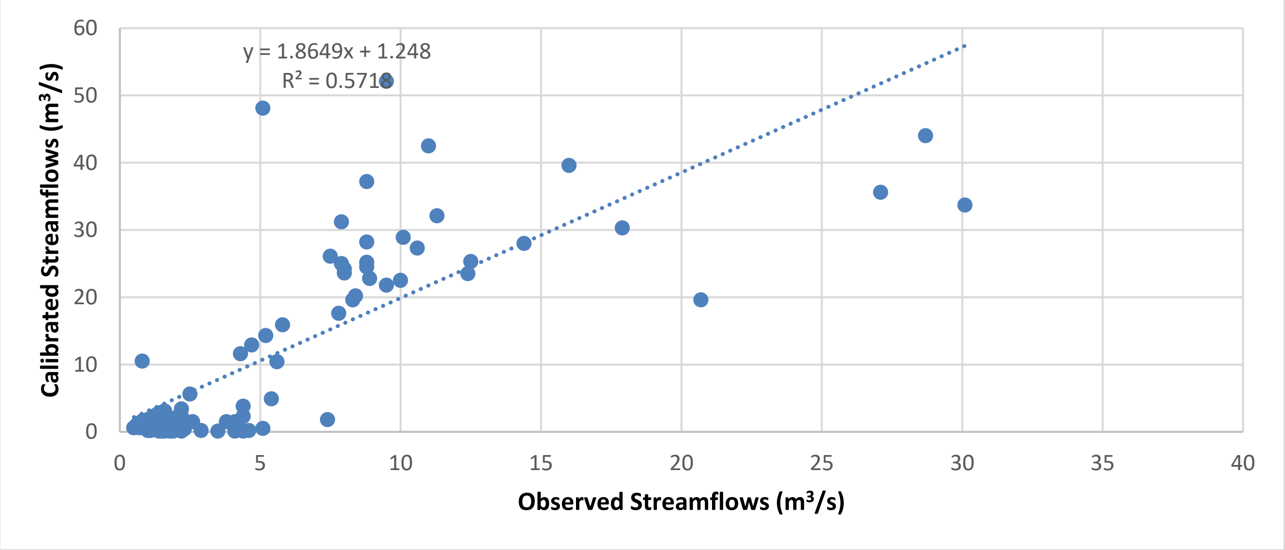

Fig. 8 Scatter plot for the calibration period for sub-basin 1.

The peak values of the simulated streamflow match well with the observed peak values. The performance measures of the model calibration and validation months for both sub-basins are shown in Table 2.

Table 2 indicates that PEV values vary between the percentages, 12% to 21% for sub-basins 1 and 2, respectively. The PEP values range from 1.7% to 22% for sub-basins 1 and 2, respectively. The performance measures are slightly higher than the acceptable levels of accuracy. The high value of Nash-Sutcliffe model efficiency (EFF), between 0.72 and 0.51 for both sub-basins, indicates close agreement between observed and simulated runoff data. It may further be noted that the PEV, PEP, and NDTP values for the sub-basin during the non-monsoon part of calibration months lie within the range previously mentioned.

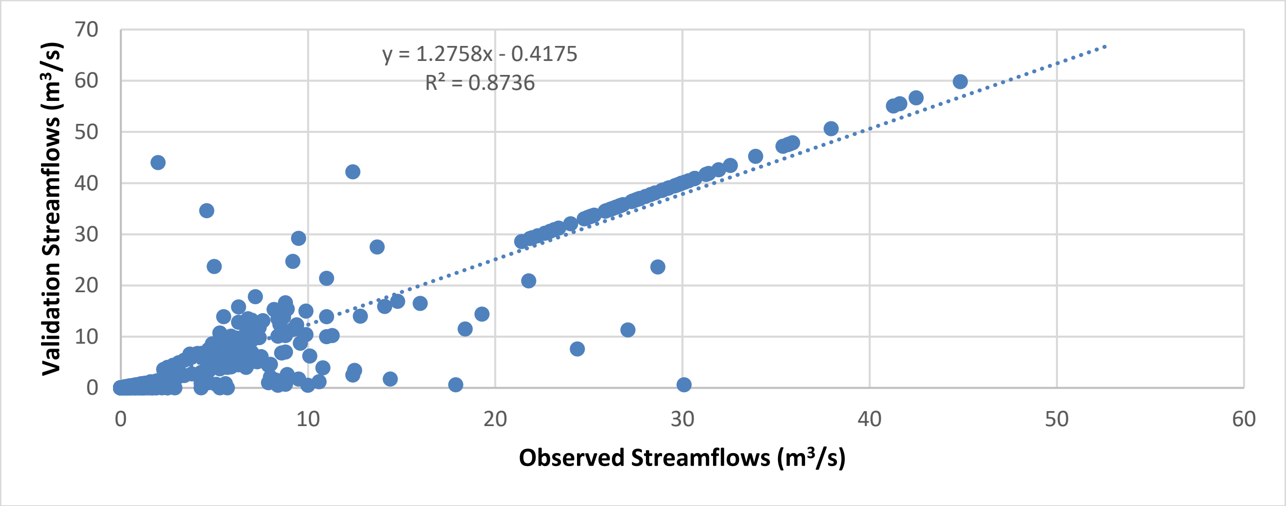

Fig. 9 Scatter plot for the validation period for sub-basin 1.

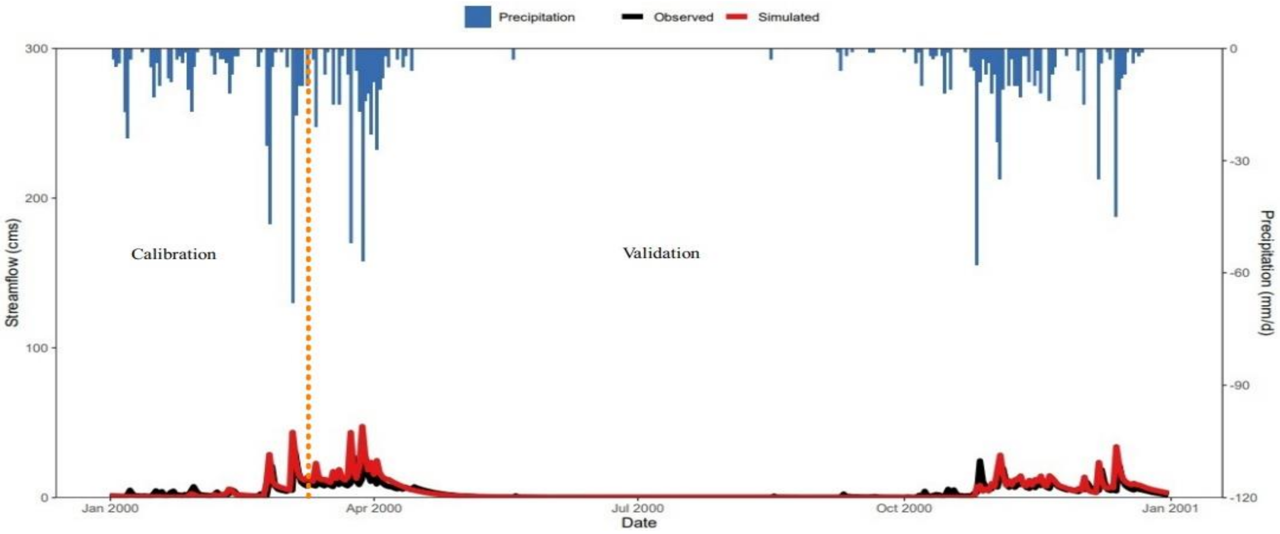

Fig. 10 Calibration and validation period of subbasin 2.

Table 2 Performance measures of the model for the calibration years for the sub-basins 2000/01.

Sub-basin	Performance measures	Units	Calibration period January to March
 1	R^2	[-]	0.72
	$RMSE$	[-]	0.61
	PEP	[-]	0.72
	PEV	[%]	12
	PEV	[%]	12
SUB BASIN	**Performance measures**	**Units**	**Validation priod March to December**
 1	R^2	[-]	0.82
	$NASH$	[-]	0.82
	$RMSE$	[-]	0.81
	PEP	[%]	21
	PEV	[%]	15

It is seen from Table 3 that PEV values vary between 12% and 21% for sub-basin 1 and 2, respectively. The PEP values vary between 11 to 22% for sub-basins 1 and 2, respectively. The performance measures are slightly higher than the acceptable levels of accuracy. The high value of the Nash-Sutcliffe model efficiency (EFF), between 0.72 and 0.51, for both sub-basins, indicates close agreement between observed and simulated runoff. It may further be noted that PEV, PEP, and NDTP values for the sub-basin during the non-monsoon part of validation months lie within the range stated above. Figs. 11 and 12 show the R^2 values for the calibration and validation periods for sub-basin 2.

For means of validation, the model was executed for the year of daily rainfall data. The runoff was simulated by using the hydrological year 1999/20 in the validation model. The simulated and observed hydrograph and regression scatter plot for the outlet section for the validation period of the year 2000 are presented in Fig. 11 and Fig. 12. The R^2 for the validation period for both sub-basins are 0.90 and 0.85, respectively, for the outlet sections. The groundwater storage depths and storage coefficients, as obtained from streamflow recession analysis, are presented in Fig. 13 and Fig. 14.

Table 3 Performance measures of the model for the validation years for the sub-basins 2000/01.

Sub-basin	Performance measures	Units	Calibration Jan to Mar
 2	R^2	[-]	0.51
	NASH	[-]	0.52
	RMSE	[-]	0.52
	PEP	[%]	11
	PEV	[%]	12
Sub-basin	**Performance measures**	**Units**	**Validation Mar to Dec**
 2	R^2	[-]	0.72
	NASH	[-]	0.82
	RMSE	[-]	0.91
	PEP	[&]	22
	PEV	[%]	21

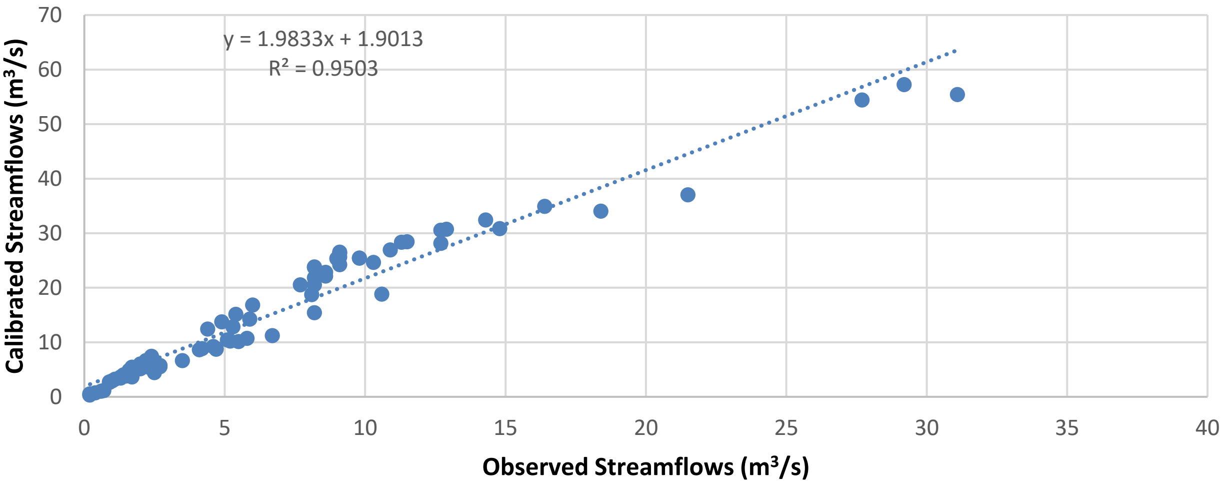

Fig. 11 Scatter plot for the calibration period for sub-basin 2.

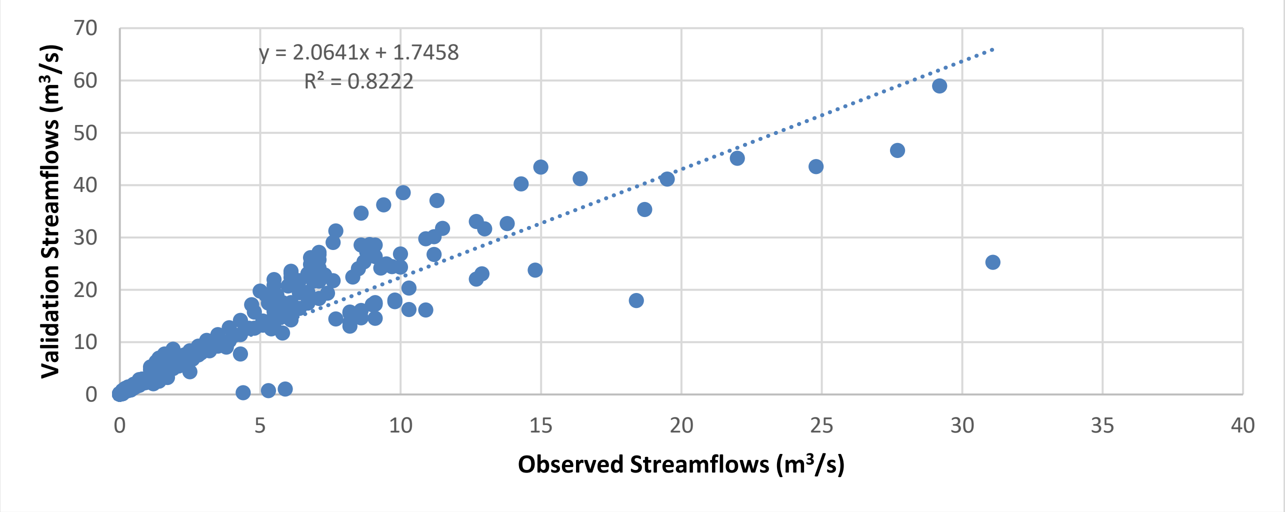

Fig. 12 **Scatter plot for the validation period for sub-basin 2.**

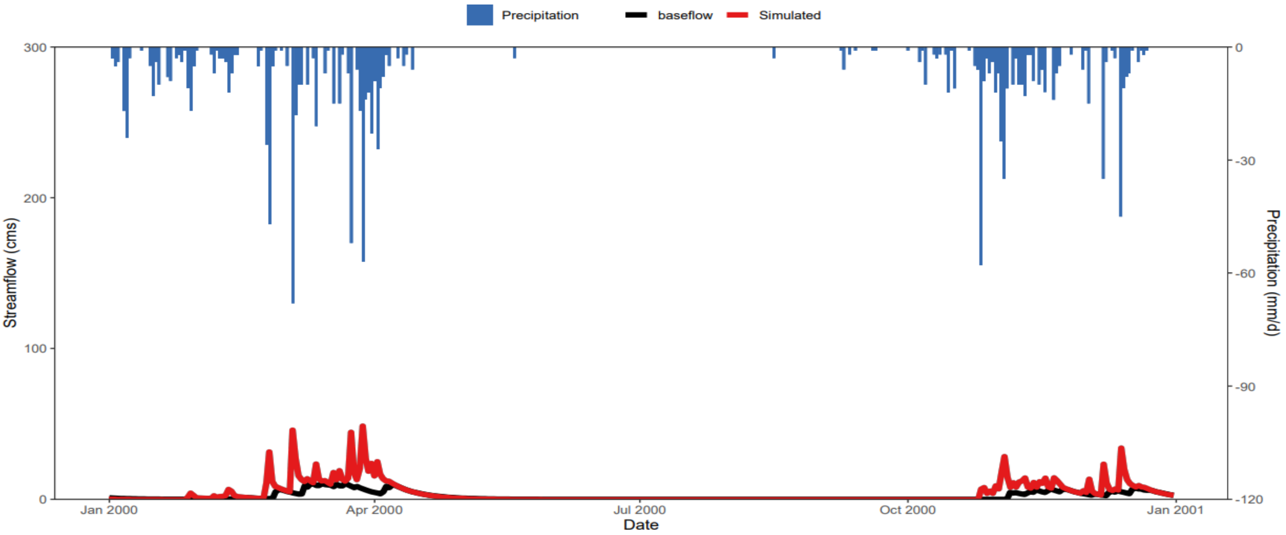

Fig. 13 **Sub-basin 1 groundwater baseflow.**

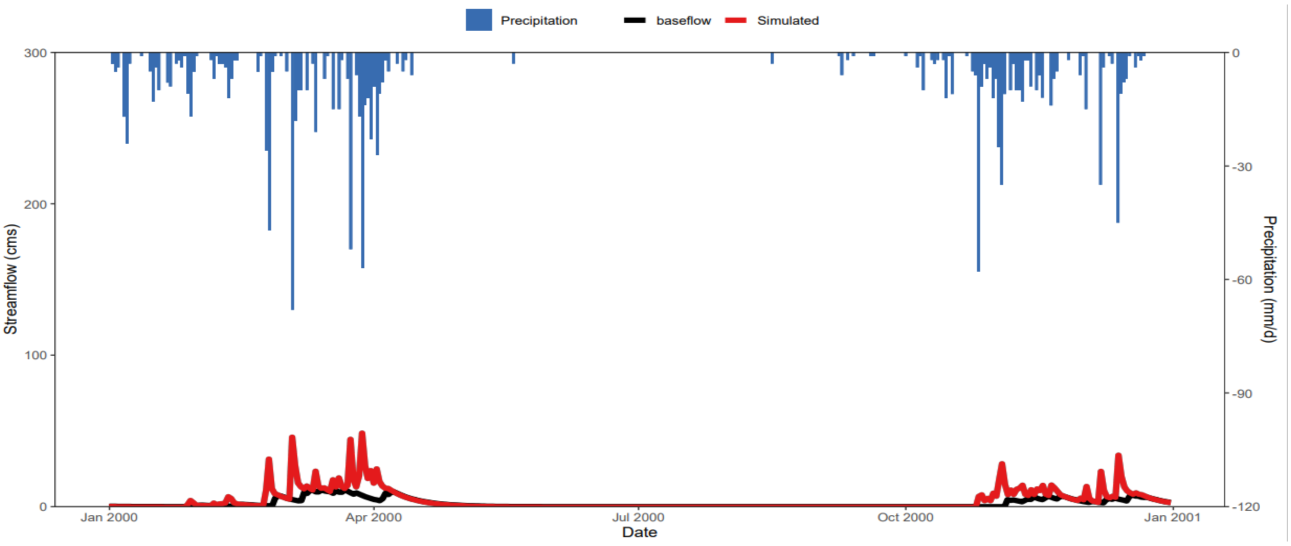

Fig. 14 **Sub-basin 2 groundwater baseflow.**

Table 4 Results of a simulated peak discharge for Cambamba sub-basins 1 and 2.

Sub-basin	Date	Observed discharge [m^3/s]	Simulated discharge [m^3/s]	Baseflow [m^3/s]
1	25/03/2000	30.1	45.7	11.9
2	14/03/2000	32	45.9	12.8

The performance of the HEC-HMS model was noticeably appropriate for the evaluation of the hydrological processes of the basin. Results show that the subdivision of the catchment does not necessarily lead to improvement of the performance of the HEC-HMS model if no relevant variations in physiographic characteristics.

The model used in the above-elaborated research on the Cambamba sub-basins shows useful predictions of runoff volumes and flooding, portraying that the peaks of discharges relating to the hydrological year 1999/20 took place between January and March period; which was seen as the time in which harsh flooding took place.

Thereafter it is also crucial to note that from January to March period there was an increase in volume and depth, thus, in the coming years, exceptional attention must be given to outlet management.

5. Conclusion

From the results attained in this study, it is evident-and can be concluded that the calibration and validation using the HEC-HMS catchment simulation model along with SMA (soil moisture accounting algorithm) of the Cambamba River Basin to identify flow by simulated rainfall-runoff processes was successful, therefore, a comparison and simulation with the observed stream flows were established for both outlet flow discharges.

The results show an adequate agreement between observed and simulated flows, obtaining an R2 of 0.9 for both calibration and validation. The concluded observations from the analysis are listed below:

- For attaining fair and simulated hydrological models, it is crucial to consider the implementation of HEC-HMS which by forecasting rainfall amounts, manages dam storage thus making it a valuable tool;
- The results obtained from the observed show a slight difference as opposed to the ones acquired from the simulation results of runoff discharge;
- The final simulated flow obtained from the model was nearly close to the observed peak flow, and it was 69.9 m^3/s while the observed peak flow was 20.7 m3/s for sub-basin 1. The final baseflow obtained from the model was 34.5 m^3/s;
- The final simulated flow obtained from the model was nearly close to the observed peak flow, and it was 31.2 m^3/s whilst the observed peak flow of 31.2 m^3/s for the sub-basin, The final baseflow obtained from the model was 23.8 m^3/s;
- The development of serious water policy and planning strategies under the results obtained from this study could reduce the probability of floods and may help in the management and control of the dam outlet;
- Curve number and then initial abstraction are the foremost parameters affecting runoff quantities When modeling with HEC-HMS;

Its model results were good for flood predictions for both Catumbela sub-basins. For the simulation of a 2-dimensional flood inundation map applying a hydraulic model like HEC-RAS, data is meant to be exported to perform such a procedure. They can also be used for forecasting rainfall using a suitable program to predict flooding for long-time periods.

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