Application of HEC-HMS for rainfall-runoff modelling in Mozambique and France

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Abstract. In the present study, the suitability of HEC-HMS to simulate event-based rainfall-runoff in the catchments of Revubue in Mozambique and Ardèche in France was evaluated. These are tributaries of two important rivers in Africa (Zambezi) and Europe (Rhône). Despite the low mean discharges in both rivers, it is common to observe floods in certain periods (October – January). The hydrologic models were calibrated and verified based on observed (historical) precipitation and runoff data. As for many developing countries, availability of reliable hydrologic data remains an important issue in Mozambique. Indeed, the study highlighted some limitations imposed by the scarcity and lower resolution of hydrological data in Mozambique. Despite the difficulties related to the unsatisfactory quality of the data in Revubue basin, it was found that the model performs relatively well in terms of time and magnitude of peak flows of the studied flood events. Very good results were observed for Ardèche catchment. The good performance suggest that HEC-HMS may be suitable for flood modelling and/or forecasting in the studied catchments.

1 Introduction

The south of France is well-known to be exposed to flash floods. These events represent one of the most destructive natural hazards in the Mediterranean region (Adamovic et al. 2016). On the other hand, the relatively long Mozambican coast exposes the country to tropical cyclones in the Indian Ocean, often accompanied by heavy rain, leading to floods. Furthermore, the country is at the downstream of several large catchments. Therefore, floods observed in Mozambique are sometimes caused by heavy rainfall occurred in the upstream countries. Important efforts to improve flood management and mitigate its negative impacts were observed in the past decades. For example, non-structural measures such as flood forecasting systems and flood plain zoning (Hipolito and Vaz 2013) are recognized as important tools in the river basin management. The increased use of computer programs allowed improving the modelling capabilities of many hydrologic processes. In the present study, the suitability of the open-source program HEC-HMS to perform simulations of rainfall-runoff processes in the catchments of Revubue (sub-basin of Zambezi river in Mozambique) and Ardèche (sub-basin of Rhône river in France) rivers was tested. The Rainfall-runoff models can be useful for a wide range of applications, such as hydrologic design of hydraulic structures, flood forecasting, etc.

HEC-HMS was developed by the Hydrologic Engineering Center, from the US Army Corps of Engineers (USACE). Over the past years, it has been used

to develop hydrologic models for flood forecasting in many regions of the world. Oleyiblo and Li (2009) validated models for two Chinese catchments. Chu and Steinman (2009) applied joint event-based and continuous analysis for a catchment in Michigan, USA. Halwatura and Najim (2013) have validated a rainfall-runoff model for a Sri-Lanka basin, whereas Unduche et. al (2018) concluded that the model was suitable to be applied for flood forecasting in Canada. The models developed herein are event-based, implying that they are suitable for simulating rainfall-runoff processes of single events or floods. During such intense rainfall events, other processes such as evapotranspiration are negligible comparing with rainfall and surface runoff (USACE 2017). They must however be accounted if the models are to simulate rainfall-runoff processes on a continuous base. Event-based models require less data, since it includes only the determinant hydrologic processes during floods.

In France, the rainfall-runoff warning is issued by Météo-France, while Vigicrues is a service responsible for flood warning. The Regional Directions of Environment, Planning and Habitation (DREAL) include Services for Flood Forecasting (Service de Prévision de Crues - SPC) that operate flood forecasting models. The forecasting performed by these services is shared through Vigicrues in real-time. The SPC-Grand Delta (SPC-GD), attached to DREAL Auvergne-Rhône-Alpes uses rainfall-runoff models for flood forecasting in Ardèche catchment. The level of accuracy of an existing model is used as reference for the present model developed in HEC-HMS.

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The main goal of this study is to apply the program and methodology used to validate the Ardèche model to the Revubue catchment in Mozambique, where no hydrological model has ever been developed. Only a part of the Ardèche catchment will be studied (Ardèche at Vogue), where effects of dams is negligible for moderate and large floods (SPC-GD 2013). There are no dams in Revubue River, indicating that in both cases the rainfall-runoff process is potentially independent of external factors (other than the main hydrologic processes such as infiltration, initial retention, etc.).

In section 2, a short description of the study areas and the data used for the analysis will be described. The methodology to perform flood modelling based on unit hydrograph will be presented in section 3. Section 3 will present the results and discussion, followed by conclusions in section whereas section in 4.

2 Study areas and hydrological data .

2.1 Study areas

Revubue River is one of the main tributaries of the Zambezi River in Mozambique and its basin is located entirely in Mozambique. The two main gauges in the Revubue river are E-367 Maue-Angonia (upstream) and E-302 Tete (downstream). The distance between these stations is 250 km, roughly the length of the river itself. Figure 1 illustrates the Zambezi basin in Mozambique, with focus on Revubue sub-basin. According to a report by Coba et al. (2017), the average instantaneous discharge is about 30 m³/s. During floods, the flow rises to over 1000 m³/s. Based on the same report, the Rio Revubue can be described as being composed of 3 sub-basins: Higher Revubue, Lower Revubue Revubue and Condezi. The black line in Figure 1 illustrate the repartition of the catchment.

Figure 1. Map of Revubue catchment (adapted from Coba et al. 2017); yellow points are correspond to locations of raingauges and flow gauges.

The Ardèche river has a length of 125 km. It is one of the major tributaries of the Rhône river that drains into the Mediterranean Sea near Arles, southern France. It has its

source in Massif Central and flows into the Rhône river near Pont-Saint-Esprit (Adamovic 2014). At Vogue, the catchment area is 623 km². The hydrological year consists mainly of two periods. There is a rainy season (September-February) with maximum precipitation intensity in autumn and high discharge. During the dry season (March-August), the runoff is low (Adamovic et al. 2016).

Figure 2 Map of Ardèche catchment (adapted from Adamovic et al. 2016)

2.2 Hydrological data

For Revubue basin, it is assumed that some of the most reliable stations are those currently used for the monitoring inundation risks in Revubue basin. These are P333 at Maue in the upstream region and P438 at Tete, at the outlet. They are included in the monitoring reports “*boletim hidrológico*”. However, more stations, at the upper Revubue should be included in order to retrieve an average rainfall by the Thiessen method. The included stations in each sub-basin are illustrated in Figure 1. **Error! Reference source not found.** Unfortunately, it was not possible to properly cover the entire catchment due to lack of reliable data. The data is collected by the Regional Water Administration of Zambeze (ARA-Zambeze) on daily basis. The only station with reliable flow data is the station downstream. Upstream stations data consists only of level measurements and no rating curves are available. This imposes some important limitations. Ideally, the modelling should comprise a rainfall-runoff analysis for each subbasin, followed by a flood routing down the basin. With only one reliable flow gauge this can not be performed. The catchment will be divided only in three subbasin, but the flow generated in each of them cannot be verified. Only the total runoff at the outlet can be analyzed in terms of observed and model results.

For Ardèche basin, three stations were used: Antraigues, Aubenas and Barnas. They were selected in order to cover the study region in roughly equal

proportion. The used data was obtained from Meteo-France, with a time step of 3h.

It is crucial to confirm that the rainfall data is consistent with the occurrence of the flood events. This simple verification may illustrate potential inconsistencies in the data used to build the model. It suffices to check, for the chosen events, that there is indeed an increase in rainfall in the selected stations, before and/or during the flood events. This verification was used to exclude some several events from the analysis. This was mostly the case for Revubue, but few events in Ardèche also displayed inconsistencies between the rainfall and runoff data. This suggests that even in catchments well equipped and monitored, it is difficult to avoid data errors completely. In the program, the rainfall data will be used to define a meteorological model. In the present case, the meteorological model is heavily simplified, since only precipitation data is required. Weighting factors should be assigned to each rain gauge in order to determine the a uniform precipitation depth over the catchment. Herein, they were estimated from Thiessen polygons. Additionally, in HEC-HMS the user can specify the temporal distribution of that uniform precipitation.

Sub-basins	Area (km2)	Rain gauges		
Alto Revubue	10241	P-333 Angonia	P-434 Mitengo	P- 43 Zobue
Baixo Revubue	2495	P-438 TETE		
Condezi	3559	P-902 Tsangano		
Total	16.295			

Table 1. Rain gauges in Revubue basin

3 Flood modelling based on Unit Hydrograph theory

3.1 Loss function – SCS CN/Initial and loss method

In order to estimate the effective rainfall, the base flow should be separated from direct runoff. The effective rainfall volume is defined as approximately equal to the volume of direct runoff. Once the effective rainfall volume is determined, it should be distributed in time, using the selected loss method.

First, it is necessary to choose a method for base flow separation. Here, the fixed base method according to Chow et al. (1988) is considered. In this method, the based flow in the beginning of the event is extended up to the time of peak. From then, it is connected to the inflection point, where recession begins. This point can be identified by plotting the logarithmic values of the discharge. In the recession stage, a linear trend is observed Shaw (1994). The runoff hydrograph can be integrated to retrieve the volume of effective rainfall. The next step is to distribute the estimated effective runoff volume at each time step. This requires selecting a loss method. Note that this approach should serve as a prelinar determination of the loss method parameter, since it allows to estimate the

hyetograph that corresponds approximately to the observed direct runoff. Two of the most widely used methods were tested, namely, SCS-Curve Number (SCS-CN) and the Initial and Constant Rate.

The strength of the model is because it includes cumulative rainfall, soil type, land use and antecedent soil moisture (Maidment 1993). The effective rainfall is given by:

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \quad (1)$$

where P_e is the precipitation excess at time t , P is accumulated rainfall depth at time t , I_a is the initial abstraction (initial loss), often described as $I_a = 0.2S$ and $S = (25400 - 254CN)/CN$ is the potential maximum retention, which describes the ability of the watershed to abstract and retain storm precipitation. The curve number CN varies between 30 (soils with high infiltration rates) to 100 (water bodies/impermeable surfaces). Some assumptions have been adapted to local characteristics. For example, Subramanya (2008) refers that the Indian experience indicates that $0.1S < I_a \approx 0.3S$. Thus, this is a parameter subject to calibration if data is available.

The initial and constant rate method is a simpler method, but has shown to be applicable in wide range of conditions (USACE 2017). The concept of the method is that the maximum potential rate of precipitation loss (f_c) remains constant during a flood event USACE (2000). Additionally, until the accumulated precipitation exceeds the initial loss volume, no runoff occurs. The effective rainfall is determined by:

$$p_e = \begin{cases} 0 & \text{if } P_i < I_a \\ 0 & \text{if } P_i > I_a \text{ and } p_t < f_c \\ p_t - f_c & \text{if } P_i > I_a \text{ and } p_t > f_c \end{cases} \quad (2)$$

where p_e is the excess rainfall during a time interval (time step), p_t is the total precipitation during the time interval and P_i is the accumulated rainfall at a given time. Note that the rainfall intensity is directly taken into account in this method, contrarily to SCS method. As pointed by USACE (2000), the method predicts same loss for 25 mm rainfall in 1 hour or 1 day.

Given the advantages and limitations of each method, the two methods were tested for both catchments. Overall, the SCS-CN seems to provide better results for Revubue, whilst the initial-constant method seems to perform slightly better for Ardèche

3.2 Transform function – SCS Unit Hydrograph

The unit hydrograph (UH) concept, introduced in the United States of America by Sherman in 1932, was a major step forward in hydrological analysis (Shaw 1994). He defined it as the hydrograph of direct runoff resulting from unit depth (often 1 cm) of effective rainfall falling in a given duration, such as 1 hour or 1 day, generated uniformly in time and space over the catchment area.

From the definition, the UH is always associated with a given duration. This duration depends on the excess rainfall duration used to derive it. From the assumptions of the method, the duration should be long enough for the entire catchment to respond, but it should not be too long, as the assumptions of the method become unrealistic. In the case of single storms, the determination of UH is straightforward. For multi-period storms, a deconvolution method should be applied to retrieve the UH. Because single-period storms are rare and deconvolution methods are instable, synthetic hydrographs are widely used in practical situations. The availability of data allows the estimations of the parameters in a realistic manner. The SCS UH is a (synthetic) dimensionless unit hydrograph, defined by one parameter, the time of rise or time of peak (T_p).

$$q_p = \frac{CA}{T_p} \quad (3)$$

where A is the area (km^2), $C = 2.08$, $T_p = t_r/2 + t_p$, with $t_p = 0.6T_c$. T_c is time of concentration and t_r the duration of the storm. In HEC-HMS, the UH is systematically defined based on the duration equivalent to the time step of the calculations. In the present case, as the calculations will have 1h time step, the software computes the 1h-UH, according to the specified lag time t_p . Instead of defining it based on time of concentration, we can evaluate it from the rainfall and runoff data. Analysis of several flood events have shown that it varies around $t_p = 4 - 6$ h for Ardèche and 32 - 40h for Revubue. The adopted duration (after the calibration) for Ardèche (Revubue) was $t_p=350$ (2000) min, corresponding to 5 (33.3) h. This value seems to be adequate for a wide range of analyzed events. Calculations of 1h SCS-UH can be performed in a simple excel sheet. This was tested for Ardèche catchment, where higher data resolution is available. As this is only a preliminary estimate, data from only one rain gauge can be used. Figure 3 shows the determined 1h SCS-UH using a simple excel sheet, for the flood event of September 2000. The loss method was the initial and constant. Figure 4 shows the application of the determined SCS-UH for the same event. The good agreement of the model and observed direct runoff indicate that the preliminary estimation of the model parameters is relatively accurate. They can serve as initial parameters in the HEC-HMS model, and modified to improve the agreement with the observed hydrographs. This corresponds to the calibration process. However, this analysis was carried only for Ardèche, where high temporal resolution data was available. For example, for this preliminary analysis of the 1h SCS-UH, 1h rainfall and runoff data was used. Therefore, this would be difficult if not impossible in Revubue basin, where only 24h rainfall data is available.

Figure 3 Computed 1h SCS-UH in Ardèche

Figure 4. Application of SCS-UH to Sep2000 flood event in Ardèche (Observed- -; Estimated-)

Other parameters to be defined in HEC-HMS model are the recession constant $k=0.8$ (0.9) and the ratio to peak $Rtp=0.5$ (0.4). Because these parameters do not change dramatically, they can be considered as quasi-constant model parameters, contrarily to the parameters of the loss method, which varies as function of the antecedent conditions (initial storage, saturation of soils, etc.).

4 Results and discussion

The results of calibration and verification of the model are presented in this section. The SCS-CN method preconizes a change in initial conditions based on the value of CN. The initial abstraction and the continuous infiltration are all function of CN. By initial and constant rate method, the initial loss was taken as the main calibration parameter, as function of antecedent soil moisture. However, the loss rate seems to be heavily affected by antecedent conditions also. Thus, in the calibration processes, the parameters to be determined are mainly the CN value and both initial and constant rate parameters. The results of the calibration process are displayed in the following Tables and Figures.

Revubue								
	CN	I_a (mm)	Initial Const.	Loss Rate	NSE	Lag (min)	Recession Const.	Rtp
13-Feb-14	90	0	0	0.2	0.78			
12-Jan-15	90	15	27	0.2	0.66			
17-Jan-15	82	15	22	0.6	0.65	2000 ¹	0.9	0.4
22-Feb-15	45	30	40	1.7	0.61	400 ²		
2-Feb-17	65	15	15	0.65	0.22	300 ³		

24-Mar-17	95	27	33	0.01	0.87			
Ardèche								
Time	CN	I _a (mm)	Initial Const.	Loss Rate	NSE	Lag (min)	Recession Const.	Rtp
28-Sep-00	52	45	70	6.5	0.94			
12-Nov-00	65	27	65	2	0.85			
24-Dec-00	53	43	80	3	0.87			
18-Oct-01	55	35	80	3	0.98	350	0.7	0.5
27-Oct-04	65	27	55	2.8	0.95			
3-Nov-04	65	27	55	3.5	0.89			

Table 2. Calibration events (¹Upper Revubue; ²Condezi; ³Lower Revubue)

Revubue								
Time	CN	I _a (mm)	Initial Const.	Loss Rate	NSE	Lag (min)	Recession Const.	Rtp
9-Mar-06	60	15	30	1.7	0.55			
13-Feb-07	70	10	20	1.2	0.46	2000 ¹		
4-Jan-08	70	10	28	1	0.70	400 ²	0.9	0.5
2-Apr-12	90	3	5	0.3	0.18	300 ³		
27-Jan-12	85	3	5	0.6	0.71			
Ardèche								
Time	CN	I _a (mm)	Initial Const.	Loss Rate	NSE	Lag (min)	Recession Const.	Rtp
21-Oct-08	97	0	1	0.2	0.82			
01-Nov-08	99	10	10	0.0	0.90			
12-Oct-14	90	0	0	1.2	0.92			
23-Nov-18	99	0	2	0	0.71	350	0.7	0.5
22-Nov-19	99	4	6	0	0.94			
19-Dec-19	99	4	7	0	0.93			

Table 3. Verification events

A relatively good agreement between the simulated and observed hydrographs is observed. This agreement is quantified using the Nash-Sutcliffe efficiency (NSE) criterion and the relative difference of the flood volume. NSE values closer to 1 indicate better agreement of the simulated hydrograph to the observed. They are also displayed in the table of calibration and verification results. In Ardèche catchment, the average value of the Nash criterion taking 83% of the events with the best agreement, corresponds to about 0.92, indicating a very good performance. The model calibration from SPC-GD displays an accuracy level of the same order. They presented a NSE greater than 0.7 for 75% of the cases. One general difficulty is to simulate floods with more than one peak. This was observed also in the simulations from SPC-GD. Results of two simulations from SPC-GD is shown. The performance is more modest for Revubue catchment, where the average value of NSE of the 82% of the events with the best agreement is about 0.66. However, given the tremendous limitations linked to data resolution and reliability, this result is considered satisfactory.

If the model is to be applied for forecasting floods, one of the most important issues concerns the initial moisture condition. The parameters determined by initial moisture conditions can be analyzed in order to observe their pattern. An important indicator of initial moisture conditions is the accumulated rainfall over the past few days Shaw (1994), for example previous 7 days (P_7). To increase the reliability of this initial guess, one additional

parameter may be the discharge at the beginning of the event (Q_{initial}). For example, for a dry condition, it may be expected lower values of P_7 and/or Q_{initial} . Although not shown here, it was seen that small values of P_7 were correlated with lower values of CN or higher loss rate. Overall, this trend was confirmed in both basins.

Figure 5. Calibration - Ardèche

Figure 6. Calibration - Revubue

Figure 7. Verification - Ardèche

Figure 8. Verification - Revubue

5 Conclusions

In the present study, event-based hydrological models of Revubue catchment in Mozambique and part of Ardèche catchment in France was presented. The models were built with the program HEC-HMS. The hydrological data was collected from ARA-Zambeze in Mozambique (24h rainfall and 6h discharge), whereas for Ardèche catchment, higher resolution data was obtained from Meteo-France (3h rainfall) and HYDRO data base (1h discharge). It was seen that most of the model parameters were determined from the analysis of rainfall and discharge data of the catchments. This preliminary analysis was carried out using simple excel sheets. This allows evaluating in advance the acceptable range of values for the main model parameters.

For Ardèche catchment, the modelled peak discharge and its time of occurrence displayed a good agreement with the observed data. The values of NSE is above 0.85 for most events evaluated. Overall, the model provides the same level of accuracy as the model used by the authorities responsible for flood monitoring in the region.

For Revubue catchment, the values of NSE remain above 0.6 for most events. Additionally, the relative difference in terms of flood volume remained below 15%. Although the agreement is lower than in Ardèche, given the data limitations, it is considered relatively good result. The relatively large lag time may be a determining factor allowing to obtain acceptable results with such low resolution data.

The good performance of the developed models suggest that HEC-HMS may be suitable for flood modelling and/or forecasting in both catchments. Particularly for case of Mozambique, the results suggest that improvements in the data collection may significantly enable the operation of flood forecasting systems.

6 References

- Adamovic, M. (2014). Development of a data-driven distributed hydrological model for regional scale catchments prone to Mediterranean flash floods. Application to the Ardèche catchment, France (Doctoral dissertation, Grenoble).
- Adamovic, M. Branger, F. Braud, I. Kralisch, S. (2016). Development of a data-driven semi-distributed hydrological model for regional scale catchments prone to Mediterranean flash floods. *Journal of Hydrology*, 541, pp. 173-189.
- ARA-Zambeze. Avaliação das Cheias na Sub-bacia do Revubue 2018-2019.
- Coba, Consultec, Salomon. (2017). Elaboracao do Plano Estrategico para utilizacao e desenvolvimento da bacia do rio Zambeze. Volume 1.
- Chow, V., Maidment, D.R, Mays, L.W. 1988. Applied Hydrology. McGraw-Hill, New York.
- Chu, X. and Steinman, A., 2009. Event and continuous hydrologic modeling with HEC-HMS. *Journal of Irrigation and Drainage Engineering*, 135(1), pp.119-124.
- Halwatura D. Najim M. (2013). Application of the HEC-HMS model for runoff simulation in a tropical. *Environmental Modelling. & Software*. Volume 46: pp. 55-162.
- Hipólito ,J. R and Vaz, A.C. (2012) Hidrologia e Recursos Hídricos, IST Press.
- Maidment, D.R. (1993). Handbook of hydrology. McGraw-Hill.
- Oleyiblo J., Li Z. (2009). Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China. *Water Science and Engineering*. 3(1):14-22.
- Subramanya, K. (2013) *Engineering hydrology*, 4e. Tata McGraw-Hill Education.
- Shaw, E. M. (1994). Hydrology in practice, VNR Int.
- Service de Prévision de Crues. (2013). Règlement De Surveillance de Prévision et de Transmission De L'information Sur Les Crues.

14. Unduche, F., Tolossa, H., Senbeta, D., & Zhu, E. (2018). Evaluation of four hydrological models for operational flood forecasting in a Canadian Prairie watershed. *Hydrological Sciences Journal*, 63(8), 1133-1149.
15. US. Army Corps of Engineers (USACE). (2000). Hydrologic Modeling System: Technical Reference Manual. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center.
16. U.S. Army Corps of Engineers (USACE). (2017). Hydrologic Modeling System: Applications Guide. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center.