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Development of rainfall-runoff modelling using the HEC-HMS at the catchment of Kelantan River, Malaysia

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Abstract. The simulation of rainfall-runoff is important to be analysed at the Kelantan River catchment as flood is one of the common natural disasters in Kelantan. Sustainable water management in this region is only feasible following the availability of reliable information on the rainfall-runoff and other hydrological determinants that affect the water system. This study aims to evaluate the effects of extreme rainfall on the runoff at the catchment of the Kelantan River where recurrent floods have been occurring since 1988 to 2019. The study employs the remote sensing and geographic information system (GIS) integrated with the Hydrologic Engineering Center–Hydrologic Modelling Systems (HEC-HMS) to delineate the catchment line and simulate the river discharge. The observed discharge is used during the calibration and validation process to evaluate the performance of the integrated model. The model performed satisfactorily by obtained R^2 with the range of 0.80-0.97 and 0.64-0.93 in each sub-catchment during the calibration and validation period. The finding indicates that the developed HEC-HMS model has the ability to simulate event-based runoff.

1. Introduction

Rapid land development, increase in extreme rainfall, and inadequate water drainage system are among the potential contributors to the serious case of recurrent floods in Kelantan that poses major threats to humans as well as causing significant damage to properties, infrastructures, and the agricultural sector. Hence, countermeasures such as sustainable water management must be adopted to mitigate the issue. According to Kiedrzyńska et al., the effectiveness of sustainable water management depends on a deep understanding towards the temporal and spatial, which refers to the need of understanding the condition from the past till the present with consideration of the climate scenarios as well as the significant part of river and floodplain on a variety of scales [1].

The assessment of water management demands in-depth information on the hydrological processes. The relationship between rainfall and runoff is believed to have significant effects on water balance [2]. Thus, the simulation of rainfall-runoff by the hydrologic model plays an essential role in environmental management. HEC-HMS is a hydrologic model that offers various simulation options processes of rainfall-runoff and it has been widely employed to understand the hydrologic processes and hydrologic

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prediction in a catchment. For this study, the integration of the HEC-HMS model with the Geographic Information System (GIS) and remote sensing imagery is employed to enhance better output performance. The employment of remote sensing image is intended for the generation of the land use and land cover maps while the GIS is known as an efficient tool for input data preparation [3]. The methods used in the study are the Soil Conservation Service Curve Number loss method, Soil Conservation Service Curve Number unit hydrograph method, Constant Monthly baseflow method, and Lag routing method. The modelling process result shall provide an insight about the discharge and peak flow computation along the Kelantan River catchment.

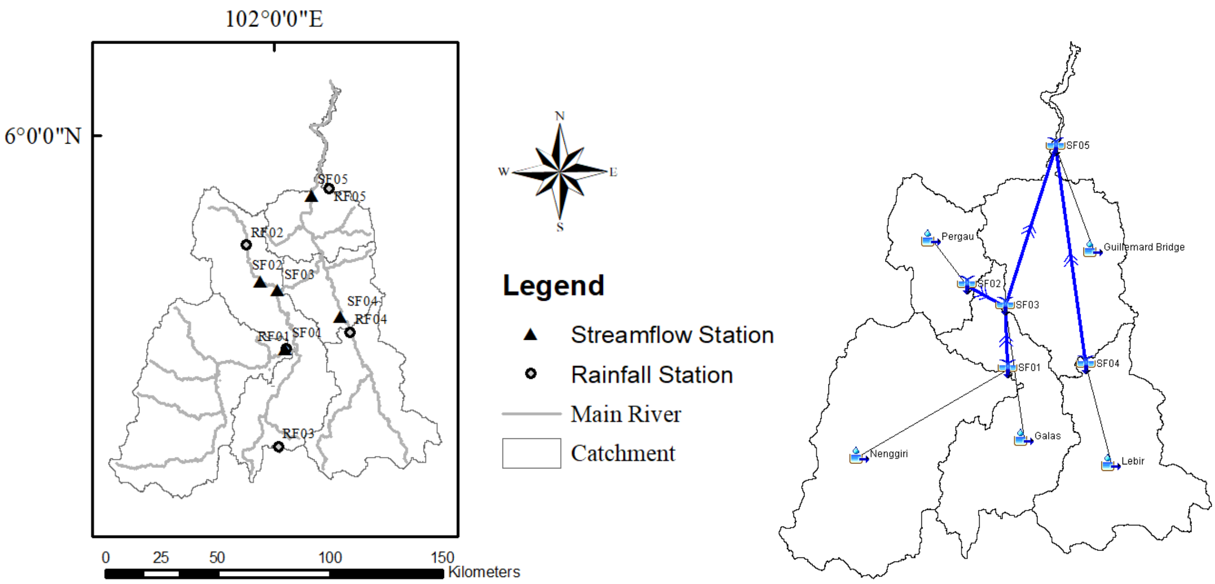
2. Study area and data

2.1. Study area

The focus area of this study is the Kelantan River catchment as shown in figure 1(a). With a drainage area of approximately 420 km^2, the Kelantan River represents one of the largest streams in Malaysia. Its upstream begins at the district of Gua Musang and ends at the downstream located at the Kota Bharu district. The Lebir River and Galas River are the tributaries for the Kelantan River. The Kelantan River is particularly known for its vulnerability to the annual monsoon flooding where the annual rainfall is recorded at 1183 mm.

2.2. Data description and processing

The rainfall-runoff analysis requires hydro-meteorological data such as the rainfall and discharge, Digital Elevation Model (DEM), present land use, and land cover map to classify the type of soil in the catchment. Figure 1(b) indicates the schematic of the basin model created by HEC-HMS which shows the sub-catchments, reaches, and junctions located at the Kelantan River catchment.



(a) **(b)**

Figure 1. (a) Location of the rainfall and discharge stations and **(b)** the basin model of the Kelantan River.

Several processes have been executed as in figure 2 in the Geographic Information System (ArcGIS) with the extension of HEC-GeoHMS using raw database such as the DEM to delineate and generate watershed information. Information such as elevation, river lengths, longest flow path, defined stream network, and slope will assist in the hydrologic model development and discover the hydrologic parameter estimations. The HEC-HMS model in this study is built from two storm events on 16 Dec

2011 - 22 Dec 2011 (calibration) and 10 Dec 2013 - 16 Dec 2013 (validation) as most flood cases happened in the month of December. Data such as the amount of rainfall and discharge are taken on an hourly scale from five selected rainfall stations and five discharge stations as shown in table 1.

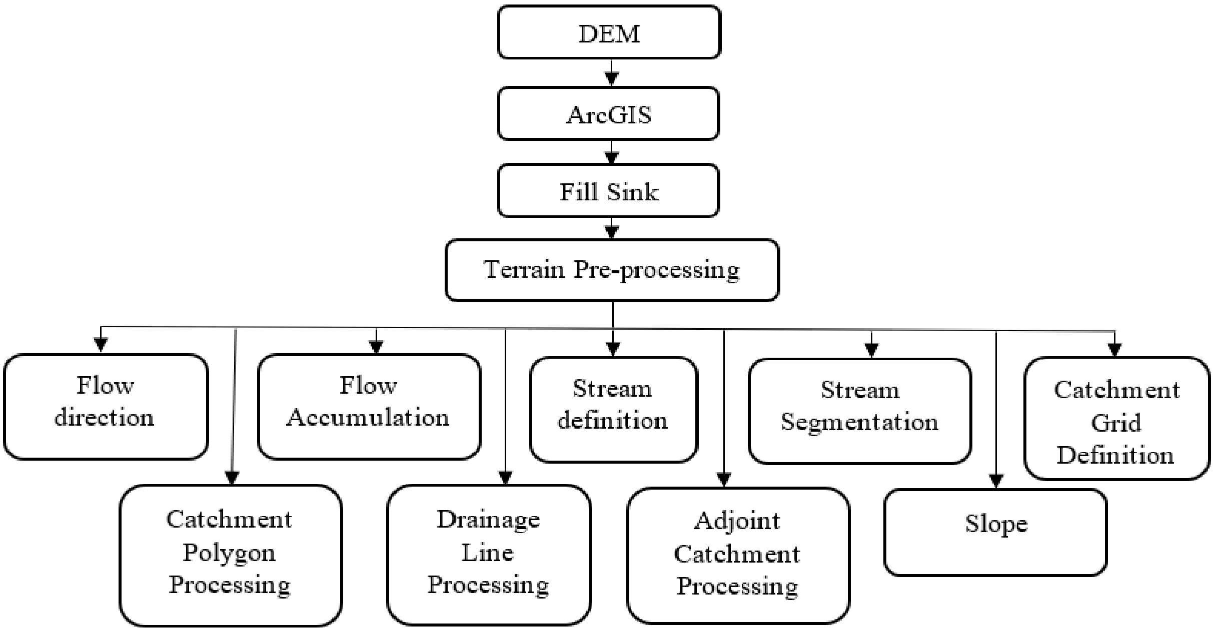


Figure 2. Processes to develop the basin model.

Table 1. The stations utilized in the study.

Sub-Catchments	Station Code	Type of Data	Station Name	Lat. (° ' " N)	Long. (° ' " E)
Nenggiri	RF01	Rainfall	Balai Polis Bertam	05 08 45	102 02 55
	SF01	Discharge	Sg. Nenggiri at Bertam Bridge	05 08 55	102 02 45
Pergau	RF02	Rainfall	Sek. Keb. Lubok Bungor	05 33 40	101 53 20
	SF02	Discharge	Sg. Pergau at Batu Lembu	05 25 05	101 56 45
Galas	RF03	Rainfall	Ldg. Mentara	04 45 20	102 01 00
	SF03	Discharge	Sg. Galas at Bukit Apit Dabong	05 22 55	102 00 55
Lebir	RF04	Rainfall	Kg. Lebir, Paloh	05 12 45	102 18 15
	SF04	Discharge	Sg. Lebir at Kg. Tualang	05 16 30	102 16 00
Guillemard Bridge	RF05	Rainfall	JPS Machang	05 47 15	102 13 10
	SF05	Discharge	Sg. Kelantan at Guillemard Bridge	05 45 45	102 09 00

3. HEC-HMS

3.1. Description of the HEC-HMS model

The United States Army Corps of Engineers Hydrologic Engineering Center (HEC) developed the Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS) as an integration of many hydrological simulations of dendritic watershed systems [4]. The HEC-HMS version 4.3 is adopted in this study to simulate the rainfall-runoff process at the catchment of the Kelantan River. This is justified by its ability and simplicity to be adopted in the worldwide hydrological study as well as the fact that it is a physically-based and conceptually semi-distributed model which is capable to solve problems for a broad range of geographic areas including humid, arid, tropical, and subtropical watersheds [5].

The model was employed to identify the parameter values in the studied catchment. Commonly, the adjustment of the HEC-HMS model parameters was done initially by the trial-and-error method. This is because the initial parameter value is considered true in the calibration period and the modelled discharge is then compared with the measured discharge. However, the parameters can be adjusted if the conformity between the pre-calibration results and the observation data is not satisfactory. Through the trial-and-error method, the modeller can achieve an agreement between the modelled and observed hydrographs by adjusting the best parameters based on the previous model run.

3.2. Model optimization, calibration, validation and statistical evaluation

During the calibration, the parameters from available methods are estimated with an hourly simulation time step. The model combines the three model components (basin, meteorological, and control specifications) to run each model analysis. Several inputs with appropriate variables are set to represent the inflow values. The HEC-HMS computations include loss methods, direct runoff methods, baseflow methods, and routing methods. Direct runoff from excess precipitation is measured using the transform process. For the rainfall-runoff modules, the Soil Conservation Service Curve Number (SCS-CN) method estimates the rainfall abstraction by determining the empirical rainfall-runoff relationships. The SCS-CN model takes into the assumption that the runoff volume depends on cumulative precipitation, soil and surface condition, land use, moisture conditions, and the effect from human activities. Accumulated rainfall-excess is calculated using equation (1) as follow:

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

where Pe = cumulative rainfall excess (mm), P = cumulative rainfall depth (mm), Ia = initial abstraction before ponding (mm) with Ia equals to 0.2S, and S is the potential maximum retention (mm).

Excess rainfall calculated from equation (1) is used by the transform method to convert direct runoff into a point runoff on the watershed. Thus, the present study utilises the SCS Unit Hydrograph to transform excess precipitation into an outflow hydrograph. This method requires each sub-catchment time lag and can be estimated as follows, where Tlag and Tc are in minute.

$$T_{lag} = 0.6T_c \tag{2}$$

The Lag method available in HEC-HMS is applied to estimate the outlet hydrograph from the upstream inflow with all ordinates being interpreted by a given duration (lagged in time). This simple method does not change the hydrograph shape as it does not consider the flow attenuation. Therefore, the downstream outflow can be calculated by using:

$$O_t = \begin{cases} I_t & t < \text{lag} \\ I_{t-lag} & t >= \text{lag} \end{cases} \tag{3}$$

O_t is at time outflow hydrograph, I_t is at time t inflow hydrograph, and lag is the lagged time for all inflow ordinates.

As previously mentioned, the trial-and-error approach was utilised for the pre-calibration of the model. The pre-calibrated parameters applied in this study is obtained by referring to previous studies that managed to model appropriate HEC-HMS for the application at the Kelantan River catchment. Then, the obtained results from the pre-calibrated process are compared with the observed and modelled hydrograph. The modelled hydrograph results that manage to capture the observed hydrograph in the good agreement are maintained while the poor results are proceeded with the optimisation stage. The optimisation function is provided in the HEC-HMS to generate the best parameter values that correspond to the sensitive parameters and defined objective. According to Zheng et al. [6], initial abstraction, CN and Lag parameters are the significantly sensitive parameters for the HEC-HMS model. Therefore, these parameters are focuses to be optimised. Subsequently, the optimised values of particular sensitive parameters are then evaluated for the calibration of the model. The parameters used in this study contain initial abstraction (Ia), Curve number (CN), Impervious (I_{mp}), lag time (L_t), and L_g as presented in table 2-3.

Table 2. The optimised parameters for each sub-catchment at the Kelantan River.

Sub-basin	Area (km^2)	I_a (mm)	CN	I_{mp} (%)	L_t (min)
Nenggiri	3708.7	0.66900	21	0.034	1100
Pergau	1243.1	0.49331	32	0.063	780
Galas	2261.1	0.78522	72.113	0.030	500
Lebir	2392.0	0.25066	60	0.910	1320.8
Guillemard Bridge	2323.7	0.57430	74	1.000	1850

Table 3. Lag (L_g) values for routing reaches elements.

Reach	L_g (min)
1	120
2	50
3	150
4	500

For the purpose of verifying the suitability of the parameter values in the calibration process, the modelled hydrograph is examined with the observation hydrograph data. Parameters from the calibrated HEC-HMS have been validated using the rainfall and discharge data in different time simulation. In this process, three statistical performance indicators are used to evaluate the performance of the model for each sub-catchment. The first indicator is the Percent Error in Peak Flow (PEPF) that only considers the magnitude of the measured peak flow and disregards the total volume or peak timing as defined in equation (4). The second indicator is the Percent Error in Volume (PEV) that takes into account the measured volume and does not consider the peak flow magnitude or timing as shown in equation (5). Finally, the evaluation of coefficient determination (R^2) provides greater accuracy and satisfies the suitability of the model for predicting the runoff for the Kelantan River catchment as displayed in equation (6).

$$PEPF = 100\left|\frac{Q_o\,(peak) - Q_m(peak)}{Q_o(peak)}\right| \tag{4}$$

Where Q_o is the observed discharge and Q_m is the modelled discharge.

$$PEV = 100\left|\frac{V_o - V_m}{V_o}\right| \tag{5}$$

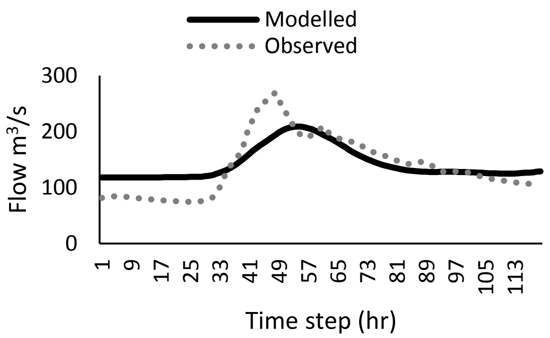
For V_o is the observed hydrograph volume and V_m is the modelled hydrograph volume.

$$R^2 = \frac{(y-\bar{x})^2}{(x-\bar{x})^2} \quad (6)$$

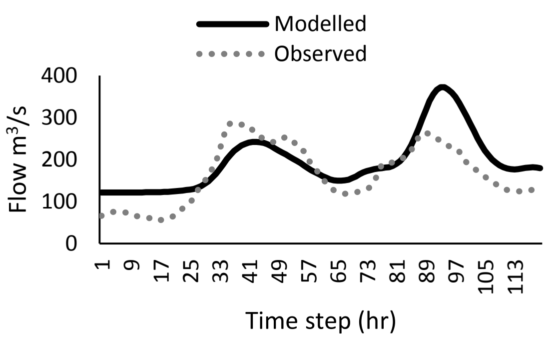
Where y is the modelled hydrograph and x and $\bar{x}$ are the observed and mean observed hydrograph. The R^2 ranges from 0 to 1, with value closer to 1 describes the percent of data closest to the line of best fit.

4. Results and discussion

Modelling in the HEC-HMS is executed for the storm events at the Kelantan River catchment involving five sub-catchments. Two simulation times of storm events (rainfall) are chosen and separated for the calibration (16 Dec 2011 - 22 Dec 2011) and validation (10 Dec 2013 - 16 Dec 2013) period. The observed hydrograph for both storm events in each sub-catchment is also needed to make a comparison between the observed and modelled hydrograph in order to evaluate the potential of the model. The overall results for the HEC-HMS analysis using the calibrated parameters at the Kelantan River catchment are shown in figure 3 and 4 as well as table 4.



(a)



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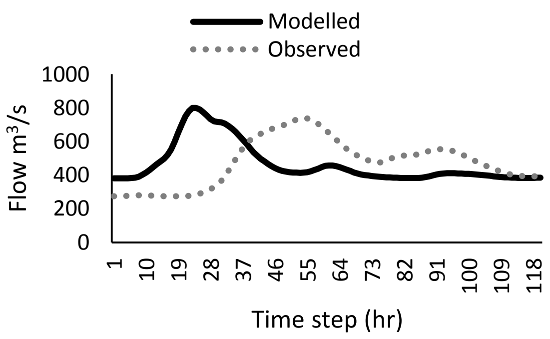

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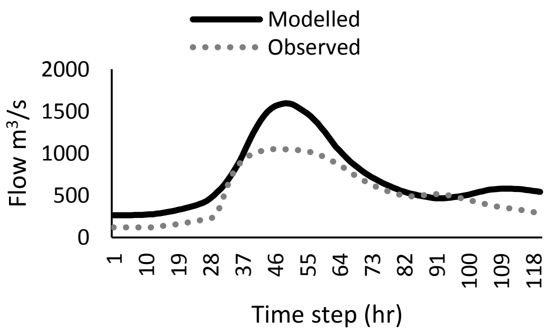

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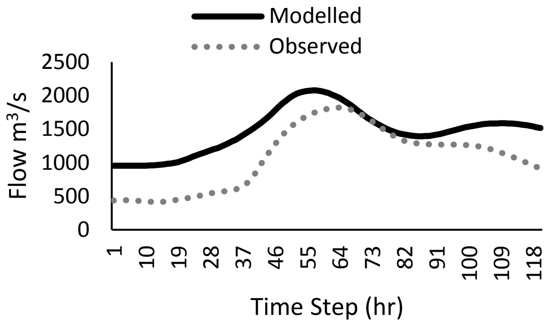

(e)

Figure 3. Performance of the HEC-HMS model during the calibration period at **(a)** Nenggiri, **(b)** Pergau, **(c)** Galas, **(d)** Lebir, and **(e)** Guillemard Bridge sub-catchment.

Visual comparisons between the observed and modelled hydrographs in the representation of the agreement of the model are detailed in figure 3 and 4. The data show that the modelled hydrograph from the HEC-HMS model is able to capture the pattern of the observed hydrograph but shows under-and-overestimation surface runoff. The observed and modelled discharge at the Galas and Guillemard Bridge sub-catchments are not well agreed in terms of the hydrograph shape and timing of peaks. Such poor performance at the Galas sub-catchment may be due to the hydroelectric dam located at the upstream of the Pergau region which causes unpredictable flow to the Galas catchment [7].

Similar outcomes are shown during the validation period. However, during the validation, the comparison was done for only four sub-catchments as no discharge data is available for the Pergau sub-catchment. The moderate visual performance shown by the overall sub-catchment can be attributed to the implementation of the loss method of SCS CN that is insensitive to rainfall intensity [8] and unsuitable to be applied at the tropical watershed. The HEC-HMS model developed by Halwatura and Najim [9] using the SCS CN loss method also shows a poor representation of tropical catchment. Other than that, the Lag routing method does not consider the attenuation effects such as the backwater caused by man-made structure (e.g. dam) and tributary inflows [10]. Therefore, these two methods could be the most plausible explanation of under-overestimating the cumulative runoff and peak flow, especially in complex watershed such as at the Kelantan River catchment.

The performance of the HEC-HMS model is also evaluated by the statistical PEPF, PEV, and R^2 as presented in table 4. However, the application of the PEPF and PEV as objective functions may give a negative effect on the simulated hydrograph shape.

Table 4. Performance of the HEC-HMS model during calibration and validation period.

	Calibration			Validation		
Sub-catchments	PEPF (%)	PEV (%)	R^2	PEPF (%)	PEV (%)	R^2
Nenggiri	22.39	5.86	0.80	1.87	31.46	0.64
Pergau	29.38	19.51	0.94	-	-	-
Galas	8.18	1.27	0.82	15.69	23.12	0.93
Lebir	51.77	37.39	0.97	36.69	13.65	0.88
Guillemard Bridge	14.12	40.41	0.95	23.14	6.27	0.91

During the calibration and validation, the acceptable range performance of PEPF is obtained for most sub-catchments except for the Lebir sub-catchment. For PEV, the smallest percentage errors are seen at the Galas and Guillemard Bridge sub-catchment during the calibration and validation. Meanwhile, higher percentage errors are obtained for the Lebir, Guillemard Bridge, and Nenggiri sub-catchment. The lower performance of the PEPF and PEV for the HEC-HMS model at some sub-catchments might be possibly associated with the interpolation of rainfall that might not be well represented by the model. The R^2 values for the five sub-catchments in the developed HEC-HMS model range from 0.80 to 0.97 during the calibration and 0.64 to 0.93 during the validation. Values greater than 0.5 are considered acceptable while values greater than 0.9 represent that the percentage of agreement between the modelled and observed hydrographs is nearly perfect. It also indicates that this hydrologic model is highly capable of representing the flow in each sub-catchment.

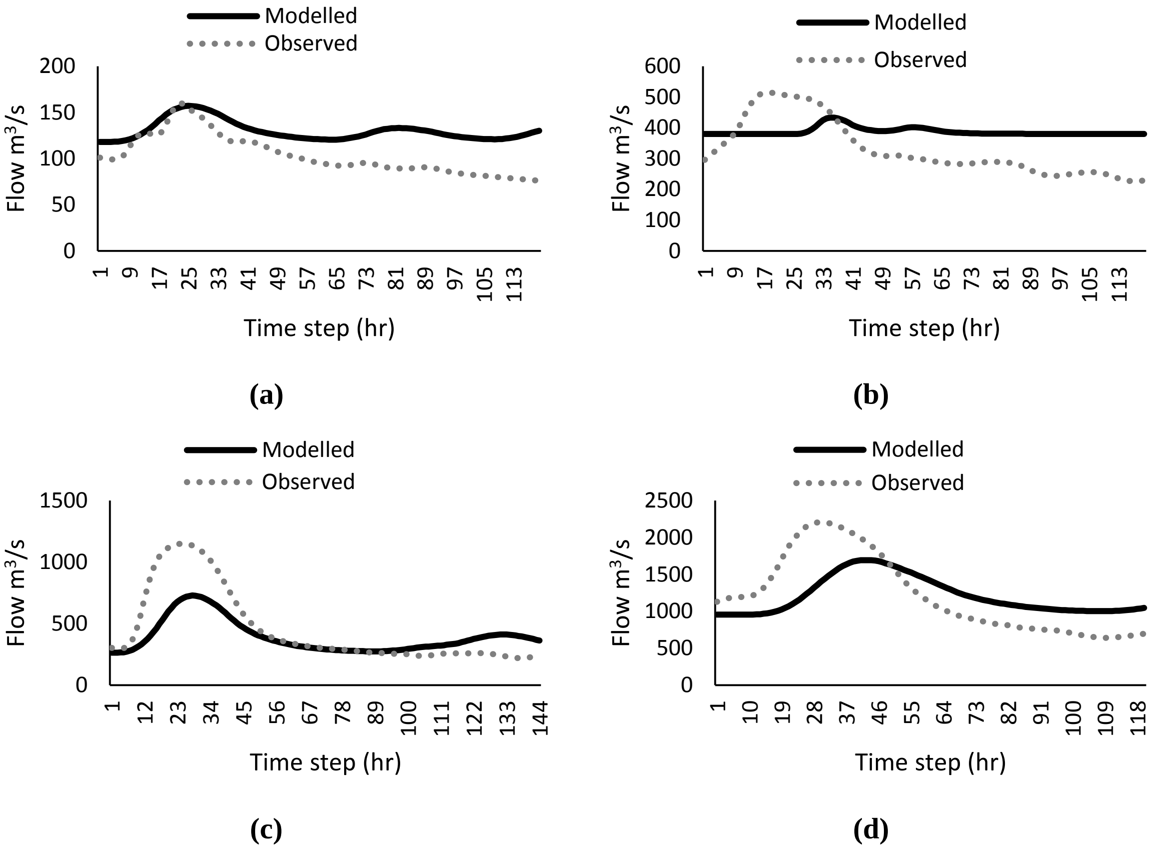

Figure 4. Performance of the HEC-HMS model during the validation period at **(a)** Nenggiri, **(b)** Galas, **(c)** Lebir**, (d)** Guillemard Bridge sub-catchment.

5. Conclusion

The present study simulates runoff by employing the rainfall-runoff model of HEC-HMS based on the hourly rainfall data at the Kelantan River catchment for two extreme rainfall events in December. The HEC-HMS is integrated with the remote sensing data and geographical information system (GIS) to help for the better execution of reliable flood simulation. Simulating rainfall-runoff analysis is effectively executed by utilizing the HEC-HMS model. The model was run while adjusting the parameters during the calibration followed by the watershed delineation using the GIS tool as the basin component, assigning the meteorological component, and characterising the control specifications. The sufficiently good values of R^2 corresponding to the hydrograph are obtained. This shows that the employment SCS-CN (loss method), SCS-UH (transform method), constant monthly (baseflow method), and Lag (routing method) can be reliably utilised for flood modelling of the catchment. This study shall help with better water management of the Kelantan River catchment. However, the study suggests on utilising the proper method parameters in the HEC-HMS model to affirm its appropriateness for the Kelantan River catchment.

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