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ORIGINAL ARTICLE

Quantification of Runoff as Influenced by Morphometric Characteristics in a Rural Complex Catchment

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Abstract

This study addresses the critical scientific question of assessing the relationship between morphometric features and the hydrological factors that increase the risk of flooding in Kelantan River basin, Malaysia. Two hypotheses were developed to achieve this aim, namely: the alternate hypothesis (runoff, is influenced by morphometric characteristics in the study watershed) and the null hypothesis (runoff is not influenced by morphometric characteristics). First, the watershed was delineated into four major catchments, namely: Galas, Pergau, Lebir, and Nenggiri. Next, quantitative morphometric characters such as linear aspects, areal aspects, and relief aspects were determined on each of these catchments. Furthermore, HEC–HMS and flood response analyses were employed to simulate the hydrological response of the catchments. From the results of morphometric analysis, profound spatial changes were observed between runoff features of Kelantan River and the morphometric characteristics. The length of overflow that was related to drainage density and constant channel maintenance was found to be 0.12 in Pergau, 0.04 in both Nenggiri and Lebir, and 0.03 in Galas. Drainage density as influenced by geology and vegetation density was found to be low in all the catchments (0.07–0.24). Results of hydrological response indicated that Lebir, Nenggiri, Galas, and Pergau recorded a flood response factor of 0.75, 0.63, 0.40, and 0.05, respectively. Therefore, Lebir and Nenggiri are more likely to be flooded during a rainstorm. There was no clear indication with regard to the catchment that emerged as the most prevailing in all the morphological features. Hence, the alternate hypothesis was affirmed. This study can be replicated in other catchments with different hydrologic setup.

Keywords Morphometric parameters · Remote sensing · GIS · Runoff · HEC–HMS · Malaysia

1 Introduction

These features are known to be essentially linked to the transmissibility, permeability, and water holding capacity of a drainage basin. Examples of these features include; soil, land use, geomorphology and geology (Romshoo et al. 2012; Ward and Robinson 2000). The accurate quantification of the morphological, geomorphic, and topographic features of a watershed becomes imperative, as this will help in evaluating the hydrologic response of watersheds.

Morphometric analysis can be used for the numerical description of a drainage basin, which is a vital component needed for classification of watersheds. It entails the quantification of linear characteristics, aerial features, relief aspects, and channel slope network of a basin as well as the contributing ground slope of a basin as reported by previous investigators (Magesh et al. 2012; Rai et al. 2014). The geomorphology, soil, geology, structural components, and vegetation of a watershed play a major role in the development of a drainage system and its flowing pattern. In addition, morphometric analysis can be used to study soil parameters such as texture, permeability, porosity, infiltration, runoff, and erosion conditions.

The major determinant of flood inundation is topography (Brasington and Richards 1998; Romshoo et al. 2012) which is also regarded as the first-order control on the runoff

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behaviour of a basin rainfall (Bates and De Roo 2000; Romshoo et al. 2012). Likewise, morphological aspects of a basin such as drainage density, channel slope, stream order, relief, length of overland flow, and stream frequency are all vital for a better assessment of the hydrology of a watershed (Chow 1964; Romshoo et al. 2012; Strahler 1964). Besides, rainfall–runoff features of a watershed vary with changes in geomorphological features of watershed.

A large number information relating to the initiation and evolution of land surface processes are extracted by morphometric characterization of a watershed, since hydrologic and geomorphic characteristics are occurring within a basin (Dar et al. 2013; Rai et al. 2014; Singh 1992, 1995). According to studies conducted by Barry and Chorley (1998) and Ward and Robinson (2000), runoff behaviour of a basin differs according to geomorphological characteristics of the basins. Prioritization concept can aid in evaluating the morphology of individual watersheds (Brooks et al. 2006; Hlaing et al. 2008; Javed et al. 2009; Patel et al. 2013; Strahler 1957). Several investigators have reported that morphometric analysis and prioritization of basins are vital for water resource modelling and flood control (Bali et al. 2012; Patel et al. 2013; Youssef et al. 2011). Estimation and prediction of discharge in a watershed after high rainfall event can easily be done through characterization (Patel et al. 2013; Thomas et al. 2012). Better result could be achieved for the characterization of watershed when results from the morphometric analysis are integrated with estimated discharge from hydrological modelling, since the hydrological response of a watershed depends on its morphometric parameters to a certain extent, which is known to be useful in producing its runoff characteristics and water balance. Quantitative morphometric characterization and investigation of a basin are regarded as one of the most acceptable ways for better basin control, planning as well application of soil and water conservation measures.

Although researches based on natural disasters among geoscientists are continuously increasing, however, there exists a noteworthy gap in our knowledge of the features associated with flood disaster in Kelantan River basin. As no study presently exists in the literature that has attempted to quantify the basin drainage system as well as integrate the hydrologic response of the watershed for flood control planning. Therefore, this research is aimed at addressing the critical scientific question of assessing the relationship between morphometric features and the hydrological factors that increase the risk of flooding. Two hypotheses were developed to achieve this aim, namely: the alternate hypothesis, which states that runoff, is influenced by morphometric characteristics in the study watershed, while the null hypothesis is that runoff is not influenced by morphometric characteristics. The novelty of this study lies in the ability to establish a relationship between morphometric characteristics and hydrological behaviour of Kelantan River basin, which is mostly limiting in literature.

2 Materials and Methods

2.1 Study Area

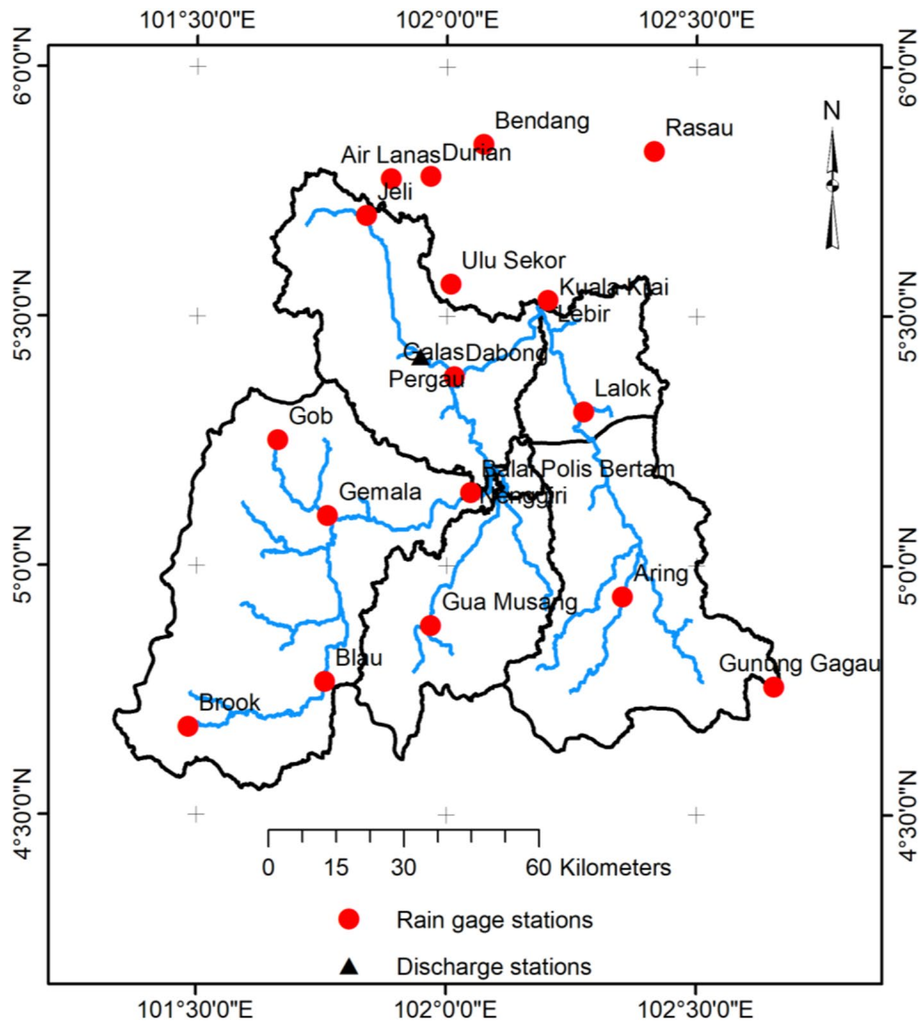
Kelantan state is one of the 13 states situated at the eastern region of Peninsular Malaysia opposite the South China Sea. Kota Bharu is the capital and developmental city of Kelantan, situated at the Northern part of the state. Kelantan state occupies 4.40% of Malaysia's total area with a total of 15,099 km^2. Kelantan state has an estimated population of 1.539 million. Majority of the rainfall is received during the northeast monsoon between the months of October and January, which is estimated to be 2500 mm per annum. Average river discharge in Kelantan River taken at Guillemard Bridge is 557.50 m^3/s. The main river in the state is Kelantan River, which has four main tributaries, viz. Galas, Nenggiri, Lebir, and Pergau. The basin is the influence of northeast monsoon flooding which is an annual event that happens between November and January.

Kelantan River has a drainage length of about 13,100 km^2, which occupies over 60% of the area in Kelantan state. The River is divided into Galas River and Lebir River close Kuala Krai. Kelantan River has a flow direction that blows northward where it progress along major towns like like Tanah Merah, Kuala Krai, Kota Bharu, and Pasir Mas. The major area of the catchment comprises of steep mountain lands rising up to a height of 2135 m occupying about 95% of the area, while the rest is undulating land. The top soil consists of mostly granite with a combination of fine to coarse sand and clay. The depth of the top soil is approximately 1 m deep in most cases, but deeper depths can be obtained in some places. In the extreme of the southern half of the basin, the major soil type found is fine sandy loam soil which has its depth rarely exceeding a few meters. The other part that consists of almost 40% of the basin is covered by top soil that varies in depth, which is about 1 m to more than 9 m. The forested areas mostly in the Lojing highlands are experiencing serious logging activities which some people believe is the major cause of recent floods in the basin. The map of the study area is shown in Fig. 1.

2.2 Data Used

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) ASTER GDEM (30 m resolution) were used to derive the Digital elevation model (DEM) and slope of the area. Rainfall and discharge data were obtained from the Department of Irrigation and Drainage, Malaysia (DID). Soil

Fig. 1 Map of Kelantan river basin showing Galas, Pergau, Lebir, and Nenggiri catchment



series and land use maps were obtained from Department of Agriculture, Malaysia for curve number (CN) calculation as well as hydrologic model simulation.

2.3 Tools and Techniques Used

DEM was processed using ArcMap 10.3 for the extraction of characteristics of Kelantan River basin. ArcMap re is designed for basic visualization, an analysis of spatial queries, generating the integrated database, and basic modelling. Various geo-processing techniques were used in the ArcMap software for delineating the four major catchments in the basin, namely: Galas, Pergau, Nenggiri, and Lebir.

HEC–GeoHMS an ArcMap extension was utilized in pre-processing HEC–HMS model. This means that, important features, which are vital for hydrological modelling, were assembled by this extension. The inputs which include DEM, LULC change map, and soil map were later used in defining watershed outlet, merging basins, creating river profile, executing basin characteristics (e.g., upstream and downstream elevation and river length), and creating HMS parameters and sub-basin parameters.

2.4 Morphometric Analysis

Morphometric analysis is the numerical assessment of a basin altitude, volume, slope, profiles of a land as well as drainage basin characteristics of an area in question (Clarke 1966; Singh 1972 Strahler 1964). The basic understanding and quantification of environmental hazards such as flooding using geomorphic principles recorded a tremendous success in areas of research aimed at detecting the interactions that exist between watershed morphometric features and flood characteristics (Patton 1988). For a better understanding of geomorphological effects on a flood, it becomes imperative to conduct a morphometric analysis, which should, in turn, be related to the hydrology of a basin.

It is a well-known fact that conducting research to derive information of major basin features from conventional methods carried out through map measurements is laborious and time-consuming. Apart from few measurable parameters that can be extracted from maps like elevation and relief, measurement of more complex parameters such as stream length, drainage density, mean basin elevation, and channel gradient for streams of different orders is hindered by lengthy time spent to get this information from the maps. For this reason, DEM was used for the computation of morphometric characteristics with higher precision and much more effectiveness. In the last few decades, a number of authors have acknowledged the greater relevance attained by geospatial techniques (Aher et al. 2014; Masoud 2016; Romshoo et al. 2012).

Several geo-processing steps were involved in the hydrology model of spatial analyst module of ArcMap. DEM was used in evaluating the drainage network, basin geometry, drainage texture, and basin relief characteristics of morphometric parameters. Slope aspect map and stream order maps were all developed using this tool. Thereafter, morphometric features were analyzed using mathematical formulae, as described in Table 1.

2.5 Hydrological Modelling and Flood Response Analysis

The schematic presentation of basin model of the study area showing Galas, Pergau, Lebir, and Nenggiri is presented in Fig. 2. Hydrological components of the basin were prepared in the model and their features such as sub-basins, river, reach, junction etc. are all shown here. Rainfall event was converted to flood discharge using four processing steps that include loss rate, transform, base flow, and river reach.

2.5.1 Loss Model

Loss model was used to calculate actual infiltration, which is interacted by infiltration, surface runoff, and sub-surface processes together at the sub-basin. The NRCS–CN model was used for this study, because this method is ideal for event simulation. The model is based on the principle of estimating precipitation excess as a function of cumulative rainfall, soil cover, land use, and antecedent moisture.

Table 1 Empirical formulae used in computation of morphometric parameters of Kelantan river basin

Aspect	Morphometric parameters	Equation	Description	References
Linear aspect	Stream order (N_u)	N_u	Hierarchical order	Strahler (1964)
	Length of main channel (L_m)	L_m	Length along longest water course from the outflow point of to the upper limit of catchment boundary	
	Stream length of the order u	L_u	Length of the stream	Horton (1945)
	Mean stream length (L_{sm})	$L_{sm} = {}^{L_u}/_{N_u}$		Strahler (1964)
	Stream length ratio (R_L)	$R_L = {}^{L_u}/_{L_u} - 1$		Horton (1945)
	Bifurcation ratio (R_b)	$R_b = \frac{N_u}{N_u+1}$	Where Nu = total no. of stream segments of order 'u', $Nu + 1$ = number of segments of the next higher order	Schumm (1956)
	Length of overland flow (L_g)	$L_g = {}^1/_2 D_d$	Where L_g = length of overland flow, D_d = drainage density	Horton (1945)
	Basin length (L_b)	L_b	Distance between outlet and farthest point on the basin boundary	Ratnam et al. (2005)
Areal aspect	Basin area (A)	A	Area enclosed within the boundary of watershed divide	Horton (1932)
	Drainage density (D_d)	$D_d = {}^{L_u}/_A$		
	Constant of channel maintenance (C)	$C = {}^1/_{D_d}$		Schumm (1956)
	Elongation ratio (R_e)	$R_e = \sqrt{(4 \times A/3.142)}/L_b$	Where L_b is the farthest distance from ridge to outlet	Schumm (1956)
	Form factor (F_f)	$F_f = {}^A/_{L^2}$	Where L^2 is the basin length	Horton (1932)
Relief aspect	Total relief (H)	$H = R - r$	Maximum vertical distance between the lowest (r) and highest points (R) on the valley floor of a watershed	Hadley and Schumm (1961)
	Relief ratio (R_h)	$R_h = {}^H/_{L_b}$		Schumm (1956)
	Ruggedness number (R_n)	$R_n = H \times D_d$		Melton (1957)
	Infiltration number (I_f)	$I_f = D_d \times F_s$		

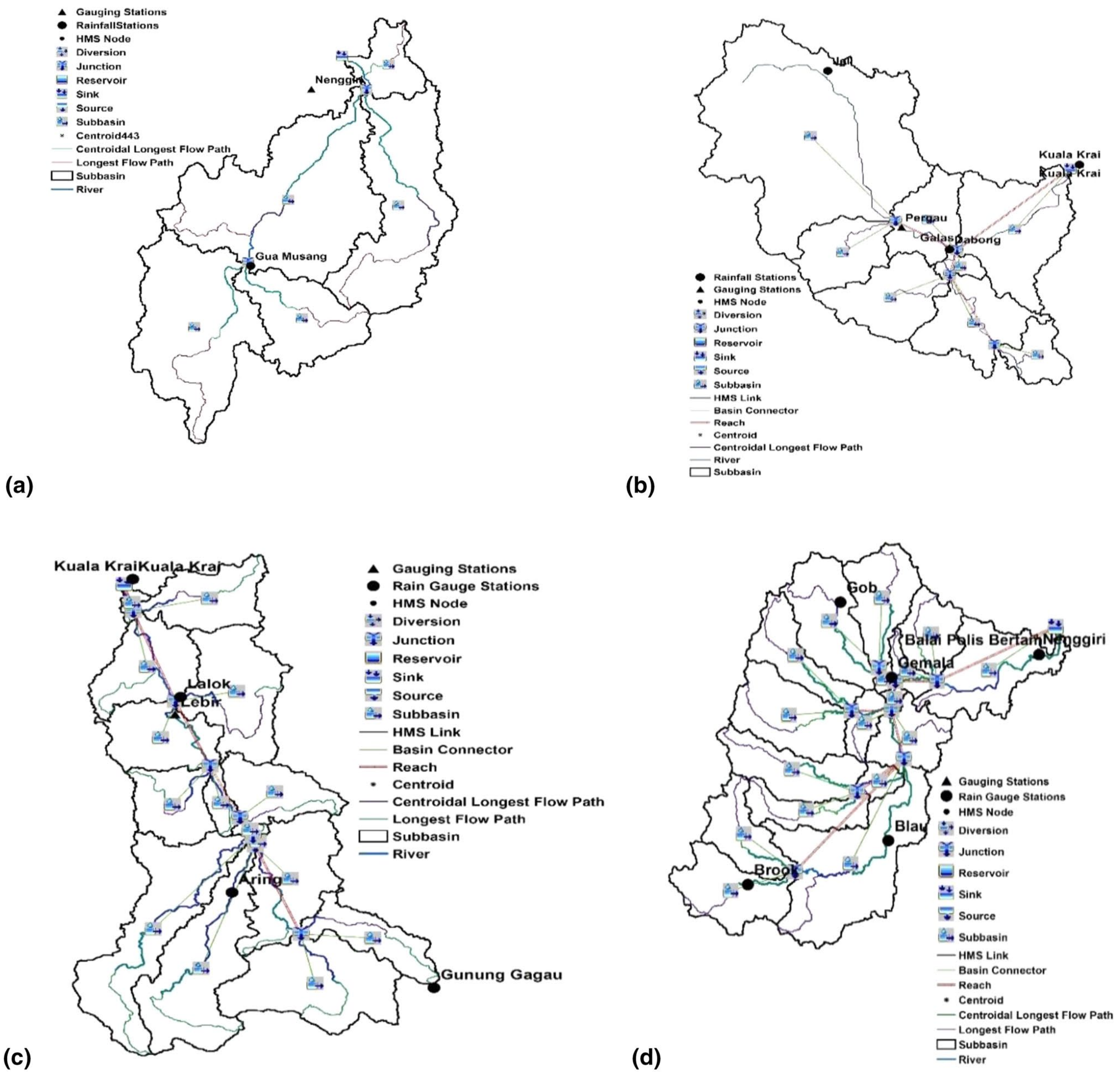


Fig. 2 Schematic diagram of HEC-HMS Model Structure at Kelantan river basin, **a** Galas, **b** Pergau **c** Lebir, and **d** Nenggiri

CN values of AMC II (CN_{II}) were provided as a composite curve number for the catchments using the following equation:

$$\mathrm{CN}_{\mathrm{II}} = \frac{\sum_{i=1}^{n}(\mathrm{CN}_i \times A_i)}{\sum_{i=1}^{n} A_i}, \tag{1}$$

where CN_{i} is curve number value for every land use and hydrological soil group, and A_{i} is the area of every land use and HSG.

2.5.2 Transform

This method presents the actual surface runoff, which was executed by a transform method within the sub-basins. NRCS method using Eqs. (2) and (3) was adopted as the direct runoff method for this study:

$$U_{\mathrm{p}} = 2.08\frac{A}{T_{\mathrm{P}}}, \tag{2}$$

$$T_{\mathrm{P}} = \frac{\Delta T}{2} + T_{\mathrm{lag}}, \tag{3}$$

where U_p is unit hydrograph peak discharge (m^3/s), A is the basin area (km^2), T_P is the time of peak hydrograph (h), ΔT is the calculated time intervals in HEC–HMS which is necessary in defining slight discharge of unit hydrograph, and its estimated rate is less than 29% basin lag time (USACE–HEC 2010).

2.5.3 Base Flow Separation

Recursive digital filter method was selected as the baseflow separation method in this study. The method has two parameters: recession constant (0.980 and 0.995) and a maximum value for the baseflow index (BFI_{max}) of 0.50 for ephemeral streams with porous aquifers and 0.80 for perennial streams with porous aquifers. The Web-Based Hydrograph Analysis Tool (WHAT) was used in calculating recursive digital filter method in this study, which is presented in equation:

$$b_t = \frac{\left(1 - \mathrm{BFI}_{\mathrm{max}}\right) \times \alpha + b_{t-1} + (1 - \alpha) \times \mathrm{BFI}_{\mathrm{max}} \times Q_t}{1 - \alpha \times \mathrm{BFI}_{\mathrm{max}}}, \tag{4}$$

where b_t is filtered baseflow at time step t, b_{t-1} is filtered baseflow at time step $t - 1$, $\mathrm{BFI}_{\mathrm{max}}$ is the maximum value of long term ratio of baseflow to total streamflow, α is the filter parameter, and Q_t is total streamflow at time step t.

2.5.4 River Reach

The concept of HEC–HMS model involves routing flood hydrograph is each reach. The Muskingum method is a hydrologic river routing technique based on the equation of continuity. Given the inflow at the upstream end of a river reach, the outflow at the downstream end is expressed as

$$\frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} = \frac{S_2 - S_1}{\Delta t}, \tag{5}$$

where I is the inflow rate to the reach, Q is the outflow, S is the volume of water stored, and ∇t is the time increment. The subscripts 1 and 2 denote the values of the respective terms at the beginning and end of the time interval considered. Storage S in the routing reaches as described in the Muskingum method using the discharge–storage Eq. (6):

$$S = K[xI + (1 - x)Q], \tag{6}$$

where KQ is the reach in rism storage, K is a proportionality coefficient, and the volume of the wedge storage is equal to Kx $(I - Q)$, x is a weighting factor having a range of $0 \leq x \leq 0.5$, and most streams (Maidment 1993) have X values between 0.10 and 0.30). In this study, X range from 0.15–0.20 h, the value of K was dependent upon inflow and outflow at the gaging stations.

2.5.5 Rainfall Data and Flood Hydrograph Entry

Hourly rainfall data corresponding to selected flood events (20–30 December 2014) were collected from DID. Seven rain gauge stations were found to have more complete records of the selected flood events, and daily records of selected rainfall stations. On the other hand, measured hydrographs were collected from some stations based on these rainfall events.

2.5.6 Lag Time Calculation

The NRCS lag method (NRCS 1997) was used in calculating lag time in this study, as shown in Eq. (7). The sub-basin lag time values varied from 0.02–0.93 h:

$$t_{\mathrm{L}} = \frac{(L)^{0.8} \times (S + 1)^{0.7}}{1900 \times Y^{0.5}}, \tag{7}$$

where t_L = lag time or basin lag, L = watershed hydraulic length (km), S = potential maximum after runoff begins, and W_s = average watershed slope (%). Both the aforementioned values were estimated using ArcMap.

2.5.7 Time of Concentration Calculation

The lag method (NRCS 1997) was used in calculating time of concentration, as shown in Eq. (8):

$$T_c = \frac{L}{0.6}. \tag{8}$$

2.5.8 HEC–HMS Model Calibration and Validation

Initial values fitted into HEC–HMS were used for the calculation of runoff hydrographs. The model compares calculated and observed hydrographs at this step. Comparison was done to judge whether model fit well with the measured data. In reality, model validation is an extension of the calibration process. Normally, in hydrology, validation is carried out by comparing and finding the relationship between simulated and observed values. A simple split-sample method developed by Ewen and Parkin (1996) was used in this study. The method involves classifying observed floods into two groups; the first data sets were used for calibration by adopting a criterion of maintaining a percentage error in peak discharge, while validation was carried out using the second group (Saghafian et al. 2008).

2.5.9 Design Rainfall

Furthermore, IDF curves from the state of Kelantan were used for rainfall input in HEC–HMS. Design rainfall distribution in sub-basins was determined using inverse distance weighing (IDW) method and according to 10-year return period. Rainfall values that define design rainfall hyetograph were used in calibration and validation of HEC–HMS model. Subsequently, the peak discharge according to 10-year return period was calculated for 1984, 2002, and 2013 LULC conditions. In view of this, total time of concentration for the basin was calculated by summing concentration time from the hydraulically most distant area having the longest travel time to the basin outlet. Table 2 shows intensity duration frequency (IDF) coefficients from Kelantan used in this study, whereas Table 3 shows storm characteristics of Kelantan River basin. The basin total time of concentration was found to be 21.06 h. Hence, 24-h duration storms were used for the determination of rainfall intensity and rate at different return periods using the formula in Eq. (9):

$$i = \frac{a}{(t + b)^{c}}. \tag{9}$$

2.5.10 Flood Response

Flood response was calculated using response factor proposed by Hewlett and Hibbert (1967). The response factor is given in Eq. (10):

$$R_{\mathrm{p}} = \frac{V}{P}, \tag{10}$$

where R_{p} is the response factor, V is the surface runoff, and P is total precipitation. The values of R_{p} ranged from 0 to 1, the closer it is to 1.00, the higher the flood response. The response factor was chosen to compare of the catchments, although they are different in terms of distance as well as rainfall characteristics. As such, the response factor was expressed in simplest form by expressing the fraction of rainfall that flows as a quick flow.

3 Results and Discussion

3.1 Results of HEC–HMS Model Validation

In this study, results of the model implementation for the December 2014 were compared based on 1984, 2002, and 2013 LULC conditions. Example of hydrographs produced by HEC–HMS based on the different LULC conditions is shown in Fig. 3. Visual examination was carried out to assess the observed and the simulated peak discharges. From the examination, an acceptable agreement was observed between the observed and simulated peak discharges. This method of visual comparison was also carried out by Saadatkhah et al. (2016) who reported similar results while working on 20–30th December 2014 flood in Kelantan River basin.

Table 3 Storm characteristics of Kelantan river basin

Return period	Rainfall depth (mm)	Intensity (mm/h)
2	144.00	23.70
5	168.00	34.19
10	216.00	35.14
20	228.00	36.57
50	288.00	42.93
100	360.00	46.26

3.2 Morphometric Analyses

Morphometric features of the basin such as linear aspects, aerial aspects, and relief aspects were computed in this study.

3.2.1 Linear Aspects

The linear aspects of Kelantan river basin computed in this study are; stream order (u), stream number (N_{u}), stream length (L_{u}), mean stream length (L_{sm}), stream length ratio (R_{L}), Bifurcation ratio (R_{b}), and length of overland flow (L_{g}). Catchments' drainage network characteristics that include drainage basin area, perimeter, basin length, and length of main channel are presented in Table 4.

3.2.1.1 Stream Order (*u*) Quantification of stream order is considered as the primary stage of quantitative analysis of a watershed according to hierarchic making of streams. The use of stream order was initially founded by Horton (1945), but Strahler (1964) made a modification to this method. In this study, the procedure developed by Strahler (1964) was used, as shown in Table 5. Galas and Lebir catchments were

Table 2 IDF coefficients from Kelantan (adopted from DID 2012)

Coefficient	Return period (year)					
	2	5	10	20	50	100
A	4.6132	3.8834	4.6080	4.7584	4.6406	4.6734
B	0.6009	1.2174	0.8347	0.7946	0.9382	0.9782
C	− 0.2250	− 0.3624	− 0.2848	− 0.2749	− 0.3059	− 0.3152
D	0.0114	0.0213	0.0161	0.0154	0.0176	0.0183

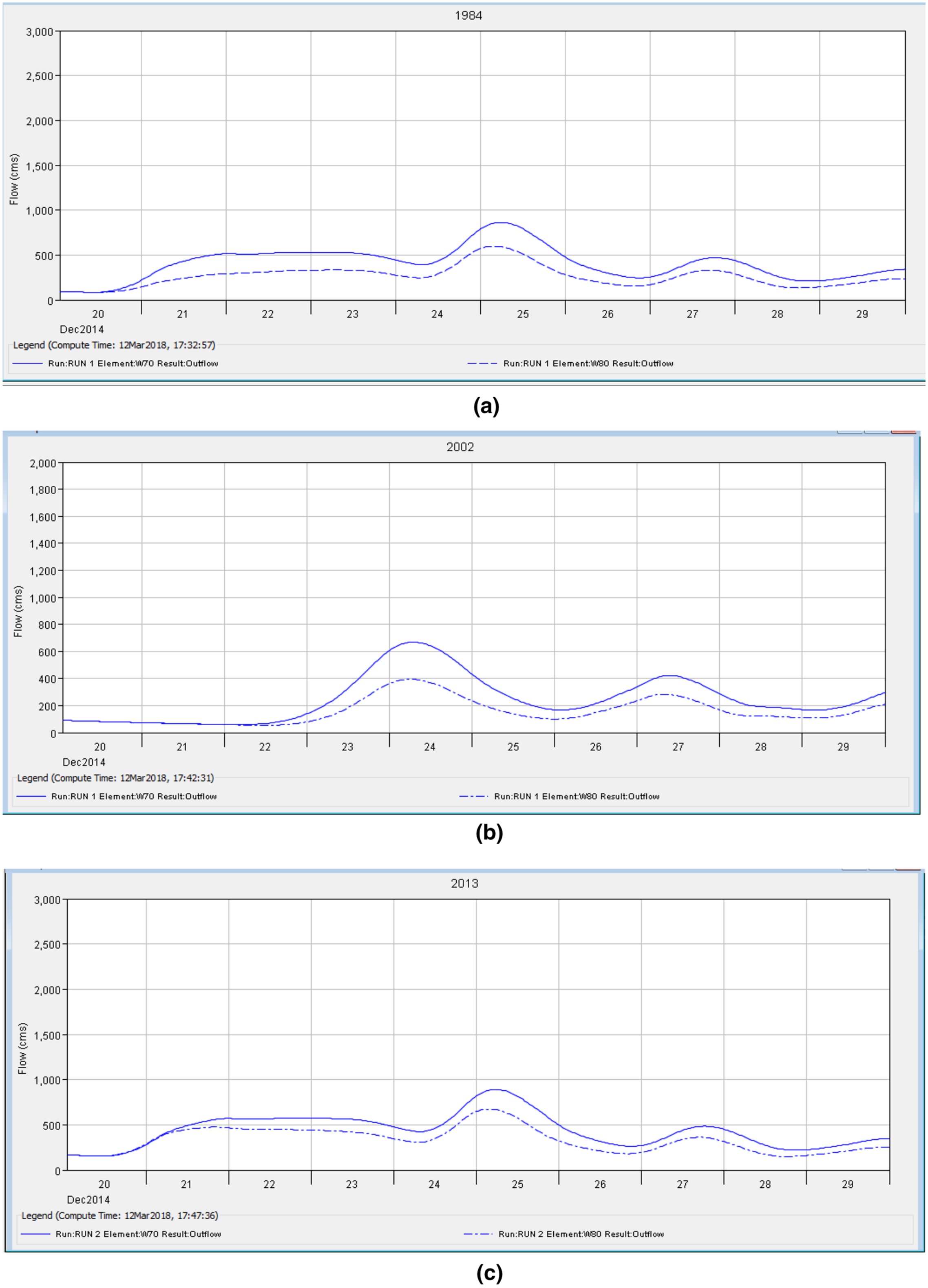


Fig. 3 Hydrographs produced by HEC-HMS calibration, **a** 1984, **b** 2002, and **c** 2013

found to have II orders each, while Pergau and Nenggiri have III ordered streams (Fig. 4).

Strahler (1964) reported that the smallest fingertip streams with no tributaries are considered as order I. Order II streams are formed, where two order I streams merge; likewise, an order III segment is created, where two stream orders join and so on. In most cases, high-ranking stream orders are directly related to greater velocity of the stream flow.

Table 4 Watershed drainage network parameters

Basin	Area (km^2)	Perimeter (km)	Basin length (km)	Length of main channel (km)
Galas	1650.81	348.69	96.28	76.28
Pergau	2322.52	444.84	165.70	87.88
Lebir	3350.05	569.39	149.41	105.11
Nenggiri	3958.75	497.21	180.75	91.64

Table 5 Stream orders and lengths of Kelantan river basin

Basin	Stream number in different order				Order wise total stream length (m)				Mean stream length (m)		
	I	II	III	Total	I	II	III	Total	I	II	III
Galas	5	2	–	7	62,350	47,560	–	110,810	12,650	23,780	–
Pergau	4	3	4	11	265,260	157,130	141,510	563,900	14,980	52,380	35,380
Lebir	8	7	–	15	148,870	99,810	–	248,680	18,610	14,260	–
Nenggiri	9	4	4	17	128,320	94,290	89,370	311,980	14,260	23,570	22,340

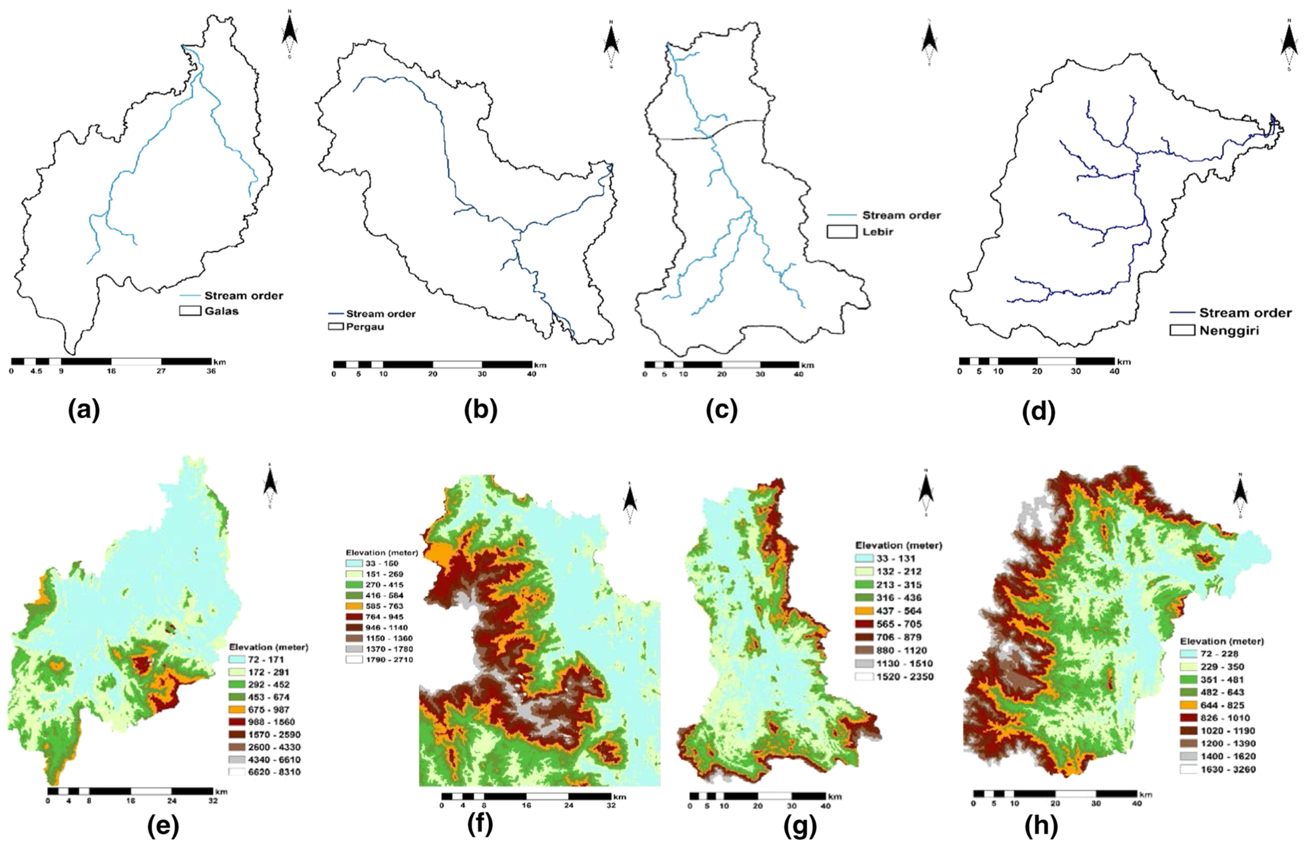


Fig. 4 Stream-order map and DEM map of the major catchments in Kelantan river basin, **a** Galas stream order, **b** Pergau stream order 1984, **c** Lebir stream order, **d** Nenggiri stream order, **e** Galas DEM, **f** Pergau DEM, **g** Lebir DEM, and **h** Nenggiri DEM

3.2.1.2 Stream Number (N_u) This is the amount of stream channels in each order as reported by Horton (1945). Stream numbers of different orders, as well as basin total number of streams, were computed using ArcMap. From the results, N_u decreased as stream order increase. This difference in stream order and size of tributary of the catchments are mainly dependent on catchment's physiographical, geomorphological, and geological features. The presence of large number of streams is an indication of low permeability and infiltration (Romshoo et al. 2012) which will in turn result to high runoff. There are 5 and 2 streams in orders I and II, respectively, found in Galas catchment, while in Lebir, 8 streams each were found in order I and 7 streams in order II (Table 5).

3.2.1.3 Stream Length (L_u) This is the entire length of single stream segment of each order. It measures the average length of a stream in each order. In areas where there is permeable layer due to the presence of bedrock, only a slight number of comparatively longer streams are developed. While in a more porous watershed with less permeability, a large number of streams of smaller length are developed. The physical variation of rock characteristics makes streams flow from high altitude to lower altitude. Longer streams are more likely to flood more areas around the catchment compared to shorter streams.

It was observed in this study that higher cumulative stream length was observed in first-order streams, but drops with increase in stream order in all catchments (Table 5). This is in conformity with the Horton's (1932) "Law of stream length". The law affirms that a direct geometric ratio is carefully estimated by mean length of each stream in each order in a watershed. The longest stream length was recorded in Pergau with 56,390 m, followed by Nenggiri (311,980 m), Lebir (248,680 m), and Galas (110,810 m).

3.2.1.4 Mean Stream Length (L_{sm}) This dimensional property is essential in determining the physical features of components of a drainage network and its contributing basin surface. It was quantified by dividing the total stream length by the number of stream segments in the order (Table 5). An increase in mean stream lengths was observed as the order increases, for example, in Galas (where L_{sm} for order I = 12,650 m and that of order II = 23,780 m), in Pergau (where L_{sm} for order I = 14,098 m, order II = 52,380 m and order III = 35,380 m), and in Nenggiri (where L_{sm} for order I = 14,260 m, order II = 23,570 m and order III = 22,340 m). However, in some catchments, it shows opposite relation, where higher order streams are observed to have a small mean length such as what is obtained in Lebir (where L_{sm} for order I = 18,610 m and order II = 14,260 km). The values of L_{sm} are basin specific, due to its direct relationship with the physical features of a basin as reported by Strahler (1964).

3.2.1.5 Bifurcation Ratio (R_b) The ratio serves as a valuable index for distinguishing hydrograph shape of identical watersheds. In addition, the values of R_b range from 3 to 5 for basins, whose geologic structures do not disturb the drainage pattern (Aher et al. 2014; Suresh 2007). R_b values lower than 3 are as a result of the features of physically less disturbed basins without any alteration in drainage pattern (Javed et al. 2009; Magesh et al. 2012; Patel et al. 2013). High R_b values indicate quick peak discharge with a possibility to be flooded during storm events (Rakesh et al. 2000; Romshoo et al. 2012). Therefore, higher R_b for Galas (3.50) and that of Nenggiri (3.25) indicates its vulnerability to flooding (Table 6). No two different orders have the same R_b values, mainly due to differences in basin geometry and lithology, which happens to be the same throughout the series (Strahler 1957). R_{bm} in all the catchments in Kelantan river basin ranges from 2.14 to 3.50 (Table 6).

3.2.1.6 Stream Length Ratio (R_L) Galas and Lebir with two stream orders are reported to have R_L values of 0.33 and 0.49, respectively (Table 6). While in Pergau and Nenggiri with III orders each, it showed a decrease from lower to higher order (Table 6). Variations observed in stream length ratio from different orders are an indication of early stages of geomorphic growth of that stream (Vaidya et al. 2013). This variation may also be due to differences in slope and topographic conditions which also bears a significant connection with the streamflow (Sreedevi et al. 2009; Aher et al. 2014).

3.2.1.7 Length of Overland Flow (L_g) This parameter denotes to that flow of rainfall water, which moves over soil

Table 6 Linear aspects of Kelantan river basin

Basin	Bifurcation ratio			Stream length ratio		L_g
	1/2	2/3	R_{bm}	2/1	3/2	
Galas	3.50	–	3.50	0.33	–	0.03
Pergau	2.33	1.75	3.21	2.33	1.75	0.12
Lebir	2.14	–	2.14	0.49	–	0.04
Nenggiri	3.25	2.00	2.63	0.36	0.06	0.04

surface and leads to stream channels. It is usually dependent on slope length and land cover conditions. A vital independent variable influences the hydrologic and physiographic developments of a drainage basin. Values of L_g of catchments in this study as shown in Table 6 are: Pergau (0.12) indicating the presence of more gentle slopes and longer flow paths than Nenggiri (0.04), Lebir (0.04), and Galas (0.03). These values are an indication that runoff at the outlet will be faster in the case of Galas followed by Nenggiri, Lebir, and later Pergau, in that order. Hence, Galas shall be more vulnerable to flood compared to other catchments. There is an inverse relation that exists between L_g and average channel slope (Patel et al. 2013). In a relatively homogeneous area such as what is obtain in Kelantan river basin, where the forest is the dominant LULC change; hence, low amount of rainfall is needed to contribute to a substantial volume of runoff to streamflow when the value of L_g is small than when it is large.

3.2.2 Areal Aspect

The parameters computed for the aerial aspects are the area, drainage density, stream frequency, circulatory ratio, form factor, and drainage texture.

3.2.2.1 Drainage Density (D_d) This parameter gives an idea of land use in a watershed and influence infiltration as well as the timing of the basin response to rainfall and discharge. It is also of geomorphological importance mainly for the development of slopes. Geology and vegetation density are the major factors influencing D_d. The effect of vegetation density on D_d is slowing down of the rate of overland flow because of binding of the surface layer, which in turn leads to water storage for a short duration. Results of D_d are shown in Table 7. Low D_d observed in Galas (0.07), Lebir (0.07), and Nenggiri (0.08) is an indication of highly permeable sub-surface earth conditions, where land is covered with dense vegetation and relief is low, which lead to increase in permeability and can favor ground recharge zones. However, high D_d (Table 7) observed in Pergau (0.24) suggests that the catchment has high density of streams, less/impermeable sub-surface materials, sparse vegetation, high relief, and, therefore, a quick storm response (Srivastava et al. 2008; Suresh 2007). In addition, a high D_d is an indication of drainage basin that is highly divided which respond quickly to rainfall events, i.e., large proportion of the precipitation runs off. While a low D_d represent a basin, whose hydrology do not respond well to runoff. Generally speaking, the rainfall–runoff behaviour of a basin varies significantly as D_d changes. Concisely, results of D_d of Pergau have the tendency to favor more runoff to streams as compared to Galas, Lebir, and Nenggiri. Since a very close relationship exists between D_d and mean annual flood, therefore, Pergau with the highest D_d is more likely to be flooded than Nenggiri, Lebir, and Galas in that order.

Table 7 Areal aspects of Kelantan river basin

Basin	D_d (km/km^2)	C	R_e	F_f
Galas	0.07	14.90	0.47	0.18
Pergau	0.24	4.12	0.32	0.15
Lebir	0.07	13.47	0.43	0.10
Nenggiri	0.08	12.69	0.39	0.12

3.2.2.2 Constant of Channel Maintenance (C) This parameter is estimated as the inverse of drainage density (Schumm 1956). It is the proportion between drainage basin and total lengths of all channels expressed as square per meter. The constant is used to indicate the number of square kilometre of basin surface that is needed for the sustainable development of 1 km channel. High values of C indicate higher strong control of lithology with a surface permeability composed of bedrocks. From the results, it was observed that high values of C were recorded in all the catchments with Pergau (4.12) recording the lowest, followed by Nenggiri (12.69), Lebir (13.47), and Galas (14.90), as presented in Table 7. It should, however, be noted that the higher the value of C the more will be the drainage basin area and the value of C increases with increase in drainage basin area.

3.2.2.3 Elongation Ratio (R_e) This is the ratio of diameter of a circle of the same area as a basin to the maximum basin length (Schumm 1956). Therefore, higher elongation ratio is an indication of more circular basins, while low elongation indicates less circular basins. Values of R_e have been classified into four, namely: elongated (<0.7), less elongated (0.8–0.7), oval (0.9–0.8), and circular (>0.9). R_e values (Table 7) obtained in this study indicated that all the four catchments are elongated (<0.7) because of high relief and steep slope of the entire study area. As reported by (Singh and Singh 1997), elongated basins are less efficient in runoff discharge as compared to circular basins.

3.2.2.4 Form Factor (F_f) Values of F_f lie between 0.1 and 0.8. Smaller values of F_f indicate that a basin will be elongated, while larger values represent circular basins. Basins with high form factors are characterised with peak flow of shorter duration, while elongated watersheds with low F_f has low-to-moderate peak flow with longer duration having the possibility of being flooded easily. The F_f values of Galas, Pergau, Lebir, and Nenggiri are 0.18, 0.15, 0.10, and 0.12, respectively (Table 7). These values indicate the elongated shape of the basins that will have constant peak flow over a long period. In addition, it gives the basins conducive nature for more groundwater recharge which helps to man-

Table 8 Relief aspects of Kelantan river basin

Basin	H (m)	Rh	N
Galas	19,840	0.21	1.33
Pergau	22,480	0.14	5.46
Lebir	9370	0.06	0.70
Nenggiri	3040	0.02	0.24

Table 9 Topographic analysis

Basin	Maximum elevation (m)	Minimum elevation (m)	Mean (m)
Galas	8303	72	255
Pergau	2713	33	431
Lebir	2345	33	278
Nenggiri	3264	72	645

age flood easily even they are more likely to be flooded than those of the circular basin.

3.2.3 Relief Aspect

The parameters computed for the basin relief are basin relief, relief ratio, ruggedness number, and infiltration number. Their description is given below.

3.2.3.1 Basin Relief (*H*) Basin relief is measured along the longest dimension of a watershed equal to major drainage line as reported by Schumm (1956). While Strahler (1957) computed it as the mean heights of the entire basin boundary above the outlet. To obtain accurate precision in H estimation for the elongated watersheds in this study, the procedure developed by Schumm (1956) was adopted and the results are presented in Table 8. The basin relief was highest in Pergau (22,480 m) followed by Galas (19,840 m), Lebir (9370 m), and Nenggiri (3040 m).

3.2.3.2 Relief Ratio (R_h) This is used to measure the total steepness of a basin and is also considered as an indicator for the intensity of erosion process occurring in a watershed. Schumm (1956) reported a direct relationship between relief ratio and gradient of a channel, while an inverse relationship exists between R_h and other shape parameters. R_h decreases with increase in drainage area and size of a given watershed (Gottschalk 1964). Table 8 shows R_h of catchments computed in this study which are between 0.02 and 0.20, implying the moderately-to-steeply (> 35%) slope nature of the watershed (Schumm 1956).

3.2.3.3 Ruggedness Number (R_n) This is a dimensionless number calculated as a product of H and D_d in the same unit (Melton 1957; Strahler 1957). It is an indication of structural complexity of terrains in a basin. Long and steeper slopes are

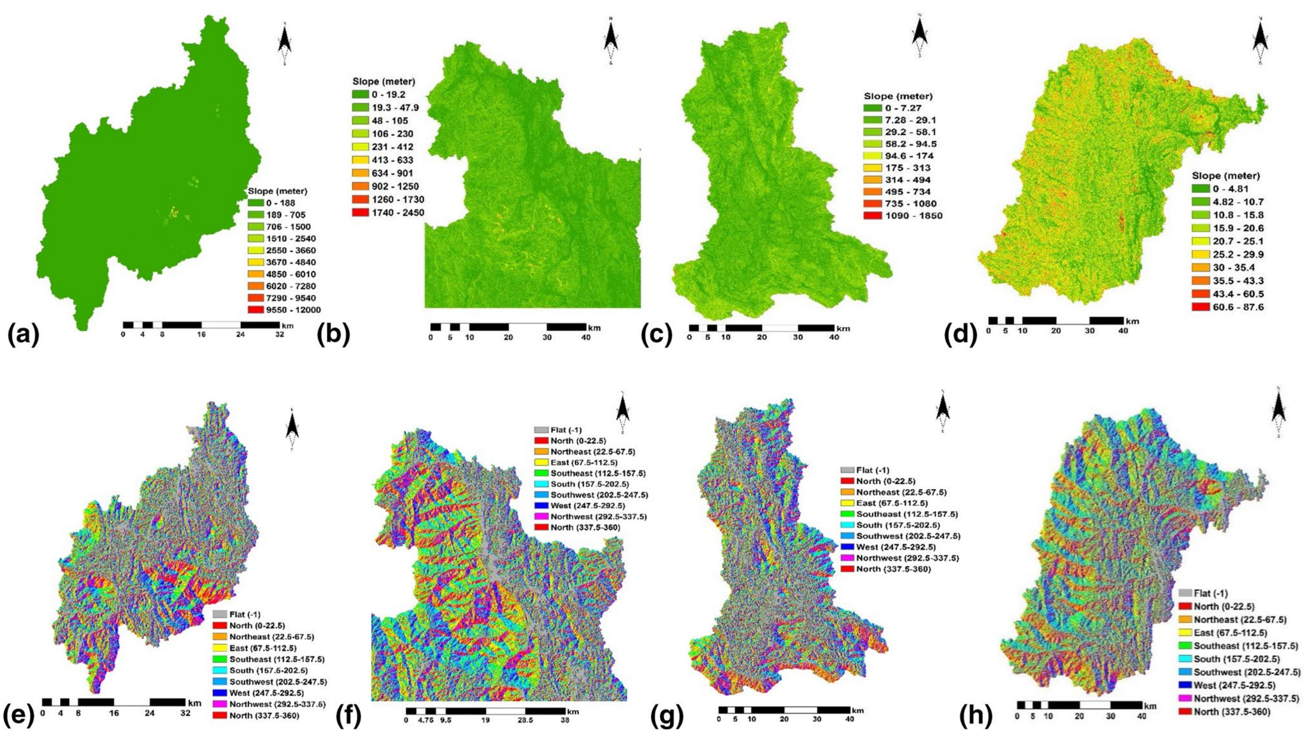


Fig. 5 Slope and aspect map of the major catchments in Kelantan river basin, **a** Galas slope, **b** Pergau slope 1984, **c** Lebir slope, **d** Nenggiri slope, **e** Galas aspect, **f** Pergau aspect, **g** Lebir aspect, and **h** Nenggiri aspect

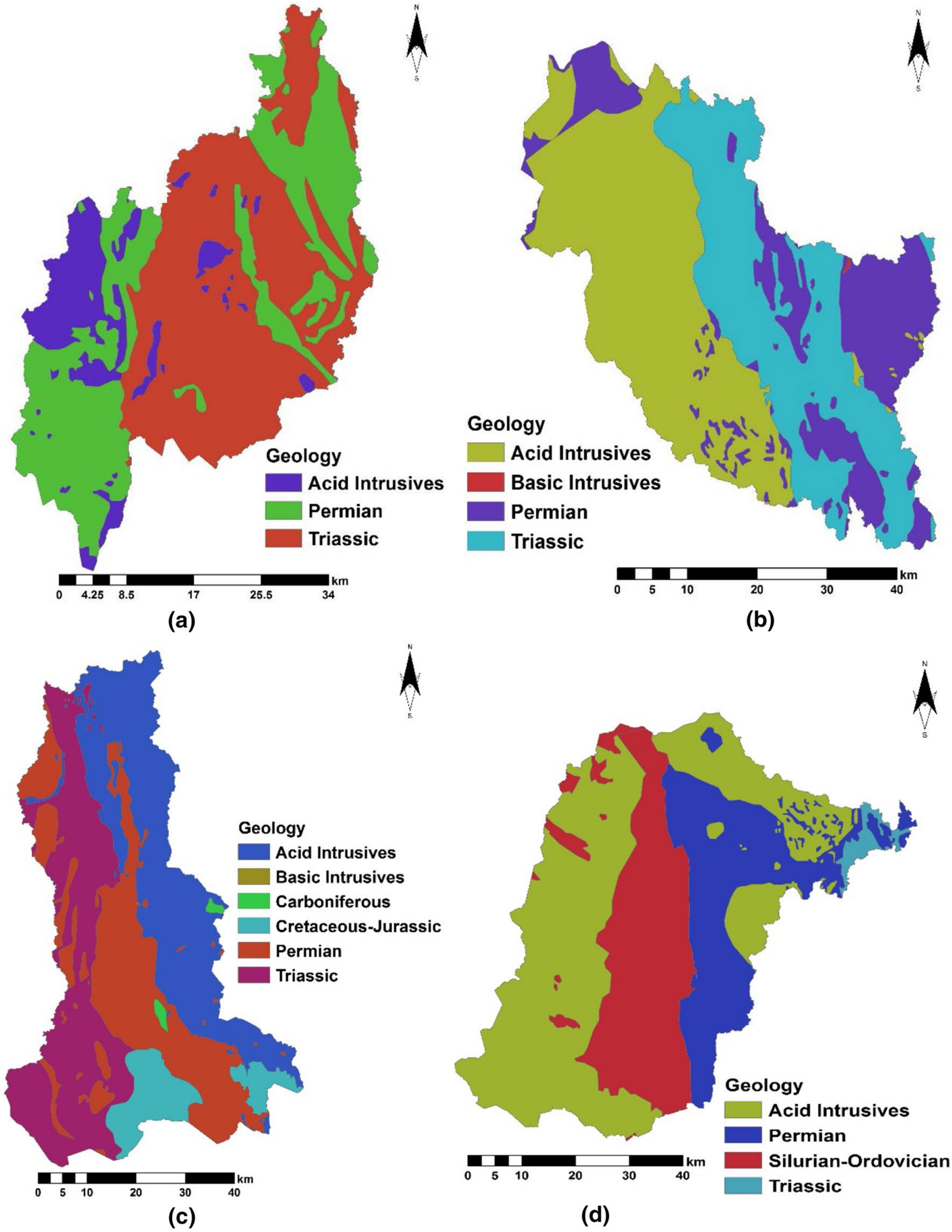


Fig. 6 Geology map of Kelantan catchments, **a** Galas, **b** Pergau, **c** Lebir, and **d** Nenggiri

responsible for the occurrence of extremely high ruggedness number in a basin. According to R_n, as D_d increases, average horizontal distance from drainage provided relief remains constant. There is decreased average horizontal distance from drainage divide to the adjoining channel. Furthermore, by increasing the H and keeping D_d constant, there will be increased average horizontal distance from drainage divide to the adjoining channel. In the present-day catchment, R_n

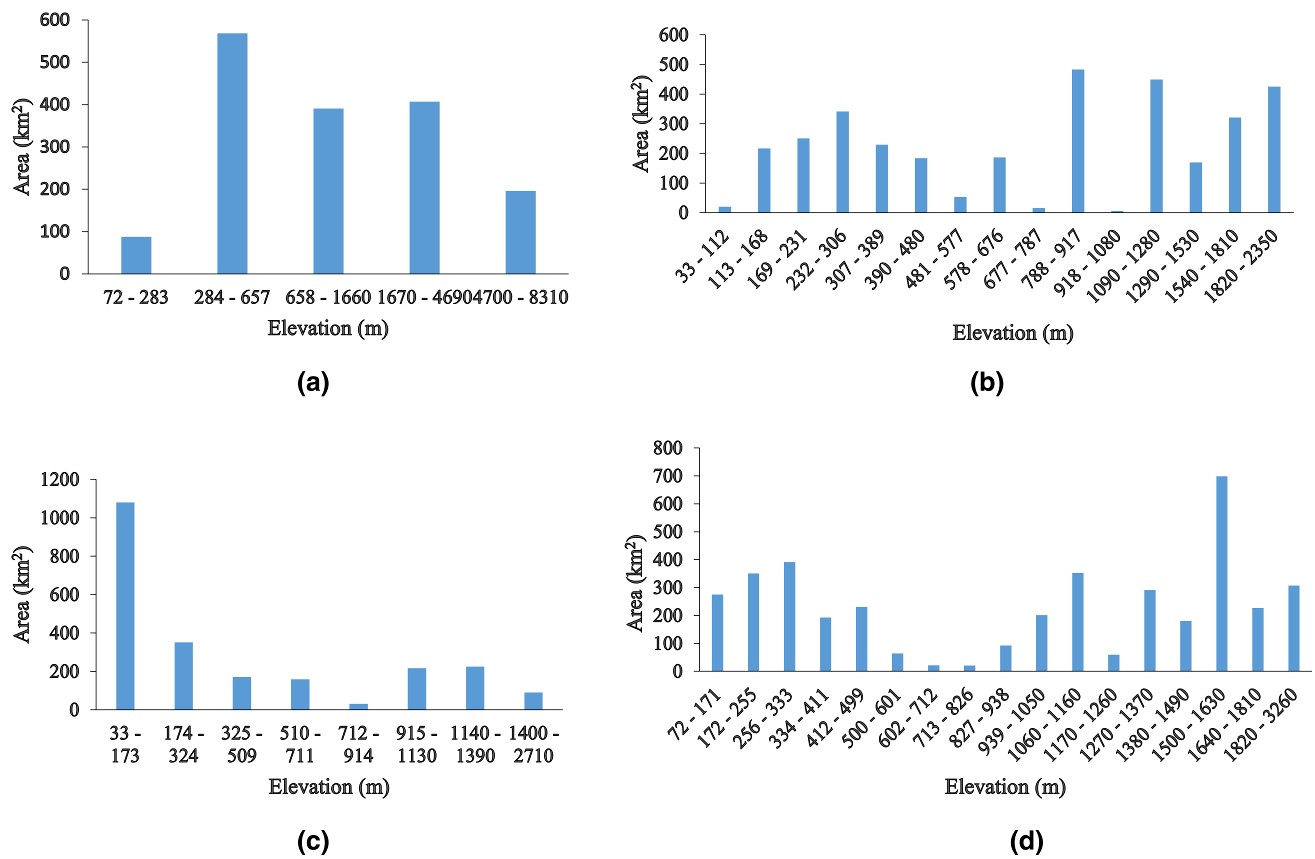


Fig. 7 Elevation area analysis of Kelantan river basin, **a** Galas, **b** Lebir, **c** Pergau, and **d** Nenggiri

varies from 0.24 for Nenggiri with moderately steep slope to 5.46 for Pergau (Table 8) with a high steep slope as well as high basin H and D_d.

3.3 Topographic Analysis

Topographic parameters of Galas, Pergau, Lebir, and Nenggiri were calculated using DEM and the results are shown in Table 9 (Romshoo et al. 2012; Tarboton 1989). The minimum and maximum elevations in Pergau and Lebir are and 33 and 2713 and 33 and 2345 m, respectively, as illustrated in Fig. 4. While higher elevations are found in Galas and Nenggiri with a minimum of 72 m each and a maximum of 8308 and 3264 m, respectively. Average slope Galas, Pergau, Lebir, and Nenggiri are 10.9°, 25.92°, 21.5°, and 16.90°, respectively. The highest slope was found in Pergau (2445.08°) and Galas (11,979.90°). A quick runoff during rainstorms is more likely to occur in the catchments with the higher average slope. The slope maps for the different catchments are shown Fig. 5. Slope aspect which is the compass direction that a slope face was also determined and the maps are presented in Fig. 5.

From the hydrogeological point of view, Kelantan river basin is covered by a thickness sequence of Quaternary deposits as revealed from information on geoelectric and well drilling in the area. In the coast, the thickness can reach up to 200 m. The quaternary alluvium lies beneath Mesozoic granites, but in some localities, metamorphic rocks are found as bedrock. An aquifer is formed because of the thickness in the northern part of Kelantan comprising of Pergau and some parts of Lebir and aquifer thickness according to location. An impervious clay layer that is soft, blue–grey clay, and shells detaches the aquifer from absorbing water which leads to more frequency of flooding. Figure 6 shows the geology map of the study area.

3.3.1 Elevation-Area Analysis

An elevation-area analysis of the catchments (Fig. 7) that was conducted clearly indicates that larger areas occupy higher elevation in Lebir and Nenggiri as compared to those

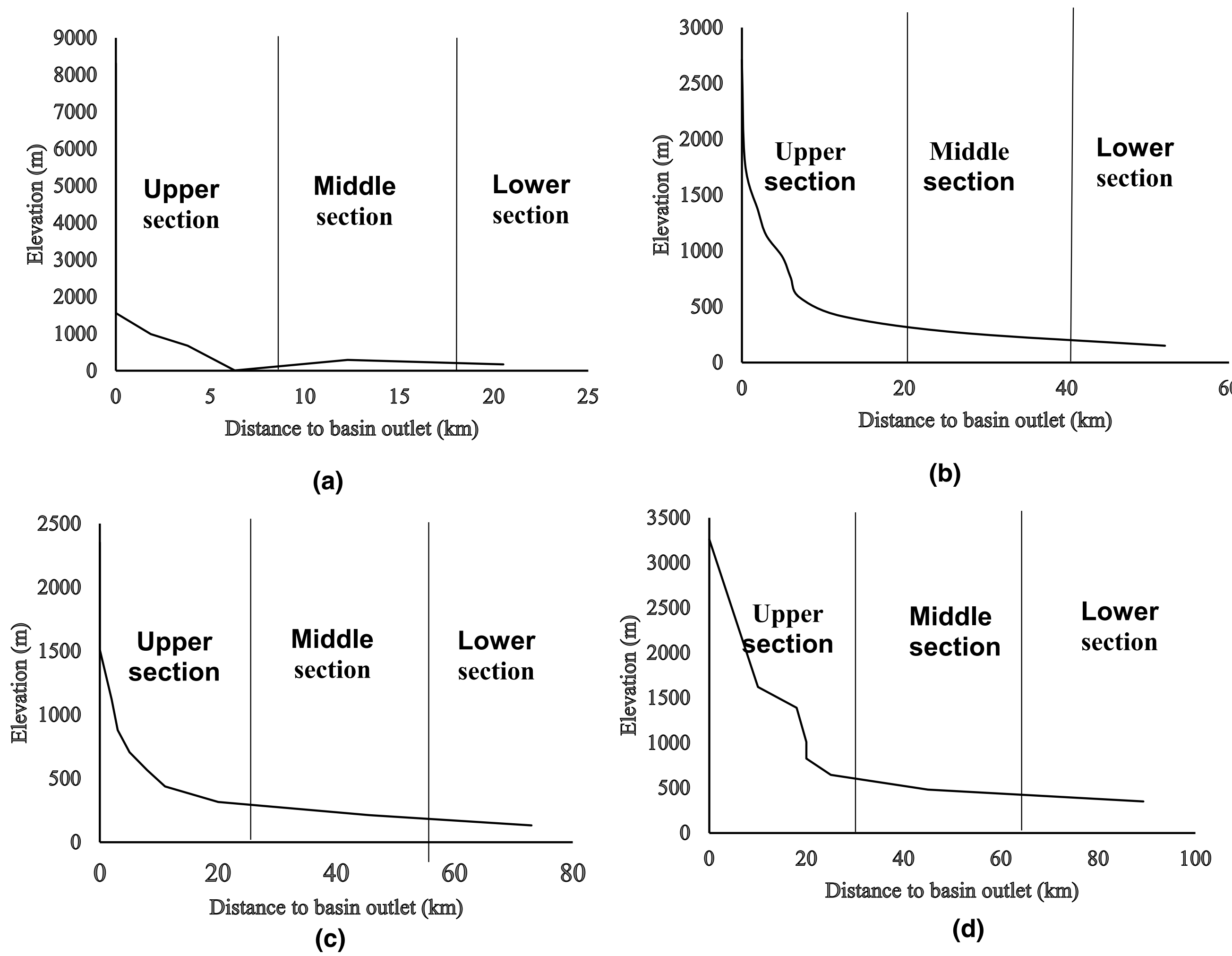


Fig. 8 Elevation distance to basin outlet analysis, **a** Galas, **b** Pergau, **c** Lebir, and **d** Nenggiri

in Galas and Pergau. This is also an indication that quicker runoff may be produced by these catchments that may lead to floods during heavy rain storm.

3.3.2 Elevation Distance to Basin Outlet Analysis

The results of the elevation distance to basin outlet analysis are shown in Fig. 8. In all the catchments, 80% of the high elevations are located in the upper section of the river. This affirms the catchments high runoff characteristics. Although these areas of high are mostly forested (with low CN values), the higher elevation favors high runoff of water in the watershed.

3.3.3 Slope Distance to Basin Outlet Analysis

Unlike the elevation distance to basin outlet analysis, the slope distance to river mouth analysis differs across the four catchments (Fig. 9). In Galas, 60% of the sloping patterns are found in the upper section of the river mouth, while the middle and lower sections occupy 20% each. In Pergau and Nenggiri, the upper and lower sections occupy 40% each, while the section takes 20%. In Lebir, 50% of the different sloping patterns are found in the upper and lower sections of the river mouth. In this case, the likely order of flooding will be Galas, Lebir, Pergau, and Nenggiri.

3.4 Hydrological Model Simulation and Flood Response Analysis

Hydrological modelling in this study was performed using the HEC–HMS (USACE–HEC 2010). The simulation was carried out using an average recurrent interval (ARI) of 10 years. Results of the simulation indicated that Lebir (2490 m^3/s) has the highest peak discharge, followed by Nenggiri (1314.1 m^3/s), Galas (836.50 m^3/s), and Pergau

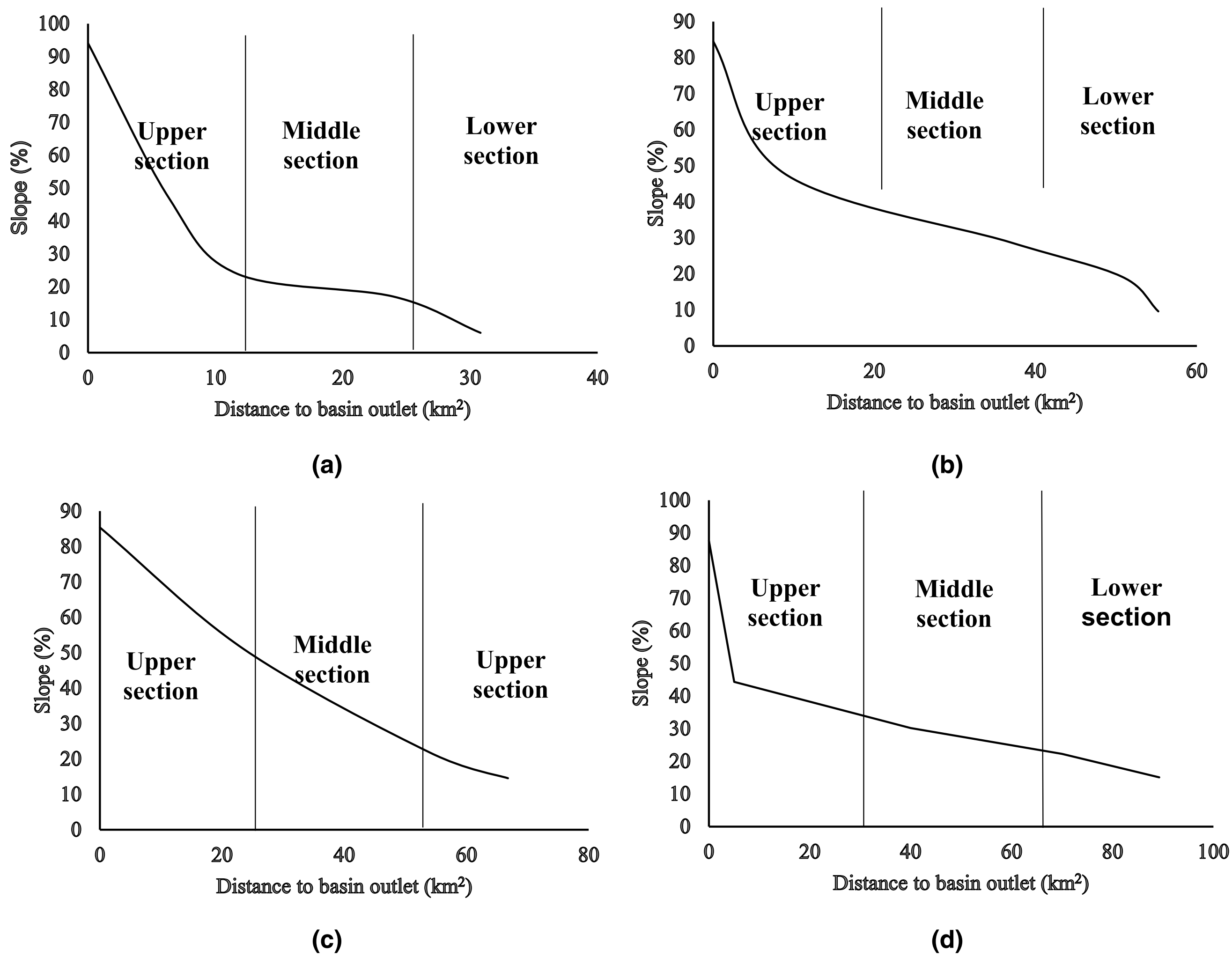


Fig. 9 Slope distance to basin outlet analysis, **a** Galas, **b** Pergau, **c** Lebir, and **d** Nenggiri

Table 10 Simulated peak discharge and flood volume of Kelantan river basin

Basin	Drainage area (km^2)	Peak discharge (m^3/s)	Flood volume (m^3/yr)	R_p
Galas	1650.81	836.50	39.73	0.40
Pergau	2322.52	115.20	6.81	0.05
Lebir	3350.05	2490.00	52.93	0.75
Nenggiri	3958.75	1314.10	14.90	0.63

(115.20 m^3/s), as presented in Table 10. Although Galas appears to be the catchment with higher values in most of the morphological features, it was found to be third in terms of total peak discharge. This may be mainly due to its size compared to that of other catchments, even though it recorded the highest elevation among all the catchments. However, in terms of annual runoff statistics (Table 10), Galas ranked second to Lebir with an estimated annual runoff volume of 52.93 and 39.73 m^3/year. From the hydrological simulation, it can be inferred that Lebir and Galas will be more likely to be flooded compared to other catchments. The catchments in Kelantan river basin are relatively large compared to other natural watersheds. This gives them the tendency to be flooded compared to other smaller catchments, since size which is a important factor in controlling the amount of water reaching the outlet.

Table 10 presents the results of flood response analysis. R_p is an index use to indicate how watersheds control rainfall. The flood analysis ranked the catchments similar to the hydrological model analysis. This ranking shows and is used to show which watershed have the greatest source of potential to flood waters. Although there is uncertainty as to whether these waters are responsible or increase the flood volume, this is dependent on many other factors that include land use, soil type, geology, and geomorphology of the basin.

Results of the hydrological model are somewhat in conformity with those of morphometric analysis earlier discussed.

Even though there is no clear trend, in all the morphological features, that favors one or more of the catchments but rather only a few features favored different catchments. Galas, which appears to be dominant in some features, was also not favored by important features such as D_d, H, and N (a product of D_d and H), and Pergau appears to be dominant in these features. This may be due to the reason earlier stated that the size of Galas catchment as compared to others influenced its L_u for the drainage density computation.

4 Conclusions

A combined study of morphometric analyses with runoff predictions from HEC–HMS model was carried out to quantify catchments based on their contributions to flooding in the Kelantan river basin. From the results, it was found that geomorphological studies are essential for understanding the rainfall–runoff response of a watershed as well as for prediction of flood peaks in conjunction with hydrological models. The order of flooding following a rainstorm in the major catchments of the watershed was found to be Lebir < Nenggiri < Galas < Pergau. In view of this, the alternate hypothesis, which states that morphometric features in the study watershed influence runoff, was affirmed. The results of these studies are vital in water resources planning and flood control management. The morphometric characterization of the watershed using GIS with the integrated results from the hydrological model will curtail the loss of lives and properties in areas identified to be flood prone. Conversely, there is a need to carry out this type of study at the sub-basin level in each of the four catchments in Kelantan River basin. This will provide an opportunity for establishing a better understanding of the basin geomorphology and hydrological response as well as help in developing a simple model that will relate geomorphology with the hydrology to predict flood peaks and water discharge.

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