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Rainfall-Runoff Response of A Suburban Area

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Abstract: Batu Pahat experiences flash flood whenever intense rainfall coincides with high tide. Another factor causing flash flood in Batu Pahat is due to its flat and low-lying geographical features. Two-fold goals of this study are to analyse frequency of rainfall events for SMK Munshi Sulaiman station; and to estimate runoff generated by severe rainfall events in study area. Observed daily rainfall depth record from year 2010 to 2021 was obtained from the Department of Irrigation and Drainage (DID) Malaysia. Rainfall frequency within the 11-year period is examined using empirical equation. Most daily rainfall events were found to have frequency of 1-year return period. Three events were found to have return period of up to 2-year ARI, with maximum rainfall depth of 110.67 mm. Rainfall-runoff of 5 most intense rainfall events in 2021 is simulated using HEC-HMS. One of the events, which occurred in June 2021 has frequency larger than 100-year return period while others have return period ranging from 1- to 5-year. Simulations produced by HEC-HMS for these events in January, April, May, June, and September 2021 have resulted in peak flow of 6.7 m^3/s, 26.8 m^3/s, 24.7 m^3/s, 39.9 m^3/s and 39.9 m^3/s, respectively. Based on frequency analysis, rainfall-runoff simulations and field observations, it is concluded that floods are highly possible due to high intensity rainfall as well as lowland topographical features of study area. Therefore, flood mitigations measures need to be carried out to improve drainage system for the suburban area.

Keywords: Rainfall-runoff response, floods, HEC-HMS, peak flow estimation, rainfall frequency, suburban

1. Introduction

Malaysia located within Southeast Asia region experiences humid and dry weather annually and is influenced by monsoon wind [1]. Climate of West Malaysia is impacted directly by the Northeast (normally from November until March) and Southwest monsoons (from May until September) winds, while East Malaysia is influenced by marine weather [2], [3]. Due to presence of monsoons, Malaysia is often subjected to high intensity rain, which normally leads to monsoon floods [3].

Flood is an overflow of large body of water over areas not usually inundated [4]. Floods happened in Malaysia due to unavoidable circumstances of weather climates [5], [6], geographical profile [1], [7] and seasonal monsoon [18]. When catchment area is unable to accommodate excessive rainfall, overflow will occur. Floods also may occur due to topographic features of the region coupled with frequency of occurrence of high intense rain events [1]. 'Once in 100-year' floods that resulted from torrential rain in many states of Peninsular Malaysia expose the reality of extreme weather patterns caused by climate change [1], [5], [6]. Meanwhile, flash flood typically occurred in urban area or area with rapid development. Urban flash flood normally starts within the first 6 hours, and often within 3 hours of heavy rainfall; or generally occur less than 6 hours [17] or most often due to extremely heavy rainfalls that may occur within minutes or a

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few hours; or other causes such as mudslides or debris flow [8], [17]. Malaysia typically is hit by monsoonal floods and flash floods.

Batu Pahat is a suburban area which is rapidly developing, with mushrooming new residential and industrial areas. Typically, a developing area is susceptible to floods due to insufficiency of drainage and high probability of extreme rainfall [7]. In addition, the lowland geographical feature of Batu Pahat also contributed to risks of flash floods. Prolonged heavy rainfall during north-east monsoon also causes widespread flooding leading to both agricultural and property losses. According to Department of Irrigation and Drainage Malaysia [9], lower and middle reaches of Batu Pahat river basin experiences tidal intrusion during high tides, which exacerbates floodings in inner land when coincide with heavy rainfall.

Hydrological and meteorological data such as rate of flow and intensity of rainfall are typically required in design of flood mitigation structures [10]. Magnitude and frequency of rainfall can be determined through flood-frequency analysis, based on annual maximum instantaneous peak discharge [2], [11]. In order to obtain catchment response under rainfall events, return period analysis can be carried out to identify characteristics of each rainfall event [12]. Hydrological modelling is also used as a tool to predict hydrological responses of catchment due to rainfall events [13]. Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) is one of the popular watershed models for rainfall-runoff process simulation [2], [13], [14]. Lumbroso & Gaume [15] in their study highlighted several indirect methods for extreme flash flood estimation such as Manning equation, comparing estimated discharges with estimated rainfall intensities; measuring relationship between peak flood flow discharge and its catchment area; estimates travel times and its mean velocities; use of simple rainfall-runoff and routing models; use of pictures and videos of flood events; and estimation of mean Froude number. Therefore, this paper investigated characteristics of rainfall events and carries out peak flow simulations for Batu Pahat, using HEC-HMS to understand its hydrological responses.

2. Study Area and Methods

Area of study is approximately 2.72 km^2 of SMK Munshi Sulaiman located along Kluang road. Kluang road is the main road within Batu Pahat. Fig. 1 shows location of Kluang road sub-catchment captured on Google Earth Pro map. Red circle shows an area which is susceptible to flash floods (see Fig. 1 and Fig. 2).

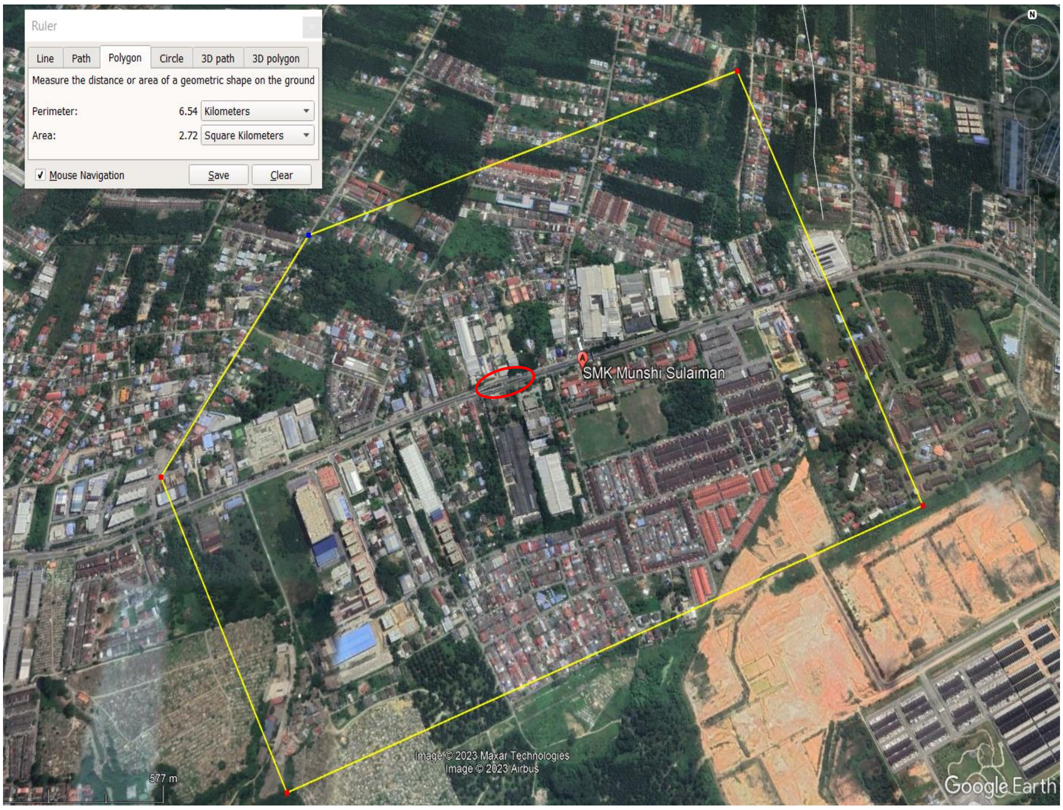


Fig. 1 - Location of flash flood-prone area of SMK Munshi Sulaiman with its sub-catchment area

Eleven years of daily rainfall depth (year 2010 to 2021) observed at SMK Munshi Sulaiman rainfall station (0340251RF) are used in the study. Fig. 2 shows topography of study area with its 3-dimensional elevation. Meanwhile, Fig. 3 shows the longitudinal cross section and latitudinal cross section of road along SMK Munshi Sulaiman, which is often subjected to flash flood. Frequent flash floods of the area may also be attributed to its geographical landform.

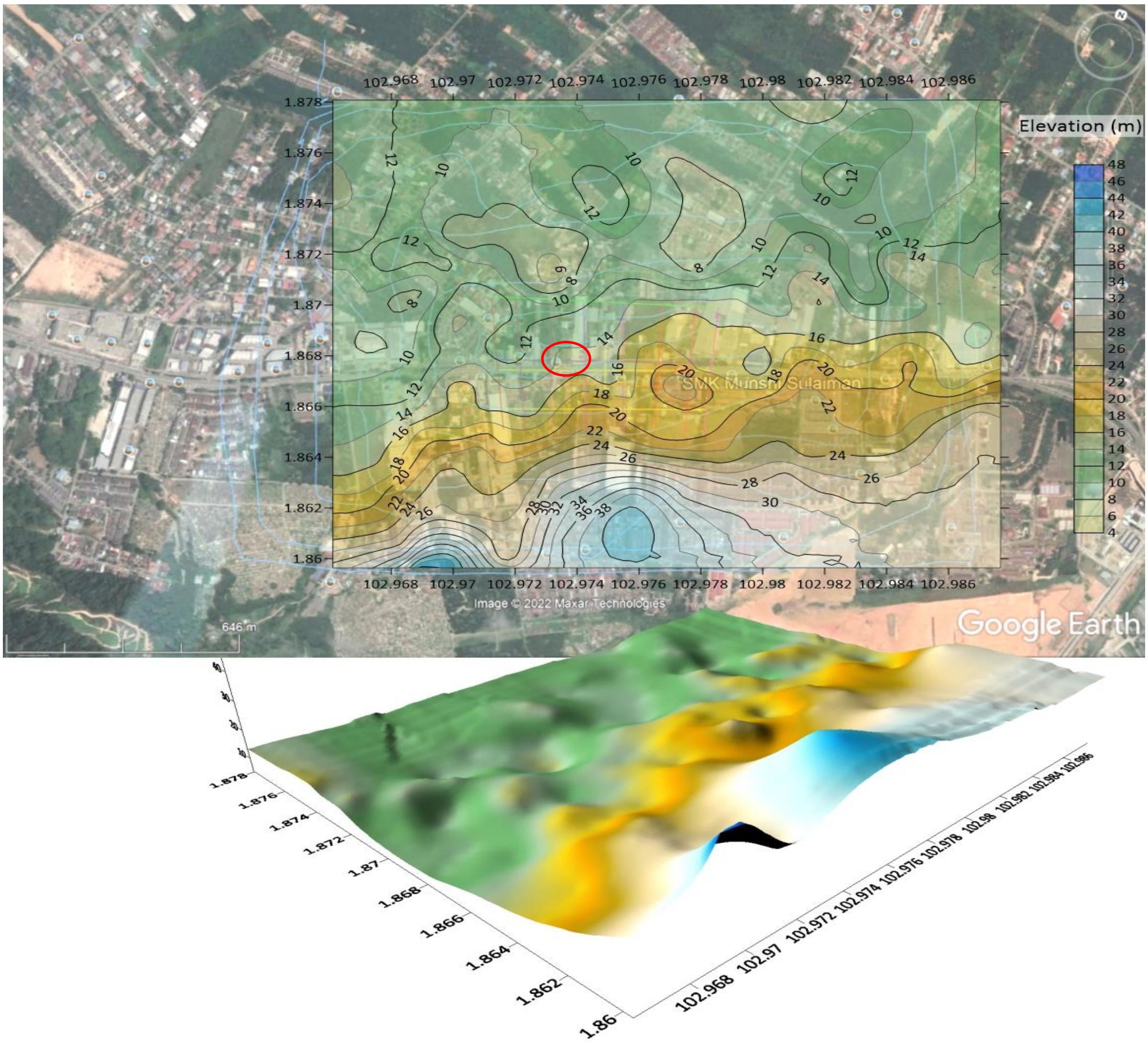
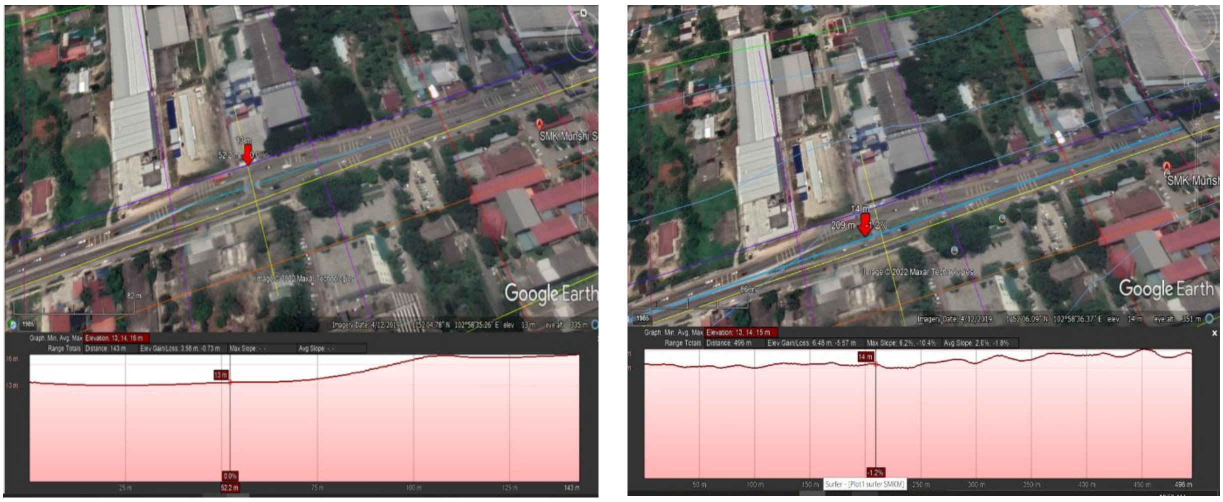


Fig. 2 - Topography of SMK Munshi sub-catchment area with its 3D surface elevation



(a) (b)

Fig. 3 - Cross section of flash flood-prone area of SMK Munshi (a) longitude of 102.977°, and; (b) latitude of 1.8675°

2.1 Intensity of Rainfall

Daily rainfall record of study area (see Fig. 4) is analysed to determine its return period. Intensity-based return period is based on the empirical intensity-duration-frequency formulation (Eq. (1)) of Urban Stormwater Management Manual for Malaysia [16]. Fitting constants of $\lambda = 64.099$, $\kappa = 0.174$, $\theta = 0.201$, and $\eta = 0.826$ at Setor JPS Batu Pahat Station (ID 1829002) have been utilized.

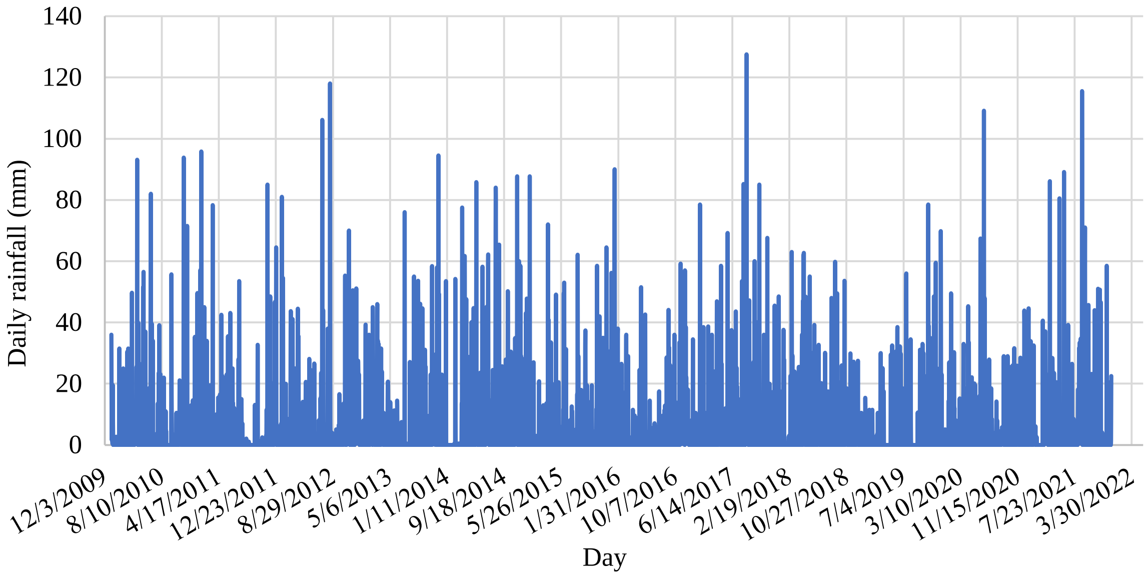


Fig. 4 - Daily rainfall observed at SMK Munshi Sulaiman station from 2009 to 2021

$$i = \frac{\lambda T^{\kappa}}{(\delta + \theta)^{\eta}} \tag{1}$$

where, i = average rainfall intensity (mm/hr), T = return period (year), d = duration of rainfall (hr), and λ, κ, θ and η = fitting constants.

2.2 HEC-HMS Simulations

In simulations of rainfall-runoff using HEC-HMS Version 4.3, the study area is assumed to be without canopy, and without dry-weather surface and no base flows. In the runoff computation, the method used to estimate loss and flow transformation are SCS curve and SCS unit hydrograph, respectively.

Rainfall depth of five most intense events occurred in 2021 at SMK Munshi Sulaiman, Batu Pahat were obtained from the DID real-time online monitoring platform at https://publicinfobanjir.water.gov.my. They are events on 01/01/2021, 05/04/2021, 18/05/2021, 07/06/2021 and 30/09/2021 with total rainfall of 122 mm, 97 mm, 81 mm, 93 mm and 110 mm, respectively. 5-minute interval rainfall depth records were used in HEC-HMS simulation. These rainfall data were then used to estimate the direct flow.

3. Results and Discussion

Fig. 5 compares daily rainfall events (denoted by triangles) against Batu Pahat depth-duration-frequency (DDF) curves [16]. Most of the 24-hour rainfalls observed between 2010 and 2021 fall within depths of less than 1-year return period. Only two rainfalls events have return periods of more than 1-year with total rainfall of 115.5 mm and 118.0 mm on 24/08/2021 and 16/08/2021, respectively. One rainfall event is observed to have depth greater than 2-year return period, i.e. with total rainfall depth of 127.5 mm on 15/08/2017.

3.1 Frequency of Rainfall

Based on Eq. (1), the IDF relationship for study area is established. Five solid circles in Fig. 5 represent the five 2021 rainfall events used in runoff simulation. Highest total daily rainfall depth is 110.67 mm. Rainfall event on 07/06/2021 with total rainfall of 93 mm has the highest rainfall intensity, i.e. 1116.5 mm/hr with rainfall frequency greater than 100-year average recurrence interval (ARI). Another rainfall event on 05/04/2021with 97 mm depth, has lower rainfall intensity at 29.4 mm/hr of 5-year ARI. Remaining three rainfall events have return period varying between 1- to

5-year return period. Return period of any event is crucial as flash flood occurrence can be predicted based on establish threshold.

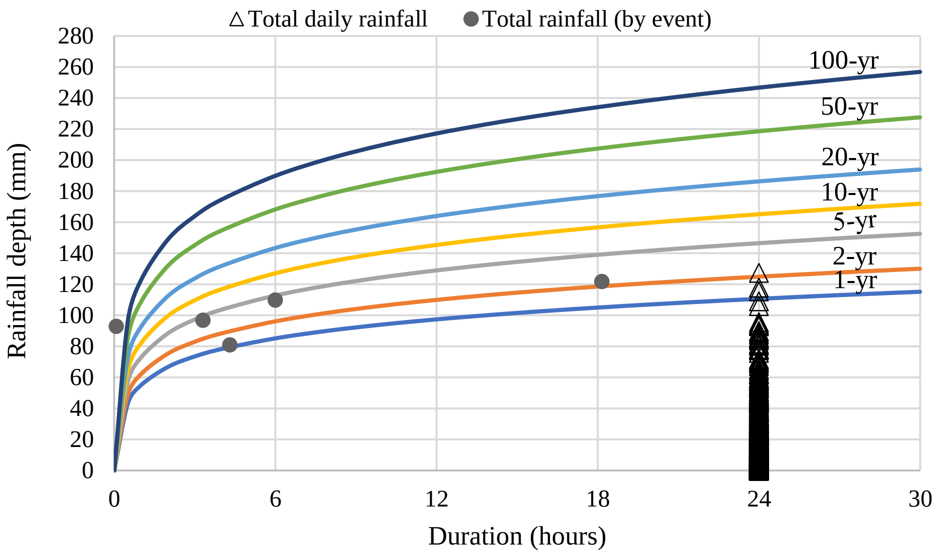
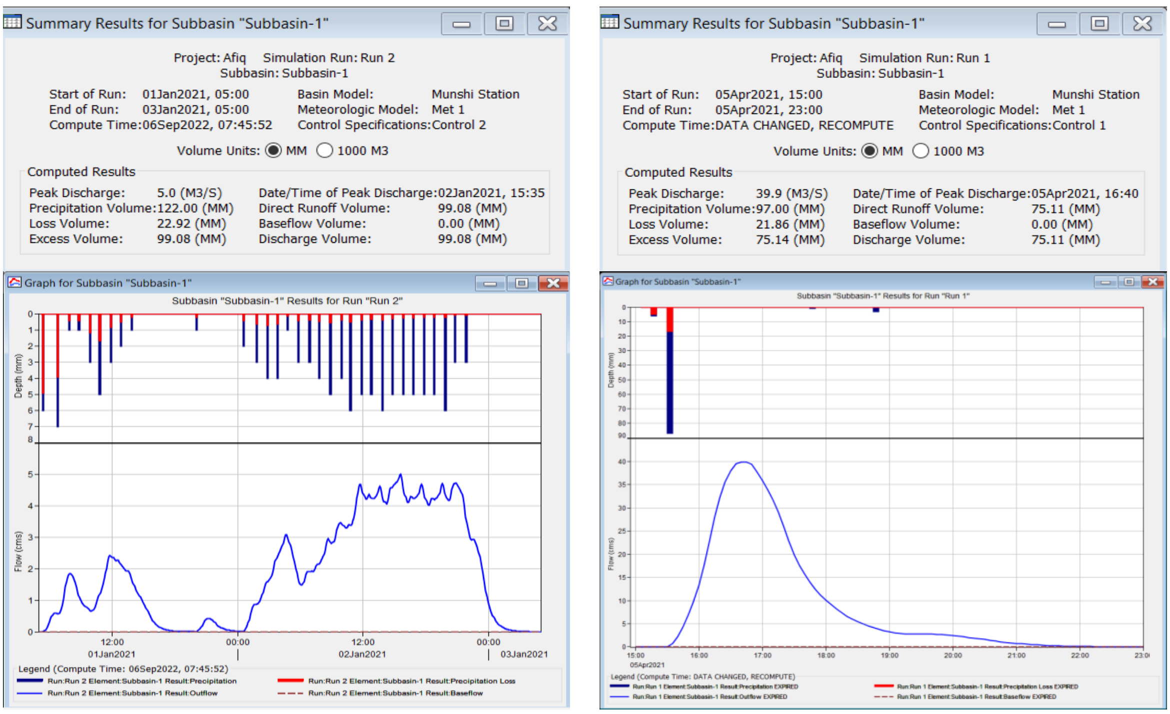


Fig. 5 - Five rainfall events observed in 2021 and total daily rainfall of 2010-2021 plotted on Batu Pahat depth-duration-frequency curves

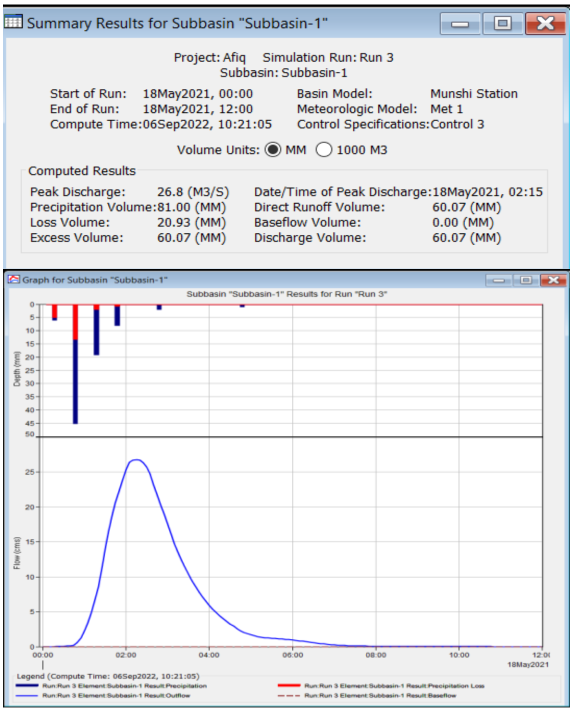
3.2 Peak flow Estimation Using HEC-HMS Simulation

Fig. 6 shows rainfall-runoff simulation of the five rainfall events on five days specifically at 01/01/2021, 05/04/2021, 18/05/2021, 07/06/2021, and 30/09/2021, having total rainfall depth of 122 mm, 97 mm, 81 mm, 93 mm, and 110 mm, respectively. Rainfall event on 01/01/2021 with duration of 18 hours 9 minutes has the lowest peak flow of 6.7 m^3/s. It shows that rainfall event with low intensity and long duration has low probability to cause flash flood.

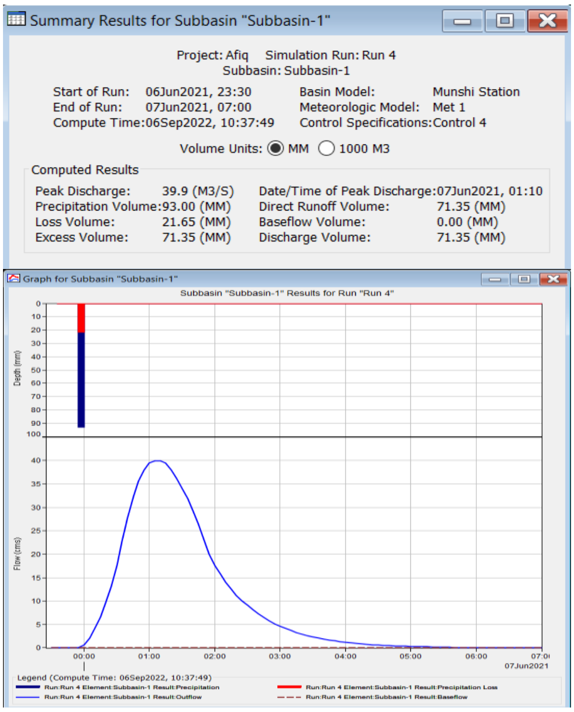
Other four events have rainfall intensity ranging between 18.3 mm/hr and 1116.5 mm/hr. Events on 18/05/2021 and 30/09/2021 have almost the same intensity, i.e. 18.8 mm/hr and 18.3 mm/hr with peak discharges of 26.8 m^3/s and 24.7 m^3/s, respectively. These events, however, have different frequencies where event in May has return period more than 1-year while event in September has frequency of 5-year ARI.



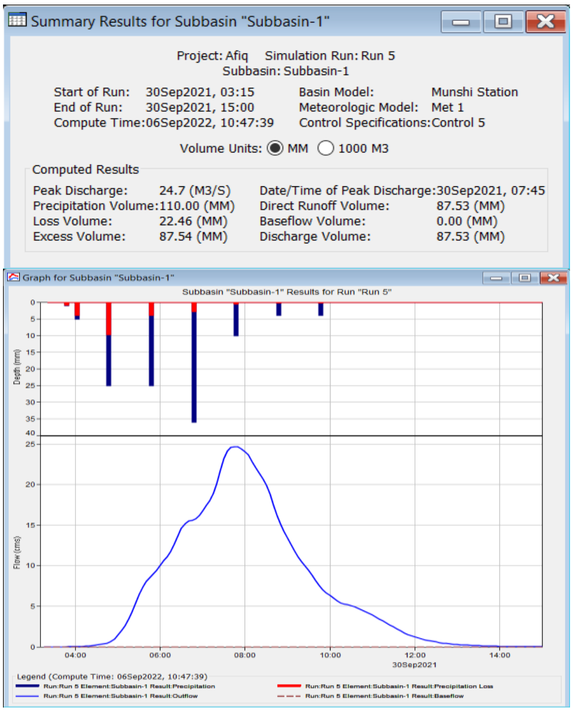
(a) (b)



(c)



(d)



(e)

Fig. 6 - Rainfall-runoff simulation for events of (a) 01/01/2021; (b) 05/04/2021; (c) 18/05/2021; (d) 07/06/2021, and; (e) 30/09/2021

Event on 05/04/2021 has total rainfall depth of 97 mm with intensity of 29.4 mm/hr and peak discharge of 39.9 m^3/s. Peak rainfall of 87 mm is observed at 15:35 hour, followed by peak discharge after 1 hour 5 minutes at 16:40 hour. The runoff continues for another 6 hours until 22:50 hour. Although event on 07/06/2021 has an extreme intensity of 1116.5 mm/hr, it exhibits similar hydrograph characteristics and same peak discharge as 05/04/2021 event. The June rainfall event has peak discharge of 39.9 m^3/s, with lag time to peak of almost 1 hour from peak rainfall; and the runoff stopped after 5 hours 45 minutes.

4. Conclusions

Based on the rainfall frequencies, rainfall-runoff simulations, peak flow estimation and field observations, flash flood occurrences at the SMK Munshi Sulaiman station, Kluang road, Batu Pahat is highly attributed to lowland topography as well as intense rainfall. Frequencies of rainfall events between 2010 and 2021 observed in study area are generally found to have return period between 2- and 5-year. Although in June 2021, a rainfall event was found to have magnitude of rainfall with more than 100-year return period. Compared to typical daily rainfall depth, the event has extreme intensity of 1116.5 mm/hr, due to 93 mm rainfall within duration of 5 minutes. Based on the 11-year rainfall record, most events can be categorized as having less than 1-year return period.

HEC-HMS is used to simulate rainfall-runoff response within the 2.72 km^2 study area. Two rainfall events having almost the same total depths in 2021 were found to have much different rainfall frequencies, i.e. 5-year and 100-year ARI, although they produced the same peak flow of 39.9 m^3/s. In summary, peak flows of more than 24.7 m^3/s in current drainage system of study area would pose risk of flash flood occurrence.

Based on findings of this study, currently used flood mitigation method needs to be further improved for SMK Munshi Sulaiman station, Kluang road. More surface runoff storage facilities are necessary at the upper part of the catchment area.

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