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The Effects of Rainfall Event and Land Use Characteristics on River Basin Hydrological Response: A Case of Sg. Kayu Ara, Malaysia

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ABSTRACT

As a crucial demand in urban areas, flood risk management has been considered by researchers and decision makers around the world. In this case, hydrological modelling that simulates rainfall-runoff process plays a significant role. This paper quantified the roles of three main parameters in river basin hydrological response, namely, rainfall event duration, rainfall event ARI (magnitude) and land-use development condition. The case study area of this research was Sungai Kayu Ara basin which is located in the western part of Kuala Lumpur, Malaysia. A total of twenty seven scenario were defined for this research, including three different rainfall event durations (60, 120 and 360 minutes), three different ARIs (20, 50 and 100 years) and in three different land-use conditions (existing, intermediate and ultimate). The results of this research indicate that rainfall event duration, rainfall event ARI (magnitude) and land-use development condition have considerable effects of the surface runoff hydrographs in terms of peak discharge and volume.

Keywords: Hydrological modelling, rainfall duration, rainfall ARI, land-use development, Sungai Kayu Ara

INTRODUCTION

Water is a basic requirement for sustaining life and development of a society. Nonetheless, proper management, protection and development of water resources are challenges imposed by population growth, increasing pressure on water and land resources by competing usage, and degradation of scarce water resources in many parts of the world.

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River flood is defined as a high flow that exceeds or over-tops the capacity, either the natural or the artificial banks of a stream (Hoyt & Langbein, 1958; Walesh, 1989; Knight & Shiono, 1996; Omen *et al*., 1997; Smith & Ward, 1998). Floods occur due to excessive rain on land, streams overflowing channels or unusually high tides or waves in coastal areas. Some of the most important factors that determine the features of floods are rainfall event characteristics, depth of the flood, velocity of the flow, and duration of the rainfall event (Smith, 1996). Most floods are caused by intense precipitation, in combination with other factors, such as snow melt, inadequate drainage, water-saturated ground or unusually high tides or waves. Floods are the most damaging phenomena that affect both the social and economic aspects of the population (Smith & Ward, 1998).

There is a relationship between urbanization and hydrological characteristics, such as decrease of infiltration, increase of overland flow, increase in frequency and height of flood peak, increase in range of discharge (variability) and decrease lag time. The dangers of floodwaters are associated with a number of different characteristics of the floods, such as depth of water, duration, velocity, sediment load, as well as rate of rise and frequency of occurrence (Kingma, 2002).

In most cases, floods are additionally influenced by human factors. Although these influences are very diverse, they generally tend to aggravate flood hazards by accentuating river flood peaks. Thus, river flood hazards in built environments have to be seen as the consequence of the natural and man-made factors. The factors contributing to river floods can be categorized into three classes, namely; meteorological factors, hydrological factors and human factors, as shown in Table 1.

Hydrological models are regarded as powerful tools for predicting river basin response to rainfall events and assessment of the impacts of parameters such as land-use cover change on river basin hydrology (Whitehead & Robinson, 1993).

Hydrological modelling is a powerful technique of hydrologic system investigation for both the research hydrologists and practicing water resources engineers who are involved in the planning and development of integrated approach for management of water resources. In the recent years, hydrological processes in the river basins have increasingly been studied in order to quantify the possible impacts of changes in land-use, land cover or soil surface conditions and urbanization on river basin hydrological processes, water quality, as well as extreme hydrological events, such as floods and droughts. The objective of the present study was to illustrate the effects of rainfalls and land-use characteristics on hydrological response of a rural basin. To this aim, three factors were considered including rainfall duration, rainfall ARI and percentage of imperviousness. Hydrological response of the river basin to the rainfall and land-use characteristics were evaluated quantitatively based on runoff peak and volume at the outlet of the river basin.

CASE STUDY

Sungai Kayu Ara basin is the case study in this research, and it is located in Kuala Lumpur, Malaysia. Sungai Kayu Ara basin covers an area of 23.22 km^2. The main river of this river basin originates from the reserved highland area of Penchala and Segambut. Sungai Kayu Ara

Table 1: Factors contributing to river floods

Meteorological factors	Hydrological factors	Human factors
● Rainfall ● Cyclonic storms ● Small-scale storms ● Temperature ● Snowfall and snowmelt	● Soil moisture level ● Groundwater level prior to storm ● Natural surface infiltration rate ● Presence of impervious cover ● Channel cross-sectional shape and roughness ● Presence or absence of over bank flow, channel network ● Synchronization of run-offs from various parts of watershed ● High tide impeding drainage	● Surface sealing due to urbanization, deforestation) increase run-off and may be sedimentation ● Occupation of the flood plain obstructing flows ● Inefficiency or non-maintenance of infrastructure ● Too efficient drainage of upstream areas increases flood peaks ● Climate change affects magnitude and frequency of precipitations and floods ● Urban microclimate may enforce precipitation events

basin is geographically surrounded within N 3°6′ to N 3°11′ and E 101°35′ to E 101°39′. Fig.1 illustrates the boundaries of Sungai Kayu Ara basin in the western Kuala Lumpur, Malaysia.

The Sungai Kayu Ara basin is a suitable study river basin for this particular research because of the following reasons: firstly, a large part of this particular river basin area is a well developed urban area with different land uses and also high population density (parts of the Kuala Lumpur rural area) that shows the importance of this river basin; secondly, the availability of high density rainfall station network (10 rainfall stations and one water level station), and according to the area of Sungai Kayu Ara basin (23.22 km^2), the rainfall station network density is equivalent to 2.3 km^2/station, which justifies the minimum requirement of one station per 25 km^2 in case of precipitation over small mountainous river basins (Linsley *et al*., 1992); thirdly, the availability of stage discharge curve which has been developed by the DID, Malaysia, and finally, the availability of river basin digital topographic information which can be used in Geography Information System (GIS). This data have been produced by the Department of Survey and Mapping, Malaysia. Table 2 shows the area and the percentage of the coverage types of land-use (Leong, 2007).

MATERIALS AND METHODS

In this research, HEC-HMS3.1.0 was used as the hydrological model. HEC-HMS3.1.0 is a hydrological model developed by the Hydrologic Engineering Centre of the United States Army Corps of Engineers. In fact, HEC-HMS is a well-known hydrological computer model, which is considered as one of the most utilized hydrological models in water cycle studies (Yawson *et al*., 2005; Cunderlik & Simonovic, 2005; Stehr *et al*., 2008; Ellouze *et al*., 2009). The programme simulates a rainfall-runoff response of a river basin system to a precipitation

Fig. 1: The location and base-map of Sungai Kayu Ara in Malaysia

Table 2: Area and Percentage of the Coverage Types of Land-use in Sungai Kayu Ara Basin

Types of land-use	Area (Km^2)	Coverage percentage (%)
Rural residential	1.60	6.90
Urban residential	11.61	50.00
Central business district	1.16	5.00
Cultivated land	3.25	14.00
Cleared land	1.70	7.30
Forest	0.39	1.70
Park and lawn	1.93	8.30
Shrub land	0.21	0.90
Miscellaneous	1.37	5.90
Total	23.22	100

input by representing the entire river basin as an interconnected system of hydrologic and hydraulic components, which include river basins, streams and reservoirs (HEC-HMS, 2006). Green-Ampt, Snyder unit hydrograph, recession and kinematic wave methods were selected and applied for the rainfall-runoff simulation in Sungai Kayu Ara basin. Some of the inputs were prepared and computed using HEC-GeoHMS, such as river basin sub-division, river network extraction, calculation of area, river basin perimeter, and slope of sub-river basin and river network (Fig. 2).

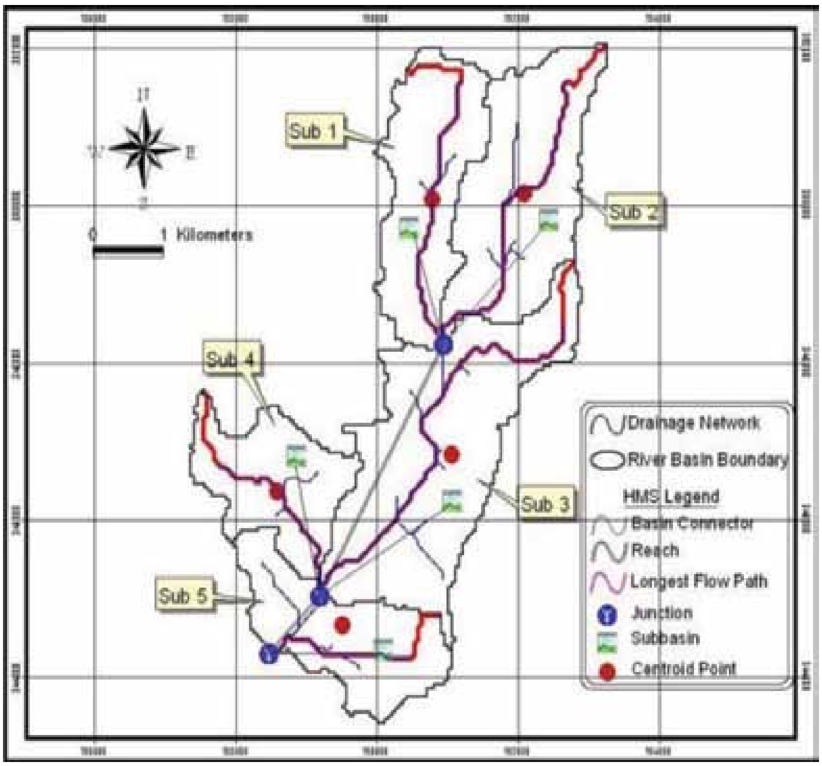


Fig.2: The characteristics of the Sungai Kayu Ara basin generated by HEC-GeoHMS

The identification of the hydrological model in the transformation of rainfall to runoff is related to river basin processes. Therefore, the most important data for hydrological modelling are recorded time series of rainfall and runoff. There were 10 rain gauges installed within the Sungai Kayu Ara river basin. These rain gauges are self-recording and the rainfall data were stored in the built-in data logger memory. Meanwhile, the amount of the recorded rainfall was based on the frequency of the series of tips (tipping budget rain gauges) generated by rainwater. Such information is useful to determine rainfall intensity, rainfall duration and daily total rainfall. The hydrological record was retrieved on site using SRAM (Static Random Access Memory) Card by the DID staff. Furthermore, all data were converted into the Time Dependent Data Processing System (TIDEDA®) in the DID hydrology unit. The software system was developed and supplied by the National Institute of Water and Atmosphere Research of New Zealand (NIWA) and version 1.9 is currently being used. The DID Hydrology Unit, at Jalan Ampang, Kuala Lumpur, was the main reference for extracting the required data in this research. The location for the rain gauges and the water level station at the Sungai Kayu Ara river basin is illustrated in Fig.3. In order to assess the data related to the runoff of the Sungai Kayu Ara river basin, the water level record from station No.3111404 (WL4 in Fig.3) located at Taman Mayang, Damansara was also downloaded from DID. These recorded water stage data were transferred from the water level station to the DID Hydrology Unit through a telemetry system. The stage-discharge data were provided by DID, which were developed using the record at the water level station.

The basic step for the development and application of a model is establishing of the credibility of the model which comprises of sensitivity analysis, calibration and validation processes. The results derived from the sensitivity analysis for the HEC-HMS in Sungai Kayu Ara basin revealed that imperviousness, initial discharge of recession method, peak flow coefficient, lag-time, hydraulic conductivity, moisture deficit and wetting front suction were the most effective on the runoff volume (with more than 5% changes). On the other hand, lag-time, imperviousness, peaking flow coefficient, hydraulic conductivity, moisture deficit, wetting front suction and initial discharge were more important parameters on the runoff peak discharge (with more than 5% change). These parameters must be taken into consideration and focused on during hydrological modelling.

Among the recorded rainfall and water level time series obtained from rainfall and water level stations, 18 rainfall events were selected for calibration and 18 rainfall events for validation process (Fig.3). By applying the 18 calibration rainfall events dataset, the best set of values for each parameter was identified to best represent the hydrologic model of the Sungai Kayu Ara basin. Meanwhile, the credibility of the hydrological model was evaluated using 18 validation rainfall event datasets. The result of the calibration process for one of the calibration events is illustrated in Fig.4.

The established hydrological model for Sungai Kayu Ara basin was simulated based on the rainfall design hyetograph for each ARI (20, 50 and 100 years) and different durations (60, 120 and 360 minutes) in the existing, intermediate and ultimate river basin land-use development

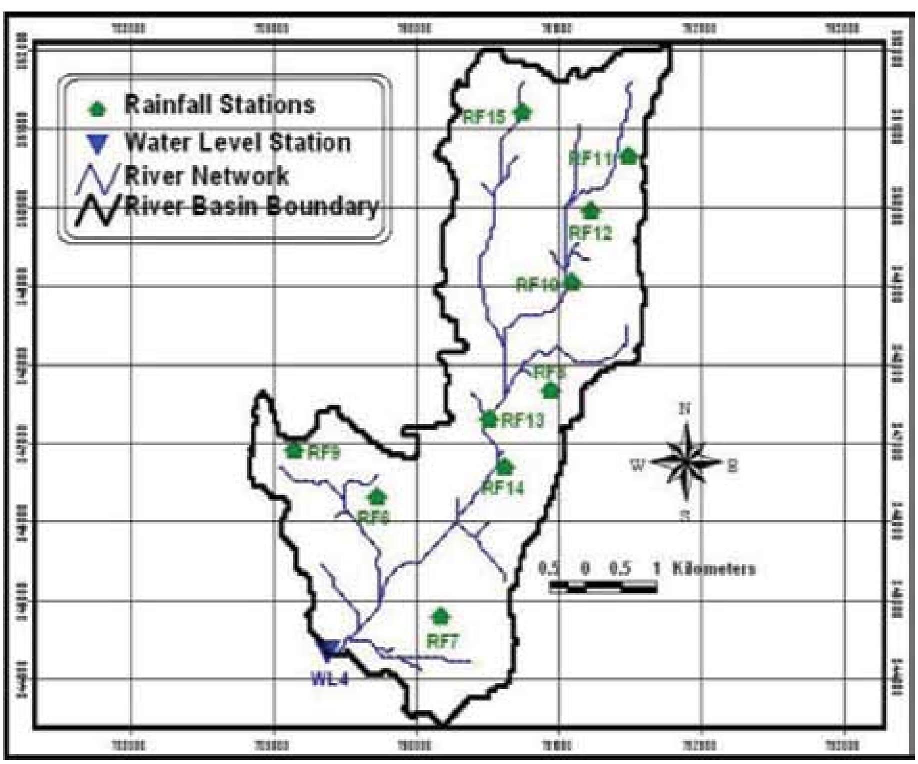


Fig.3: The location of the rainfall and water level stations at Sungai Kayu Ara basin

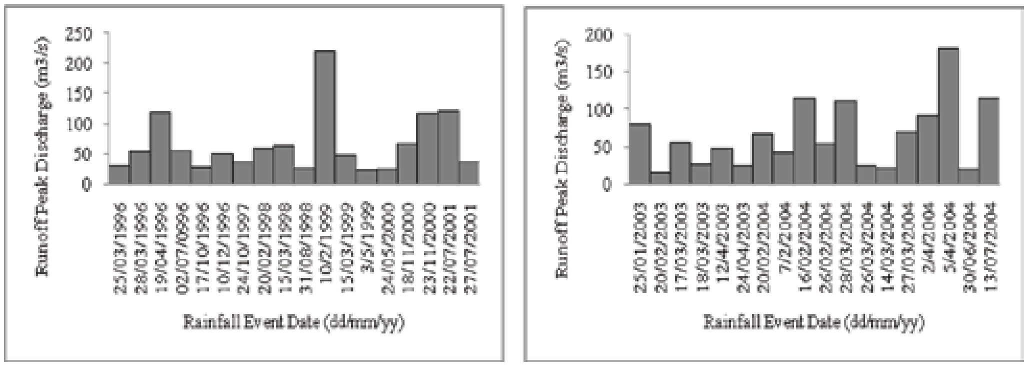


Fig.4: The selected rainfall events for the hydrologic model calibration and validation processes

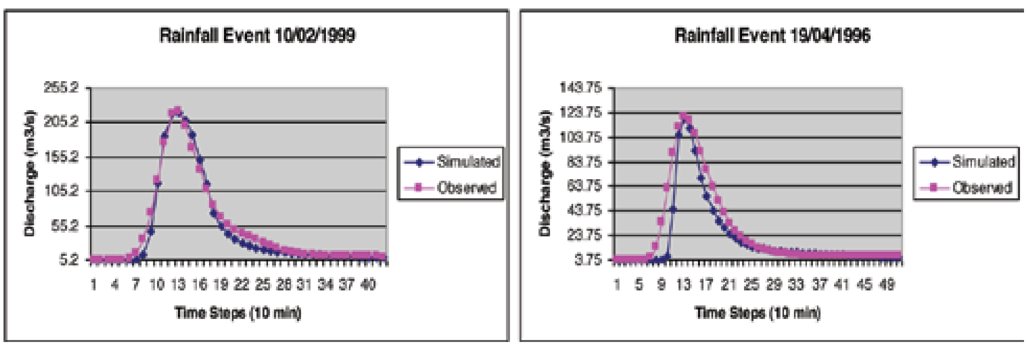


Fig.5: The calibration result for the rainfall event of 10/02/1999 and 19/04/1996

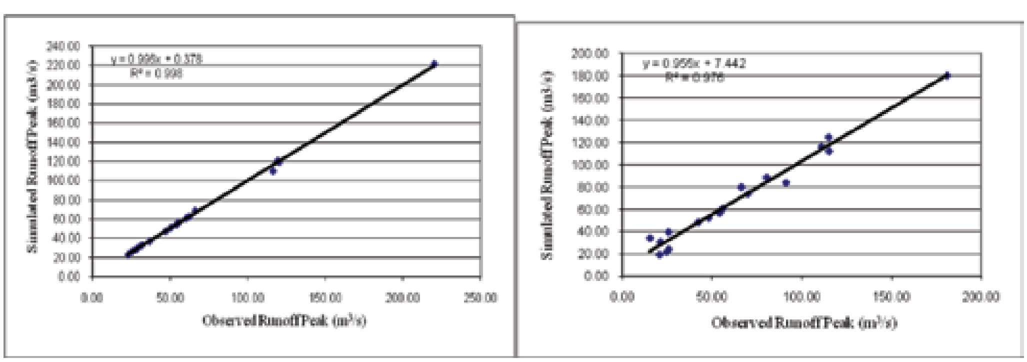


Fig.6: The correlation of the observed and simulated run-off peak discharge in the calibration and validation processes

conditions which were derived based on the storm water management manual (DID, 2000). A total of twenty seven direct run-off hydrographs were produced by the hydrological model. The effects of the different land-use development conditions and the rainfall event characteristics (ARI and duration) were assessed and investigated. Table 3 indicates the total defined study scenarios of this research.

Table 3: Scenarios of the hydrological modelling for Sungai Kayu Ara basin

Land-use development condition	20 years ARI	50 year ARI	100 year ARI
Existing	1 hr	1 hr	1 hr
	2 hr	2 hr	2 hr
	6 hr	6 hr	6 hr
Intermediate	1 hr	1 hr	1 hr
	2 hr	2 hr	2 hr
	6 hr	6 hr	6 hr
Ultimate	1 hr	1 hr	1 hr
	2 hr	2 hr	2 hr
	6 hr	6 hr	6 hr

This research focused on the three scenarios of river basin land-use development conditions, namely, existing, intermediate and ultimate. To this end, three types of the land-use coverage percentages were applied in the HEC-HMS hydrologic model. Table 4 shows the percentage of the imperviousness area in each sub-river basin for each development condition in Sungai Kayu Ara basin.

Finally, the hydrological simulation was applied for three scenarios development conditions (existing, intermediate and ultimate), and each development condition consisted of three different ARIs (20 years, 50 years and 100 years) with three event durations (60 minutes, 120 minutes and 360 minutes).

Table 4: The percentage of the impervious area in each sub-river basin

Development Condition	Imperviousness (%)		
	Existing	Intermediate	Ultimate
Sub-River Basin 1	25	50	90
Sub-River Basin 2	25	50	90
Sub-River Basin 3	65	80	90
Sub-River Basin 4	35	70	90
Sub-River Basin 5	65	80	90

RESULTS AND DISCUSSION

The hydrological models, such as HEC-HMS, simulate the hydrograph of the generated runoff caused by a rainfall event. Based on this definition of hydrological modelling, the main input for the hydrological model is rainfall event hyetograph. Beside rainfall event hyetograph, some values for various components parameters are required, as discussed in the previous section. To simulate the HEC-HMS for Sungai Kayu Ara basin, input design rainfall hyetograph is required for each scenario. The input hyetograph for each scenario, with a total of 36 rainfall hyetographs, was extracted according to the storm water management manual (DID, 2000). Table 5 shows the results of the HEC-HMS simulation for all 36 scenarios, it is clear that the runoff peak discharge and runoff volume were calculated for each scenario.

Table 5: Results of the HEC-HMS3.1.0 for the 36 scenarios

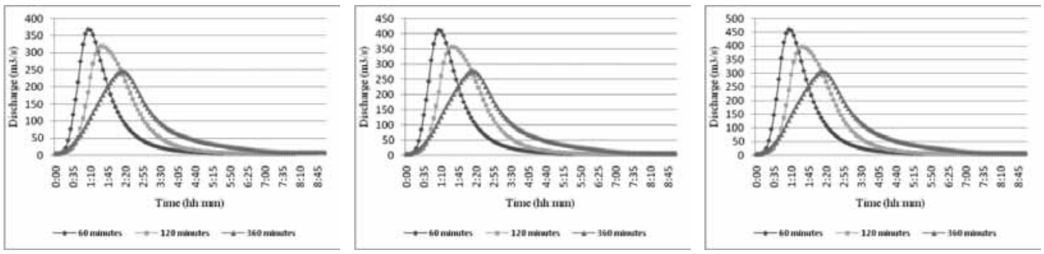
Development condition	Duration	ARI20year		ARI50year		ARI100year	
		Runoff peak (m^3/s)	Runoff volume ($1000m^3$)	Runoff peak (m^3/s)	Runoff volume ($1000m^3$)	Runoff peak (m^3/s)	Runoff volume ($1000m^3$)
Existing	1 hr	368.7	1856	413.1	2107	460	2354
	2 hr	319.9	2197	357.6	2480	397.6	2761
	6 hr	246.1	2426	277	2697	306.73	3052
Intermediate	1 hr	396.5	2088	441.2	2254	488.1	2486
	2 hr	347.3	2428	384.9	2696	425	2980
	6 hr	270.8	2856	301.5	3124	331.3	3472
Ultimate	1 hr	427.9	2164	472.6	2417	519.5	2683
	2 hr	378	2649	416	2938	456.1	3225
	6 hr	298.6	3280	325	3692	359	3960

ROLE OF RAINFALL EVENT DURATION

Duration is one of the most important characteristics of the rainfall event which can significantly affects on the generated runoff hydrograph. In order to investigate on the role and the importance of the rainfall event duration on the river basin hydrological response, three different rainfall event durations were defined, namely, 60 minutes, 120 minutes and 360 minutes. As depicted in Table 5, the increase in the rainfall events duration, i.e. from 60 minutes to 360 minutes in the same rainfall magnitude (ARI) and land-use development condition, reduces the runoff peak discharge and runoff volume.

For instance, the runoff peak discharge for 60 minutes rainfall event with 20 years ARI in the existing land-use development condition is $368.7m^3/s$, and this was $246.1m^3/s$ for 360 minutes' rainfall event. This shows that the increase of the rainfall event duration from 60 minutes to 360 minutes will to 33% reduction in runoff peak discharge in this case. On the other hand, the runoff volume for the above mentioned rainfall events were $1856000m^3$ and $2426000m^3$, respectively, indicating that the increase of the rainfall event, from 60 minutes to 360 minutes, will increase the runoff volume up to 30%. By considering to other values for the runoff peak discharge and the volume, it is obvious that the increase of the rainfall event duration will lead to a decrease in the runoff peak discharge and the increase of the runoff volume. Fig.7 illustrates the generated runoff hydrographs for different durations of the rainfall events (20, 50 and 100 years ARI) in the existing land-use development condition.

As shown in Fig.7, it appears that the rainfall event with shorter duration has a sharper shape compared with those with longer durations. In other words, shorter rainfall event reaches the peak discharge and comes down faster than those with longer rainfall event. As for the longer rainfall duration, the runoff hydrograph has a gentle slope in both rising and falling limbs of the runoff peak discharge. In term of the runoff volume, it was revealed that longer rainfall event contributed more amount of rainfall but it was distributed in a longer time period. Hence, the rainfall event with longer duration has lower peak discharge and higher runoff volume in comparison to those with shorter rainfall events. It also indicates that the rainfall event with



a. 20 years ARI b. 50 years ARI c. 100 years ARI

Fig.7: The runoff hydrographs for the rainfall events with 20, 50 and 100 years ARI in the existing land-use development condition with different durations

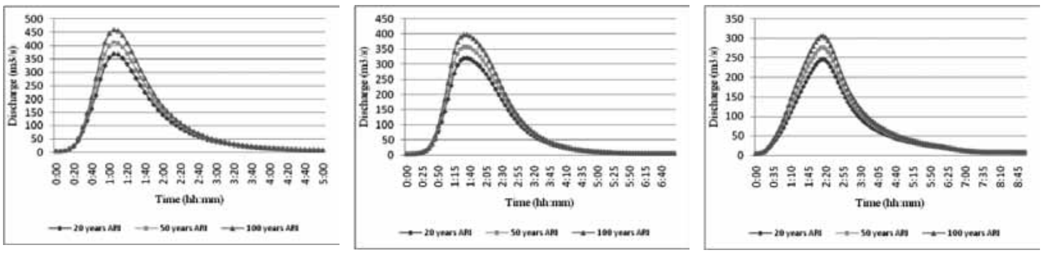
longer duration has less intensity in compare with rainfall event with shorter duration in similar ARI and land-use development condition.

Moreover, rainfall event duration has a considerable effect on the time to peak of the runoff hydrograph. For example, for the rainfall event with similar ARI in the existing land-use development condition with 60 minutes, 120 minutes and 360 minutes durations, the times to peak were found to be 1 hour and 5 minutes, 1 hour and thirty five minutes, and two hours and fifteen minutes, respectively. In other words, shorter rainfall event duration causes shorter time to peak, while longer duration leads to a longer time to peak (see Fig.7).

Role of the Rainfall Event ARI

The other rainfall event characteristic which was investigated in this research was the rainfall event ARI (magnitude). As depicted in Table 5, the rainfall event ARI apparently plays an important role in the river basin hydrological response. As an example, for a 60 minutes' rainfall event in existing land-use development condition for 20 years, the ARI peak discharge is 368.7m^3/s, whereas this value (ARI) is 460 m^3/s for 100 years. In other words, the increase in the rainfall event ARI from 20 to 100 years increases the runoff peak discharge up to 25%. In term of the runoff volume, the same trend can be observed. This is because the volume increases from 1856000m^3 to 2354000m^3 for the above mentioned rainfall events runoff when the rainfall event ARI which is equivalent to 26% increases. Fig.7 demonstrates the generated runoff hydrographs for the different rainfall events ARI with different durations of 60 minutes, 120 minutes and 360 minutes in the existing river basin land-use development condition.

Fig.7 illustrates the effects of the rainfall event ARI on the generated runoff hydrographs for the different rainfall durations in the existing river basin land-use development condition. It is important to note that this particular trend is the same for other land-use development conditions. In addition, Fig.7 also depicts that the rainfall ARI does not have any consequence on the time to peak of the rainfall hydrograph. To sum up, it has been proven that rainfall event ARI has a direct relation with runoff peak and volume. In other words, with the increase in the rainfall event ARI, the runoff peak discharge and volume will increase as well.

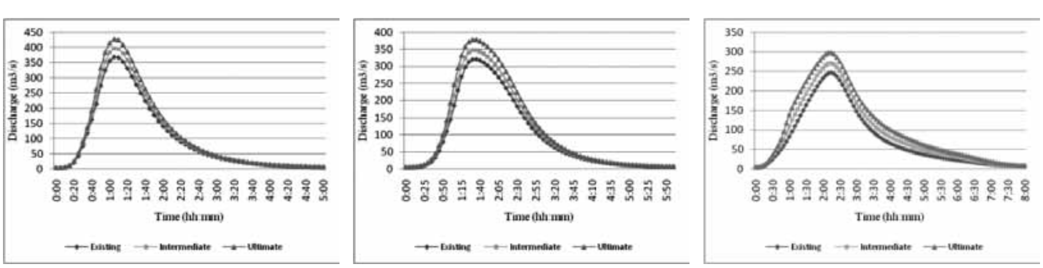


a. 60 minutes b. 120 minutes c. 360 minutes

Fig.8: The runoff hydrographs for different durations of 60 minutes, 120 minutes and 360 minutes in the existing land-use development condition with different ARIs

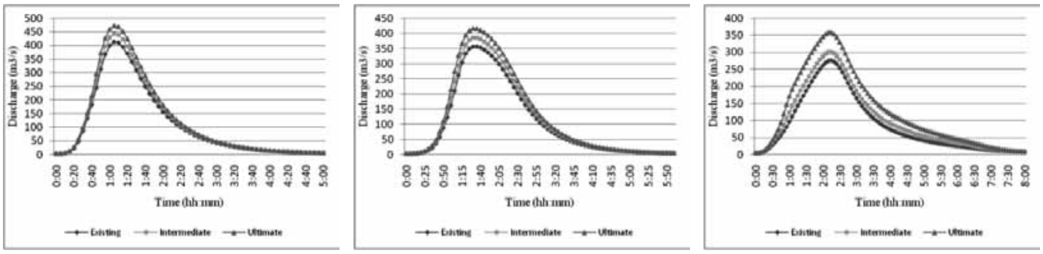
Role of River Basin Land-use Development Condition

In order to study on the responsibility of the river basin land-use development condition on the river basin hydrological response, three types of land-use scenarios were defined; the existing, intermediate and ultimate. These land-use scenarios were differentiated based on the percentages of imperviousness (Table 4). The results presented in Table 5 clarify that the river basin land-use development from the existing to the ultimate condition increases the runoff peak discharge and the runoff volume as well. As evidenced, the runoff peak discharge for the 60-minute duration rainfall event with 20 years ARI in the existing condition is 368.7m^3/s, while this value for the same rainfall event in the ultimate condition is higher, i.e. 427.9m^3/s, revealing a 16% of increase. Beside this, runoff volume is also influenced by the development changes as well as the runoff peak discharge as the runoff volumes for the above mentioned rainfall events are 1856000m^3 and 2164000m^3, respectively. In other words, in the case of Sungai Kayu Ara, the increase in development from the exiting to the ultimate condition will lead to 16% increase in the runoff volume. The reason relies on the increase of imperviousness percentage caused by the river basin land-use development. Increasing the imperviousness percentage of the river basin, the percentage of the generated surface runoff by a specific rainfall event is also increased. This also means that more developed river basin contributes to higher amount of runoff in terms of peak discharge and volume. Meanwhile, changes can be observed in the trend of the generated runoff hydrographs, as illustrated in Fig.8-10, which demonstrate the runoff hydrographs for all the twenty seven defined scenarios.



60 minutes b. 120 minutes c. 360 minutes

Fig.9: The runoff hydrographs for the rainfall events with 20 years ARI in different development conditions at Sungai Kayu Ara basin



a. 60 minutes b. 120 minutes c. 360 minutes

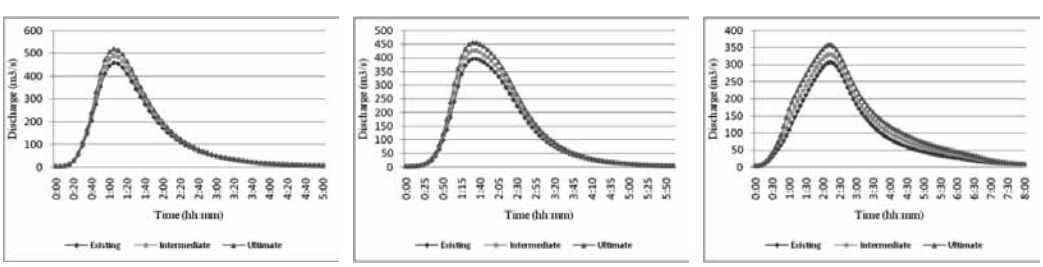
Fig.10: The runoff hydrographs for the rainfall events with 50 years ARI in different development conditions in Sungai Kayu Ara basin

As depicted in Fig.8-10, changes in land-use development apparently have obvious effects on the river basin hydrological response. In fact, land-use development has a direct relation with both the runoff peak discharge and volume. Hence, for the rainfall events with similar duration and ARI, the runoff peak discharge and volume are higher in the ultimate development condition as compared to the existing condition.

Time to peak is another runoff hydrograph characteristic which is considerable beside runoff peak and volume. Based on the information given in Table 5 and Fig.8-10, it can be approved that land-use development is not responsible for the time to peak changes for the rainfall events with similar duration and ARI. Hence, it must be noted that the quantitative results of the effects of land-use development in this research were investigated based on Sungai Kayu Ara basin or any river basin with similar land-use development condition.

The Multi-relationship between Rainfall Duration, ARI and Land-use Condition for Sungai Kayu Ara Basin

The results of this research have given a better understanding of the effects of the rainfall event characteristics and river basin land-use development on river basin hydrological response. According to these results, it is possible to investigate on a multi-relationship between rainfall duration, rainfall ARI, land-use development and runoff peak discharge and volume for Sungai Kayu Ara basin (Fig.11 and Fig.12).



a. 60 minutes b. 120 minutes c. 360 minutes

Fig.11: The runoff hydrographs for the rainfall events with 100 years ARI in different development condition at Sungai Kayu Ara basin

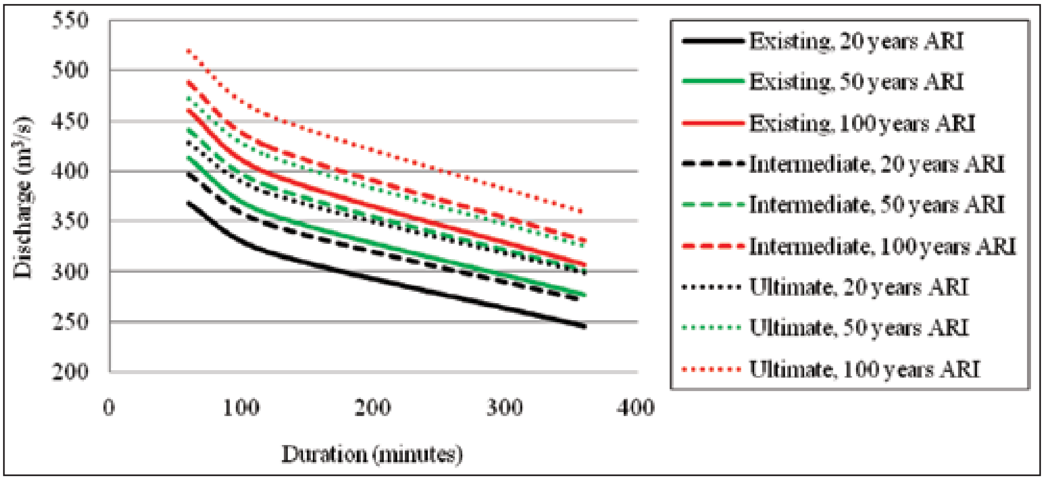


Fig.12: The relationships between rainfall duration, rainfall ARI, land-use development and runoff peak discharge for Sungai Kayu Ara basin

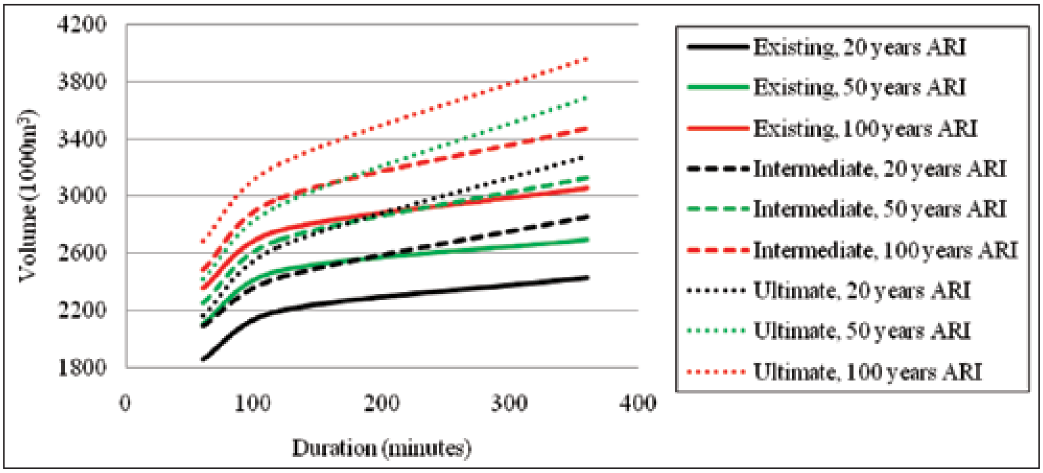


Fig.13: The relationships between rainfall duration, rainfall ARI, land-use development and runoff volume for Sungai Kayu Ara basin

As illustrated in Fig.11 and Fig.12, the results indicated in sub-sections 4.1, 4.2 and 4.3 are approved. Based on the graphs given in Fig.11 and Fig.12, the increase in the rainfall event duration, the runoff peak discharge also increases, but the runoff volume adversely decreases. For similar rainfall event duration, on the other hand, the increases of the rainfall event ARI and river basin land-use development increase the runoff peak discharge and volume. In fact, Fig.11 and Fig.12 can be counted as a local model for Sungai Kayu Ara basin. In other words, these figures are quantified forms of interactions between rainfall event durations, ARIs and river basin land-use development conditions.

CONCLUSIONS

This research has shown the capability of the HEC-GeoHMS which can be readily employed as a reliable and accurate tool for extraction of input geometric data for the HEC-HMS hydrological model. Beside this, it was found that with increased development (from the existing to the ultimate development condition), the runoff peak discharge and runoff volume also increased, and this can be attributed to the increase in the impervious area in the river basin. Furthermore, the effect of development condition in the river basin's response is more pronounced than the ARI. For example, a comparison made between the runoff peak discharges and the runoff volumes of 20 year ARI and 100 year ARI in the existing development condition shows 19% and 33% increases, respectively, whereas the increase of the development from the existing condition to the ultimate condition, gives an increase of 91% and 45%, respectively. These findings prove that that the runoff peak discharge is more sensitive to development condition changes, but the runoff volume is more sensitive to ARI changes.

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