Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment

Z. Yusop*, C.H. Chan* and A. Katimon**

*Institute of Environmental and Water Resource Management (IPASA) Univeristi Teknologi Malaysia, Skudai 81310 Johor, Malaysia (E-mail: *zulyusop@utm.my*)

**Department of Hydraulics and Hydrology, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia

Abstract Rainfall-runoff processes in a small oil palm catchment (8.2 ha) in Johor, Malaysia were examined. Storm hydrographs show rapid responses to rainfall with a short time to peak. The estimated initial hydrologic loss for the oil palm catchment is 5 mm. Despite the low initial loss, the catchment exhibits a high proportion of baseflow, approximately 54% of the total runoff. On an event basis, the stormflow response factor and runoff coefficient ranges from 0.003 to 0.21, and 0.02 to 0.44, respectively. Peakflow and stormflow volume were moderately correlated with rainfall. The hydrographs were satisfactorily modelled using the Hydrologic Engineering Centre–Hydrologic Modelling System (HEC-HMS). The efficiency indexes of the calibration and validation exercises are 0.81 and 0.82, respectively. Based on these preliminary findings, it could be suggested that an oil palm plantation would be able to serve reasonably well in regulating basic hydrological functions.

Keywords Baseflow; rainfall-runoff modelling; stormflow; storm hydrograph

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Introduction

An oil palm (*Elaeis guineensis*) plantation currently constitutes the second major land use in Malaysia, covering approximately 4 million ha or about 12% of the country's total land mass. The annual export of oil palm products from Malaysia has exceeded USD 8.6 billion (MPOB, 2005). Due to a lucrative return of this commodity, neighbouring countries, especially Indonesia, Thailand and Vietnam, are also expanding their palm oil industries. The establishment of oil palm plantations initially involved the clearing of land, mostly tropical forests. Replanting to replace less productive old trees is carried out after 25 to 30 years. Depending on the nature and extent of disturbances, land use activities could have a moderate to permanent and irreversible impact on the hydrological regimes (Bruijnzeel, 1990).

The population increase and expansion of industrial and commercial sectors have resulted in greater demands for water. Consequently, the traditional source of clean water from forested catchments is no longer sufficient to meet the new demand. In this regard, plantation areas, especially oil palm and rubber, could play a crucial role as the intermediary between forested landscapes in the upstream and urban or developed ecosystems in the downstream. If properly managed, plantation catchments can provide substantial runoff with suitable quality for domestic and non-domestic uses. As such, it is logical to extend more stringent conservation strategies for water and land resources beyond the forest boundaries.

Despite the importance of plantation ecosystems for socio-economic development and conservation of water resource, their hydrological role is yet to be fully understood. In the past, hydrological studies in the tropics were mainly confined to impact forestry activities (Abdul Rahim and Harding, 1992; Yusop *et al.*, 1998; Yusop *et al.*, 2006). Thus far, the only report on oil palm hydrology is that of the Sungai Tekam Experimental Catchment in Pahang, Malaysia (DID, 1989). However, this study only covered the early stage of

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plantation establishment and was terminated before the oil palm reached maturity. The knowledge gathered from this study is at best inconclusive to support environmentally sustained plantation practice. Therefore, it is timely to have more comprehensive scientific understanding of the effects of this man-made ecosystem on the environment, particularly the hydrological regimes. Such information is crucial for the effective and improved management of water and other catchment resources. This paper presents the runoff characteristics and results of hydrograph modelling for an oil palm catchment.

Methods

Study catchment

This study was carried out in a small catchment (8.2 ha) in the upstream of Skudai River in Johor, Malaysia at 1° 43.48′ N and 103° 32.29′ E (Figure 1). It is drained by a second order stream which had been partly straightened during the establishment of the plantation. The catchment's topography is undulating with an average slope of 7%. The soil texture is characterised by coarse sandy clay loam of red yellow ultisols and belongs to Rengam series. Table 1 shows the physiographic conditions of the catchment.

The general climate of the study area is characterised by continuous warm and humid conditions with annual rainfalls over 12 years ranging from 1,860 mm to 2,763 mm (average 2,297 mm). The mean temperature and relative humidity are 25.6 °C and 87%, respectively. The monthly rainfall shows two peaks in the months of April and December, suggesting the influence of south-west and north-east monsoons. With monthly rainfall seldom dropping below 100 mm, the area is not prone to prolonged dry spells (Figure 2). Most of the rainfall events are of the convective type, characterised by short durations but high intensities.

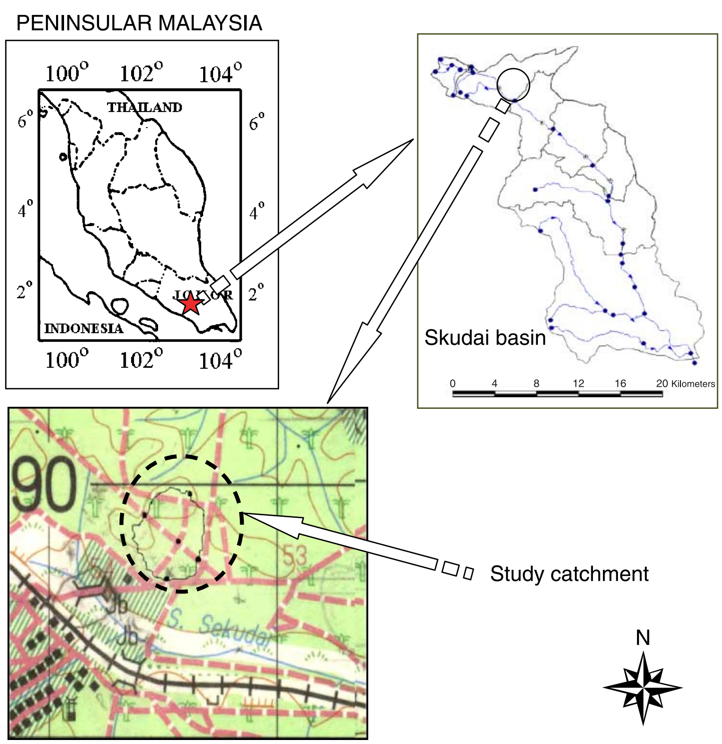

Figure 1 Location of the study catchment

Table 1 Physiographic parameters of the oil palm catchment

Parameter		Value
Area		8.17 ha
Elevation	Maximum	60.85 m.a.s.l
	Minimum	47.20 m.a.s.l
Aspect		N-E
Shape	Form factor	0.27
	Circularity ratio	0.95
	Elongation ratio	0.76
Stream order		2
Average slope		7%
Average stream gradient		2.41%
Drainage density		1.6 km/km^2
Total stream length		131 m

Rainfall and runoff monitoring

Rainfall and runoff were recorded during three different periods; firstly, in October and November 2002; secondly, from April to June 2003; and thirdly, from January to April 2004. Rainfall was measured by an automatic tipping bucket rain gauge (ONSET RGM-2) which records rainfall cumulatively every 0.2 mm. One rain gauge should be sufficient for this small catchment and basically conforms to the standards for rain gauge density in the tropics (DID, 2000). The water level was measured continuously over a 120° V-notched weir by an MDS-Dipper pressure sensor at 5 min intervals. Discharge over the weir was measured by volumetric gauging during several storm events. A strong correlation between discharge and water level was obtained with coefficient of determination, $r^2 = 0.98$. This level-discharge rating curve was used to convert water levels into discharge values.

Hydrograph separation

Baseflow and stormflow components of the hydrographs were separated using a constant slope method (Hewlett and Hibbert, 1967). This technique separates the hydrographs by drawing a straight line upwards from the point of hydrograph rise at a slope of 0.0055 l/s/ha/hr until it intercepts the falling limb of the hydrograph (Figure 2).

Hydrograph modelling

Modelling of the storm hydrograph is useful to provide estimates of flow when the streamflow record is missing. In this study, a storm hydrograph was modelled using the Hydrologic

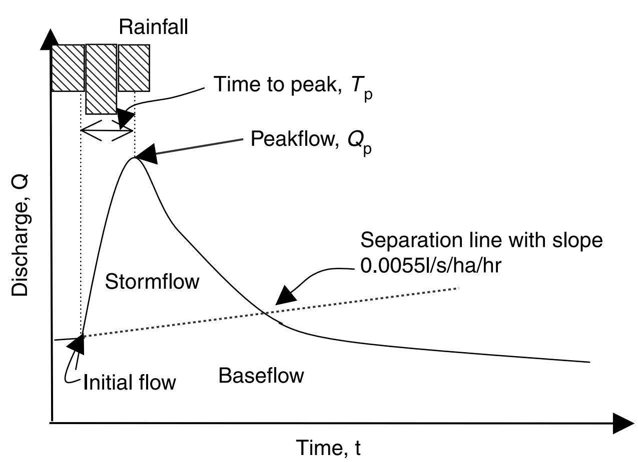

Figure 2 Hydrograph separation technique (after Hewlett and Hibbert 1967)

Engineering Center-Hydrologic Modeling System (HEC-HMS). It is public domain software developed by the US Army Corps of Engineers (USACE). HEC-HMS is relatively easy to use as it provides user-friendly graphical interfaces. It also has a wide range of methods to set up and control variables for simulating a rainfall-runoff (HEC, 2000). In this model, interception, evaporation and infiltration processes in a catchment are determined from loss components while runoff processes are computed as pure surface routing using transform component. Groundwater contributions are represented by baseflow component. The selected methods used for parameterisation were the initial/constant method for loss component, Clark Unit Hydrograph method for transformation routines, and the recession method for baseflow components. The initial and constant methods correspond to interception and depression storages with an initial loss. All other losses were assumed to follow a constant loss rate.

In this analysis, the calibrated model was validated using an independent set of rainfall and runoff records. The model adequacy was evaluated based on the efficiency index (*EI*) (Nash and Sutcliffe, 1970), which has been widely used for model performance evaluation (Crooks and Davies, 2001). *EI* detects system errors and the goodness of fit between simulated and observed values in the following form:

$$EI = 1 - \left[\sum_{i=1}^{n}(Q_{oi} - Q_{si})^2 / \sum_{i=1}^{n}(Q_{oi} - Q_a)^2\right] \qquad (1)$$

where *EI* is efficiency index, Q_{oi} is observed flow at time i, Q_{si} is simulated flow at time i, Q_a is an average observed flow, and n is the number of data points.

Results and discussion

Runoff characteristics

Out of 31 rainfall events recorded, only 28 produced measurable increases in streamflow. The incident rainfalls analysed range from 0.4 to 36.4 mm with intensities between 0.8 and 129.0 mm/h. The observed event hydrographs generally show a rapid response to rainfall with a short time to peak, ranging from 6 to 48 min with an average of 18 min. A flashy shape of hydrograph is not uncommon for small catchments even under forested conditions (Abdul Rahim, 1990). Approximately 58% of the hydrographs analysed have baseflow proportions higher than the stormflow. On an event basis, the stormflow components made up between 9.5 and 82.6% of the total flow with an average of 46.1% (Figure 3). The high proportion of baseflow suggests that a substantial amount of rainwater can still infiltrate into the soil and sustain the streamflow during dry days. Except on the compacted plantation

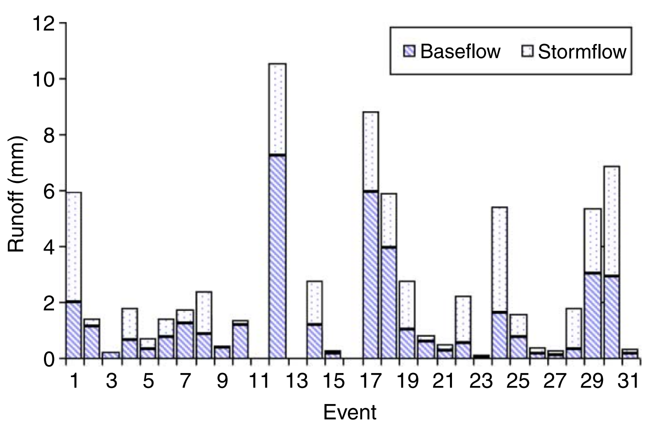

Figure 3 Baseflow and stormflow fractions of individual hydrographs

Table 2 Pearson correlation of various rainfall and hydrographs parameters

	P	P_i	Q_{total}	SF	BF	T_p	Q_p
P	1	0.469*	0.519**	0.676**	0.314	0.322	0.761**
Pi		1	0.08	0.091	0.059	0.201	0.21
Qtotal			1	0.881**	0.931**	0.346	0.33
SF				1	0.647**	0.357	0.511**
BF					1	0.281	0.137
Tp						1	0.076
Qp							1

Note: P is rainfall, P_i is rainfall intensity, Q_{total} is total runoff, SF is stormflow, BF is baseflow, T_p is time to peak and Q_p is peakflow
* Significant at the 0.05 level ($p < 0.05$)
** Significant at the 0.01 level ($p < 0.01$)

roads, which cover approximately 10% of the catchment, the remaining area is still pervious and covered with oil palms or cover crop. A much higher baseflow, approximately 70% of the total annual flow, was reported in forested catchments (Abdul Rahim and Harding, 1992; Yusop, 1996). In urban catchments, baseflow is usually small as infiltration opportunities are very limited (Sharma, 1986).

The Pearson correlation matrix (Table 2) could provide a convenient technique to check whether relationships exist between rainfall and hydrograph parameters. The analysis suggests that total flow has strong relationships with baseflow and stormflow whereas rainfall is moderately correlated against total flow, stormflow volume and peakflow. On the other hand, rainfall intensity has no significant influence on the hydrograph characteristics. The rainfall–runoff relationships for the present catchment are best expressed in linear forms, as shown in equations 1 and 2:

$$Q_p = 3.176P - 10.083 \quad (r^2 = 0.59;\ \ n = 31) \tag{2}$$

$$V_S = 0.0731P - 0.171 \quad (r^2 = 0.59;\ \ n = 31) \tag{3}$$

where Q_p is peakflow (l/s), V_S is stormflow volume (mm) and P is rainfall depth (mm). Only storms greater than 5 mm would produce measurable stormflows and significant increases in peakflow (Figures 4). This value basically represents the initial hydrologic losses due to interception by oil palm stands, the undergrowth and the fraction of water that is required to replenish soil moisture storage before stormflow can be generated. The value obtained here is much lower than those reported for tropical forest sites, between 22 and 30 mm (Noguchi *et al.*, 1997; Chan, 2003).

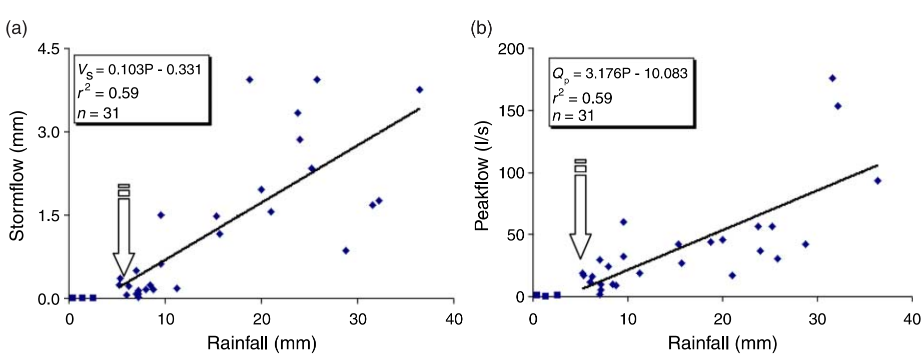

Figure 4 Relationship between (a) stormflow volume and (b) peakflow against rainfall

Table 3 Tested model parameters for the oil palm catchment

Parameter	Unit	
Initial losses	mm	5.94
Constant losses	mm/h	33.25
Imperviousness	%	10
Time of concentration	hr	0.10
Storage coefficient	hr	0.20
Recession constant		0.59

Apparently, the low initial loss in oil palm plantation does not necessarily lead to a smaller baseflow compared to stormflow (Figure 3). This could be associated with a lower interception loss, which is the portion of rainwater that is evaporated back to the atmosphere immediately after the rainfall has ceased without even reaching the ground. Interception storage is influence by the structure and density of the vegetation canopy (Marin *et al.*, 2000; Hall, 2003). Oil palm has a simpler structure and less dense canopy compared to tropical forest, which is characterised by a multilayer canopy and thick undergrowth. Among oil palm stands, the interception loss is also expected to vary with the stand age, being smaller in young stands compared to the older ones. This, however, needs to be substantiated by field measurements.

The catchment response to rainfall can be assessed by calculating the stormflow response factor and runoff coefficient. The former is defined as the ratio of stormflow volume to rainfall whereas the latter is the ratio of total runoff to rainfall. On an event basis, the stormflow response factor ranges from 0.003 to 0.21 while the runoff coefficient ranges from 0.02 to 0.44. The response factor obtained from this catchment (mean = 0.07, median = 0.07) is comparable with those found in tropical forests, from 0.04 to 0.1 for Berembun in Negeri Sembilan (Abdul Rahim, 1990) and 0.08 to 0.09 in Kerling, Selangor (Yusop, 1996).

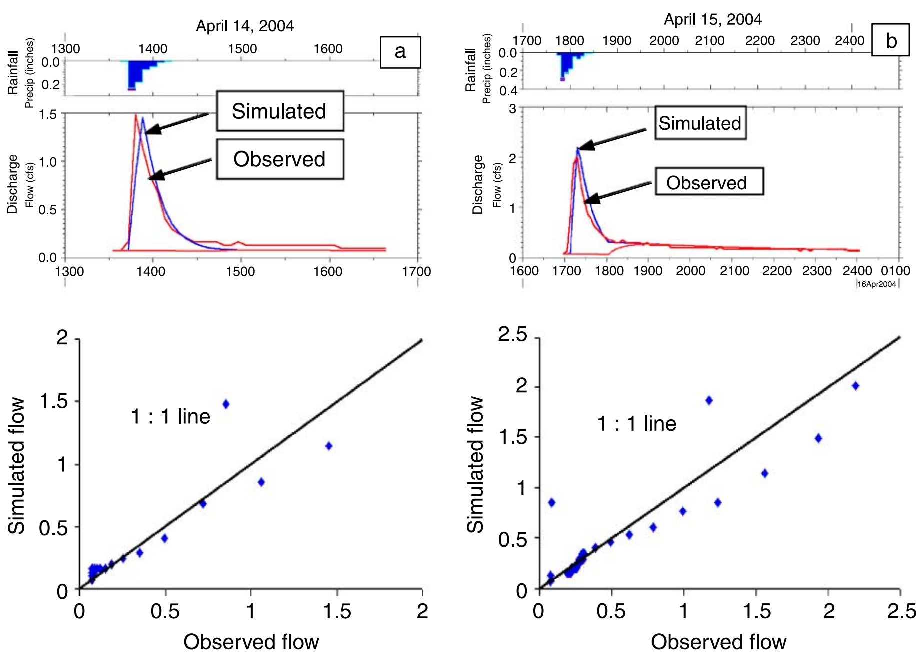

Figure 5 Results of runoff modelling using HEC-HMS and comparison of simulated and observed flow (cfs) on 1:1 line; (a) calibrated hydrograph (b) validated hydrograph

Rainfall-runoff modelling

Rainfall and runoff data on the 14th and 15th April 2004 were used to calibrate and validate the HEC-HMS. The corresponding storms sizes were 15.4 and 25.2 mm, respectively. The model parameter values obtained during calibration were based on the storm on April, 14 and are shown in Table 3. Figure 5a and 5b shows the calibrated and validated hydrographs, superimposed on the observed hydrograph. The shape of the modelled hydrograph generally follows the observed hydrographs. However, the simulated peakflow during calibration and the time to peak during validation were quite different from the observed values. The simulated flow was also plotted against the observed flow on a 1:1 scale. With few exceptions, the points generally fall close to the 1:1 line. HEC-HMS, however, tends to overestimate stream flows on the falling limb. Judging from the high *EI* values for the calibration and validation exercises of 0.81 and 0.82, respectively, the performance of HEC-HMS for modelling runoff is considered satisfactory.

Conclusions

This study has revealed several interesting results on the rainfall-runoff response patterns. Storm hydrographs generated by small to medium rainfalls generally produced a higher proportion of baseflow than the stormflow. On an event basis, baseflow made up approximately 54% of the total flow. Similar to many small catchments, the hydrographs of the oil palm catchment show a rapid response to storms with short time to peak. Storm hydrographs were successfully modelled using HEC-HMS. The model performance was satisfactory with efficiency indexes for the calibrated and validated models of 0.81 and 0.82, respectively. Therefore, it is possible to use HEC-HMS for filling missing runoff and predict runoff from rainfall data. The present catchment shows quite similar runoff characteristics with forested catchments in terms of baseflow proportion and response factor. With more stringent plantation practices, especially in the early stage of planting, oil palm catchments may function reasonably well in maintaining their hydrological regime. However, detailed and longer observations are required to substantiate this tentative claim.

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