

PARTITIONING OF RAINFALL AND FLOWPATH PROCESSES IN SMALL
OIL PALM CATCHMENTS

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OIL PALM CATCHMENTS

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*To my dearest and greatest inspiration,
God, Lydia, Glyns Meyes, Grace Nala, Mom and Dad*

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ABSTRACT

Oil palm area forms the second largest land-use fraction in Malaysia, after forest. Therefore, scientific understanding of hydrological processes in oil palm catchment is crucial for an improved catchment and water resources management. This important issue was examined, involving three small catchments, namely C1, C2 and C3 in Sedenak, Johore. Rainfall and streamflow were continuously recorded in all catchments. Throughfall and stemflow were monitored for interception loss computation. Neutron scattering and resistivity imaging system were applied for measuring soil moisture and generate stratigraphy pattern. Storm water samples were analysed for oxygen-18 and silica concentration for hydrograph separation to determine event and pre-event water. The revised Gash's model was also applied to estimate interception loss. On an average, 28.9% of the gross rainfall was intercepted by the canopy and 71.1% reaches the ground surface in C3. Throughfall and stemflow account for 66.9% and 4.2% of the rainfall, respectively. About 14.5% of the rainfall was infiltrated into the soil and recharge the soil moisture. During storm events, stormflow and baseflow constituted up to 56.6% of the total rainfall. The hydrographs were dominated by event water during wet seasons and by pre-event water during dry seasons. The stratigraphy patterns revealed that streamflow leakage to deeper layer might contribute to lower stormflow response factors and runoff coefficient in C1. The four components of the interception loss in C3, i.e. canopy storage capacity, trunk storage capacity, evaporation and evapotranspiration were estimated at 8.8%, 0.3%, 8.5% and 11.3%, respectively. The predicted interception loss derived from the revised Leyton and Gash methods were 13% and 11%, respectively. Both models were found to underestimate the measured interception loss and therefore not applicable in oil palm catchments. Radioisotope technique is a better approach for establishing time of concentration as it is able to determine the actual travelling times of both overland and channel flow in the field. The water budgets in the study catchments seem comparable with forested catchments. However, detailed study on the long term flow regime and water quality is still necessary to formulate management guidelines for protecting water resources in oil palm catchment.

ABSTRAK

Kawasan kelapa sawit membentuk bahagian penggunaan tanah yang kedua terbesar di Malaysia, selepas hutan. Oleh itu, pengetahuan saintifik proses hidrologi di tadahan kelapa sawit adalah penting bagi penambahbaikan pengurusan tadahan dan sumber air. Isu yang penting ini telah dikaji, melibatkan tiga tadahan kecil, iaitu C1, C2 dan C3 di Sedenak, Johor. Hujan dan aliran sungai telah direkodkan berterusan di semua tadahan. Jatuhan telus and aliran batang disukat untuk pengiraan pemintasan kehilangan. Penyerakan neutron dan sistem bayangan keberintangan telah digunakan untuk pengukuran kelembapan tanah dan penghasilan pola stratigrafi. Sampel air ribut telah dianalisis untuk oksigen-18 dan kepekatan silika dan seterusnya digunakan untuk pemisahan hidrograf kepada air peristiwa dan pra-peristiwa. Model Gash semakan turut digunakan untuk menganggar kehilangan pintasan. Secara purata, 28.9% daripada hujan kasar telah dipintas oleh kanopi dan 71.1% sampai ke permukaan tanah di C3. Jatuhan telus and aliran batang membentuk 66.9% dan 4.2% masing-masing daripada hujan kasar. Dianggarkan sebanyak 14.5% daripada hujan kasar telah menyusup ke dalam tanah dan mengimbuh kelembapan tanah. Semasa peristiwa ribut, aliran ribut dan aliran dasar membentuk sehingga 56.6% daripada jumlah hujan. Hidrograf telah di dominasi oleh air peristiwa semasa musim tengkujuh dan oleh air pra-peristiwa semasa musim kering. Pola stratigrafi menunjukkan kebocoran aliran sungai ke lapisan lebih dalam dan mungkin menjadi penyebab faktor sambutan dan pekali air larian yang rendah bagi aliran ribut di C1. Empat komponen pemintasan kehilangan iaitu keupayaan simpanan kanopi, keupayaan simpanan batang, sejatan dan penyejatpeluhan telah di anggarkan, masing-masing sebanyak 8.8%, 0.3%, 8.5% dan 11.3% di C3. Kehilangan pintasan yang diperoleh daripada kaedah kajisemula Leyton dan Gash, masing-masing adalah 13% dan 11%. Kedua-dua model didapati terkurang anggar bagi ukuran kehilangan pintasan dan dengan itu kurang sesuai untuk tadahan kelapa sawit. Teknik radioisotop adalah pendekatan yang lebih baik untuk mengira masa penumpuan kerana ia berupaya menentukan masa kembara bagi kedua-dua aliran atas permukaan dan aliran sungai di lapangan. Keputusan analisis imbalan air di tadahan kelapa sawit hampir menyamai nilai yang dilaporkan dari tadahan hutan. Namun begitu, kajian terperinci ke atas regim aliran jangka panjang dan kualiti air penting untuk merumus garis panduan pengurusan bagi melindungi sumber air di tadahan kelapa sawit.

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LIST OF SYMBOLS

$C1$	-	Catchment 1
$C2$	-	Catchment 2
$C3$	-	Catchment 3
ET	-	Evapotranspiration
E	-	Evaporation
RF	-	Rainfall
R	-	surface runoff
G	-	ground flow
I	-	infiltration
TF_i	-	throughfall beneath the canopy
TF_d	-	direct throughfall
SF	-	stemflow
E_i	-	interception loss
CR_{soil}	-	counts s^{-1} in soil
CR_{water}	-	counts s^{-1} in water tank
W	-	gravimetric water content
NMM	-	Neutron Moisture Meter
$NMM_{reading}$	-	neutron count/second
A	-	Area of the catchment (unit km^2)
P	-	Perimeter of the catchment (unit km)

L_b	-	Length of the main stream (unit km)
W_b	-	Average width of the catchment (unit km)
F_f	-	Form factor
C_r	-	Circularity ratio
E_r	-	Elongation ratio
L_m	-	maximum length (m) of the basin parallel to the principal drainage lines.
S	-	Average catchment slope
m	-	total length of contour lines (km)
h	-	contour height interval (km)
D_d	-	Drainage Density (unit km/km ²)
V	-	measured voltage difference
I	-	applied current
k	-	geometric factor
t	-	elapsed time after injection (minute)
C	-	count rate (cps)
Δt	-	time interval (second)
t_c	-	Time of concentration
δ	-	delta units
^{18}O	-	Oxygen-18
‰	-	parts per thousand
$V\text{-SMOW}$	-	Vienna Standard Mean Ocean Water
TH	-	Throughfall
SF	-	Stemflow
FR	-	funneling ratio
BA	-	basal area (m ²)

P_G	-	gross rainfall
c	-	canopy cover
S	-	canopy storage capacity
\bar{R}	-	mean rainfall rate
\bar{E}	-	Mean evaporation rate
S_c	-	canopy storage per unit area of canopy cover
\bar{E}_c	-	evaporation rate from the canopy
Q_T	-	total runoff
Q_n	-	runoff components
$c_n^{t_i}$	-	respective concentrations of one observed tracer
t_i	-	observed tracer
Q_E	-	contribution of event water for oxygen-18
Q_P	-	contribution of pre-event water for oxygen-18
Q_S	-	contribution of event water for dissolved silica
Q_G	-	contribution of pre-event water for dissolved silica
Δf	-	Gaussian standard error
CN	-	runoff Curve Numbers
RC	-	Rainfall ceased
RFM	-	Rainfall mass center
OF	-	overland flow
BF	-	baseflow
$BH1$	-	Bore Hole 1
$BH2$	-	Bore Hole 2
$BH3$	-	Bore Hole 3
HZ	-	Hard zone area;

L	-	Stream leakage
HP	-	High permeability
SS	-	Shallow water saturated strata
S_{tr}	-	Stream
$C.V.$	-	Coefficient of variation
p	-	Free throughfall coefficient
S_{c1}	-	Canopy storage per unit area of canopy cover (Leyton's method)
S_{c2}	-	Canopy storage per unit area of canopy cover (Gash's method)
p_t	-	Proportion of rainwater diverted to trunks
S_t	-	Trunk storage capacity
IQR	-	Interquartile Range
S_i	-	Silica
NSC	-	Nash and Sutcliffe
t_{co}	-	observed time of concentration
t_{ce}	-	estimated time of concentration
t_{cm}	-	mean of all the observed time of concentration
t_o	-	overland flow time
t_d	-	channel flow travelling time

CHAPTER 1

INTRODUCTION

1.1 Research Background

Runoff generation processes represents a key parameter in understanding the global catchment hydrology system. These runoff generation processes data are used by various researchers to assess and understand pathway pattern of where water goes when it rains for catchment modelling and quantification of water quantity and quality, sediment and solute loadings and land denudation. It must also be recognised that runoff generation processes have an important social and economic dimension related to the problem of solute and contaminant transport in headwater catchment and other aspects of water resources management downstream.

In Malaysia, increasing land conversion to more profitable land development such as oil palm plantation has raised concern among relevant authorities, scientists, environmentalists and those directly affected by it. It has been associated by the removal of the primary forest and expanded significantly (Koh and Wilcove, 2008). The extensive clearance of forest for large scale oil palm plantations has been driven by high global market prices which create high profit margin compared to other types of land use.

Other activities such as urbanisation and rural development also drastically increased which directly reduce the rate of forested areas. The decline of forested area is inevitable as new land needed for the expansion of settlements to meet the

demand of the growing population which is expected to reach 32 million by year 2020 (Thang, 2009). The environmental consequences of this change have been depicted through deterioration of water quantity and quality, loss of biodiversity and soil fertility degradation (Ahern *et al.*, 2011).

As a result of rapid economic development, especially industrialisation, urbanisation and new settlement, shortage of raw water supply become a pressing issue in Southeast Asia (Goh, 2003). Water supply distresses are intricately linked with hydrological processes within the natural forested catchment areas. Conversion of forests into large scale oil palm plantation might have adverse hydrological and ecological consequences and may threaten the long term sustainability of the water environment (Soon and Hoong, 2002). For instances, studies by Lim (1990) and Hartemink (2003) found that soil compaction on pathways caused significant low infiltration of soil and high erosion in oil palm plantation. Additionally, mature oil palms normally have closed canopies which only create little protective ground vegetation.

It is essential to first understand the hydrological behaviour of the catchment system in order to assess any form of disturbances associated with land uses (Dykes and Thornes, 2000). Black box approach in hydrological study, by relying only on rainfall and discharge data often has limitation in describing numerous different processes or combination of process that influence a catchment hydrologic regime (Beven, 1991; Latron and Gallart, 2008). For example the hydrograph behaviour is the interplay of several processes such as rainfall characteristics, canopy interception storage and loss, evapotranspiration, surface runoff, hydrograph separation to quantify event and pre-event water, and soil water content.

All these components are needed to quantify runoff generation processes for ensuring sustainable land use. In addition, the conversion of complex structure of forest canopies in the tropics into mono-structure canopies might alter the runoff generation processes within catchment area and are suggested to be sensitive to such

land use changes (Shuttleworth, 1988). The rates of flow paths and partitioning of rainfall within oil palm catchments are still not documented, despite rapid growth of interest in the processes involved. Consequently, it is vital that the runoff generation processes are properly study in oil palm ecosystems.

1.2 Statement of Problem

Malaysia as an upper middle-income country is rapidly developing economy in Asia. It has transformed itself since the 1970s from a producer of raw materials into an emerging multi-sector economy country. Its goal is to attain high-income status by 2020 while ensuring that development growth is sustainable. It is also promoting tools in shaping a much more responsible business community towards the development of a green economy. Aspiration to achieve a developed nation status by 2020 has created new challenges. The growing population and increasing demand for space and resources have put pressure on the environment especially for clean water supply. Thus, Malaysia has gazetted totally protected area covering 5.16 million ha with 4.08 million ha in Sarawak and the balance of 0.85 million ha and 0.23 million ha in Peninsular Malaysia and Sabah respectively, as to ensure adequate supply of clean water to meet increasing demands for domestic, industrial and agricultural needs (Thang, 2009).

In its quest for development there is concern that Malaysia has compromised on the quality of its environment through the aggressive production and extraction of commodities such as palm oil. No doubt that the quantity and quality of water have been reduced by the depletion of water catchment for development purposes. In addition, population in Malaysia has grown from 15.68 million in 1985 to 26.75 million in 2005 or an increase of 70.6 % over the 20-year period. Thus, the growth in per capita uses of total water requirements is forecasted to double from 250-500 l/c/d in 1997 to 400-1000 l/c/d in 2050 (Anon, 2000). Moreover, the quality of raw

water is highly dependent on the river and stream in the totally protected areas which comprises only 15% of total land area in Malaysia.

The total land conversion to oil palm plantations in Malaysia has increased drastically from 1.47 million ha in 1985 to 4.85 million ha in 2010, an increment of 3.38 million ha or at an average annual rate of more than 150 thousands ha a year (Figure 1.1). This is considered the most wide spreading and rapidly expanding crops in Malaysia. Forest conversion to oil palm plantations has been identified as causing significant environmental issues in Peninsular Malaysia (Abdullah and Hezri, 2008). Consequently, many catchments areas have experienced severe environmental problems, especially those related to erosion and sedimentation (Douglas, 1972; Abdul Rahim, 1988; Lai, 1992; Yusop and Anhar, 1994), water quantity (Abdul Rahim and Yusop, 1994), and urban flooding (Jamaluddin, 2000).

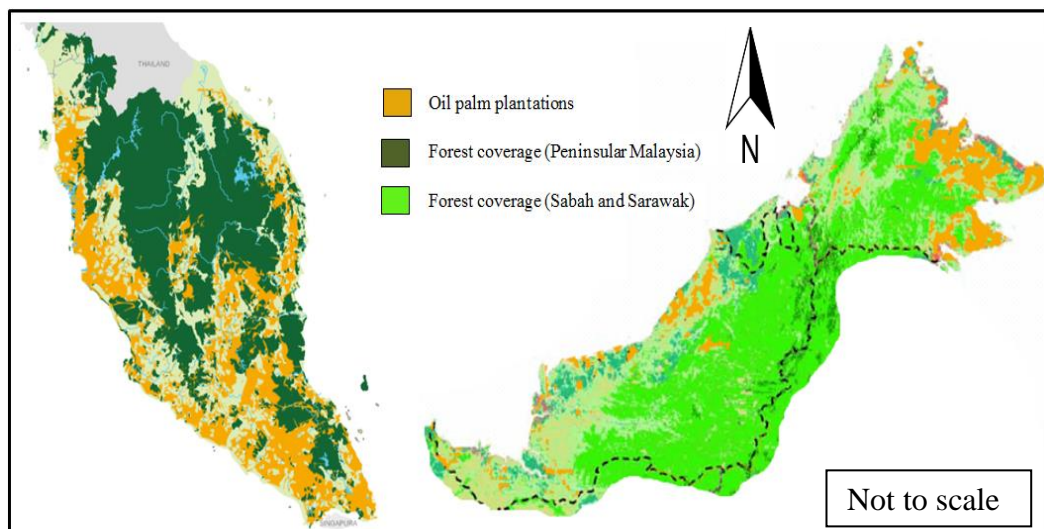


Figure 1.1 : Oil palm and forest coverage in Malaysia (Source: MPOB, 2006)

The land use changes normally link to forest functional systems disturbance and fluctuation of unstable environmental conditions in catchment areas, for example, the overland flow generation of hydrological systems (Ziegler et al., 2004). Moreover, the quantity and quality of raw water supply greatly depends on the activities within the catchment areas (Yusop, 2010). Thus, the impact of land development in Malaysia especially on runoff generation processes in agricultural plantation ecosystems has not been studied so far in a significant way. Information on runoff generation processes is still not well understood especially under oil palm catchments as many hydrological researches in Malaysia are confined to forested ecosystems. Uhlenbrook *et al.* (2003) also suggested that there are still much lacking of runoff generation processes information globally in order to understand better of the hydrological processes in any form of catchment areas.

1.3 Study Objectives

This study focuses on quantification of runoff generation processes in oil palm catchments. Intensive field data collections were carried out in order to achieve the objectives of the study. This research also seeks to contribute differently by presenting new knowledge in term of practical and computation approaches. This include the use radioisotope method for computing time of concentration, usage of isotope and silica for hydrograph separation analysis, neutron scattering for soil water content determination, and resistivity imaging monitoring system for stratigraphy pattern. In addition, the revised Gash's model was applied for modelling interception loss and compared to field data. On the basis of these primary focal points, the following specific research aims are defined :

1. To examine the rainfall-runoff pattern in three small oil palm catchments of different ages and degree of disturbance within the planted areas in order to quantify the rainfall fraction and flow pathways during wet and dry months.

2. To examine the soil water content response to storm event and assess stratigraphy pattern between the study catchments.
3. To determine the throughfall, stemflow and interception loss, and assess the reliability of revised Gash's model in predicting interception loss.
4. To evaluate the consistency of isotopic, geochemical and graphical hydrograph separation approaches to compute event and pre-event water.
5. To estimate time of concentration using radioisotope approach and compare with empirical methods.

It is hope that with the information generated from this study some valuables information is obtained. More importantly, this study will enable greater understanding of oil palm ecosystem response to hydrological processes.

1.4 Scope of Study

This study is focusing on the rainfall fraction in oil palm catchments and can be divided into four main parts. The first part involves selection of potential study sites with different oil palm planted ages and installation of all related hydrological equipment for data collection. Three small catchments were selected comprises C1 (3 years old), C2 (6 years old) and C3 (11 years old). Physiographical measurements were conducted at each catchment to determine the catchment physical characteristics. Rain gauge and water level pressure sensor were installed at these study sites to monitor continuously two years of rainfall and stream flow data for rainfall-runoff analysis. Throughfall and stemflow measurements were conducted under the oil palm canopies for interception loss and storage analysis. Further, soil moisture was measured in C3 using Neutron Moisture Meter. Storm water was sampled and analysed for oxygen-18 and silica concentration. All the three

catchments stratigraphy patterns were measured using Resistivity Imaging System. Radioisotope tracer approaches was used to compute the catchment time of concentration and the results were compared with empirical methods.

The second part of the study discussed on the limitation of time for data collection. Chapter 3 present and further discussed the detail of data collection and analysis of this study in term of space and time. The third part of the research focuses on the data analysis and interpretation. The collected storm water samples were further analysed in laboratory for hydrograph separation analysis. Statistical software (Minitab) was used to perform the statistical analysis.

Final part discussed on method implemented in the study. Among the new approaches used in this study were application of isotope and geochemical method for hydrograph separation. Radioisotope approaches was applied to determine the time of concentration. In addition, revised Gash's model was applied to predict the interception loss from oil palm canopies and compared with the measured interception loss values.

1.5 Significance of Research

The issues discussed above so far confirmed that there is clear need to improve our understanding on the quantification of runoff generation processes response in oil palm catchment. The growing significance of runoff generation processes has inevitably directed attention to assess the relative amounts of water movement via various components of the hydrologic cycle. It also helps to bridge the gap between theory and field-based research in order to define the key variables controlling runoff generation processes from small headwater catchments to larger scale of oil palm catchment. Furthermore, an understanding of runoff generation

processes that affects solute and sedimentation within and from the catchment is vital to identify sensitive areas and encouraging sustainable environmental management (Negishi *et al.*, 2007). Additionally, Blume *et al.* (2008) also revealed that the runoff generation processes is important for flood prediction, water management, erosion control, water quality, contaminant transport and the evaluation of impacts of land use change.

The study of runoff generation processes has become vitally important aspects of environmental management as there are significant portion of total area in Malaysian is now dominated by human landscapes such as an oil palm plantations. As discussed in the earlier sections, the oil palm total planted area was almost equivalent with totally protected areas. Hence, the identification of runoff generation processes required further investigations within oil palm catchment to characterize dominant water flow pathways for ensuring continuously raw water supply. This, therefore, is the focus of this research in order to obtain significant improvements in the understanding of runoff generation processes in the agricultural catchment areas. Where applicable, the results of this study are used to see how far the oil palm ecosystem helps to safeguard our water resources.

1.6 Thesis Structure

Chapter Two presents the literature reviews associated with runoff generation processes in the tropics and temperate. The chapter is divided into six main sections which consists of rainfall distribution, canopy interception losses and storage, surface flow, evapotranspiration, hydrograph analysis and soil water content. Each component of hydrological cycle is discussed in detailed in order to evaluate the rainwater pathways in oil palm catchment. However, most of the literatures are confined to forested areas and only limited studies are conducted in agricultural catchments.

Chapter Three describes the materials and methods used in the study. This includes the description of study site, catchment physical characteristics, climatic behaviour and general description of the oil palm stand. The equipment used and experimental layouts in the study areas are also described in this chapter including laboratory analysis. All models related with the computation of the runoff generation processes are discussed.

Chapters Four to Six present the results on rainfall-runoff, interception loss, and hydrograph separation. The results are also compared with studies carried out in Malaysia, elsewhere in the tropic and temperate regions. The models used to estimate or predict interception loss are compared with measured values in order to determine the model accuracy. The new approaches suggested in this study are examined carefully and compared with conventional method in order to identify reliable approach.

The conclusions of the study are presented in Chapter Seven. It provides a summary of the rainfall fraction and flow pathways to quantify the runoff generation processes in oil palm catchments in general. The study results obtained are used to assess whether oil palm catchments are able to safeguard water resources. Recommendations of future work that could be undertaken to narrow the current research gaps are also provided.

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