

RAINFALL PARTITIONING IN A YOUNG *HOPEA ODORATA* PLANTATION

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Received February 2010; accepted in revised form July 2011

SITIAISAH S, YUSOP Z, NOGUCHI S & ABD RAHMAN K. 2012. Rainfall partitioning in a young *Hopea odorata* plantation. A study on rainfall interception was conducted in a young *Hopea odorata* plantation at Bukit Tarek Experimental Watershed near Kerling, Selangor. Two interception plots were established, each consisting of 36 trees. Gross rainfall (P_g), stemflow (Sf) and throughfall (Tf) were measured to determine the interception loss. The observation period was between October 2006 and December 2007. Based on 65 successfully measured storm events, the average Tf was 83.2% of P_g in plot 1 and 77.4% in plot 2. Average Sf was 4.1% in plot 1 and 3.1% in plot 2. Interception losses were 12.7 and 19.5% for plots 1 and 2 respectively. The canopy storage S differed greatly between plots: 1.42 mm in plot 1 and 1.49 mm in plot 2, while the trunk storage capacity S_t was -0.171 mm in plot 1 and 0.127 mm in plot 2. The negative value of S_t indicated that Sf occurred immediately after rain water flowed down the tree trunk. The S_t amount was either so small or the tree trunk did not hold significant amount of water. Other parameters measured were tree height, stem diameter, crown area and crown depth. The correlation analysis showed that all tree parameters in both plots did not have relationship with Tf. Similar result was also obtained for Sf in plot 1. However, there were correlations between Sf and all tree parameters in plot 2. In multiple regression analysis, there were no key tree characteristics influencing the partitioning of rainfall except for crown depth that significantly influenced Sf in plot 1. The trees of *H. odorata* were still small that it could not significantly influence the rainfall interception. Hence, rainfall-intercepted processes for young *H. odorata* trees were only dependent on rainfall characteristics.

Keywords: Interception loss, throughfall, stemflow, trunk storage, canopy storage

SITI AISAH S, YUSOP Z, NOGUCHI S & ABD RAHMAN K. 2012. Pecahan hujan di ladang hutan *Hopea odorata* yang muda. Kajian pintasan curahan hujan dijalankan di ladang hutan *Hopea odorata* yang muda di kawasan kajian tadahan Bukit Tarek, Kerling, Selangor. Dua petak kajian pintasan curahan diasaskan, setiap satunya mengandungi 36 batang pokok. Jumlah hujan (P_g), lelehan batang (Sf) dan curahan terus kanopi (Tf) disukat untuk menentukan jumlah pintasan curahan. Tempoh kajian adalah dari Oktober 2006 hingga Disember 2007. Berdasarkan 65 kejadian hujan ribut yang dicerap didapati purata Tf ialah 83.2% daripada P_g untuk petak 1 dan 77.4% untuk petak 2. Purata Sf ialah 4.1% untuk petak 1 dan 3.1% untuk petak 2. Jumlah pintasan curahan adalah sebanyak 12.7% untuk petak 1 dan 19.5% untuk petak 2. Nilai simpanan kanopi (S) adalah sebanyak 1.42 mm untuk petak 1 dan 1.49 mm untuk petak 2 manakala kapasiti simpanan batang (S_t) adalah sebanyak -0.171 mm untuk petak 1 dan 0.127 mm untuk petak 2. Nilai negatif S_t menunjukkan yang Sf berlaku sebaik sahaja air hujan turun mengalir melalui batang pokok. Nilai S_t sama ada terlalu kecil atau batang pokok tidak dapat memegang jumlah air yang signifikan. Parameter lain yang disukat ialah tinggi pokok, diameter batang, luas kanopi dan tinggi kanopi. Analisis menunjukkan bahawa semua parameter pokok dalam kedua-dua petak kajian tidak mempunyai korelasi dengan Tf. Keputusan yang sama juga diperolehi bagi Sf dalam petak 1. Namun terdapat korelasi antara Sf dengan semua parameter pokok dalam petak 2. Dalam analisis regresi berganda, tiada ciri pokok mempengaruhi pembahagian hujan kecuali tinggi kanopi yang mempengaruhi Sf dalam petak 1. Ini menunjukkan yang pokok *H. odorata* masih kecil dan oleh itu tidak dapat mempengaruhi pintasan curahan hujan. Jadi, proses pintasan curahan hujan pokok *H. odorata* yang muda hanya bergantung kepada ciri-ciri hujan yang turun.

INTRODUCTION

Forest interception is defined as the portion of rainwater that is retained or intercepted by vegetation or litter above the ground. This

intercepted water contributes to the total amount of evapotranspiration which is categorised as loss of water from a wetted vegetated surface.

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Study using energy balance method (Asdak et al. 1998) showed that the evaporation rate during and immediately after rain in canopy-saturated conditions was higher in the unlogged plot compared with logged plot. This shows the role of vegetation in rainfall interception.

Interception is the temporary storage of precipitation as it touches vegetated surfaces with only part of it reaching the ground as throughfall (Ward & Robinson 2000). Factors controlling interception can be divided into characteristics of the vegetation structure and the rainfall (Shachnovich et al. 2008). Rainfall characteristics include the timing, duration and intensity while vegetation properties include density–spacing, canopy, form–shape, branch structure, age and surface texture such as frictional resistance and storage roughness.

The annual precipitation intercepted by vegetation which ranges from 10 to 25% is a significant amount and its loss represents a significant deficit in the potential annual runoff (Singh 1992). Water that is intercepted by tree canopies is also important hydrologically because it causes non-uniform wetting of forest soil, inhibits transpiration, reduces soil moisture content, evaporates more rapidly than transpiration and adds significantly to total evaporation loss (Singh 1992).

Most studies on rainfall interception have been carried out either in natural forest or forest plantation. Measurements of interception in matured lowland rain forests have been reported (Dykes 1997, Holwerda et al. 2006, Vernimmen et al. 2007, Wallace & McJannet 2008). A comprehensive review on rainfall interception studies in South-East Asia for both natural and plantation forests was carried out (Kuraji & Tanaka 2003). In four studies in Indonesia, the annual throughfall (Tf) ranged from 75 to 94%, stemflow (Sf) 0.3 to 8% and interception loss 6 to 21% of the rainfall which ranged from 1475 to 3563 mm (Kuraji & Tanaka 2003). Studies in Malaysia which covered 10 sites reported Tf, Sf and interception loss of 63–97, 0.4–2 and 3–37% of the gross rainfall respectively (Zulkifli et al. 2003). Rainfall ranged from 758 to 3786 mm. Kuraji and Tanaka (2003) reported only one study in Thailand with Tf of 86%, Sf of 1% and interception loss of 13% of the rainfall (1763 mm).

Interception was also studied based on forest types and different models. Gash interception

model was used by Wallace and McJannet (2008) to measure three different forest types at six rain forest locations in northern Queensland (coastal and montane rainforests). The canopy storage capacity (S) used was in the range of 2.0–3.6 mm. They found that the wet canopy evaporation rate (E) was in the range of 0.35–0.81 mm hour⁻¹ which was higher than the rate estimated by Penman-Monteith equation. The interception determined from Gash model ranged from 25–42% of the rainfall with total amount of rainfall ranging from 1215–4077 mm.

Other tropical forest types studied for rainfall interception were the lowland evergreen rainforest (LERF) and two heath forests (HF) in central Kalimantan, Indonesia (Vernimmen et al. 2007). Tf was 82.8 (LERF), 89.1 (tall HF) and 76.7% (stunted HF) of the rainfall (2995 mm). The values of Sf were 0.8 (LERF), 1.3 (tall HF) and 2.0% (stunted HF). The interception loss obtained was 16.4% from LERF and only 9.6% from the tall HF. The values were considered underestimated.

The rainfall interception was also measured under different managed forests such as that studied by Dietz et al. (2006) in lower montane forests in central Sulawesi, Indonesia. The forest management types involved were natural forest, forest subjected to small-diameter log extraction, forest subjected to selective logging of large-diameter log and cacao agroforest under trees remaining from the natural forest. The Tf with median values ranged from 70–81% of rainfall (1828 mm), while Sf was less than 1% of rainfall for all stands. The rainfall interception ranged from 18–30% of rainfall, with the highest in natural forest.

Plantation establishment usually involves clear cutting and site preparation for planting of seedlings. Such activities may have abrupt and significant hydrological effects. Forest cover removal can alter interception and affect the water balance in a watershed. It is, therefore, crucial to assess patterns of interception loss as the ecosystem undergoes recovery from a disturbed stage. Different plantation species are expected to show different interception patterns with age due to differences in canopy characteristics. Only few studies have been reported for young forest plantation (Lai & Osman 1989, Hall et al. 1992, Waterloo 1994). *Acacia mangium* in Malaysia aged 62 and 56 months intercepted 39.3 and 35.4% of rainfall (Lai & Osman 1989). Nine-

year-old *Eucalyptus* spp. in India intercepted 12% of rainfall (Hall et al. 1992). Six-year-old pine plantation in Viti Levu, Fiji intercepted rain in the range of 14.5–22.0% of the rainfall (Waterloo 1994).

The objectives of this study on *Hopea odorata* were to:

- (1) quantify Tf, Sf and interception, and
- (2) evaluate the influence of tree characteristics on Sf and Tf.

MATERIALS AND METHODS

Site

The study was carried out at Bukit Tarek Experimental Watershed (BTEW) located near Kerling, Selangor, Peninsular Malaysia at approximately 3° 31' N latitude and 101° 35' E longitude (Figure 1). BTEW consists of three small catchments, namely, C1, C2 and C3, with total area of 79.6 ha. The interception measurement was carried out in C3 which was planted with *H. odorata*, with catchment area of 14.4 ha. It has concave shape with mean slope of 27.7% and elevation between 65 and 150 m asl. The forested catchment was originally a second growth forest dominated by *Koompassia malaccencis*, *Eugenia* spp. and *Canarium* spp. before the establishment of forest plantation.

Catchment C3 was logged in 1963 (Zulkifli 1996), clear-felled and burned prior to the establishment of forest plantation in November 1999. In April 2004, the catchment was cleared again before it was planted with *H. odorata* seedlings which covered an area of about 11.0 ha or about 90% of the catchment (Noguchi et al. 2003). The age of the trees was about two years when this study was initiated.

Hopea odorata or commonly known as merawan siput jantan is a species in the family Dipterocarpaceae. A mature tree is characterised as a medium-sized to large evergreen tree with large crown growing to 45 m tall, bole straight, cylindrical, branchless to 25 m, with diameter of up to 4.5 m or more and prominent buttresses, bark surface scaly, grey to dark brown and leaves ovate-lanceolate (Soerianegara & Lemmens 1993, Oldfields et al. 1998). It is a riparian species, usually occurring on deep rich soils, most commonly along the banks of streams and in damp areas up to 600 m altitude. This species has been listed as one of the species that can be planted as forest plantation for timber production in Malaysia since it is fast growing.

The definition of a rain event in this study followed that of Noguchi et al. (1996) who defined a rain event as having at least 1 mm of rainfall with an interval of more than six hours from the preceding event. The highest rainfall

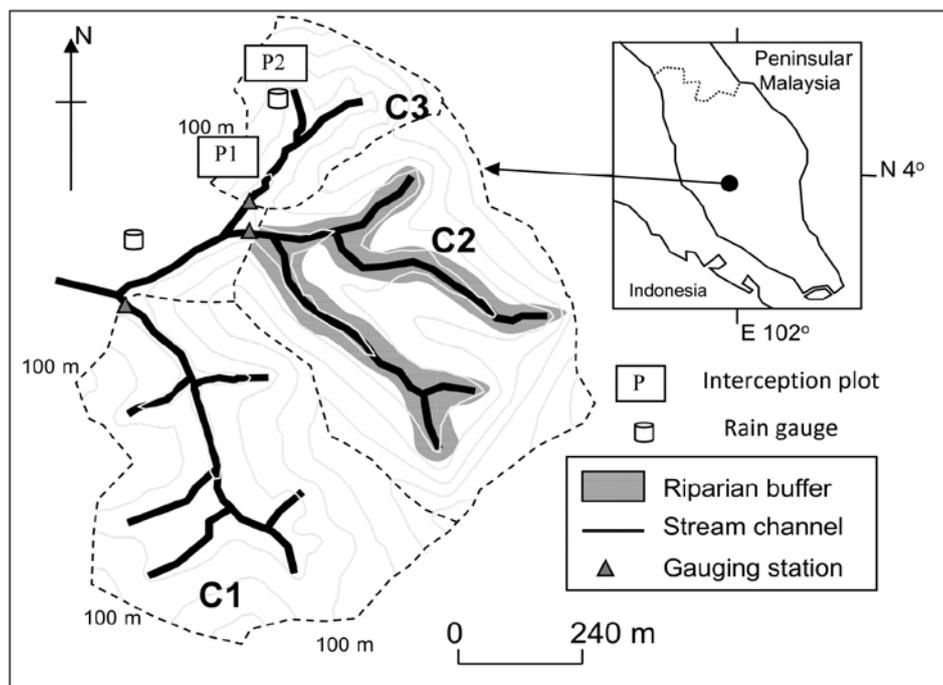


Figure 1 Bukit Tarek Experimental Watershed, Kerling, Selangor

usually occurs in September, which is during the inter-monsoon period. This area receives lots of rainfall with the highest (3476 mm) recorded in 2003. The annual average is 2686 mm year⁻¹.

Study plots

Two square study plots, namely, plot 1 (0.039 ha) and plot 2 (0.041 ha) were established in catchment C3 to measure Tf and Sf. Each plot consisted of 36 trees and the planting spacing was 4 × 3 m.

The mean slope in these two plots was 27.7%; plot 2 faced the south side, while plot 1 faced the east side of the catchment. All trees in the plots were mapped and measured for tree height (TH), diameter at breast height (DBH), crown diameter and depth. Trees which were very small in diameter and crown in plot 1, thus found not appropriate to measure the Tf, were not considered.

Crown area (CA) was calculated based on the measurement of crown diameter (πr^2 where r is crown radius).

Gross rainfall, stemflow and throughfall measurements

Measurements of gross rainfall (P_g), Sf and Tf were carried out manually when the rain occurred from October 2006 till December 2007. P_g was measured using standard manual rain gauges which were installed in an open area adjacent to both plots. As measurements of Sf and Tf were carried out manually for each of the storm, some of the readings might include more than one storm events especially when the interval between storms was short. For example, the reading was taken once a day in the morning and the next rain would fall in the late afternoon and again after midnight. As data were taken manually, the rainfall duration was not available.

Tf was measured using buckets which were randomly placed under the crown of each tree. Depending on crown size, the number of buckets per tree varied from one to a maximum of five buckets in plot 1. The CA in plot 2 was more uniform (crown diameter was between 2 and 3 m for 17 trees from a total of 36 trees, with an average of 2.6 m and SD of 0.68). As such, four buckets were placed directly under the CA and located at four points. The orifice of the bucket was 22.5 cm and the height was

19.0 cm. A convex-shaped plastic lid with a hole was used to cover the opening of the bucket in order to avoid litter from entering the bucket and to minimise evaporation. In total there were 126 and 144 buckets in plots 1 and 2 respectively.

Sf was measured using a vertically cut rubber hose, fixed around the tree trunk to route rainwater into collecting devices. Nineteen trees were selected for manual reading in plot 1 and five trees in plot 2. The larger number of trees sampled in plot 1 was because their diameter was more varied than in plot 2.

In the second part of the study, Tf and Sf were measured using tipping bucket rain gauge. Only a single tree was chosen for the measurements of Sf and Tf in each plot because of the limited number of rain gauges. Tf was measured using three troughs under the tree crown and connected to the rain gauge. The trough with average length of 2.8 m and diameter of 8.7 cm was set up in plot 1 at tree no. 21 and another unit with average length of 2.3 m and diameter of 8.7 cm at tree no. 15 in plot 2. Tree no. 21 was also measured for Sf in plot 1, while tree no. 14 in plot 2, using rubber collar method and connected to the rain gauge. Measurement was taken from September till December 2007 for Tf and from January till September 2007 for Sf.

Data analysis

Simple linear regressions were used to determine the relationships between Sf or Tf and P_g (Gash & Morton 1978, Van Dijk & Bruijnzeel 2001). The approaches by Leyton et al. (1967), Jackson (1975), and Gash and Morton (1978) were also used to determine canopy and trunk storages.

Interception loss (E_i) was calculated from manually observed event-based study and equation 1 below:

$$E_i = P_g - (Tf + Sf) \quad (1)$$

The data of Tf, Sf and P_g used in the first part of the study which were manually taken were not event-based data as the rainfall duration was not included. Only the analysis of Tf, Sf and P_g data which were observed using automatic rain gauges were event-based data. The statistical analysis was performed using R software (Version 2.6.1–Citation refers to R package) and MINITAB. The multiple linear regression and stepwise elimination technique were applied to derive

factors influencing the rainfall partitioning and rainfall interception model.

RESULTS

Study plots

The tree density in Plot 1 was higher than plot 2 (Table 1). However, with regard to basal area, plot 2 was higher than plot 1.

The DBH in plot 1 varied from 1.5 to 8.1 cm (Table 2) while plot 2, from 5.7 to 10.7 cm (Table 3). The average DBH in plot 2 was almost double (7.8 cm, SD = 1.3) that of plot 1 (4.2 cm, SD = 1.6). Trees in plot 2 were also taller (average = 5.2 m, SD = 0.8) than those of plot 1 (average = 3.0 m, SD = 0.6).

As expected, the bigger DBH in plot 2 resulted in wider and deeper crown than plot 1. The CA in plot 1 ranged from 0.5 to 5.2 m² with average of 2.5 m² while plot 2, from 1.7 to 13.5 m² with average of 5.7 m².

CA in plot 1 was more heterogeneous than plot 2. The total CA for plots 1 and 2 were 88.5 and 205.3 m² (results not shown). Hence, the crown coverage was 88.5 m² from 390 m² of plot 1 and 205.3 m² from 410 m² of plot 2. The average crown depths (CDs) in plots 1 and 2 were 1.6 and 3.2 m respectively. Plot 2 showed better growth than plot 1.

In plot 1, the DBH, CA and CD of tree no. 21 were 80.9 mm, 4.95 m² and 2.6 m while those of tree no.15 were 74.0 mm, 7.11 m² and 3.8 m respectively. Tree no. 14 with DBH of 57 mm, CA of 1.74 m² and CD of 2.62 m was measured in plot 2.

Rainfall characteristics

From July 2006 till June 2007, there was no difference in total monthly rainfall recorded by automatic tipping bucket rain gauge with a value of 3350.2 mm year⁻¹ (Figure 2). Storage was 3353 mm year⁻¹ which was higher than that of the 1996 till 2001 average of 2816 mm year⁻¹ (FRIM

Table 1 Tree density and basal area in plots 1 and 2

Tree density		Basal area	
Plot 1	Plot 2	Plot 1	Plot 2
923/ha	874/ha	0.0119 m ²	0.176 m ²
(DBH > 1.5 cm)	(DBH > 5.7 cm)		

Table 2 Tree characteristics and rainfall partitioning in plot 1

Plot 1	Canopy depth (cm)	Tree height (m)	Tree diameter (cm)	Crown area (m ²)	Throughfall (mm)	Stemflow (mm)	Gross rainfall (mm)
Mean	165.6	3.0	4.2	2.5	83.2%	4.1%	
Range	67.0–293.0	1.9–4.2	1.5–8.1	0.5–5.2	0.8–75.8	0.02–6.8	3.0–51.0
SD	53.8	0.6	1.6	1.3	15.3	0.9	

Crown area/ plot 1 area = 22.7%

Table 3 Tree characteristics and rainfall partitioning in plot 2

Plot 2	Canopy depth (cm)	Tree height (m)	Tree diameter (cm)	Crown area (m ²)	Throughfall (mm)	Stemflow (mm)	Gross rainfall (mm)
Mean	320.0	5.2	7.8	5.7	7.4%	3.1%	
Range	120.0–500.0	3.5–7.0	5.7–10.7	1.7–13.5	1.0–82.2	0.016–4.51	3.5–65.5
SD	77.0	0.8	1.3	2.9	16.8	2.8	

Crown area/ plot 2 area = 50.1%

unpublished data). Large amounts of rain were obtained in September, October and November, as measured by the two methods during this research year (2006/07) and 1996–2001.

Most of the storms occurred either in the afternoon or at night which was the characteristic of convective rainfall. Heavy rainfall occurred mainly from March till May and from October till December. The rainfall is characterised by short duration and high intensity, with 55% of the rain events lasting less than one hour (Noguchi et al. 1996, 2001).

Rainfall partitioning by *Hopea odorata*

The relationships between Tf and P_g based on individual trees from the regression analysis were expressed by the following equations:

$$Tf_1 = -1.33 + 0.934P_g, \quad r^2 = 0.906 \quad (2)$$

$$Tf_2 = -1.30 + 0.874P_g, \quad r^2 = 0.876 \quad (3)$$

Regression analysis outputs for Tf in plots 1 and 2 showed that all regression parameters for intercept/constant and slope were statistically significant at alpha 5%. It could be seen that the p values for both parameters were less than 0.05, i.e. 0.000 in plots 1 and 2. Thus, there was significant positive relationship between P_g and Tf.

The relationships between Sf and P_g rainfall based on individual trees from the regression analysis were expressed by the following equations:

$$Sf_1 = -0.171 + 0.0545P_g, \quad r^2 = 0.483 \quad (4)$$

$$Sf_2 = 0.127 + 0.0270P_g, \quad r^2 = 0.248 \quad (5)$$

The regression analysis for Sf showed that all regression parameters for intercept/constant and slope were statistically significant at alpha 5%. In plot 1, the p values for both parameters were less than 0.05, i.e. 0.017 for intercept and 0.000 for slope. In plot 2, the p values for intercept were 0.276 or greater than 0.05 and for slope 0.000 or

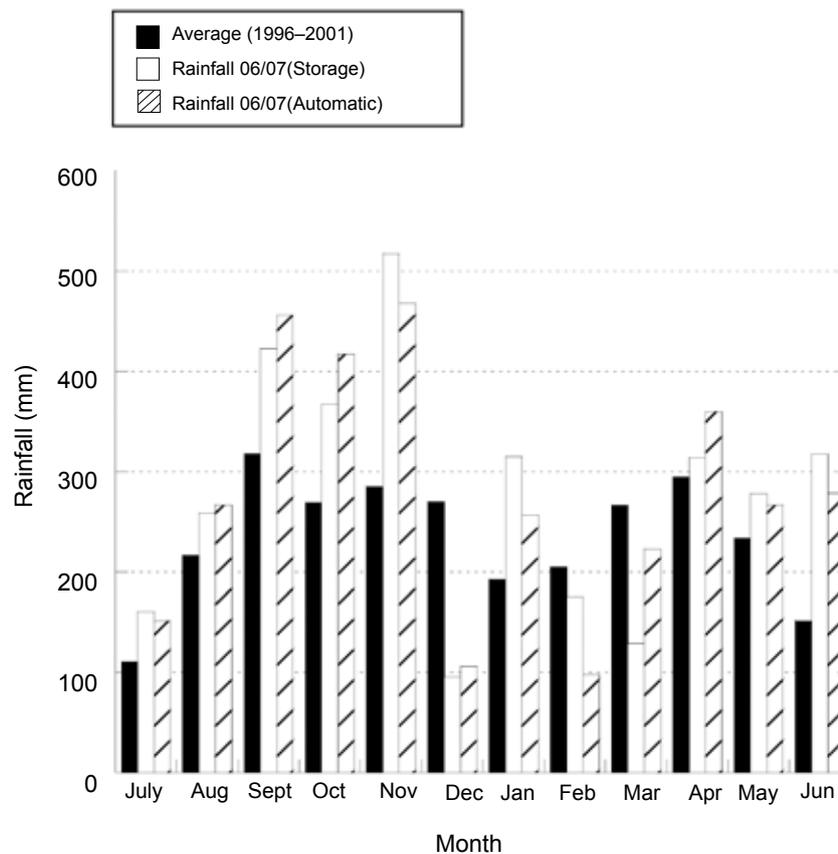


Figure 2 Monthly rainfall of water year 2006/07 at Bukit Tarek Experimental Watershed

less than 0.05. Thus, there was significant positive relationship between P_g and Sf.

The amount of water retained by the tree canopy and trunk was derived from Tf and Sf equations. The equation derived from the linear regression was used to determine the canopy storage capacity S which was obtained when Tf = 0 (equations 2 and 3), while the trunk storage capacity S_t was obtained when $P_g = 0$ (equations 4 and 5). Sf values were 1.42 and 1.49 mm while S_t values, -0.171 mm and 0.127 mm for plots 1 and 2 respectively. The values of Tf and Sf were higher in plot 1 than plot 2 (Tables 2 and 3).

The models were compared to determine if the slope and intercept in both plots were equal

at the confidence interval 95% (or alpha 5) (Tables 4 and 5).

Interception loss Ei

Hopea odorata trees intercepted 12.7% (plot 1) and 19.5% (plot 2) of the gross rainfall. The relationships between P_g and forest input (Tf + Sf) in both plots from September till December 2007 are shown in Figure 3. The regression lines suggested that the net rainfall for both plots were very similar for $P_g < 10$ mm. However, the regression lines diverge as the amount of P_g increased. Plot 2 with bigger trees intercepted more rainwater compared with plot 1.

Table 4 Comparisons of intercept and slope between plots 1 and 2 for Tf

Parameter	Plot		Conclusion
	1	2	
Intercept	-1.3273	-1.3042	Both intercepts were equal, i.e. in plot 1 significant from -1.8856 to -0.7690, and in plot 2, also significant from -1.9251 to -0.6833. These two intervals showed intersection, meaning the two intercepts were equal.
p value	0.000	0.000	
SE	0.2845	0.3164	
Confidence interval	1.9625 (-1.8856; -0.7690)	1.9624 (-1.9251; -0.6833)	
Slope	0.9339	0.8736	Both slopes were different, i.e. in plot 1 significant from 0.9148 to 0.9530 and in plot 2 also significant from 0.8529 to 0.8942. These two intervals showed no intersection, meaning two the slopes were different. It meant that the second trial had lower slope than the first.
p value	0.000	0.000	
SE	0.0097	0.0105	
Confidence interval	1.9625 (0.9148; 0.9530)	1.9624 (0.8529; 0.8942)	

Table 5 Comparisons of intercept and slope between plots 1 and 2 for Sf

Parameter	Plot		Conclusion
	1	2	
Intercept	-0.1706	0.1274	Both intercepts were different, i.e. in plot 1 significant with negative and in plot 2, zero (not significant means equal to zero)
p value	0.017	0.276	
SE	0.0713	0.1165	
Confidence interval	1.9646 (-0.3108; -0.0305)	1.9766 (-0.1029; 0.3577)	
Slope	0.0545	0.0270	Both slopes were different, i.e. in plot 1 significant from 0.0496 to 0.0593, and in Plot 2 also significant from 0.0192 to 0.0347. These two intervals showed no intersection, meaning these two slopes were different.
p value	0.000	0.000	
SE	0.0025	0.0039	
Confidence interval	1.9646 (0.0496; 0.0593)	1.9766 (0.0192; 0.0347)	

Influence of tree characteristics on rainfall partitioning

The relationship between Tf or Sf with tree characteristics was analysed using correlation analysis. There were no relationships between Tf and TH, DBH, CD, CA as well as CV in plot 1 at $p < 0.05$ (Table 6). It could be concluded based on the p values for correlation coefficients greater than alpha (5%). In plot 2, the same results were also found (Table 6). Thus, in these plots no key canopy factor had significant relationship with the Tf partitioning of precipitation.

It was also found that there were no relationships between Sf and TH, DBH, CD and CA at $p < 0.05$ in plot 1 (Table 7). This was based on the p values for correlation coefficients greater than alpha (5%). Thus, in plot 1 no key canopy factor had significant relationship with the Sf partitioning of precipitation.

Only plot 2 showed that there were relationships between Sf and TH, DBH, CD and CA at $p < 0.05$. This was based on the p values for correlation coefficients less than alpha (5%). Thus, in plot 2 the correlation analysis indicated that tree parameters had significant relationship with the partitioning of precipitation.

Stemflow and throughfall responses to rainfall event measured by automated rain gauge

It was not an easy task to analyse based on rainfall event when there were missing data in P_g , Sf and Tf. The results from the available rainfall events can be categorised as single storm with single peak, double or multiple peaks. Most of the rainfall events fell in the range of 10 to 40 mm for one to two hours and only in big storms the rains dragged for two to four hours.

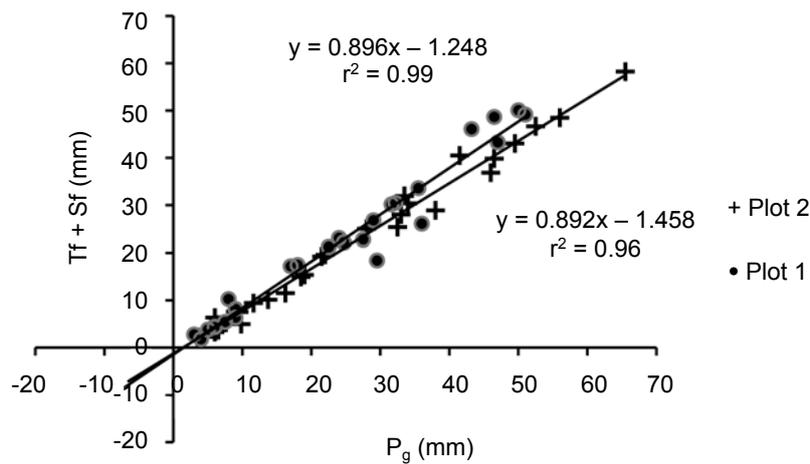


Figure 3 Interception loss (Tf + Sf), Ei against gross rainfall, P_g in plots 1 and 2

Table 6 Pearson correlation p values for analysis of Tf and tree characteristics

Plot	Tree height	Tree diameter	Crown depth	Crown area	Crown volume
1	0.546	0.695	0.478	0.401	0.433
2	0.335	0.322	0.110	0.391	0.911

Table 7 Pearson correlation p values for analysis of Sf and tree characteristics

Plot	Tree height	Tree diameter	Crown depth	Crown area
1	0.766	0.285	0.542	0.122
2	0.000	0.003	0.000	0.000

Rainfall intensities of 10 to 30 mm hours were recorded (Figures 4 and 5). Tf and Sf values were lower in tree no. 21 in plot 1 than tree no. 14 and 15 in plot 2. CA of tree no. 15 was larger than tree no. 21, so more Tf amount was captured. The tree diameter of tree no. 14 was bigger than tree no. 21, so more Sf was captured by tree no. 14 even though they have the same CD.

The changes in Tf and Sf captured every 5 min interval are shown in Figures 6 and 7 respectively for P_g of 50.5 mm with P_g intensity of 31.2 mm hour⁻¹ on 20 October 2007. Sf changed rapidly until rainfall intensity reached maximum. Sf then decreased slowly when rainfall slowly ceased with decreasing rainfall intensity. The Tf change of tree no. 21 in plot 1 was different from tree no. 15 in plot 2 with the latter showing rather straight line than curve (Figure 6).

Factors affecting throughfall and stemflow processes and rainfall partitioning model

Multiple linear regression and stepwise elimination analysis could help determine the explanatory variables (independent) that most affected Tf or Sf. The following multiple regression models were obtained for Sf and Tf in plots 1 and 2:

$$Sf_1 = 1.10 - 0.319 TH - 0.00822 DBH + 0.985 CD - 0.0919 CA \quad (6)$$

(p = 0.015) (p = 0.397) (p = 0.388)
(p = 0.016) (p = 0.315)

$r^2 = 2.4\%$, r^2 adjusted (adj) = 1.6%

$$Sf_2 = 1.63 + 0.15 TH + 0.0052 DBH - 0.34 CD - 0.103 CA \quad (7)$$

(p = 0.556) (p = 0.884) (p = 0.765)
(p = 0.742) (p = 0.303)

$r^2 = 17.5\%$, r^2 (adj) = 15.2%

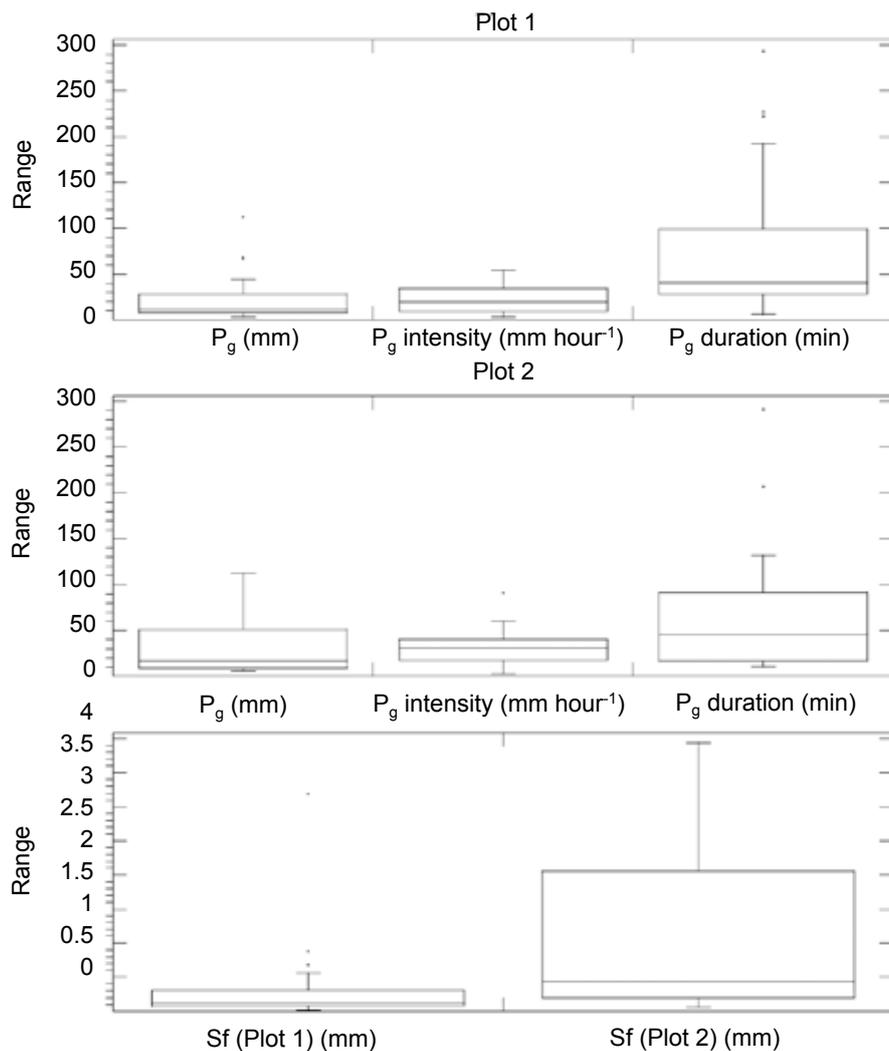


Figure 4 Stemflow in plots 1 and 2 for selected number of storm events; P_g = gross rainfall

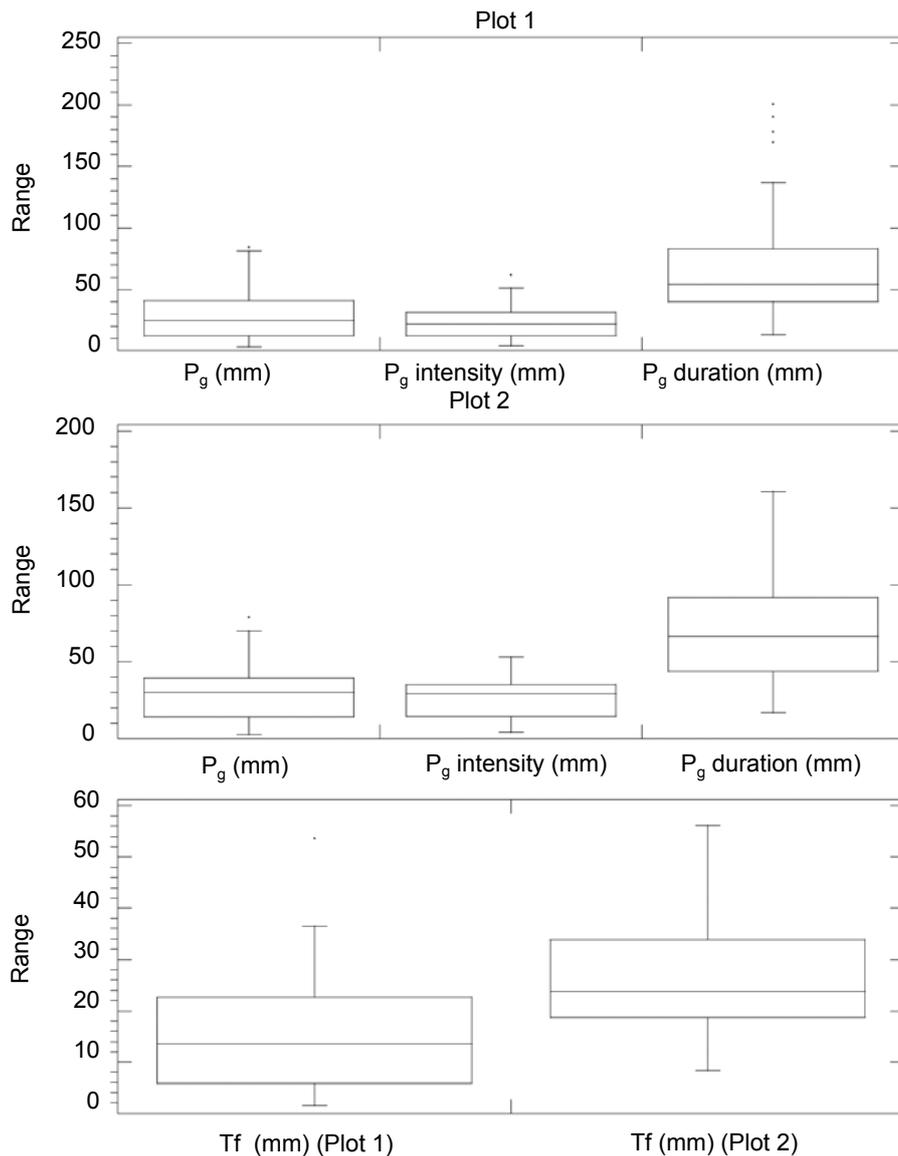


Figure 5 Throughfall in plots 1 and 2 for selected number of storm events; P_g = gross rainfall

$$Tf_1 = 23.7 + 0.48 TH + 0.0365 DBH - 2.17 CD + 1.27 CA + 1.21 CV \quad (8)$$

(p = 0.000) (p = 0.886) (p = 0.631)
 (p = 0.577) (p = 0.476) (p = 0.639)
 r² = 0.1%, r² (adj) = 0.0%

$$Tf_2 = 31.4 + 1.65 TH - 0.0671 DBH - 5.12 CD - 1.04 CA + 1.15 CV \quad (9)$$

(p = 0.000) (p = 0.405) (p = 0.297)
 (p = 0.121) (p = 0.346) (p = 0.195)
 r² = 0.7%, r² (adj) = 0.2%

The regression analysis of Sf in plot 1 (Sf₁) showed that only CD significantly influenced Sf based on the p values for the regression coefficients. For plot 2 (Sf₂), tree parameters did not significantly influence the Sf even though the

correlation analysis showed that all independent variables had significant relationships with the dependent variable. Based on the high correlation between independent variables for this second plot, there was multicollinearity problem.

For the Sf analysis in plot 1, the final model with stepwise elimination method using alpha 15% for removing independent variables from the model is as follows:

$$Sf_1 = 0.7665 - 0.19 CA + 0.54 CD \quad (10)$$

(p = 0.002) (p = 0.002)

r² = 1.97%, r² (adj) = 1.59%

The output from plot 1 showed that both parameters were significant at p < 0.005 which

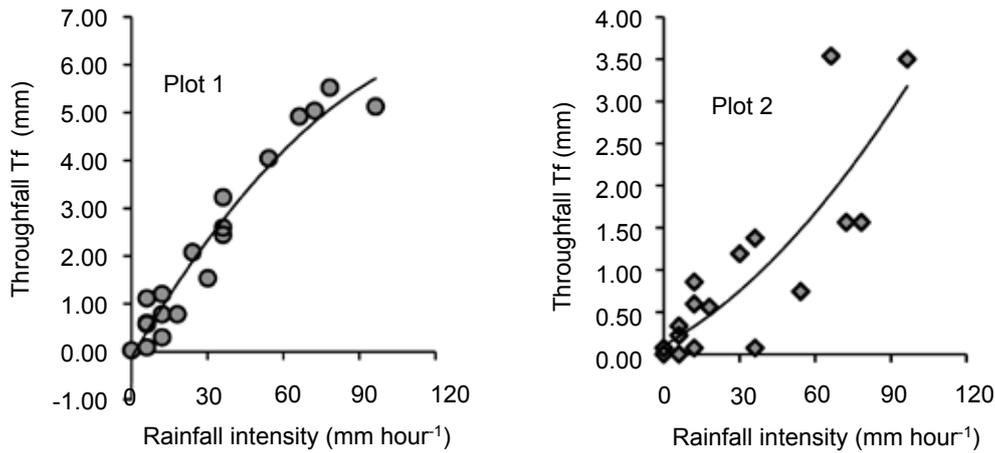


Figure 6 Throughfall changes in plots 1 and 2 according to rainfall intensity at 5 min interval on 20 October 2007

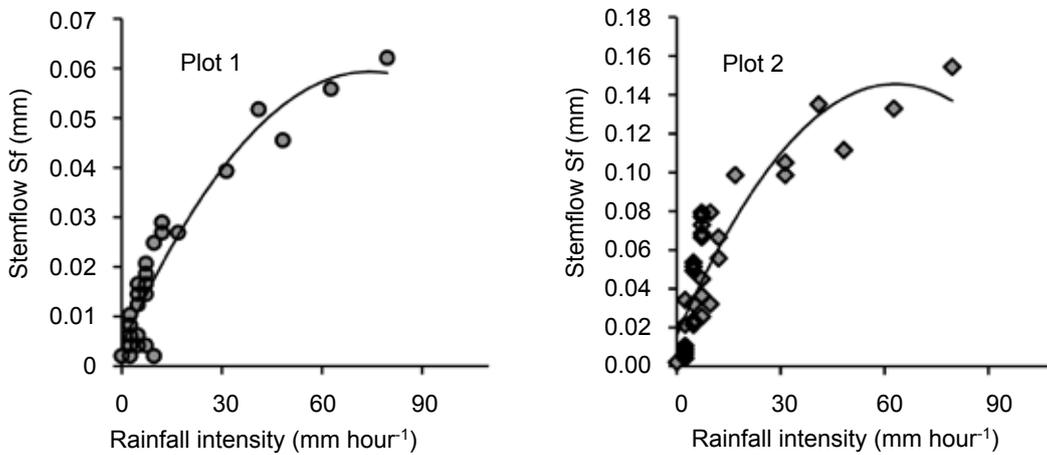


Figure 7 Stemflow changes in plots 1 and 2 according to rainfall intensity at 5 time interval on 20 October 2007

meant that CA and CD significantly influenced Sf. It could be concluded based on the p values for these variables that were less than 0.05, i.e. 0.002 for both CA and CD.

Multiple regression analysis when P_g was included:

$$Sf_1 = -0.594 - 0.1924 CA + 0.565 CD + 0.0545 P_g \quad (11)$$

(p = 0.000) (p = 0.000) (p = 0.000)
(p = 0.000)

$$r^2 = 0.5035, r^2 (adj) = 0.5006$$

For Sf in plot 2, the final model with stepwise elimination method using alpha 15% for removing independent variables from the model is as follows:

$$Sf_2 = 1.749 - 0.111 CA \quad (12)$$

(p = 0.000)

$$r^2 = 16.80\%, r^2 (adj) = 16.22\%$$

The output from plot 2 showed that the parameter model was significant at $p < 0.05$ which meant that CA significantly influenced Sf. It could be concluded based on the p value for this variable at 0.000 (less than 0.05).

Multiple regression analysis when P_g was included:

$$Sf_2 = 1.0949 - 0.111 CA + 0.0269 P_g \quad (13)$$

(p = 0.000) (p = 0.000) (p = 0.000)

$$r^2 = 0.4147, r^2 (adj) = 0.4065$$

The regression analysis for Tf in plot 1 (Tf_1) and plot 2 (Tf_2) showed that all the TH, DBH, CD, CA and CV did not significantly influence Tf. It could be concluded based on the p values for the regression coefficients, $p > 0.05$.

Hence, the stepwise elimination method also could not find the best model, i.e. regression model with significant factor in plot 1. It meant that this method also showed no significant factor influencing the partitioning of precipitation.

For Tf analysis in plot 2, the final model with stepwise elimination method using alpha 15% for removing independent variables from the model is as follows:

$$Tf_2 = 24.86 - 2.13 CD \quad (14)$$

ns (p = 0.025)

$$r^2 = 0.52\%, r^2 (\text{adj}) = 0.31\%$$

The output showed that only CD significantly influenced Tf at alpha 5%. This could be concluded based on the p value for this variable at less than 0.05, i.e. 0.025.

Multiple regression analysis when P_g is included:

$$Tf_2 = 2.126 - 1.087 CD + 0.879 P_g \quad (15)$$

ns (p < 0.001) (p < 0.001)

$$r^2 = 0.8747, r^2 (\text{adj}) = 0.8745$$

DISCUSSION

The variability in the measurement of Tf has always occurred, in which accurate estimation will be difficult. The commonly employed methods use trough of various sizes, plastic collectors and standard rain gauges. The gauges were randomly relocated in some studies (Lloyd & Marques-Filho 1988). Helvey and Patric (1965) suggested random relocation of gauges for measuring Tf on a periodic basis or individual events would reduce the standard error of the mean Tf. Lloyd and Marques-Filho (1988) found extreme value of Tf due to drip points by leaf shapes. The forming of drip point through channelling effect by leaves, branches and stems was also reported by Carlye-Moses et al. (2004) in a small Madrean watershed in north-eastern Mexico. A large variation in Tf values within a plot was observed by Bryant et al. (2005) in south-west Georgia. They found that 10% of the gauge catch was greater than the P_g .

In this study, the systematic and fixed position of the buckets may influence Tf values. Canopy openness was not determined in this study. The buckets should be randomly positioned after each sampling. Some of the buckets were placed just under the tree perimeter which tended to receive higher Tf than rainfall

especially during heavy rainfall. Rainwater on leaf surfaces may concentrate and coalesce to produce higher volume of Tf at certain points under the canopy. The coalescence may also be influenced by wind direction (Bryant et al. 2005, Shachnovich et al. 2008). Small trees (DBH < 2 cm) which had rather thin canopy density could allow more rain drops to fall directly into the buckets.

According to Loustau et al. (1992a), there was a negligible effect between the spatial distribution of stems and Tf partitioning beneath the canopy of mature maritime pine stand (18-year-old stand). Carlye-Moses et al. (2004) found no significant relationship between Tf and distance of the gauges to the tree bole for P_g larger than 5 mm.

Several studies have reported spatial heterogeneity of Tf under forest canopies using randomly distributed fixed gauges (Loustau et al. 1992a, Staelens et al. 2006, Shachnovich et al. 2008) and fixed together with roving gauges (Holwerda et al. 2006). Loustau et al. (1992a) found that the spatial distribution of stems had negligible effect on the Tf partitioning beneath maritime pine (*Pinus pinaster*) stands. The distance from the tree stem did not influence the amount of Tf. Although Shachnovich et al. (2008) found highly heterogeneous spatial distribution of Tf, they did not find any relationship between the degree of canopy openness and canopy characteristics against Tf. Under dominated beech (*Fagus sylvatica*) stands, Staelens et al. (2006) showed that Tf during the growing periods significantly decreased with increasing canopy cover above the sampling positions and closely correlated with branch cover. Rodrigo and Avila (2001) suggested that error associated with Tf sampling in Mediterranean holm oak forests could be reduced to 5% when using more Tf collectors.

It was found that the Sf was underestimated during heavy storms. This is due to the overflows of the capacity of the collector. Compared with Tf, it is considered small and scientists are sometimes not interested to measure because of the difficulty in getting accurate measurement especially in tropical rainforest (Liu 1997). The Sf estimation by 1% of incident rainfall was used by Bruijnzeel (1988) for young *Agathis dammara* following finding by Blake (1975).

Based on measurements of 66 trees with DBH more than 1 cm in lowland tropical forests in

Sarawak, Manfroi et al. (2004) found that 3.5% of the rainfall contributed to Sf. The understorey trees with DBH less than 10 cm played an important role in producing Sf for rainfall less than 20 mm. They also found that Sf correlated positively with DBH, TH and CA but negatively with ratio of crown diameter to CD.

The results of Tf and Sf presented in this paper are important because this study is the first to examine interception of *H. odorata* in Malaysia. Okuda et al. (2003) evaluated canopy and stand structure in lowland dipterocarp forest using aerial photographs. Airborne LiDAR (Light Detection and Ranging) have been used to measure three-dimensional forest structure over extensive areas (Clark et al. 2004, Andersen et al. 2005). The aerial photographs or airborne LiDAR data in this watershed will be useful information to better generalise interception characteristics in *H. odorata* plantation.

The Ei obtained for young *H. odorata* at the present site is comparable to other studies in natural and plantation forests with interception loss in the range of 20% of rainfall. The values were comparable with *A. mangium* interception loss studied in Kemasul, Pahang by Lai and Osman (1989) and *Acacia auriculiformis* in Ubrug, Indonesia by Bruijnzeel and Wiersum (1987).

The present average Tf for *H. odorata* of about 80% of the rainfall was smaller than those reported for natural rainforests (Manfroi et al. 2004). In central Java, Bruijnzeel (1988) found Tf in *A. auriculiformis* and *A. dammara* of more than 90% of the rainfall, much higher than those reported under *A. mangium* (Lai & Osman 1989), oil palm (Zulkifli et al. 2003) and *H.odorata* (this study). This could be due to tree characteristics, length of study and amount of rainfall.

Canopy storage found in this study was higher compared with other forest types even though the results were based on the calculation of individual trees in the plots. For example under mature maritime pine stands (18 years old), Loustau et al. (1992b) found lower values of S (0.52 mm) and S_t (0.098 mm). For lowland rainforest types, Vernimmen et al. (2007) obtained S and S_t in the range of 0.77–1.48 and 0.022–0.028 mm respectively. According to Calder (1996) and Calder et al. (1996) forest canopy retained greater depth of water when individual raindrop volume was small.

Variations in Tf for natural forests was between 77.6 and 94% of the rainfall (Manokaran 1979,

Asdak et al. 1998) while in plantation forest, between 61.5 and 93% of the rainfall (Bruijnzeel 1988, Lai & Osman 1989). The Sf in plantation forest was between 0.4 and 8% and tropical rainforest, between 0.6 and 3.5% of rainfall (Manokaran 1979, Calder et al. 1986, Lai & Osman 1989, Manfroi et al. 2004).

The study by Park and Cameron (2008) on two-year-old plantation of four different species showed that the results obtained for Tf were comparable but the values for Sf were smaller in comparison with this study. The interception found from this study was also within the range determined by Park and Cameron.

Multiple linear regressions analysis and stepwise elimination method could not find the best model of rainfall partitioning as the trees were still young. The model did not significantly influence rainfall interception.

CONCLUSIONS

In the interception study, the average Tf and Sf ranged from 77.4 to 83.2% and from 3.1 to 4.1% of the rainfall respectively. The interception loss ranging from 12.7 to 19.5% was obtained from the young forest trees in C3. The S and S_t ranged from 1.42 to 1.49 mm and from -0.171 to 0.127 mm respectively.

Tf and Sf were highly dependent on rainfall. Strong linear relationships between Tf and Sf against rainfall were observed.

The Sf of *H. odorata* was not influenced by tree characteristics of TH, DBH and CA except for CD. These parameters influence took effect as the trees grow.

Tf in young *H. odorata* trees was not influenced by tree characteristics of TH, DBH, CD, CA and crown volume.

The amount of interception loss from two-year-old *H.odorata* was compatible with matured tropical forests of C1. Factors such as vegetation types, densities and rainfall have major influence on interception processes.

The role of interception in the forest is to reduce the impact of rainfall when falling on the forest floor. Hence, soil erosion will be controlled and the volume of sediment that reaches the streams will be reduced. Normally, the whole area of forest is clear-cut when establishing forest plantation and the effect of soil erosion will be high. Thus, a large forest area that is to be converted to forest plantation should be divided

into phases so that forest clearance and planting can be done phase by phase so as to reduce the effect of soil erosion. This is because after two years of forest planting, as seen in the present study, rainfall still plays an important role in interception and not tree characteristics.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Science, Technology and Innovation (MOSTI) for providing the fund through grant No. 31300203003.

REFERENCES

- ANDERSEN H, MCGAUGHEY RJ & REUTEBUCH SE. 2005. Estimating forest canopy fuel parameters using LiDAR data. *Remote Sensing of Environment* 4: 441–449.
- ASDAK C, JARVIS PG, VAN GARDINGEN P & PRAZER A. 1998. Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia. *Journal of Hydrology* 206: 237–244.
- BLAKE GJ. 1975. The interception process. Pp 60–81 in Chapman TG & Dunin FX (eds) *Prediction in Catchment Hydrology*. Australian Academy of Science, Canberra.
- BRUIJNZEEL LA. 1988. Estimates of evaporation in plantation of *Agathis dammara* Warb. in south central Java, Indonesia. *Journal of Tropical Forest Science* 1: 145–161.
- BRUIJNZEEL LA & WIERSUM KF. 1987. Rainfall interception by young *Acacia auriculiformis* (A. Cunn) plantation forest in west Java, Indonesia: application of Gash's analytical model. *Hydrological Processes* 1: 309–319.
- BRYANT ML, BHAT S & JACOBS JM. 2005. Measurements and modeling of throughfall variability for five forest communities in the southeastern US. *Journal of Hydrology* 312: 95–108.
- CALDER IR. 1996. Dependence of rainfall interception on drop size: 1. Development of the two-layer stochastic model. *Journal of Hydrology* 185: 36–378.
- CALDER IR, HALL RL, ROSIER PTW, BASTABLE HG & PRASANNA KT. 1996. Dependence of rainfall interception on drop size: 2. Experimental determination of the wetting functions and two-layer stochastic model parameters for five tropical tree species. *Journal of Hydrology* 185: 379–388.
- CALDER IR, WRIGHT IR & MURDIYARSO D. 1986. A study of evaporation from tropical rainforest—West Java. *Journal of Hydrology* 89: 13–31.
- CARLYLE-MOSES DE, LAUREANO FJS & PRICE AG. 2004. Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. *Journal of Hydrology* 297: 124–135.
- CLARK ML, CLARK DB & ROBERT DA. 2004. Small-footprint LiDAR estimation of sub-canopy elevation and tree height in a tropical rain forest landscape. *Remote Sensing of Environment* 91: 68–89.
- DIETZ J, HÖLSCHER D, LEUSCHNER C & HENDRAYANTO. 2006. Rainfall partitioning in relation to forest structure in differently managed montane forest stands in central Sulawesi, Indonesia. *Forest Ecology and Management* 237: 170–178.
- DYKES AP. 1997. Rainfall interception from a lowland tropical rainforest in Brunei. *Journal of Hydrology* 200: 260–279.
- GASH JHC & MORTON AJ. 1978. An application of the Rutter model to the estimation of the interception loss from Thetford forest. *Journal of Hydrology* 38: 49–58.
- HALL RL, CALDER IR & ROSIER PTW. 1992. Measurements and modelling of interception loss from a *Eucalyptus* plantation in southern India. In Calder IR, Hall RL & Adlard PG (eds) *Growth and Water Use of Forest Plantations*. John Wiley and Sons Ltd, Chichester.
- HELVEY JD & PATRIC JH. 1965. Design criteria for interception studies. *International Association of Hydrological Sciences Bulletin* 67: 131–137.
- HOLWERDA F, SCATENA FN & BRUIJNZEEL LA. 2006. Throughfall in a Puerto Rican lower montane rain forest: a comparison of sampling strategies. *Journal of Hydrology* 327: 592–602.
- JACKSON IJ. 1975. Relationship between rainfall parameters and interception by tropical rainforest. *Journal of Hydrology* 24: 215–238.
- KURAJI K & TANAKA N. 2003. Rainfall interception studies in the tropical forest. *Journal of Japanese Forest Society* 85: 18–28. (In Japanese)
- LAI FS & OSMAN S. 1989. Rainfall interception, throughfall and stemflow in two *Acacia mangium* stands in Kemasul, Pahang. IHP-UNESCO-FRIM Regional Seminar on Tropical Forest Hydrology. Kuala Lumpur.
- LEYTON L, REYNOLDS ERC & THOMPSON FB. 1967. Rainfall interception in forest and moorland. Pp 163–178 in Sopper WE & Lull HW (eds) *International Symposium and Forest Hydrology*. Pergamon Press, Oxford.
- LIU S. 1997. A new model for the prediction of rainfall interception in forest canopies. *Ecological Modeling* 99: 151–159.
- LLOYD CR & MARQUES-FILHO ADO. 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rain forest. *Agricultural and Forest Meteorology* 42: 63–73.
- LOUSTAU D, BERBIGIER P, GRANIER A & HADJ MOUSSA FEL. 1992a. Interception loss, throughfall and stemflow in a maritime pine stand. I. Variability of throughfall and stemflow beneath the pine canopy. *Journal of Hydrology* 138: 449–467.
- LOUSTAU D, BERBIGIER P & GRANIER A. 1992b. Interception loss, throughfall and stemflow in a maritime pine stand. II. An application of Gash's analytical model of interception. *Journal of Hydrology* 138: 469–485.
- MANFROI OJ, KURAJI K, TANAKA N, SUZUKI M, NAKAGAWA M, NAKASHIZUKA T & CHONG L. 2004. The stemflow of trees in a Bornean lowland tropical forest. *Hydrological Processes* 18: 2455–2474.
- MANOKARAN M. 1979. Stemflow, throughfall and rainfall interception in a lowland tropical rain forest in Peninsular Malaysia. *Malaysian Forester* 42: 174–201.
- NOGUCHI S, ABDUL RAHIM N, BAHARUDDIN K, AHMAD CAS, SITI AISAH S, TANI M, TSUBOYAMA Y & OHNUKI T. 2001. *Stormflow, Stream Recession and Stream Regimen Characteristics in Bukit Tarek Experimental Watershed*. Research Report of the NIES/FRIM/UPM Joint Research Project 2001.

- NOGUCHI S, ABDUL RAHIM N, BAHARUDDIN K, SAMMORI T, TANI M & TSUBOYAMA Y. 1996. Rainfall characteristics of tropical rain forest and temperate forest: comparison between Bukit Tarek in Peninsular Malaysia and Hitachi Ohta. *Japan Journal Tropical Forest Science* 9: 206–220.
- NOGUCHI S, NEGISHI JN, SASAKI S, TANI M, ABDUL RAHIM N, AHMAD CAS & SITI AISAH S. 2003. *Establishment of Hopea odorata Plantation at Bukit Tarek Experimental Watershed*. Annual report of the NIES/FRIM/UPM Joint Research Project on Tropical Ecology and Biodiversity.
- OKUDA T, SUZUKI M, ADACHI N, QUAH ES, HUSSEIN A & MANOKARAN N. 2003. Effect of selective logging on canopy and stand structure and tree species composition in a lowland dipterocarp forest in Peninsular Malaysia. *Forest Ecology and Management* 175: 297–320.
- OLDFIELDS S, LUSTY C & MACKINNEN A. 1998. *The World List of Threatened Trees*. World Conservation Press, Cambridge.
- PARK A & CAMERON JL. 2008. The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation. *Forest Ecology and Management* 255: 1915–1925.
- RODRIGO A & AVILA A. 2001. Influences of sampling size in the estimation of mean throughfall in two Mediterranean holm oak forests. *Journal of Hydrology* 243: 216–227.
- SHACHNOVICH Y, BERLINER PR & BAR P. 2008. Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid zone. *Journal of Hydrology* 349: 168–177.
- SINGH VP. 1992. *Elementary Hydrology*. Prentice Hall Inc, London.
- STAELENS J, AN DE SCHRIJVER, KRIS VERHEYEN & VERHOEST NEC. 2006. Spatial variability and temporal stability of throughfall water under a dominant beech (*Fagus sylvatica* L.) tree in relationship to canopy cover. *Journal of Hydrology* 330: 651–662.
- SOERIANEGARA I & LEMMENS RHMJ (eds). 1993. *Plant Resources of South-East Asia No. 5(1): Timber Trees: Major Commercial Timbers*. Backhuys Publishers, Leiden.
- VAN DIJK A & BRUIJNZEEL LA. 2001. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. 2: Model validation for a tropical upland mixed cropping system. *Journal of Hydrology* 247: 239–262.
- VERNIMMEN RRE, BRUIJNZEEL LA, ROMDONI A & PROCTOR J. 2007. Rainfall interception in three contrasting lowland rain forest types in central Kalimantan, Indonesia. *Journal of Hydrology* 340: 217–232.
- WALLACE J & McJANNET D. 2008. Modelling interception in coastal and montane rainforests in northern Queensland, Australia. *Journal of Hydrology* 348: 480–495.
- WARD RC & ROBINSON M. 2000. *Principles of Hydrology*. McGraw Hill Publishing Company, London.
- WATERLOO MJ. 1994. *Water and Nutrient Dynamics of Pinus caribaea Plantation Forests on Former Grassland Soils in Southwest Viti Levu, Fiji*. Febodruk Bv, Enschede.
- ZULKIFLI Y. 1996. Nutrient cycling in secondary rain forest catchment of Peninsular Malaysia. PhD thesis, University of Manchester, Manchester.
- ZULKIFLI Y, CHAM SY & CHONG JH. 2003. Throughfall, stemflow and interception loss of old rubber trees. *Jurnal Kejuruteraan Awam* 15: 24–33.