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Simple Net Rainfall Partitioning Equations for Nearly Closed to Fully Closed Canopy Stands

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ABSTRACT

Many net rainfall models have been developed, but they are often complex, data demanding and usable only for a specific vegetation type. The focus of this study was to develop and validate two simple equations (a two- and a three-coefficient equation) for nearly full canopies of oil palm, rubber and pine trees. Throughfall and stemflow data from seven past studies were used to determine the best-fit coefficients for the two equations. The three-coefficient equation was Pn = Pg x exp [- {0.3443 – (Pg / (58.9748 + Pg)} x 0.1639)] and the two-coefficient equation was Pn = 0.7724 x Pg – 0.5845 (R^2 = 0.91), where Pn and Pg are the net and gross rainfall, respectively. To validate these two equations, field data collections were started. Thirteen rain gauges fit with data loggers were used for rainfall measurement. Three sampled trees were selected randomly for stemflow measurement and one rain gauge was installed at a nearby open area. Two error indices were used as a goodness-of-fit measure for equation accuracy: index of agreement and normalised mean absolute error. The results showed that the two- and three-equation equations performed nearly equally well. They predicted the net rainfall with an error of between 12 to 23% (ranked as “Fair” to “Good” in terms of overall equation accuracy) and with an index of agreement of more than 90%. The results showed that these two equations can be used fairly accurately to estimate throughfall and net rainfall, and, to a lesser degree, stemflow. Estimation errors occurred most probably because canopy and rainfall characteristics were not taken into account in the two equations.

Keywords: Interception loss, oil palm, pine, rainfall, rubber, stemflow, throughfall, water balance

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INTRODUCTION

Water balance refers to water input (precipitation and snowmelt) and output (evapotranspiration, ground water recharge and stream flow). The major input of water is from precipitation and output from evapotranspiration (Kerkides et al., 1996). Knowledge of water balance is useful in managing water supply; this includes irrigation, water erosion, flood and pollution control and water shortage control.

In some areas, the amount of rainfall is adequate for crop water requirements. However, some places experience insufficient rainfall to meet crop water requirements; therefore, irrigation is required (Odhiambo & Murty, 1996). Crop development, soil water movement and agricultural water management would be highly affected by the amount of irrigation during the crop growing season. This is true especially in arid regions, where water is scarce (Jalota & Arora, 2002).

The daily soil water balance within a plant's rooting system can be described in the following equation:

$$Pn + I + CR = P + ET_a + \Delta\Theta + OF \quad [1]$$

where, Pn is net rainfall, I is irrigation, CR is capillary rise, P is deep percolation, ET_a is actual evapotranspiration, $\Delta\Theta$ is the change in soil water content and OF is surface runoff or overland water flow. All the above components are in the unit mm day^{-1}.

Tree canopies partition gross rainfall (rain above canopies) can be divided into throughfall, stemflow and interception. A portion of the rainfall is intercepted and temporarily retained by the canopies and would subsequently evaporate. This process is known as interception loss. Canopy interception loss is influenced by canopy architecture and meteorological properties (Crockford & Richardson, 1990). Canopy interception loss ranges from 10% to 40% of gross rainfall in natural forests (Zinke, 1967) and may even exceed 50% (Calder, 1990). Redistribution of throughfall and stemflow by canopies modifies evaporation, which plays an important role in water balance on local and catchment scales (Herbst et al., 2006, 2007). Both throughfall and stemflow have an important influence on the hydrological budget of forest ecosystems. The solute composition of rain also affects soil chemistry, nutrients and pollutants, soil moisture gradients, ground water recharge, soil erosion and the location of epiphytes (Ahmadi et al., 2009).

Other than influencing the hydrological budget, rainfall interception also contributes to weather pattern (Amell et al., 2002). Evaporation rates, for instance, are higher in forests than in short vegetation due to the former's higher aerodynamic conductance compared to that of the latter (Rutter, 1967; Stewart, 1977; Calder, 1979). Therefore, knowledge of the rainfall partitioning process is needed to predict the hydrological effects of a site. The importance of hydrology has received more attention after the mid-20th century (Ward & Elliot, 1995).

Many interception models, such as the numerical, analytical and stochastic simulation models, have been developed to predict interception loss (Herbst et al., 2006) to understand the water balance in a particular location. Muzylo et al. (2009), who reviewed several rainfall interception models, remarked that only three models out of 15 models are widely used today. This is because most rainfall models are data demanding and have intensive and complex calculations.

Hence, one of the questions that shaped this study was: *Can net rainfall be predicted by using only a single equation for different types of closed canopy without requiring detailed or intensive measurement and information?* The main objective of this study was to develop and validate a two- and a three-coefficient equation for rainfall partitioning parameters (throughfall, stemflow and net rainfall) under three nearly closed canopies of pine, oil palm and rubber.

MATERIALS AND METHOD

Development of the Three-Coefficient Equation for Net Rainfall

Net rainfall is assumed to decrease exponentially with increasing values of an empirical coefficient called G-factor. This can be described as:

$$Pn = Tf + Sf = Pg * \exp(-G) \qquad [2]$$

where, Pn is the net rainfall (mm), Tf is the throughfall (mm), Sf is the stemflow (mm) and Pg is the gross precipitation (mm). The smaller the G, the greater the increase of the Pn, following an exponential function (Figure 1). Furthermore, it is assumed that G is related to gross rainfall, Pg, by a rectangular hyperbola relationship (Figure 1). G ranges between two extremes, G_{min} and G_{max}, so that with increasing gross rainfall (Pg), G decreases according to Eq. [3]:

$$G = G_{max} - \frac{Pg}{(C+Pg)} *(G_{max} - G_{min}) \qquad [3]$$

where, G_{max} , G_{min}, and C are empirical coefficients obtained by minimising the error between fitted and observed values using the Microsoft Excel add-in called Solver (Microsoft Corp, Redmond, Washington, USA).

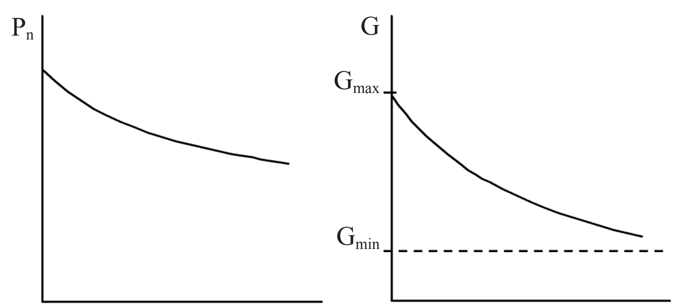

Figure 1. Three-coefficient equation: Net rainfall (Pn) is assumed to decrease exponentially with increasing value of a parameter called G which, in turn, follows a rectangular hyperbola relationship with gross rainfall (Pg). G varies between two extreme values denoted by G_{min} and G_{max}

The Two-Coefficient Equation for Net Rainfall

In addition to the three-coefficient equation for net rainfall, a two-coefficient equation, which is a linear regression equation, was also derived. The purpose of this derivation was to check whether a single-linear regression equation could be used for estimating net rainfall for various canopies.

Assumptions and Limitations of the Equations

These two equations do not take into account detailed information such as age of tree, leaf area index, canopy characteristics, stem characteristics, rainfall characteristics (amount, intensity and duration), wind speed and direction, temperature and other meteorological parameters. The two equations in this study are applicable only for nearly- to fully-closed canopy stands. The only input required is the daily gross precipitation.

Validation of Equations

Equation [2] and [3] were tested on seven studies selected from literature. These studies were selected because they provided raw data on rainfall partitioning (Table 1). Two error indices were used to measure the goodness-of-fit of these two equations. These indices were the index of agreement, d (Willmott et al., 1985; Legates & McCabe, 1999), and the normalised mean absolute

Table 1
Seven studies used to derive the two- and three-coefficient equations

Reference	Tree	Age (years)	LAI (m^2m^{-2})	Location	No. of Rain Days	Range for Pg (mm)	% I of Pg	% Tf of Pg	%Sf of Pg
Bentley (2007)	Oil palm (*Elaeis guineensis*)	8	NA+	Skudai Johor, Malaysia (1°43´N; 103°32´E)	55	2.50-98.40	41.08	56.93	1.99
Damih (1995)	Oil palm	NA	NA+	Skudai Johor, Malaysia	31	0.50-39.50	33.29	63.81	2.90
Lubis (unpublished data)	Oil palm	15	6.0	Pekan baru, Indonesia (0°32′0″N; 101°27′0″E)	252	0.50-153.00	29.62	68.82	1.56
Zulkifli et al. (2006)	Oil palm	8	NA+	Skudai Johor, Malaysia	21	0.20-36.32	32.17	65.10	2.73
Germer et al. (2006)	Tropical rainforest	NA	5.4	Rondonia, Brazil (10°18´S; 62°52´W)	97	0.50-78.23	2.38	89.81	7.81
Loustau et al. (1992)	Maritime Pine (*Pinus pinaster*)	22	3.0	Bordeaux, France (0°46´W; 44°-42´N)	32	0.30-62.70	17.38	79.07	3.55
Zulkifli et al. (2003)	Rubber (*Hevea brasiliensis*)	35	NA+	Skudai Johor, Malaysia	28	2.55-54.43	12.13	86.73	1.14
						Average	24.00	72.90	3.10

+ Mature trees, NA = not measured, I = Interception loss, Tf = Throughfall, Sf = Stemflow, Pg = Gross rainfall error, NMAE. The second error index used was a modified form of MAE index (mean absolute error) from Legates and McCabe (1999). The estimated Pn from Eq. [2] and [3] were compared with field measurements and validated by these two error indices.

Normalized Mean Absolute Error, NMAE index is given by

$$NMAE = \frac{\frac{\sum_{i=1}^{N}|P_i - O_i|}{N}}{M_o} * 100 \qquad [4]$$

where, P_i and O_i are the predicted and observed values, respectively; N is the number of observation, and; M_o is the mean observed values. NMAE is given in percentage. The lower the NMAE value, the more accurate the model's estimations. According to Jamieson et al. (1991), the overall prediction accuracy can be defined as "Great" when the NMAE ranges from 0 to 10%, "Good" from 10% to 20%, "Fair" from 20% to 30% and "Poor" for greater than 30%.

Index of agreement, d, is given by

$$d = 1 - \frac{\sum_{i=1}^{N}|y_i - \hat{y}_i|}{\sum_{i=1}^{N}\left(|\hat{y}_i - \bar{y}| + |y_i - \bar{y}|\right)} \qquad [5]$$

where, y_i, $\hat{y}_i$ and $\bar{y}$ are the value of measured, value of estimated and average of measured, respectively. The error index ranges from 0 (worst fit) to 1 (perfect fit). The higher the d value, the lower the overall prediction error.

Field Studies

Field data collections were carried out at three sites; each site had different tree crops. The tree canopies were nearly closed. The trees were pine (*Pinus caribaea*), oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*). A description of the sites is given in Table 2.

Table 2
Description of the three field sites in this study

	Pine	Oil Palm	Rubber
Location	Serdang, Selangor (03°00.067'N, 101°43.392'E)	Jengka, Pahang (03°53.882'N, 102°31.972'E)	Sungai Buloh, Selangor (03°09.502'N, 101°33.479'E)
Age of Trees, Years	28	12	26
Hill Slope, %	15	0-1	0-1
Mean Elevation, m	58	61	41
Planting Density, Trees ha^{-1}	1736	136	450
Planting Distance, m	2.4 x 2.4	8 x 8 x 8	5.5 x 2.8
Mean Height of Tree, m	26	6	12
Mean Canopy Diameter, m	4.4	14.0	13.0
Leaf Area Index (LAI), m^2m^{-2}	4.4	4.2	3.1
Mean Trunk Circumference (at breast height), m	0.9	2.6	1.0

Rain gauges (Spectrum Technologies, Inc., USA) based on the tipping-bucket concept with resolution of 0.254 mm of rain were used for rainfall measurement. The rain collector had an opening diameter of 205 mm. To avoid rain water splashes from the ground, the rain gauge was screwed on a metal rod, which was hammered into the ground. The distance between the gauge and the ground was about 1 m. The rain gauge was connected to a data logger, which gave data in 1 decimal point, for the recording of rainfall parameters (throughfall, stemflow and gross rainfall) at five-minute intervals.

For throughfall measurement, 10 rain gauges were arranged along a straight line in North-South direction at a 10-m distance between every two gauges, while for stemflow measurement, three sampled trees were selected randomly. The bark of selected trees were gently removed to fix a rubber collar and sealed with nails and bitumen to direct stemflow into the rain gauge. Finally, for collecting gross precipitation above the canopies, another rain gauge was installed in a nearby open area that was not hindered by tall plants and buildings. It was taken as representative of the gross precipitation (above canopies) at the experiment sites.

RESULTS AND DISCUSSION

Derivation of the Coefficient Values for the Two Equations for Net Rainfall

Table 1 reports the rainfall partitioning of seven studies. The number of rain days ranged from 28 to 252 days and daily rainfall from as low as 0.30 to as high as 153 mm was recorded. This provided data with a good range from low to heavy rainfall.

An average of 63.67% from gross rainfall contributed as throughfall and 2.30% as stemflow for oil palm. At the forest sites, throughfall contributed about 79.07% and 89.81% at maritime pine and tropical rainforest, respectively, whereas stemflow was 3.55% and 7.81%, respectively. Lastly, throughfall was 86.73% and stemflow, 1.14% at the rubber site.

Results from the seven studies were used to fit the three-coefficient equation of Eq. [3]. The coefficients were fit using the Solver add-in (a component of Excel) in Excel by minimising the mean differences between the estimated and measured values. Those data were compiled and analysed, and the values for G_{max}, G_{min}, and C were found to be 0.3443, 0.1804 and 58.9748, respectively. The equations were thus:

$$Pn = Pg * \exp(-G) \quad [6a]$$

$$G = 0.3443 - \frac{Pg}{58.9748 + Pg} * (0.3443 - 0.1804) \quad [6b]$$

$$\therefore Pn = Pg * \exp\left[-\left(0.3443 - \frac{Pg}{58.9748 + Pg} * 0.1639\right)\right] \quad [6c]$$

A two-coefficient equation (linear regression) was also derived from the same set of data (seven studies combined). The equation was:

$$Pn = 0.7724Pg - 0.5845 \quad (R^2 = 0.91) \quad [7]$$

Accuracy of the Two- and Three-Coefficient Equations for Net Rainfall

The accuracy of the two equations, Eq. [6] and [7], was tested on the individual data set from the seven studies (Table 1). The error indices, NMAE and d in Eq. [4] and [5], were used as a goodness-of-fit measure for both equations.

Figure 2 and 3 show the overall prediction accuracy for the two equations for all the seven studies. The NMAE of the three-coefficient equation was 19.86%, which is in the "Good" prediction accuracy range, and the d value 0.88 (Figure 2). The NMAE of the two-coefficient equation was 20.10%, which was in the border between "Good" and "Fair", and the d value was the same as that of the three-coefficient equation, 0.88 (Figure 3). The two net rainfall equations' errors were similar, but the three-coefficient equation was slightly more accurate than the two-coefficient equation. This is because the three-coefficient equation for net rainfall is more flexible in representing the distribution of data, as it has three coefficients, whereas the other equation had only two coefficients.

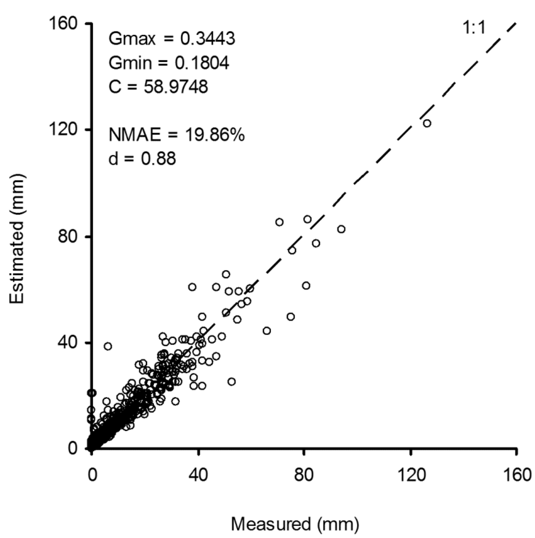

Figure 2. Derivation of the three-coefficient equation, Eq. [3], for net rainfall, where G_{max} = 0.3443, G_{min} = 0.1804 and C = 58.9748. NMAE and d are the normalised mean absolute error and the index of agreement, respectively. The dash line (1:1) is the line of agreement

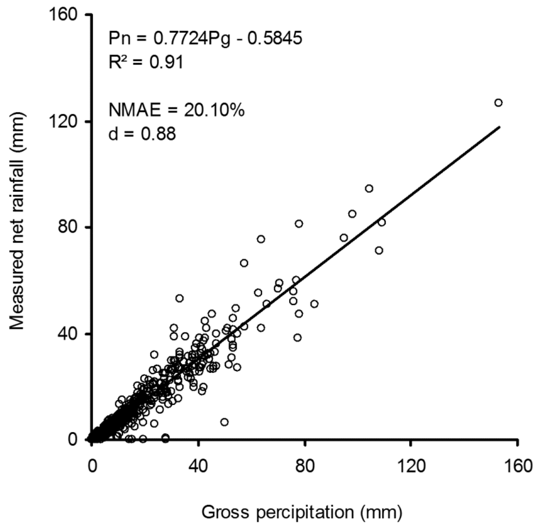

Figure 3. The two-coefficient equation between measured net rainfall (Pn) and gross rainfall (Pg). NMAE and d are the normalised mean absolute error and the index of agreement, respectively. The solid line is the linear regression

Table 3 shows the degree of accuracy when Eq. [6] and [7] were tested on the individual seven studies. The mean errors (NMAE and d) for the two- and three-coefficient equations were nearly the same, showing that the performance of the simpler two-coefficient equation was equal to that of the slightly more complex three-coefficient equation.

Table 3
Average errors for the two- and three-coefficient equations for estimating the net rainfall (Pn)

Reference	Tree	Three-Coefficient Equation		Two-Coefficient Equation	
		NMAE, %	d	NMAE. %	d
Bentley (2007)	Oil Palm	30.70	0.81	30.16	0.82
Damih (1995)	Oil Palm	21.44	0.89	19.86	0.90
Lubis (Unpublished data)	Oil Palm	15.58	0.91	15.96	0.91
Zulkifli et al. (2006)	Oil Palm	33.72	0.83	34.19	0.83
Germer et al. (2006)	Tropical Rainforest	27.26	0.85	27.90	0.84
Loustau et al. (1992)	Maritime Pine	15.16	0.88	15.47	0.87
Zulkifli et al. (2003)	Rubber	15.14	0.86	15.54	0.86
	Average	22.72	0.86	22.73	0.86

NMAE = Normalised Mean Absolute Error, d = Index of agreement

The average NMAE and d value for the three-coefficient equation at the oil palm sites were 25.36% and 0.86, respectively. However, the average NMAE for the two-coefficient equation at the oil palm sites was slightly better at 25.0%, while the d value was 0.87. For forest sites (Maritime pine and tropical rainforest), the three-coefficient equation performed slightly better than the two-coefficient equation, giving a reading of was 15.16% versus 15.47% for Maritime pine and 27.26% versus 27.90% for tropical rainforest. However, this was not the case for the d value. For the rubber sites, same as for the forest sites, the NMAE for the three-coefficient equation was slightly better at 15.14% than for the two-coefficient equation, 15.54%; the d values for both equations were the same.

Estimation of Throughfall and Stemflow Component:

This study also attempted to estimate Tf and Sf separately using the general equation form of Eq. [6] and [7] based on the methods described previously. Both the Tf and Sf equations are summarised below.

The three-coefficient equation:

$$Tf = Pg * \exp\left[-\left(3.9100 - \frac{Pg}{0.1089 + Pg} * (3.9100 - 0.3016)\right)\right] \quad [8]$$

$$Sf = Pg * \exp\left[-\left(4.0771 - \frac{Pg}{2.3328 + Pg} * \left(4.0771 - 3.8837\right)\right)\right] \quad [9]$$

The two-coefficient equation:

$$Tf = 0.7511Pg - 0.6790 \quad (R^2 = 0.91) \quad [10]$$

$$Sf = 0.0213Pg + 0.0946 \quad (R^2 = 0.28) \quad [11]$$

Most of the R^2 for the stemflow linear regression equation was high in the seven individual studies. However after combining the studies, the two-coefficient equation for stemflow gave a low value of R^2 (Eq. 11). This might have been due to the difference in tree morphology (trunk texture, trunk diameter, branch inclination degree, bark roughness, leaf architecture and leaf zenith angle distribution) that influenced the production of stemflow at the same gross precipitation amount received (Ward & Robinson, 1990; Xiao et al., 2000).

Accuracy of the Throughfall and Stemflow Equations

The equations above were tested again on the previous studies to check the accuracy of estimating throughfall or stemflow itself. Table 4 shows the error indices for Tf and Sf for the two- and three-coefficient equations for each individual study. The estimation of Tf for oil palm had the highest error (highest NMAE and lowest d), while Sf had a more varied error range. However, the average NMAE for both Tf equations were in the range of "Fair" and the d values

Table 4
Average 4rrors for the two- and three-coefficient equations for estimating throughfall (Tf) and stemflow (Sf)

Reference	Tree	Three-Coefficient Equation				Two-Coefficient Equation			
		NMAE, %		d		NMAE, %		d	
		Tf	Sf	Tf	Sf	Tf	Sf	Tf	Sf
Bentley (2007)	Oil Palm	31.24	9.70	0.81	0.93	30.55	26.58	0.82	0.80
Damih (1995)	Oil Palm	22.46	44.30	0.87	0.72	20.60	39.35	0.88	0.73
Lubis (Unpublished Data)	Oil Palm	16.07	110.70	0.78	0.30	16.49	128.56	0.74	0.45
Zulkifli et al. (2006)	Oil Palm	34.19	49.87	0.83	0.72	34.67	67.68	0.83	0.59
Germer et al. (2006)	Tropical Rainforest	25.15	74.24	0.86	0.55	25.97	65.21	0.86	0.58
Loustau et al. (1992)	Maritime Pine	13.56	54.74	0.89	0.60	14.78	55.41	0.88	0.56
Zulkifli et al. (2003)	Rubber	16.38	77.80	0.85	0.61	17.40	129.99	0.84	0.43
	Average	22.72	60.19	0.84	0.63	22.92	73.26	0.84	0.59

NMAE = Normalised Mean Absolute Error, d = Index of Agreement

showed low average estimation errors. These Tf equations were further tested on field experiments. For Sf equations, both NMAE and d values showed high average estimation errors. These Sf equations would be further tested to check their accuracy using the field experiments.

Field Studies

A total of 47, 33 and 28 rain days were recorded at the pine, oil palm and rubber sites, respectively. Table 5 indicates that interception loss ranged from 18 to 23%, throughfall from 65 to 81% and stemflow up to 3% of total gross rainfall for these three crops.

Table 5
Total precipitation, throughfall, stemflow and average rainfall under three test crops for duration of study

Parameter	Pine	Oil Palm	Rubber
Duration of Study (day)	60	85	57
No. of Rain Days Used in Study (day)	47	33	28
Total Gross Precipitation (mm)	623.90	291.40	335.40
Total Throughfall (mm)	506.68	203.21	217.94
Total Stemflow (mm)	4.22	8.53	1.30
Throughfall as % of Rainfall	81.21	69.74	64.98
Stemflow as % of Rainfall	0.68	2.93	0.39
Interception Loss as % of Rainfall	18.11	27.33	34.63
Maximum Precipitation (mm)	74.7	57.4	44.7
Minimum Precipitation (mm)	0.3	0.3	0.2
Average Rainfall per Rain Day (mm)	13.3	8.8	12.0

Rainfall Partitioning at Pine, Oil Palm and Rubber Sites

Pine had the lowest interception loss among the three crops, 18% of total gross precipitation. This was similar to that reported by Loustau et al. (1992), who obtained 13-21% interception loss for maritime pine in Bordeaux, 17% for a pine forest in central Portugal (Valente et al., 1997), 19% for a pine forest in Mexico (Cantu-Silva & Rodriguez, 2001), 17.6 and 22% for a pine plantation and mature pine forest, respectively, in the US (Bryant et al., 2005). In Portugal, a sparse pine forest recorded 17% interception loss, which was higher compared to the 11% recorded at a sparse eucalyptus forest. This may have been due to the higher canopy storage capacity and the larger aerodynamic conductance resulting from the greater height of the ground at the pine forest (Valente et al., 1997).

Throughfall for pine was 81% of total gross precipitation, which was similar to that obtained by Bryant et al. (2005) (77 to 81%) and within the range of the study of Loustau et al. (1992), 77-83%. For stemflow, the study of Bryant et al. (2005) on maritime pine obtained 0.5%, which was close to this study of 0.7%, but slightly lower than that obtained at the pine plantation (1.96%) and by Loustau et al. (1992), (1-6%). These differences may have been due to tree age and tree spacing. Teklehaimanot et al. (1991) reported that Sitka spruce, in a 2-m tree spacing treatment (close stands), had higher stemflow (17%) than in 4-m (2.9%), 6-m (10%) and 8-m spacing (0.5%). The larger number of trees per unit ground area in the 2-m spacing treatment resulted in the overlapping of the tree crowns; thus, when the rain was intercepted by the upper branches of tree, there were several layers of canopy for the rain to drip through, resulting in a higher chance of water being conducted towards the trunk as stemflow. Similar tree sizes may receive up to three times the stemflow amount at 2-m spacing than at 8-m spacing. Teklehaimanot et al. (1991) further clarified that their lower stemflow was only 17% compared to that obtained by Ford and Deans (1978), 27%, because of tree age. The younger trees in Ford and Dean's study meant that the branches were steeper, leading to a larger volume of stemflow.

The rubber site in this study recorded the highest interception loss with 35% of total gross precipitation. This was different from the results reported by Teoh (1977) and Zulkifli et al. (2003), whose studies reported that interception loss was only 12% and about 15-16%, respectively, of total gross precipitation.

Dinata (2007) studied net rainfall under rubber trees at three ages, 10, 15, and 25 years old, and with planting distance 3 x 3.3 m in Sumatera. He reported that interception loss was 31.5, 40.7 and 51.8% at age 10, 15 and 25 years old, respectively. The study showed that canopy storage capacity can be estimated from canopy area and canopy density. Age of tree is the main factor that influences canopy density. In the study, the author cited Pramono and Ginting (1997) that the denser the canopy, the higher the intercepted amount of rain. The 10-year-old canopy area was small, 52.9 m^2, compared to that of the 15-year-old (95.2 m^2) and 25-year-old (126.9 m^2). Therefore, canopy storage capacity at age 25 years old is expected to be higher than that at 15 and 10 years old, and interception loss is expected to be higher for rubber trees at age 25. The age of tree and planting distance may explain the reason interception loss in this study (35%) was closer to that in Dinata's study for 10-year-old rubber trees (31.5%) and 17% lower for the same age range (25 years old) and higher than the figures recorded in Zulkifli (12%) and Teoh's (15-16%) studies.

Throughfall at the rubber site obtained 65% of total gross precipitation, which was close to that obtained for Dinata's 10-year-old trees (60.6%) but higher than for the 25-year-old trees (43.8%) and lower than recorded in Zulkifli's study (87%, 36 years old). According to Dinata (2007), throughfall amount is inversely related to tree age. This means that when a tree becomes older, canopy storage capacity increases with increasing dimension canopy, and as such, the throughfall amount decreases. However, when older trees reach a certain threshold, they tend to leave larger canopy gaps due to their having more branches and their higher leaf death rate; as such, the throughfall amount increases instead (Pypker et al., 2005). Stemflow in this study (0.4%) was similar to that recorded by Zulkifli (1.1%) but different from that obtained by Dinata's study on 25-year-old trees (4.4%).

In this study, the rubber site showed the highest interception loss compared to the other tree sites probably due to differences between tree types in terms of canopy storage capacity (Loustau et al., 1992). The rubber trees had a storage capacity of 0.682 mm, the pines, of 0.656 mm and the oil palms, of 0.515 mm. Other possible explanations could be the difference between tree types in terms of their vegetal morphology, leaf arrangement along the branches and stem surface area (Ward & Robinson, 1990; Xiao et al., 2000).

Interception loss at the oil palm site was 27% of total gross precipitation. Kee et al. (2000) reported interception loss by 11-17% in the oil palm study in Malaysia (estimated by difference between gross rainfall and net rainfall). However, some Malaysia studies indicated interception loss of 32-41% and 29.6% in Indonesia, readings that were more similar to those obtained in this study. Banabas (2007) remarked that these differences may have some relevance to the acutely-angled leaves in redistribution of rainfall during high and low crop seasons. In low crop season, fronds are generally at an acute angle as palms go through a male phase, resulting in generating more stemflow. In contrast, in high-crop season, fronds are pulled down by heavy fruit bunches, causing a less acute angle between the fronds and trunk. This was where intercepted rain water was mostly intercepted, held up by the bunches, frond buds and the trunk, although the frond pinnae intercepted only a small amount of rain water. Therefore, more rain water was intercepted, generating less rain as stemflow (Banabas, 2007).

Throughfall accounted for 70% of Pg, similar to the findings of a study by Kee et al. (2000), who found that 70-78% of rainfall would turn to throughfall in oil palm in Malaysia and 72-104% in Papua New Guinea (Banabas, 2007); this was slightly higher compared to findings of other oil palm studies, which ranged between 57 and 69%. On the other hand, stemflow was also slightly higher (2.9%) than 2.0-2.7% in Malaysia studies. However, Kee et al. (2000) reported stemflow at 11-13% in Malaysia and Banabas (2007), at 10-14% in Papau New Guinea. As mentioned earlier, the variation in interception, throughfall and stemflow fractions could be linked to oil palm fruit bunch production seasons.

Validation of Throughfall and Stemflow Equations, NMAE and d

The three-coefficient equation [Eq. 8] and two-coefficient equation [Eq. 10] for throughfall were tested on the data obtained from the three field sites (Table 6). NMAE for the three-coefficient equation for throughfall was in the range of "Good" for the three data sets. The same rankings were obtained for the two-coefficient equation for throughfall except for oil palm, which was in the range of "Fair". The d value for both equations represented the same agreement. The three-coefficient equation showed slightly better results compared with the simpler two-coefficient equation. The use of the three-coefficient, Eq. [9], and the two-coefficient, Eq. [11], equations for stemflow, both seemed to register doubtful readings for NMAE and d for stemflow estimation. As mentioned earlier, the R^2 for Eq. [11] was low after the results of the seven studies were combined; this was probably due to the difference in tree morphology, rainfall intensity and the macro and microclimate. When these stemflow equations were further tested on field experiments, high error and low confidence levels were recorded.

Validation of Net Rainfall Equations, NMAE and d

Table 6 and Figure 4 indicate that the three-coefficient equation's NMAE for pine, oil palm and rubber were 12.13, 19.18 and 20.54%, respectively. This classified the three-coefficient equation's accuracy as "Good" for pine, oil palm and rubber. For the two-coefficient equation, NMAE was 12.10, 22.65 and 19.99% at the pine, oil palm and rubber sites, respectively. These readings were close to those obtained by the three-coefficient equation's NMAE. The d values for both equations were the same at the respective sites. The NMAE and d for the two- and three-coefficient equations used for the three crops were not that much different from one another.

Table 6
Accuracy of throughfall (Tf), stemflow (Sf) and net rainfall (pn) for the two-coefficient equation (2CE) and the three-coefficient equation (3CE) at pine, oil palm and rubber site

	Pine	Oil Palm	Rubber	Average
Tf				
NMAE (3CE)	13.48	19.18	19.49	17.38
NMAE (2CE)	14.42	23.32	19.88	19.21
d (3PE)	0.93	0.92	0.91	0.92
d (2PE)	0.92	0.90	0.91	0.91
Sf				
NMAE (3CE)	197.87	94.33	419.21	237.14
NMAE (2CE)	320.23	109.87	651.65	360.58
d (3PE)	0.49	0.62	0.31	0.47
d (2PE)	0.32	0.61	0.19	0.37
Pn				
NMAE (3CE)	12.13	19.18	20.54	17.28
NMAE (2CE)	12.10	22.65	19.99	18.25
d (3PE)	0.94	0.92	0.91	0.92
d (2PE)	0.94	0.90	0.91	0.92

Accuracy class for NMAE: Great (0-10%); Good (10-20%); Fair (20-30%); Poor (>30%)

Figure 4 shows a tight clustering of points along the line of agreement, especially for low to medium rainfall events. At heavier rainfall events, the three-coefficient equation, however, tended to be underestimated. This was similar to situations using the two-coefficient equation.

Equations for Oil Palm and Rubber

In Malaysia, oil palm and rubber are major crops. Table 7 shows the percentage of rainfall partitioning and the equation coefficients and error indices for oil palm and rubber. Those equations were derived using data from previous studies (oil palm and rubber in the seven previous studies) and field experiments (oil palm and rubber). For oil palm, 63% of Pg was throughfall, 5% was stemflow and about 68% was net rainfall. For rubber, 66% of Pg was throughfall, 0.5% was stemflow and net rainfall was 66%. The two- and three-coefficient equations estimated both oil palm and rubber in the rank of "Good" (with an index of agreement of about 90%). The two- and three-coefficient equations performed nearly equally well.

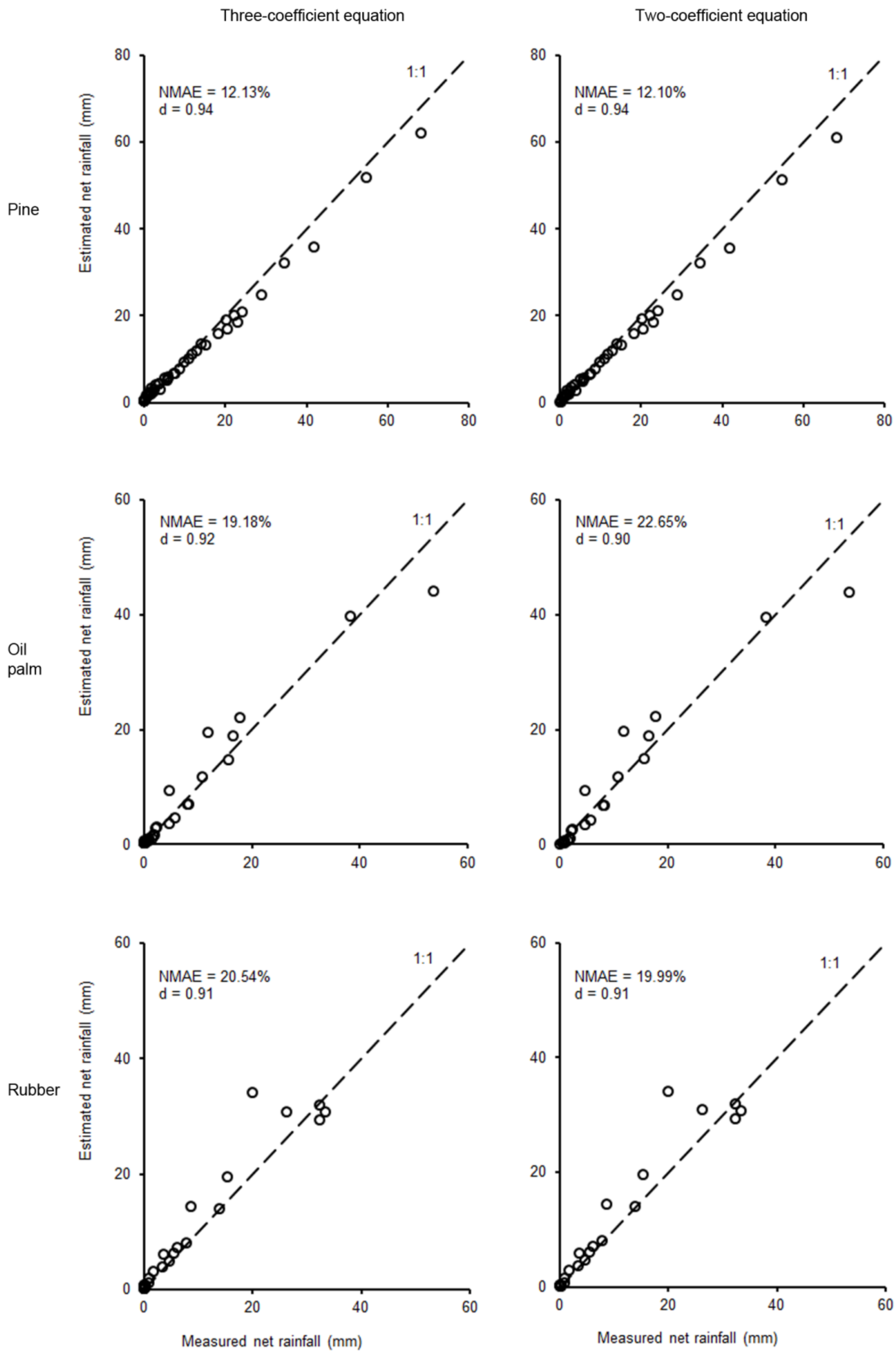

Figure 4. Error indexes for the two-coefficient equation (2CE) and the three-coefficient equation (3CE) for net rainfall at (a) pine, (b) oil palm, and (c) rubber sites. NMAE and d are the normalised mean absolute error and the index of agreement, respectively. The line of dashes (1:1) is the line of agreement

Table 7
The two- and three-coefficient equations for oil palm and rubber

		Oil Palm			Rubber		
		Tf	Sf	Pn	Tf	Sf	Pn
Two-Coefficient Equation	% of Pg	62.81	5.11	67.92	65.70	0.51	66.21
	bo	-1.023	0.117	-0.906	-0.377	-0.038	-0.415
	b1	0.718	0.013	0.731	0.809	0.011	0.820
	NMAE	19.66	93.80	19.06	13.96	57.48	14.16
	d	0.89	0.46	0.89	0.92	0.73	0.91
Three-Coefficient Equation	Gmin	0.362	3.925	0.370	0.160	3.983	0.101
	Gmax	2.149	14.448	4.478	4.136	7.281	2.930
	C	0.094	0.213	0.010	0.184	9.387	0.908
	NMAE	18.69	85.29	18.54	12.88	48.23	13.76
	d	0.89	0.58	0.89	0.92	0.77	0.92

Accuracy class for NMAE: Great (0-10%); Good (10-20%); Fair (20-30%); Poor (>30%)

CONCLUSION

Two- and three-coefficient equations for measurement of rainfall were successfully developed based on seven studies recorded in the literature and validated for each individual study against measured data from three field data collections. Two error indices (NMAE and d) were used in the goodness-of-fit measure for equations. Both net rainfall equations estimated the studies to have an average of NMAE=23% (Fair) and d=0.86; both throughfall equations estimated an average of NMAE=23% (Fair) and d=0.84; and the stemflow equations estimated an average of NMAE=60 and 73% (Poor) and d=0.63 and 0.59. In field experiments, the three-coefficient equation for net rainfall and throughfall performed slightly better than the two-coefficient equations in NMAE (12-21%) and were similar in d value. However, the two-coefficient equation was fairly accurate in estimating net rainfall for closed to nearly closed canopies with an error of NMAE=12-23%. Equations for estimating stemflow had high error. However, stemflow only contributed a small portion of the gross precipitation.

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