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Evaluation of the Gash Rainfall Interception Model in Forest Plantations

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Abstract: Interception modeling, an important part of hydrological modeling, can be used to determine water balance, infiltration processes, the function of vegetation in reducing rainfall, and the hydrological function of vegetation. This study aims to simplify Gash's model and evaluate its performance compared with the Gash model and revised Gash model in forest plantations of teak (*Tectona grandis*) and *Maesopsis eminii*. The performances of these three models of the Gash model (GM), revised Gash model (RGM), and simplified Gash model (SGM) were measured by comparing the models to the observed interception. The observed interception was calculated on the basis of daily gross rainfall, stemflow, and throughfall measurements. Canopy interception of the simplified Gash model gives the closest result to the measured canopy interception compared to the Gash model and revised Gash model. The average field-measured canopy interception of teak and young and old *Maesopsis eminii* forest plantations was 42%, 38%, and 39% of 1451-mm rainfall, respectively. The average canopy interception based on the GM, RGM, and SGM were 30%, 32%, 38%, and 42% (for teak plantation), 7%, 7%, 35%, and 38% (for young *Maesopsis eminii* plantation), and 14%, 15%, 35%, and 39% (for old *Maesopsis eminii*), respectively. The canopy interception differences between SGM and field-measured canopy interception in teak and young and old *Maesopsis eminii* plantations were 4% (59.7 mm), 3% (52.8 mm), and 3.7% (54.1 mm).

Keywords: interception, the Gash model, forest plantation, *Tectona grandis*, *Maesopsis eminii*.

人工林伤口降雨截留模型的评价

摘要：截留模型是水文模型的重要组成部分，可用于确定水平衡、入渗过程、植被减少降雨的功能以及植被的水文功能。本研究旨在简化伤口模型，并评估其与伤口模型和修正的伤口模型在柚木（柚木）和曼氏紫草人工林中的性能比较。通过将模型与观察到的拦截进行比较来测量伤口模型(通用汽车)、修正的伤口模型(RGM)和简化的伤口模型(新加坡通用汽车公司)这三种模型的性能。观测到的拦截量是根据每日总降雨量、茎流和径流测量值计算的。与伤口模型和修正的伤口模型相比，简化的伤口模型的冠层截距给出了与测量的冠层截距最接近的结果。实地测量的柚木人工林和幼龄和老龄红豆杉人工林的平均树冠拦截量分别为14

51毫米降雨量的42%、38%和39%。基于通用汽车、RGM和新加坡通用汽车公司的平均冠层截获量分别为30%、32%、38%和42%（柚木种植园）、7%、7%、35%和38%（幼龄曼氏紫草种植园)和14%、15%、35%和39%（对于老曼氏紫草）。在柚木和年轻和老的柚木人工林中，新加坡通用汽车公司与实地测量的冠层截取率差异分别为4%（59.7毫米）、3%（52.8毫米）和3.7%（54.1毫米）。

关键词：拦截，伤口模型，人工林，柚木，曼氏紫草。

1. Introduction

Interception is defined as precipitation stored in the tree canopy and evaporating without reaching the ground. Part of the rainwater reaches the ground by flowing along the stem (stemflow), and the throughfall enters the soil during infiltration and becomes runoff [11]. Interception is one of the hydrological mechanisms that affect the water storage capacity on the surface [17] and the water content in the soil [10, 14]. Interception can vary significantly because of wind, canopy structure, duration, and rainfall intensity [18].

Various conceptual models have been developed for model interception. Several widely used intercept models are the Rutter, Gash, Massman, Mulder, Xiao, Zeng, van Dijk, and Bruijnzeel, Murakami, Calder, and Liu models [4, 7, 15]. Conceptual models have advantages over empirical regression models because they can estimate the components of interception loss during a storm or after rainfall stops [1]. The Gash model is the most widely used because it is simple (simplifies the parameters in the Rutter model), has minimal data requirements, and can represent special situations, such as high evaporation conditions [7]. The Rutter model is good at modeling hourly interceptions, whereas the Gash and Liu model is more suitable for modeling daily interceptions [4].

The estimation of forest interception is mainly done using the Gash model. Gash [8] provides a physical-based interception formula by assuming that rainfall occurs in separate events consisting of wetting, saturation, and drying periods after the rain stops. An important assumption of the Gash model [8] is that the ratio of the average evaporation rate to the average rainfall intensity is constant, and the values derived from some storms represent other storms. The model was later revised by [9].

Gash et al. [9] revised the Gash model [8] with the following basic assumptions: (1) rainfall occurs continuously with rainy periods intervals not enough causing the canopy and stem to dry out; (2) meteorological conditions during canopy saturation are assumed to be the same for all rainfall events or the average rainfall and evaporation conditions can represent all rainfall and evaporation data; (3) there is no throughfall during the canopy saturation process and the water in the canopy after rain decreases rapidly (20-30 minutes) until the smallest water holding capacity is reached.

The simplified Gash model [9] focuses on (1) the interception sub-model of rain that is less than the rainfall that saturates the canopy (I_S), (2) interception of rain that more than saturates the canopy (I_b); (3) evaporation assumed to be zero, which assumes that evaporation is included in the interception; (4) additional parameters related to vegetation suitability (*Vf*) in the canopy interception sub-model (I_S) to represent the data with rainfall and vegetation characteristics.

This study evaluates interception based on the Gash model in forest plantations. The interception was calculated by comparing the interception from field data with the interception based on the Gash model (GM), revised Gash model (RGM), and simplified Gash model (SGM) on teak (*Tectona grandis*) and *Maesopsis eminii* hardwood. Interception modeling calculates the net rainfall entering the soil.

2. Materials and Methods

2.1. Study Site

Interception modelling flowchart is presented in Fig. 1. The study location and the distribution of the equipment installation and measurement locations are presented in Fig. 2.

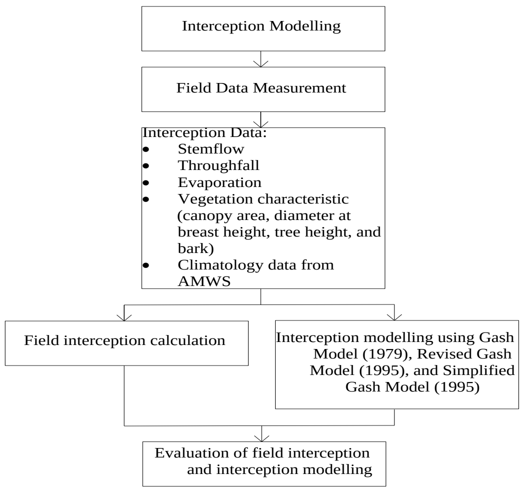


Fig. 1 Interception modeling flowchart (Developed by the authors)

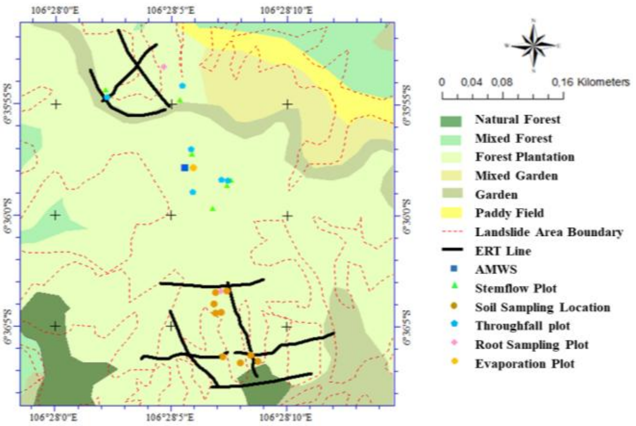


Fig. 2 Distribution of installation locations for tools and measurement locations (Developed by the authors)

2.2. Measurement of the Hydrological Data and Vegetation Characteristics

Hydrological parameters such as throughfall, stemflow, and evaporation were measured in the field. Rain gages, throughfall, and stemflow instruments were installed from December 13, 2020, to April 24, 2021. Daily rainfall intensity was measured using a manual rain gage, and hourly rainfall intensity was measured using an automatic mini-weather station (Fig. 3).

Fig. 3 (a) Manual rain gage and automatic mini-weather stations; (b) manual rain gages in forest plantations; (c) conical funnel instruments (Developed by the authors)

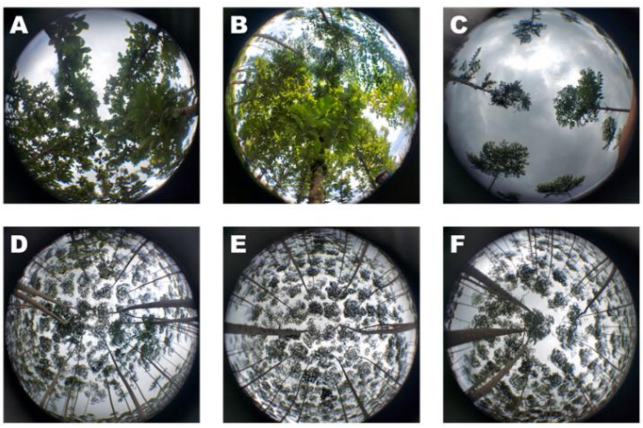


Fig. 4 Canopies taken with a fisheye lens on (a) teak, (b) teak-Maesopsis eminii, (c) young Maesopsis eminii, (d) sympodial old Maesopsis eminii, (e) monopodial old Maesopsis eminii with shrubs > 50 cm, and (f) monopodial old Maesopsis eminii with shrubs < 50 cm (Developed by the authors)

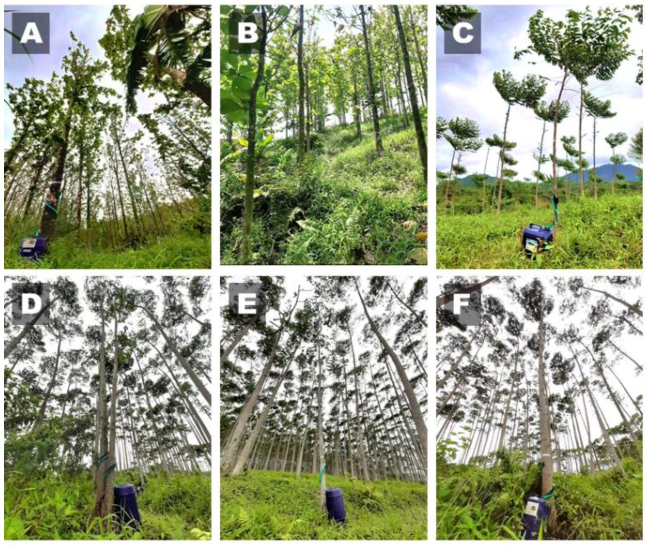


Fig. 5 Installation of a stemflow on (a) teak, (b) sympodial teak, (c) young Maesopsis eminii, (d) sympodial old Maesopsis eminii, (e) monopodial old Maesopsis eminii with shrubs > 50 cm, and (f) monopodial old Maesopsis eminii with shrubs < 50 cm (Developed by the authors)

Vegetation characteristics observed were stem height, DBH, canopy area, stem characteristics, and tree bark [12, 13]. Diameter at breast height (DBH) is measured using a phi band approximately 1.3 m above ground level. The results of the stem circumference are converted to diameter using Equation (1).

$$Diameter\ (cm)=(Circumference\ (cm))/\pi \qquad (1)$$

The canopy area is calculated on the basis of the canopy radius. The canopy area is assumed to be circular and is calculated using Equation (2).

$$Canopy\ area\ (m^2) = \pi \times r^2 (m^2) \qquad (2)$$

Tree height was measured using a Haga hypsometer, and leaf area index (LAI) was measured using a digital hemispherical photography (DHP) approach with a fisheye lens at 0.8 m and 1.8 m above the ground. The shooting point is between the conical funnel instruments. LAI values were obtained from DHP photo analysis using the HemiView 2.1 software.

Stem conditions are distinguished from straight, slightly slanted, and slightly bent, as well as monopodial and sympodial stem conditions. Meanwhile, the bark condition is differentiated smoothly or roughly (Fig. 6).

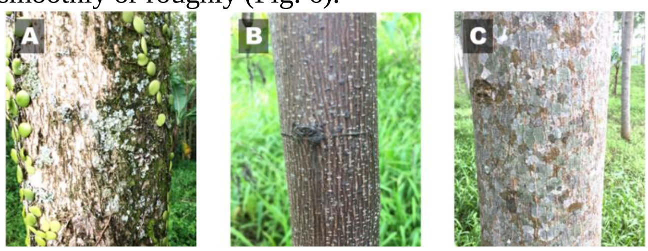


Fig. 6 Bark of (a) teak, (b) young Maesopsis eminii, and (c) old Maesopsis eminii (Developed by the authors)

2.3. Interception Modelling

Estimating interception using the Gash model consists of five submodels (Equation 3).

$$I = (I_{P_G<P_G'}) + (I_{P_G>P_G'}) + I_{ED} + I_{EW} + I_{ES} \quad (3)$$

Table 1 Summary of submodels in the GM, RGM, and SGM (Recapitulation from [8, 9])

No	Submodel	GM	RGM	SGM
1	Interception that is less than the rainfall that saturates the canopy ($I_{P_G<P_G'}$)	$(1-p-p_t)\sum_{j=1}^{m} P_{G.j}$	$c\sum_{j=1}^{m} P_{G.j}$	$Is = \sum_{i=1}^{m} P_{G.i} + Vf$ $Vf = \overline{R} \times LAI$
2	The interception that greater than the rainfall that saturates the canopy ($I_{P_G>P_G'}$)	$n(1-p-p_t)P_G' - nS$	$nc(P_G' - S_c)$	$Ib = n_S \times P_g' s$ $P_g' s = \frac{\sum_{i=1}^{n} P_G - Tf - Sf}{n}$
3	Evaporation interception from wet canopy during rain (I_{EW})	$\frac{\overline{E}}{\overline{R}}\sum_{j=1}^{n}(P_{G.j} - P_G')$	$\frac{c\overline{E_c}}{\overline{R}}\sum_{j=1}^{n}(P_{G.j} - P_G')$	Presumed 0 (zero)
4	Evaporation of interception after rain stops (I_{ED})	nS	$ncSc$	Presumed 0 (zero)
5	Interception of evaporation from the stem (I_{ES})	$qS_t + p_t \sum_{j=1}^{m+n-q} P_{G.j}$	$qS_c + p_t \sum_{j=1}^{n-q} P_{G.j}$	Presumed 0 (zero)

Table 2 Terminology used in the Gash model (Recapitulation from [8, 9])

Name	Definition	Symbol
Gross rainfall	Rainfall measured in open areas or above the forest canopy	P_G
Precipitation threshold	Precipitation that can saturate the canopy	P_G
Throughfall coefficient	Canopy porosity The canopy porosity (p) is the coefficient of the regression line direction between rainfall and throughfall.	p
Stemflow coefficient	The proportion of rainfall on the stem as stemflow	pt
Canopy area	Percentage of area affected by vegetation Functions of LAI	c
Canopy capacity	The residual water above the saturated canopy and throughfall from the canopy has stopped The canopy capacity (S) is the ratio between the total throughfall, and rainfall measured in each observation plot.	S
Canopy capacity unit	Canopy capacity per unit area	S_t
Average evaporation rate	Average evaporation rate	$\overline{E}$
Average rain intensity	Average rainfall intensity	$\overline{R}$
The ratio of average evaporation and rainfall intensity	The regression slope between rainfall and interception	$\frac{\overline{E}}{\overline{R}}$
The rate of average canopy evaporation	The rate of average canopy evaporation	$\overline{E_C}$
Stem capacity	Stem storage capacity Estimated from the regression line between rainfall and stemflow (St). The intercept of the regression line is the stem capacity (mm), while the slope of the regression line is the value of the stemflow coefficient (pt).	St
Big rainfall event	Summarize big rainfall events	n
Rainfall incident	Rainfall events sufficient to saturate the stem	q

The rainfall that saturates the canopy (P_G') used in the GM and RGM is different. Rainfall that saturates the canopy in the GM (P_{GG}') uses Equation (4), and in RGM (P_{GR}') uses Equation (5).

$$P_{GG}' = -\frac{\overline{R}S}{\overline{E}} ln\left[1 - \frac{\overline{E}}{(1-p-pt)\overline{R}}\right] \quad (4)$$

$$P_{GR}' = -\frac{\overline{R}S}{\overline{E}} ln\left[1 - \frac{\overline{E}}{c\overline{R}}\right] \quad (5)$$

Field interception is measured using Equation (1). Stemflow depth is calculated using the following canopy area-based equation:

$$I = P_G - (Tf + Sf) \quad (6)$$

$$Sdcr = \frac{Sy}{A_t} \quad (7)$$

where I is canopy interception (mm), P_G is rainfall (mm), Tf is throughfall (mm), Sf is stemflow (mm), $Sdcr$ is stemflow depth (mm), Sy is contained stemflow volume (liter), and A_t is canopy projection area (m^2).

2.4. Net Precipitation

Net rainfall is a function of stemflow and throughfall, which is calculated using the following equation:

$$P_{G_{netto}} = Tf + Sf \quad (8)$$

Net rainfall is the total rainfall minus interception and evaporation in Teak and Maesopsis eminii forest plantations. The net rainfall equals the total stemflow and throughfall.

3. Results and Discussion

3.1. Vegetation Characteristics

The study location and the distribution of the equipment installation and measurement locations are presented in Fig. 2. The interception was measured in Teak and *Maesopsis eminii* forest plantations with an area of 5.6 and 26.3 ha, respectively, and a spacing of 3 and 2.5 m, respectively. The teak and *Maesopsis eminii* densities are 1111 and 1600 trees/ha, respectively. The characteristics of teak and *Maesopsis eminii* are presented in Table 3. The LAI was obtained on the basis of the canopy density image in Fig. 4.

Table 3 Characteristics of teak and Maesopsis eminii (Primary data collected in 2021; developed by the authors)

Plot	Vegetation	Stem shape	Sample	*DBH* (cm)	Height (m)	Canopy diameter (m)	A_t (m²)	Stem condition	Bark	*LAI*
1	Teak	Monopodial	a	7.64	6.5	1.55	1.89	Straight	Rough	1.2
			b	13.69	11.5	2.54	5.07	Straight	Rough	
			c	22.29	11.5	3.80	11.35	Slightly bent	Rough	
2	Teak	Sympodial	a	16.88	11.0	2.75	5.94	Straight	Rough	2.2
			b	23.57	14.0	3.79	11.29	Slightly slanted	Rough	
3	Young *Maesopsis eminii*	Monopodial	a	4.14	3.0	2.19	3.77	Straight	Slightly rough	0.2
			b	4.78	4.0	1.43	1.61	Straight	Slightly rough	
			c	11.15	5.5	2.70	5.73	Slightly slanted	Slightly rough	
4		Sympodial	a	16.08	12.5	5.87	27.07	Slightly slanted	Slightly smooth	0.7
			b	14.01	11.0	2.22	3.85	Slightly slanted	Slightly smooth	
5	Old *Maesopsis eminii*	Monopodial	a	10.83	6.5	4.18	13.73	Straight	Slightly smooth	0.8
			b	17.20	8.5	1.89	2.81	Straight	Slightly smooth	
			c	17.52	11.5	2.72	5.81	Straight	Slightly smooth	
6		Monopodial	a	8.92	9.5	2.46	4.75	Straight	Slightly smooth	0.8
			b	18.79	10.5	4.21	13.93	Straight	Slightly smooth	

Teak has monopodial and sympodial stems, with straight, slightly slanted, and slightly bent ones, and rough bark (Fig. 6a). Teak has a DBH of 7.64–23.57 cm with a tree height of 6.5–14 m. The canopy diameter and area are 1.55–3.79 m and 1.89–11.35 m^2, respectively.

Maesopsis eminii consisted of young and old types with straight and slightly slanted stems and rough and smooth bark (Fig. 6b and 6c). Young and old *Maesopsis eminii* have diameters of 4.14–11.15 and 8.92–18.79 cm, respectively. Their tree heights are 3–5.5 and 6.5–12.5 m, respectively. The canopy diameters of old *Maesopsis eminii* and young *Maesopsis eminii* are 1.43–2.7 m and 2.22–5.87 m, with canopy areas of 1.61–5.73 and 2.81–27.07 m^2, respectively. There are two different conditions for growing *Maesopsis eminii*. The growing area is plotted with shrub heights > 0.5 m and < 0.5 m.

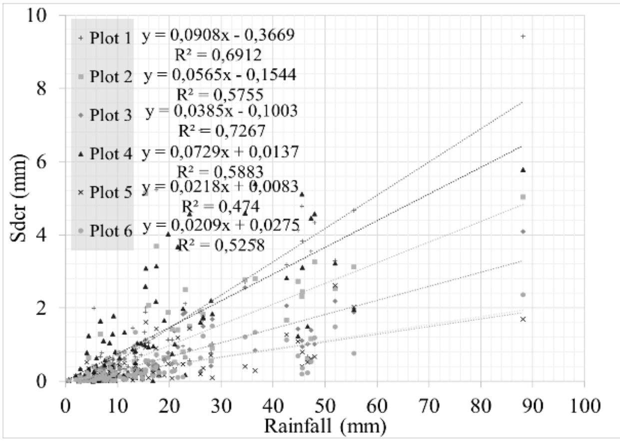
3.2. Interception Field Data

The interception of the measurement results, stemflow, and throughfall in each plot is presented in Table 4. The relationship between throughfall, stemflow, and interception with rainfall is presented in Fig. 7.

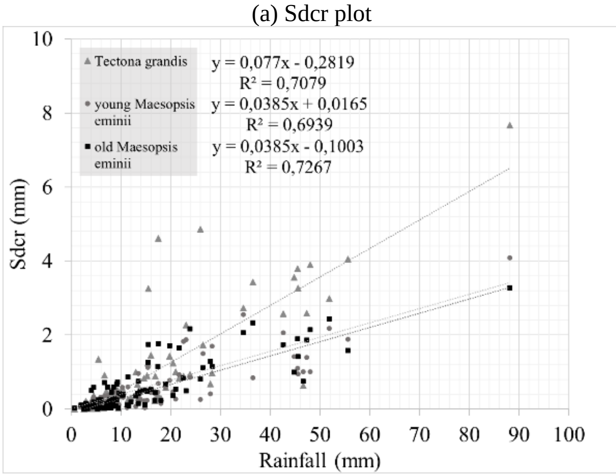
Table 4 Characteristics of teak and Maesopsis eminii (Result analysis; developed by the authors)

No	Plot	P_G (mm)	*Tf* (mm)	*Sdcr* (mm)	*I* (mm)	$P_{G_{netto}}$ (mm)	*Tf* (%)	*Sdcr* (%)	*I* (%)	$P_{G_{netto}}$ (%)
1	Teak-M	1451	832.7	98.3	520.0	931.0	57	7	36	64
2	Teak-S	1451	681.7	67.9	701.4	749.6	47	5	48	52
3	Young *Maesopsis eminii*-M	1451	850.7	46.7	553.7	897.3	59	3	38	62
4		1451	870.7	107.0	473.3	977.7	60	7	33	67
5	Old *Maesopsis eminii*-S	1451	815.7	32.5	602.9	848.1	56	2	42	58
6		1451	816.4	32.8	601.8	849.2	56	2	41	59

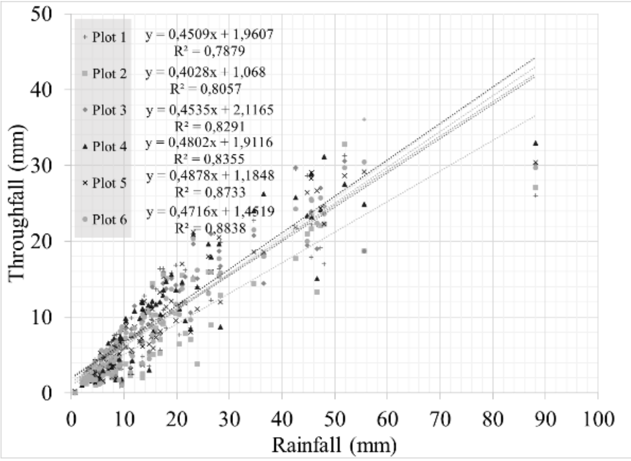
Notes: M – monopodial, S – sympodial



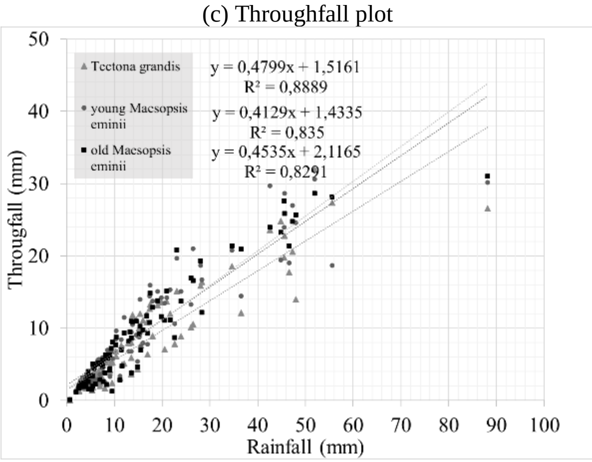
(a) Sdcr plot



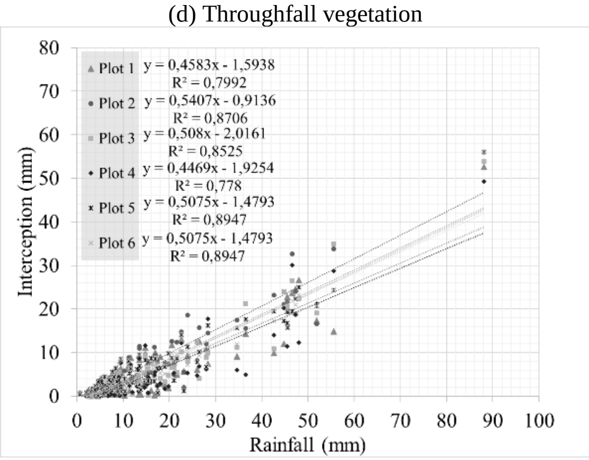
(b) Sdcr vegetation



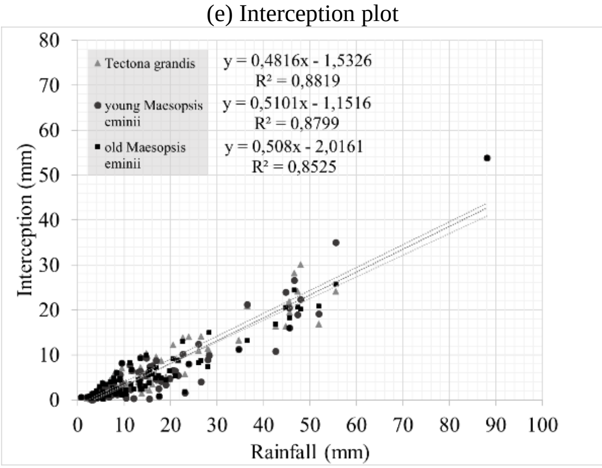
(c) Throughfall plot



(d) Throughfall vegetation



(e) Interception plot



(f) Interception of vegetation

Fig. 7 Relationships between (a) throughfall (Tf) and rainfall, (b) stemflow (Sf) and rainfall, (c) interception (I) and rainfall (Result analysis; developed by the authors)

Interception modeling in teak and young and old *Maesopsis eminii* was analyzed based on field measurement data from December 13, 2020, to April 8, 2021, during the wet period. There are 91 data of rainy days out of 117 interception measurement days with a total rainfall of 1451 mm. Daily rainfall ranges from 0.7 to 88.1 mm/day, with an average daily rainfall of 15.9 mm/day. The maximum rainfall intensity is 94.2 mm/h. The distance from the measurement plot to the rain gage is 22–187 m, whereas the farthest distance from the plot is 251 m.

The equivalent stemflow depth (Sdcr) in teak and young and old *Maesopsis eminii* is 5–7%, 3%, and 2–7%, respectively. The throughfall from field measurements in teak and young and old *Maesopsis eminii* were 47–57%, 59%, and 56–60%, respectively. Teak had higher Sdcr and lower Tf than *Maesopsis eminii* (Table 4). The relationship between Sdcr and rainfall is R^2>0.69, while the relationship between Tf and rainfall is R^2>0.82.

The interception of teak and *Maesopsis eminii* varied, with the lowest interception being in sympodial old *Maesopsis eminii* (33%), whereas the highest was in sympodial teak (48%). The average interception in teak and young and old *Maesopsis eminii* was 42%, 38%, and 38.7%, respectively. The interception of teak was relatively greater than that of *Maesopsis eminii*, whereas the interception of old and young *Maesopsis eminii* was almost the same.

Stemflow varies considerably due to the branch slope > 30° on the main stem, which can cause a stemflow process. When the branches go downward, rainwater does not flow toward the stem but becomes an addition to the throughfall water. Rainwater flows easily over smoother bark than rough bark. The bark condition is rough and cracked, causing rainwater trapping on the bark.

Differences in canopy interception are caused by various factors influencing stemflow and throughfall, vegetation (age, height, diameter, tree morphology, and vegetation type), and climatology (wind, rainfall intensity, evaporation, and transpiration). Interception is also influenced by the accuracy of measurements in the field and the tools used, which allow for measurement errors.

3.3. Interception by the Gash Model

The parameters of GM and RGM are presented in Table 5, and the submodels of the GM and RGM are presented in Table 6. The SGM parameters are presented in Table 7.

Table 5 Parameters of the GM and RGM (Result analysis; developed by the authors)

Parameter	Unit	GM									RGM								
		Teak			*Maesopsis eminii*						Teak			*Maesopsis eminii*					
		Plot 1	Plot 2	Average	Plot 3	Plot 4	Plot 5	Plot 6	Average		Plot 1	Plot 2	Average	Plot 3	Plot 4	Plot 5	Plot 6	Average	
Gross rainfall (P_G)	mm/day	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9		15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	
Average rainfall ($\overline{R}$)	mm/hour	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	
Evaporation rate in saturated canopy ($\overline{E}$)	mm	0.5	1.2	0.9	0.1	0.3	0.4	0.4	0.3		0.5	1.2	0.9	0.1	0.3	0.4	0.4	0.3	
The ratio of $\overline{E}/\overline{R}$		0.2	0.4	0.3	0.0	0.1	0.1	0.1	0.1		0.2	0.4	0.3	0.0	0.1	0.1	0.1	0.1	
Canopy porosity (p)		0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5		0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	
Canopy area, function of LAI (c, *LAI*)		-	-	-	-	-	-	-	-		1.2	2.2	1.7	0.2	0.7	0.8	0.8	0.6	
Stem capacity (St)		0.4	0.2	0.3	0.1	0.0	0.0	0.0	0.0		0.4	0.2	0.3	0.1	0.0	0.0	0.0	0.0	
Stem input coefficient (pt)		0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0		0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	
The ratio of St/Pt		4.0	2.7	3.4	2.6	0.2	0.4	1.3	1.1		4.0	2.7	3.4	2.6	0.2	0.4	1.3	1.1	
Canopy capacity (S)		0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.6		0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.6	
Rainfall that saturates the canopy (P_G')	(mm)	1.6	1.5	1.5	1.2	1.5	1.3	1.3	1.3		0.5	0.2	0.4	3.5	0.9	0.8	0.7	1.5	

Table 6 Submodel of the GM and RGM (Result analysis; developed by the authors)

Sub-model	Unit	GM								RGM							
		Teak		*Maesopsis eminii*						Teak		*Maesopsis eminii*					
		Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2
$I_{P_G<P'_G}$	mm	1.6	1.5	1.5	1.2	1.5	1.3	1.3	1.3	0.5	0.2	0.4	3.5	0.9	0.8	0.7	1.5
$I_{P_G>P'_G}$	mm	0.3	0.4	0.3	0.4	0.3	0.3	0.4	0.3	0.0	0.0	0.0	4.1	0.5	0.5	0.6	1.4
I_{ED}	mm	227.4	496.2	361.8	39.4	127.4	160.0	178.2	126.2	244.1	539.3	391.7	33.2	132.3	165.6	184.8	129.0
I_{EW}	mm	51.6	42.3	47.0	52.8	54.0	50.6	50.6	52.0	52.2	42.8	47.5	48.1	54.0	50.6	50.6	50.8
I_{ES}	mm	32.2	13.9	23.0	9.1	1.3	0.8	2.5	3.4	32.1	13.9	23.0	9.0	1.2	0.8	2.5	3.4

Table 7 Submodel of the SGM (Result analysis; developed by the authors)

Sub-model	Unit	Teak			*Maesopsis eminii*				
		Plot 1	Plot 2	Average	Plot 3	Plot 4	Plot 5	Plot 6	Average
Rainfall that saturates the canopy (I_S)	mm	5.7	7.7	6.7	6.1	5.2	6.6	6.6	6.1
Big rainfall event (I_b)	times	74	63	69	70	74	67	67	70
Rainfall of P_{Gi} ($P_G< I_S$)	mm	52.7	119.2	86.0	74.4	52.7	92.0	92.0	77.8
Vegetation suitability (Vf)	mm	3.7	6.9	5.3	0.6	2.1	2.4	2.6	1.9

The GM has 10 main parameters, while the RGM has 11 parameters. The RGM has additional parameters such as LAI and evaporation factors. Moreover, each has a value of 15.9 mm/day and 3.1 mm/hour. The evaporation rate parameter in each plot was obtained from the slope (regression coefficient) of the regression equation between dam I, which has an R^2 > 77% (Fig. 7e) with the LAI factor.

The canopy porosity (p) for each plot was obtained from the regression coefficient between rainfall (P_G) and rainfall (Tf), which has a value of 0.4–0.5 and R^2> 78% (Fig. 7c). The stem capacity (St) and stem input coefficient (pt) estimated from the interception (constant) and slope (regression coefficient) of the regression equation between stemflow ($Sdcr$) and rainfall (P_G) have values of 0.0–0.4 and R^2 50%, respectively (Fig. 6a). The low R^2 value explains why the effect of rainfall on stemflow is low in linear regression. St is 0.5–0.6, with P_G' of teak and *Maesopsis eminii* being 1.5 and 1.3, respectively. In extreme rainfall conditions, interceptions occur for some canopy capacities.

The canopy and stem capacities of the GM and RGM have the same values estimated based on the regression intercept. Meanwhile, the canopy capacity of the SGM is calculated on the basis of the average interception of all rainfall events that saturate the canopy (I_S). The canopy capacity (S) of the GM and RGM is lower than the SGM canopy capacity (I_S). Canopy and stem capacity then affect the rainfall that saturates the canopy (P_G'). P_G' has different values, which the LAI function affects in the RGM. Estimating canopy interception based on five submodels showed that the GM interception was more significant than the RGM. The RGM is influenced by LAI, which results in the RGM getting closer to field measurement interception. Meanwhile, the SGM consists of four submodels assuming that evaporation is zero because evaporation has entered the canopy interception and additional parameters are related to vegetation suitability (Vf). The SGM is a simplified form of the previous Gash models. SGM uses four parameters: I_S,

I_b, P_{Gi} (P_G<I_S), and *Vf*. The results of the recapitulation of interceptions from the GM, RGM, SGM, and field measurements are presented in Table 8.

Table 8 Recapitulation of interception modeling by the GM, RGM, SGM, and field data (Result analysis; developed by the authors)

Interception	Teak				*Maesopsis eminii*			
	Plot 1	**Plot 2**	**Plot 1**	**Plot 2**	**Plot 1**	**Plot 2**	**Plot 1**	**Average**
GM	313.1	554.3	433.7	102.8	184.5	213.0	232.9	183.3
RGM	328.9	596.2	462.5	98.0	189.0	218.3	239.2	186.1
SGM	479.3	611.7	551.0	500.9	439.7	538.3	537.7	505.8
Field data	520.0	701.4	610.7	553.7	473.3	602.9	601.8	557.9

The average rainfall that saturates the canopy (I_S) in Teak and *Maesopsis eminii* is 6.7 mm and 6.1 mm, respectively. The number of heavy rain events (*Ib*) is 69 and 70, respectively. Rainfall less than I_S in Teak and *Maesopsis eminii* is 86 and 77.8 mm, respectively. The value of vegetation suitability (*Vf*) varies depending on the *LAI* in each plot. The *Vf* values for Teak and *Maesopsis eminii* were 5.3 and 1.9, respectively, indicating each plot's characteristics (Table 8); therefore, the interception model by the SGM was close to the field measurements.

Interception of the GM < RGM < SGM < field data. The average interception based on the GM, RGM, and SGM was 30%, 32%, 38%, and 42% (teak), 7%, 7%, 35%, and 38% (young *Maesopsis eminii*), and 14%, 15%, 35%, and 39% (old *Maesopsis eminii*), respectively (Table 8). The results showed that the SGM is more suitable because it has an interception value close to the actual interception (a result of field measurements). The interception differences between the SGM and field data for teak and young and old *Maesopsis eminii* were 59.7, 52.8, and 54.1 mm (≈50 mm).

The relationship between rainfall, stemflow, throughfall, and interception was approximated by a linear regression equation, as in [5, 23]. The linear relationship indicates that the ratio of evaporation to rainfall is constant [7]. This is more representative in explaining that increasing *Pg* causes the *I:Pg* ratio to decrease. Moreover, the lower the *Pg*, the closer the lost *Pg* is to *I* [16]. Bulcock and Jewitt [3] stated that the relationship between rainfall and interception has a logarithmic relationship, indicating that there is still evaporation of the wet canopy after the canopy reaches canopy storage capacity. The interception equals the canopy storage capacity if no wet canopy evaporates.

This study assumes that *E/R*, *S*, and *c* are constant for all rainfall events according to the assumptions of the Gash model. The constant parameter for modeling *I* allows for underestimation or overestimation, resulting in differences between the predicted and measured *I*. The *E/R* coefficient should be after the canopy is completely saturated. Carlyle-Moses and Price [4] stated that canopy storage capacity is an inversely proportional function of raindrop size and kinetic energy. Another limitation is that the resulting interception is the total interception of all forest stands and not the interception of each tree or each rain event. Although some of the assumptions of the Gash model may not be valid, the model can predict the total interception well in teak and young and old *Maesopsis eminii* with a difference of 50 mm. Interception estimation recapitulation can be performed using several models presented in Table 9.

Table 9 Research recapitulation of interception modeling (Recapitulation by the authors)

No	Vegetation	Location	Tree Height (m)	DBH (cm)	Interception (%)	Interception Model					Source
						GM	RGM	SGM	Rutter (1971)	Liu (1997)	
1	Forest plantation (*Eucalyptus grandis*, *Pinus patula*, and *Acacia mearnsii*)	South Africa	13,6 – 16,1	13,5 –28,4	14,9 – 27,7 [a]						[3]
2	Northern hardwood stands	Canada	3-10	19-44	19,3±3,5						[4]
3	Secondary forest (*Quercus serrata* and *Clethra barbinervis*)	Japan	12	9,1	15,3 – 22,8						[5]
4	*Pinus brutia*	Cyprus	16	*	28 – 38						[7]
5	Oak tree	Hungary	20 – 25	*	36						[14]
6	Forest plantation	Iran	12 – 27,5	12 - 65	35 – 57						[16]
7	Teak (*Tectona grandis L.*) Plantation	Indonesia	39 – 45	*	29,4 – 58,2 [a]						[20]
8	*Pinus leuceana sp*, cashew, Neem, Gmelina, and Teak	Nigeria	*	*	17,78 – 31,96 [a]						[23]
9	Lychee (*Litchi chinensis Sonn.*)	Thailand	*	*	16						[24]
10	Tropical semi-arid region	Brazil	*	3-6	13						[25]
11	Forest Plantation (Teak and *Maesopsis eminii*)	Indonesia	3 – 14	4,14 – 23,57	7 - 42						This study

* unknown/not specified; [a] field observation

Interception is influenced by stem characteristics (diameter and height), which affect stemflow [5, 22], plant spacing, tree management, rainfall (total, frequency, intensity, pattern, and duration), and canopy characteristics (leaf shape, wettability, leaf angle, and LAI) [3, 8, 16]. Tanaka et al. [21] stated that canopy rainfall is influenced by temperature, humidity, rainfall intensity, and maximum wind speed. Interception varies greatly depending on site characteristics, stand characteristics, age, plant species, and forest management [19, 20].

The gash analytical model has a simple approach, lower input requirements, and a more realistic interception process than the Rutter model. The Rutter model is a more complex and time-consuming numerical model [4, 15]. Estimating interception based on the Gash model [8] shows that the evaporation of rainfall interception can be estimated from forest structure, evaporation rate, average rainfall, and rainfall patterns. Gash [8] assumed that the average value of evaporation for rainfall greater than 0.5 mm represents evaporation from a saturated canopy, and evaporation is a one-dimensional event. Other assumptions are that the canopy is dry at the beginning of each daily rain event and that the ratio between the average evaporation rate and average rainfall intensity is constant, originating from several storm events [7, 16]. Gash [8] needs to be more assertive in describing interception in sparse forests, which was later revised by [9].

Gash et al. [9] reformed the model by improving the boundary conditions to predict better interception in sparse forests, high stem evaporation, and long storms. In addition, the interception estimate based on the revised Gash model has a canopy storage capacity that varies with changes in LAI, and evaporation rates are influenced by meteorological conditions and canopy structure [5]. Changes in annual interception loss are negligible because of deficient rainfall and interception loss in that period. Evaporation in the saturated canopy increases in the dry season because of higher wind speeds, the aerodynamic characteristics of the trees, and reduced rain intensity, which reduces the storage capacity of the canopy [2]. Although the Gash model is more frequently used, it is limited by relatively large temporal resolution and requires time to isolate individual rainfall events [6].

4. Conclusion

Canopy interception of the developed simplified Gash model gives the closest result to the measured canopy interception compared to the Gash model and revised Gash model. The average canopy interception based on the models of GM, RGM, and SGM were 30%, 32%, 38%, and 42% for Teak Plantation, 7%, 7%, 35%, and 38% for young *Maesopsis eminii* plantation, and 14%, 15%, 35%, and 39% of 1451 mm rainfall for old *Maesopsis eminii*), respectively. The average field-measured canopy interception of teak and young and old *Maesopsis eminii* forest plantations was 42%, 38%, and 39% of 1451-mm rainfall, respectively. The canopy interception differences between SGM and field-measured canopy interception in teak and young and old *Maesopsis eminii* plantations were 4,0% (59.7 mm), 3,0% (52.8 mm), and 3.7% (54.1 mm).

Research recapitulation of interception modeling is presented in Table 9. This study shows that interception in young and old *Maesopsis eminii* and teak plantation forests is 7-42%. This research provides novelty in interception modeling in plantation forests, especially in Indonesia. Research on interception in Indonesia is limited to field measurements in teak plantation forests. Meanwhile, no similar study has been conducted in *Maesopsis eminii* plantation forests. Previous research using SGM interception modeling is rarely found in forest areas, which is the model used in this research and gives the best results that are close to interception in the field.

In this study, the interception models of the GM, RGM, and SGM are relevant for modeling interception in plantation forests in tropical regions. Interception modeling as part of forest hydrological modeling can be used to determine the water balance, the function of vegetation in reducing rainfall energy and intensity, and the hydrological function of vegetation that has implications for other hydrological processes such as infiltration and evapotranspiration.

The complexity of representing each required parameter is a challenge, especially when collecting field data. Measuring stemflow and throughfall as interception estimation parameters in the field requires high accuracy. The choice of stand location used for installing the equipment must be representative and have minimal interference. Measurements carried out every day should always be carried out at the same time to produce good data. Every day, we need to check the condition of the equipment installed; if there are any discrepancies, leaks, or tilted equipment, repair them immediately.

Interception modeling using the Gash model has limitations in resulting interception, which is the total interception in the stand, not the interception for each tree or the interception for each rain event. Although some assumptions of the Gash model may not be valid, the model can estimate total interceptions well in teak and young and old *Maesopsis eminii*, with a difference of about 50 mm in total interception. The Gash model is limited to a relatively large temporal resolution and requires time to separate individual rainfall events. Future research can conduct interception modeling in different vegetation, landscapes, and regional conditions using the Gash model and other models. Moreover, we can determine the characteristics, complexity, and best interception model.

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