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Performance Assessment of the Mulder Model in Simulating Interception Loss in Tropical Forest

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Abstract: This study evaluated the performance of the Mulder Model in estimating rainfall interception loss in the tropical rainforest of Bukit Lagong, Malaysia. Rainfall interception is a key component of the forest hydrological cycle, particularly in tropical regions characterized by high rainfall and dense canopy structures. Although the Mulder Model has been widely applied in temperate climates, its suitability for tropical environments remains insufficiently tested. A triangulation approach was adopted by comparing interception loss calculated from field measured gross rainfall, throughfall, and stemflow with model simulations. Secondary daily meteorological and canopy data from previous studies were used. The model was applied using site-specific parameters, including a canopy storage capacity of 0.8091 mm, a wet canopy evaporation rate of 0.25 mm/h, and an assumed rainfall duration of 4 hours. Model performance was evaluated using RMSE. Results indicated that the model tends to underestimate or overestimate interception during high-intensity rainfall and short dry intervals, typical of tropical climates. Variations in canopy density, leaf area index, and rainfall frequency contributed to discrepancies. The findings highlight the need for local parameter calibration to improve model reliability in tropical forests.

Keywords: interception loss, Mulder model, RMSE, tropical forest

1. Introduction

Rainfall interception is the process by which the rainwater that falling does not reach the ground. According to Azinoor et al. (2023), rainfall intersection is recognized as a hydrological process of considerable importance in water resources management but also in the context of climate change. The rainwater that falls on plant surfaces is temporarily retained and ultimately either evaporates into the atmosphere (interception loss) or makes its way to the ground either by falling as drop or by flowing down branches and stems (stemflow) (Muzylo et al., 2009). The rain that does not hit a plant surface is called free throughfall and, together with drip, is often referred to as throughfall (David, 2005). However, throughfall and stemflow together are referred to as net rainfall.

The interception loss depends strongly on the timing and intensity of rainfall, the vegetation structure and the meteorological conditions controlling evaporation during and after rainfall (Rutter, 1975). Rainfall interception loss is the proportion of total rainfall that is collected, stored and then evaporated from all parts of vegetation of following rainfall and according to Muzylo et al. (2009), rainfall interception loss is primarily influenced by the rainfall characteristics, forest structure and climatic variables governing the evaporation rates during and after rainfall events. However, in rainfall modelling, interception is one of the most neglected underestimated processes in rainfall- run off analysis (Azinoor & Lu, 2012) and some models disregards it completely, based on assumption that is small portion of the total evaporation. Furthermore, evaporation from intercepted water on leaf surfaces in rough canopies can be very efficient and could form a significant component of the total water balance in some environments.

Muzylo et al. (2009) compared these models and found the original and revised Gash's analytical models to be the most commonly employed. Model of interception loss have been developed to make predictions based on rainfall and canopy characteristics (Valente et al., 1997). From the previous study, the researchers found that canopy structure, evaporation rate during storm and rainfall rate are the factors affecting the rate of interception loss. In particular, the current issue is that the use of rainfall interception loss estimation models, such as Mulder Model (Mulder, 1985) has not been

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well tested in the complicated rain forest context. The Mulder Model has also been applied extensively in the deterministic estimation of rainfall interception loss with simple meteorological data, such as rainfall and potential evaporation data.

The model was formulated to describe the three dominant sections of the interception process: the canopy wetting, saturation, and drying phases. Nonetheless, several previous studies reported that estimation produced by this model in the tropical rainforest region is usually not realistic, either underestimating (lower estimate) or overestimating (higher estimate), depending on the canopy storage capacity performance parameterization and how well the model can simulate the perpetually wet canopy condition as in the wet canopy parameters due to frequent rainfall events (Asdak et al., 1998). This study aims to quantify interception loss in a tropical forest through field measurements, estimate interception loss using the Mulder model, and evaluate the model's performance by comparing simulated results with measured field data. Through this approach, the reliability of the Mulder model in representing interception processes under tropical conditions is assessed.

2. Methodology

2.1 Study Area and Data Collections

The study was carried out in Plot 11 of the Bukit Lagong Forest Reserve, Selangor, Peninsular Malaysia (3°15′N, 101°37′E), as shown in Figure 1. The reserve is a lowland mixed dipterocarp forest managed by the Forest Research Institute Malaysia (FRIM), with approximately 78% of the area covered by forest vegetation. Plot 11 encompasses 400 m² (20 m × 20 m) and is characterised by a predominantly monodominant stand of *Scorodocarpus borneensis* (locally known as Kulim), with all trees identified, tagged, and numbered for monitoring purposes. The plot comprises 21 trees with a diameter at breast height (DBH) exceeding 10 cm, of which 20 are *Scorodocarpus borneensis* and one is *Cinnamomum porrectum (Roxb.)*. The canopy structure in Plot 11 is moderately closed, with an average canopy height of approximately 17 m. The relatively uniform species composition provides a controlled and homogeneous canopy condition, making the plot particularly suitable for evaluating rainfall interception processes and reducing variability associated with mixed species stands.

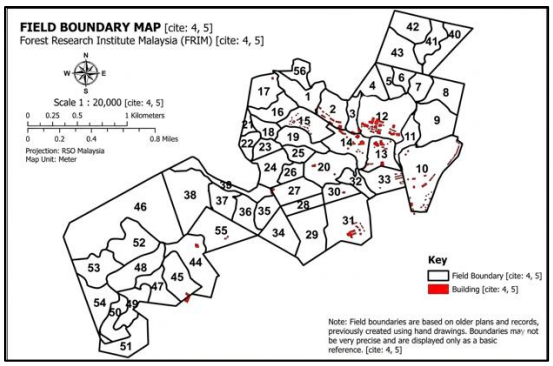

Fig. 1 – Study area.

This study utilised secondary data derived from a previous field investigation conducted in Plot 11 of Bukit Lagong Forest Reserve, Selangor, Malaysia. The dataset was collected over a 12-month monitoring period from April 2012 to April 2013 (Azinoor et al., 2012). It comprises detailed daily measurements of gross rainfall, runoff, stemflow, and canopy cover, which are essential for estimating interception loss and validating interception models. Gross rainfall (*Pg*) was measured using a non-recording manual rain gauge installed in an open area approximately 30 m from the study plot. To ensure the reliability and continuity of rainfall records, these measurements were supplemented with meteorological data obtained from the nearby Taman Tun Teja rainfall station (Station ID: 3315039), operated by the Department of Drainage and Irrigation Malaysia.

2.2 Throughfall and Steamflow

Throughfall (T_f) is defined as the fraction of gross precipitation (P_g) that reaches the forest floor after interacting with the vegetation canopy during a rainfall event. It comprises two components: (i) free throughfall, which passes directly through canopy gaps without interception, and (ii) canopy drainage, which consists of water temporarily stored on leaf and branch surfaces and subsequently released as drip once the canopy storage capacity is exceeded. Throughfall therefore represents the dominant pathway by which precipitation is transmitted beneath forest canopies and constitutes a key component of the canopy water balance. Quantitatively, throughfall is expressed as a depth (mm) and is typically calculated as the cumulative volume collected per unit ground area over a specified rainfall period.

In this study, throughfall was measured using 25 uniformly distributed rain collectors installed within a 400 m² plot arranged in a 5 m × 5 m grid pattern. Each collector, with a diameter of 225 mm, was positioned beneath the canopy to capture rainfall passing through the vegetation layer. The collected water volume was recorded daily using a graduated cylinder and subsequently converted to rainfall depth (mm) by dividing the measured volume by the cross-sectional area of the collector.



Fig. 2 – Throughfall collection.

Meanwhile, stemflow (S_f) is defined as the portion of precipitation that is funneled along branches and transported downward along the tree stem to the base of the trunk. It represents a concentrated flow pathway that redistributes rainfall from the canopy to the soil surface near the tree base.

Furthermore, stemflow was measured using the collar method. A halved rubber collar was installed spirally around each selected tree stem to intercept and channel water downward. Trees were selected based on accessibility and a diameter at breast height (DBH) greater than 10 cm. A total of 15 trees were instrumented within each plot.

The spiral collar directed stemflow into a collection tank positioned at the lower end of the collar system (Fig. 3). The accumulated volume was measured after each rainfall event and subsequently converted to an equivalent depth (mm) using an appropriate scaling factor based on the contributing basal area. Stemflow was quantified using the collar method. Fifteen trees with a diameter at breast height (DBH) greater than 10 cm were selected and fitted with spiral PVC collars installed around the tree stems. The collars directed stemflow into collection tanks with capacities ranging from 5.5 to 25 L, which were monitored and measured daily. The collected stemflow volume was then converted to depth (mm) using a correction factor based on the basal area of the respective trees.



Fig. 3 – Stemflow collection.

The locations of the trees, throughfall and stemflow at Plot 11 are shown in Fig. 4.

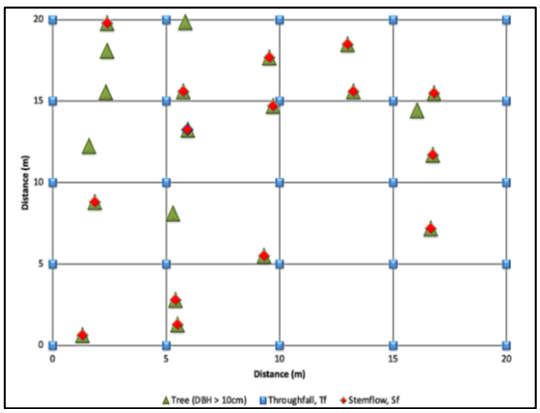

Fig. 4 – Location of the trees, throughfall and stemflow collectors.

Rainfall interception losses were estimated for 94 discrete rainfall events recorded over a 12-month period from April 2012 to April 2013. The analysis was conducted on an event basis using the corresponding gross rainfall (P_g) for each event. Measured interception loss (I_L) was determined using a simplified canopy water balance approach, expressed as:

$$I_L = P_g - (T_f + S_f)$$

where P_g represents gross rainfall (mm), T_f denotes throughfall (mm), and S_f represents stemflow (mm). This approach assumes negligible changes in canopy water storage at the event scale and no significant lateral water inputs or losses within the plot. Accordingly, interception loss represents the portion of gross rainfall retained by the canopy and subsequently evaporated back to the atmosphere.

2.3 Assumption and Limitation of Mulder Model

In this study, a canopy water storage capacity (S_c) value of 0.8091 mm was adopted as an input parameter in the Mulder interception model. This value was derived from a previous site-specific investigation conducted at the same plot in Bukit Lagong Forest Reserve by Azinoor (2015), ensuring consistency with locally observed hydrological conditions. The selected value is supported by findings from ecologically comparable tropical forests. For example, Komatsu et al. (2008) estimated a canopy storage capacity of approximately 0.7 mm in a Bornean tropical rainforest using combined sap flow and rainfall measurements. Similarly, Wang et al. (2009) reported canopy storage values ranging from 0.45 to 0.79 mm in a seasonal tropical forest in Xishuangbanna, China. These values fall within a comparable range and support the use of a site-calibrated parameter within this interval.

Furthermore, a recent global synthesis by Liu et al. (2020) indicated that canopy water storage capacity in tropical forests generally ranges between 0.5 and 1.0 mm, depending on species composition, leaf area index, and canopy structural characteristics. Given that Plot 11 at Bukit Lagong represents a closed-canopy, monodominant lowland dipterocarp forest with dense foliage (mean canopy cover of 94.1%), the adopted S_c value of 0.8091 mm is both ecologically reasonable and empirically supported. The parameter selection reflects consistency with local measurements while remaining within the globally reported range, thereby providing a robust basis for simulating interception dynamics under tropical forest conditions.

Since this study utilized secondary data from a lowland mixed dipterocarp tropical forest with high canopy cover (mean 94.1%), an intermediate canopy evaporation rate of 0.25 mm h^{-1} was adopted in the Mulder interception model. This value reflects the evaporation potential of dense and humid tropical canopies under moderate storm conditions, where limited solar radiation penetration and reduced wind speed beneath the closed canopy constrain evaporation rates. The selected value avoids potential overestimation associated with assuming higher atmospheric demand typical of open or temperate forests.

Importantly, because the dataset lacked detailed meteorological inputs (e.g., radiation, wind speed, vapour pressure deficit), the adoption of a representative constant evaporation rate ensured model stability while maintaining ecological realism. Sensitivity considerations indicate that canopy evaporation rate directly influences simulated interception loss, particularly during inter-event drying periods; therefore, selecting a moderate and literature-supported value reduces systematic bias when assessing temporal aggregation effects.

In addition, a fixed 4-hour rainfall duration was assumed to represent individual storm events within the Mulder model framework. This assumption was necessary because the available dataset consisted of daily rainfall totals without sub-daily temporal resolution. The model requires storm duration to simulate dynamic canopy processes, including wetting, storage filling, drainage, and subsequent drying. The 4-hour duration approximates typical convective rainfall patterns observed in tropical lowland regions, where intense rainfall often occurs within relatively short time windows. Although the use of a fixed storm duration introduces simplification, its influence was evaluated within the broader temporal resolution analysis. By systematically comparing interception simulations under varying rainfall aggregation intervals, this study assesses the extent to which assumed storm duration affects modeled interception dynamics. This approach ensures that conclusions regarding temporal resolution effects remain robust despite the necessary structural assumptions imposed by daily rainfall data. In the context of interception modeling, the initial canopy water content C_{wi} refers to the amount of water stored in the canopy at the beginning of the rainfall simulation period.

For this study, the value of C_{wi} was set to zero (0 mm) at the beginning of the simulation. This assumption is standard and widely accepted in interception model applications such as the Rutter, Gash and Mulder models. The rationale for using, $C_{wi} = 0$ lies in the fact that, in the absence of a previous storm or in the presence of a sufficiently long dry interval (e.g., overnight or for several days), it is reasonable to assume that the forest canopy has completely dried out. This approach simplifies model initialization and ensures that the water balance starts from a neutral baseline. According to Cisneros Vaca et al. (2018), who compared several interception models in forest ecosystems, the Rutter model was initialized with zero canopy storage at the beginning of the simulation period, and the authors emphasize that this is a common procedure to avoid bias from previously unobserved wetting events.

2.4 Statistical Evaluation

Root Mean Square Error (RMSE) is a commonly used statistical metric for evaluating the accuracy of a predictive model based on the difference between the predicted values of the model and the measured values. RMSE is a composite measure of model performance used to quantify the magnitude of this so-called error between predictions and measurements. It is of particular interest when the aim is to determine how well a model reproduces a continuous variable (e.g., interception loss in forest hydrology). RMSE is a fundamental indicator to determine the average deviation between the simulated and measured values.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(IL_{observe,i} - IL_{model,i}\right)^2}$$

where n is the number of paired data points. RMSE is expressed in the same units as the intercept (i.e., mm), making it a direct and interpretable measure of the magnitude of the error.

3. Results and Discussion

3.1 Rainfall, Throughfall, Stemflow and Interception Loss

The interception loss of rainfall for each rainfall event is obtained by subtracting the sum of the absorption and runoff values from the corresponding gross rainfall and is given in millimeters and percentage of gross rainfall. During that period, the total interception loss of rainfall is 568.986 mm or about 24.46 % of the total gross rainfall. These data are the results of 12 months of field observations containing 94 measured data.

Cumulatively, the total gross rainfall recorded during the study period was 2326.32 mm and 1757.06 mm or about 75.53% was transferred to the ground surface as throughfall. Stemflow contributed only 0.0274 mm, which is about 0.011% of the total gross rainfall. Meanwhile, the rest, which is 568.986 mm or approximately 24.46%, is considered interception loss, which is rainwater that is retained and evaporates back into the atmosphere before reaching the ground surface.

Fig. 5 shows significant variation in interception loss, reflecting the dynamic characteristics of tropical forest ecosystems and the complex interactions between canopy structure and rainfall characteristics. For example, in December 2012, interception loss was recorded at highest level, 105.931 mm, equivalent to approximately 24.61% of the monthly gross rainfall of 430.51 mm. This occurs because prolonged and moderate intensity rainfall conditions promote maximum canopy water retention before runoff to the ground.

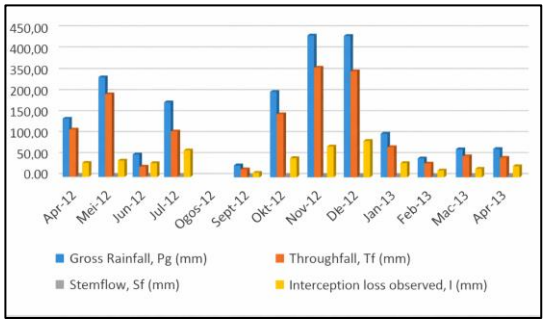

Fig. 5 - Gross rainfall, throughfall, stemflow and interception loss.

3.2 Correlation between Gross Rainfall and Interception Loss

The correlation between gross rainfall (Pg) and interception loss (I_L) recorded throughout the study period is as below. Linear regression analysis was used to assess the strength and shape of the relationship between these two variables. The regression results showed that the linear relationship equation between Pg and I_L is as follows:

$$I = 0.142Pg + 2.54$$

where I represent interception loss (mm), and Pg is the gross rainfall amount.

3.3 Rainfall Interception Loss from Mulder Model

Data analyzed using the Mulder Model, various parameters related to the loss of rain interception by the canopy were calculated for a four-hour rainfall episode. These results show the contribution of each component of the wetting-up phase and saturation drying phase to the total interception. Based on calculations carried out using the Mulder model, interception loss during the wetting up phase ranged from 2.446 mm to 14.709 mm, depending on the amount of rainfall and saturation time in a given month. The total loss for this phase over the study period were 77.067 mm (45.58%).

Meanwhile, the losses during the saturation phase showed higher values compared to the wetting phase, with a range between 2.964 mm to 17.711 mm. The total losses for this phase were recorded as 92.001 mm, which contributed about 54.42% of the total annual interception loss. This indicates that the main losses occur after the canopy surface reaches saturation, where the water stagnant on the plant surface evaporates slowly.

The total interception loss of rainfall based on the Mulder model for a one-year is 169.086 mm, which is equivalent to about 7.27% of the total annual gross rainfall. The month with the highest interception loss was November 2012, with a total of 32.420 mm, followed by December 2012 (25.238 mm) and May 2012 (19.809 mm). On the other hand, the lowest interception loss was recorded in June 2012, with only 5.409 mm. This was during the relatively dry season, which indicated less rainfall activity and shorter canopy wet time. This pattern indicates that the amount of interception loss is directly proportional to the amount of rainfall received and the time of canopy saturation.

3.4 Comparison between Measured Interception Loss and Mulder Model

Based on the analysis, the measured interception loss of rainfall is 568.986 mm, equivalent to 24.46% of the annual gross rainfall. In contrast, the Mulder model estimates the interception loss to be only 169.068 mm, which is about 7.27% of the annual gross rainfall. The large absolute difference between these two values reflects the inherent limitations of using an empirical model that is not locally calibrated.

The significant difference between the model estimates and the actual observation, which is about 399.918 mm which is about 17.19 %, raises questions about the Mulder model's ability to accurately predict interception loss. Although the absolute values are different, the monthly patterns of intercept loss between the measured values and the Mulder model show a relatively parallel trend. For example, Fig. 6 shows months with heavy rainfall such as November and December 2012 recorded high intercept loss for both methods, while September 2012, which is the driest month, showed the lowest loss.

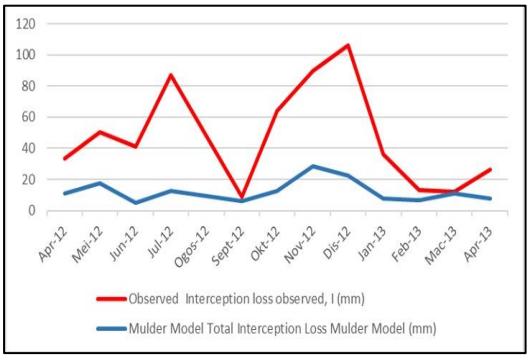

Fig. 6 - Measured Interception Loss and Mulder Model

There are several factors explain the significant differences between measured and model simulation values. First, the Mulder model uses certain parameters that are typically averaged or constant, including effective evaporation rate, canopy storage capacity, and effective rainfall rate. In real conditions, the values of these parameters can change dynamically depending on micrometeorological conditions such as temperature, relative humidity, wind speed, and rainfall intensity, which vary greatly in tropical climates.

Furthermore, the Mulder model neglected the weight of some very important components such as stemflow, which can affect the distribution of rainwater falling on the ground surface and thus affect the estimate of net interception loss. The interception component during the drying out phase after a storm is also not calculated in this data set, whereas in field observations, the evaporation process after rain also contributes to the total interception loss.

Moreover, the differences can also be attributed to variations in canopy structure, including leaf density, multilayered canopy, leaf area index (LAI), and leaf shape and surface properties that affect water retention capacity. Overall, these findings indicate that the Mulder model, in the parametric configuration used, tends to underestimate the value of rainfall interception loss compared to field observations. Therefore, this model requires a more detailed calibration process, including measurements of local evaporation rates, verification of the actual canopy storage capacity of the dominant plant species, and consideration of daily weather variations to improve the accuracy of the estimates.

3.5 Model Performance Evaluation Based on RMSE

In this study, the RMSE value obtained is 43.25 mm. RMSE refers to the average magnitude of the quantitative error between the model prediction (Mulder) value and the actual observation value without considering the direction of the difference. A smaller RMSE value usually indicates that the model has higher accuracy because the error between the simulation results and observations is minimal.

An RMSE value of this size reflects the existence of a significant difference between the model estimate and the actual data, indicating that the model fails to accurately represent interception loss on a monthly scale. This is likely closely related to the absence of important variables in the model, such as canopy saturation before rain, rainfall intensity, storm duration, or evaporation rate between rain episodes. In the context of hydrological modeling, a high RMSE value is often an indication that linear models are

inadequate to represent the very complex interception process, especially in tropical forest systems with canopy structural heterogeneity.

4. Conclusion

Quantify rainfall interception loss within a tropical forest environment, field observation data revealed that the total interception loss recorded over the study period was 568.986 mm, equivalent to 24.46% of the total gross rainfall. Estimate interception loss using the Mulder Model, the showed that the total interception loss estimated by the model was 169.068 mm, equivalent to only 7.27% of the total gross rainfall throughout the study period. This value is significantly lower than the measured field interception loss, thereby highlighting the model's tendency to underestimate the actual interception loss in tropical rainforest. the accuracy of the Mulder Model by comparing its estimated values with field observations, the comparative analysis revealed an absolute difference of 399.918 mm, equivalent to a percentage discrepancy of 17.19% between the model's estimates and the actual field measurements. This substantial deviation clearly demonstrates that the original form of the Mulder Model is unable to produce interception loss estimates that closely reflect the real hydrological conditions at the study site.

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