Effect of leaf inclination and rainfall intensity on the Canopy Wetness Index of *Artocarpus Heterophyllus*

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Abstract: Canopy characteristics have a significant influence on the process of canopy surface wetting and water canalization into the canopy reservoir. Canopy surfaces that have increased wetting until the canopy is saturated will describe the process of rainfall redistribution that occurs throughout the canopy. Canopy wetting until saturated or the canopy wetting index (β) is an indicator of rainfall redistribution by a canopy. Canopy reservoir filling can occur after the canopy surface per unit area has been completely saturated. This research was conducted with changes in rainfall intensity (R), leaf slope (α), canopy porosity, and canopy flow distribution (Tf) on *Artocarpus heterophyllus*. This study found that the rainfall redistribution process was strongly influenced by leaf characteristics, depth, and rainfall duration. Leaf characteristics, especially leaf inclination, will create a pattern of water canal from the canopy surface to the canopy reservoir. The leaf inclination characteristic will increase canopy wetting across the canopy surface simultaneously, but will not make water flow uniformly to the canopy reservoir.

Keywords: Leaf inclination, rainfall intensity, canopy wetness index, throughfall distribution

1. Introduction

Tree canopy is one of the terrestrial components that are considered to influence climate modelling. Most of the rainfall that falls in tropical forests will be intercepted by a tree canopy. A tree canopy redistributes rainfall, which will affect surface runoff and flow concentration in the watershed. Tree canopies also play a role in regional climate control [1]. Only a small portion of rainfall in tropical forests drips directly to the ground surface through canopy crevices (Tf).

In tropical trees, rainfall redistribution begins with the interaction between raindrops and the canopy surface. The canopy wetting process is strongly influenced by leaf characteristics [2] [3] [4] and the crown structure [5]. The leaf is the first element of the canopy surface that interacts with raindrops. Leaves will concentrate raindrops above the lamina to form a water canal. The flow of water on the surface of the canopy will drip directly to the ground or flowing to the canopy reservoir. In canopies that have low branch densities and high crown porosities, the ratio of direct dripping is greater than the ratio of water flowing to the canopy reservoir. Conversely, in a canopy that has a high canopy density and low crown porosity, the ratio of water flowing into the canopy reservoir is greater than dripping directly to the ground [6] [4]. The comparison of water retained in the canopy reservoir (S) from the beginning of rainfall up to the entire canopy becoming wet is performed through the canopy wetness index [7].

On the canopy surface of broadleaf trees, such as *Artocarpus heterophyllus* (jackfruit), the canopy is a dynamic structure composed of interactions between leaves and twigs. The canopy surface
structure will be deformed due to the force of rainfall drops and the amount of water retained in the lamina. The deformation of the canopy surface is strongly influenced by the contact area between the lamina and the rainfall drops, as well as leaf stiffness and rainfall intensity. Deformation that occurs on the leaf surface occurs in the direction of the inclination and azimuth.

Canopy surface deformation is also influenced by the amount of water and the duration of retained water on the lamina [2]. The amount of water and the duration of the water retained on the lamina is affected by the characteristics of leaf surface and leaf waxes [8] [9]. The amount of water retained in the leaf area just before dripping is assumed as the minimum canopy storage capacity ($C_{\text{min}}$) [10]. $C_{\text{min}}$ is the amount of water that evaporates from the surface of the lamina [11]. Rainfall that has wetted the surface of the canopy will then be concentrated into a water flow to fill the canopy reservoir.

A broadleaf canopy will be deformed non-uniformly by rainfall energy. On the surface of a broadleaf canopy with small deformations, raindrops will be concentrated in a uniform pattern. Broadleaf trees with large angular deformation (azimuth and inclination) have very diverse concentration patterns, following changes in energy from rainfall characteristics. Changes in concentration patterns will have a significant effect on $T_f$ distribution [4]. A coniferous tree canopy has greater porosity compared with that of broadleaf trees. Therefore, the effect of canopy surface deformation of a coniferous canopy is smaller when compared to broadleaf trees. Leaf inclination has a more significant effect compared to leaf orientation distribution towards water funnelling on the canopy surface [12].

*Artocarpus heterophyllus* is one of the most common trees in the tropics. *Artocarpus heterophyllus* is an evergreen tree of medium size. The tree usually reaches a common height of 8-25 m (26–82 feet) and a trunk diameter of 30 to 80 cm (12–32 in). In young trees, the *Artocarpus heterophyllus* canopy has a conical or pyramidal shape. As the tree grows older, the branching in the canopy will spread further and the shape of the canopy changes into a dome shape. The porosity of the canopy is very small with branching structures and tight twigs. The largest branch is located near the ground. When incised, all parts of the tree emit sticky white latex [13]. *Artocarpus heterophyllus* became one of the dominant tree species after the eruption of Mount Merapi in 2010. *Artocarpus heterophyllus* played a major role in the economic recovery process of rural communities around Mount Merapi.

*Artocarpus heterophyllus* tree has several uses for the local people around Mount Merapi. Jackfruit (*Artocarpus heterophyllus* Lam) produces a heavier fruit yield than any other tree species, and bears the largest known edible fruit (up to 35 kg). The villagers have also used the leaf and fruit waste to provide valuable fodder for cattle. The tree is also known for its durable timber.

2. Materials and Methods

2.1. Tree characteristics

The observed tree sample was a sparse *Artocarpus heterophyllus* tree with a diameter of 23.0 cm. *Artocarpus heterophyllus* has a leaf arrangement that is alternate and intact, elliptical to oval, rigid, angular to twigs, and up to 16 cm long. The structure of the sample tree canopy was analysed using the hemispherical photography method. In this study, we used Nikon d5200 with the Nikon AF NIKKOR 85mm F/1.4D IF lens.

The sample tree has a cone-shaped canopy and an almost circular CPA (crown projection area). Based on differences in branch structure, the canopy is divided into 3 sections. Branching and twigs in section 1 tend to grow facing upward with branch arcs forming angles smaller than 30°. Meanwhile in section 3 (the farthest), the header spreads and forms a greater angle when compared to the section above it. Branching and twigs in section 3 have angles greater than 60° to the stem. The distribution of sections and observation points are presented in Figure 1.

Leaf angle distribution in section 1 was steeper than in section 2 and section 3. This happens because the vegetative process in section 1 was more dominant compared to other sections. During the observation, no pruning of leaves and twigs was performed. The generative phase of the tree was controlled by eliminating all flowers. Estimation of the LAI (Leaf area index) was performed by the hemispherical photography method with Gap Light Analyser ver. 2.0. [14]. The observed tree canopy has a CPA of 4.62 m², LAI of 4.69, and porosity of 0.04.

The observed tree had a distribution of twig angle to branches from 11° to 163° and leaf inclination distribution from twig from 7° to 75°. The determining of the inclination of the angles of
leaves and twigs is presented in **Figure 2** and **Figure 3**. The distribution scheme of leaf angles in each section is presented from **Figure 4** to **Figure 6**.

**Figure 1.** Crown projection area (CPA) and canopy distribution area for analysis

**Figure 2.** The angle distribution of twigs against the branch ($\alpha_r$)

**Figure 3.** The angle distribution of leaves against the twig ($\alpha_d$)

**Figure 4.** The leaf angle distribution scheme for section 1 ($\alpha_{d1}$)

**Figure 5.** The leaf angle distribution scheme for section 2 ($\alpha_{d2}$)

**Figure 6.** The leaf angle distribution scheme for section 3 ($\alpha_{d3}$)
2.2. Rainfall data
Data collection was performed from January 20 to July 20, 2017. During field observations, 110 rain events occurred on 68 rainy days. To avoid data noise due to splashes, the utilized rainfall data are rainfall data that occur at wind speeds of less than 2 knots. Because water splashes from the canopy due to wind gusts will affect the water balance analysis in the canopy [15], only 13 sets of data could be used for analysis. The selected rainfall data used in this study are shown in Table 1.

| Date       | Rainfall duration (min) | Gross rainfall (mm) | Rainfall intensity (mm.hr⁻¹) |
|------------|-------------------------|---------------------|----------------------------|
| 20-Feb     | 75                      | 3.72                | 2.98                       |
| 21-Feb     | 170                     | 17.16               | 6.06                       |
| 25-Feb     | 20                      | 3.72                | 11.16                      |
| 01-Mar     | 70                      | 16.22               | 13.9                       |
| 07-Mar     | 50                      | 22.41               | 26.89                      |
| 18-Mar     | 40                      | 16.17               | 24.26                      |
| 31-Mar     | 80                      | 36.14               | 27.11                      |
| 03-Apr     | 20                      | 2.48                | 7.44                       |
| 04-Apr     | 30                      | 3.72                | 7.44                       |
| 08-Apr     | 90                      | 13.66               | 9.11                       |
| 10-Apr     | 30                      | 16.21               | 32.42                      |
| 19-Apr     | 70                      | 13.64               | 11.69                      |
| 30-Apr     | 100                     | 10.12               | 6.07                       |

2.3. Theory
Research on the process of rainfall redistribution in tree canopies has evolved along with the challenges of water resource management and land use management [16] [3] [17]. The tree canopy will temporarily hold rainwater to be distributed back to the atmosphere or ground level [18] [19] [20] [21] [4]. Rainfall redistribution in trees can be explained by the water balance method, as the following equation [7]:

$$\Delta R(t)dt = \int_0^T \Delta L(t)dt + \int_0^T \Delta I(t)dt + \int_0^T \Delta f(t)dt$$

(1)

ΔR(t) is rainfall intensity (mm/min), \( I_R(t) \) is rainwater intercepted by the canopy (mm.min⁻¹), \( I_v(t) \) is water depth measured below the canopy (mm.min⁻¹) that consists of canopy throughfall (\( T_R \)) and stemflow (\( S_f \)), \( I_t \) is water loss due to evaporation during interception in the canopy (mm.min⁻¹), \( T \) is the duration of rainfall during observation (min), \( T_i \) is the duration of rainfall during the filling process of the canopy storage (min), and \( \tau \) is cumulative duration starting from the first contact of raindrops on the canopy surface to the end of the rainfall redistribution process (min). \( T_i \) must be less than or equal to \( T (T_i \leq T < \tau) \). For broadleaf trees, \( T_R \) and \( S_f \) do not occur simultaneously. \( I_v \) changes based on time can be written in the form of the following equation [7]:

$$\int_0^T \Delta I_v(t)dt = \int_0^T T_{ff}(t)dt + \int_{T_i}^T \Delta f(t)dt + \int_{T_i}^T S_f(t)dt$$

(2)

\( T_{ff} \) is rainfall dripping to the ground through a canopy gap and is only measured during rainfall (mm.min⁻¹). \( T_{ff} \) is a throughfall formed after the process of rainfall redistribution by leaves and twigs on the surface of the tree canopy (mm/min). Forest characteristics or plantation type has a significant influence on \( T_f \) and \( T_{ff} \) [22]. \( T_f \) and \( T_{ff} \) volumes are significantly affected by variabilities in tree succession, tree age, and phenology [23]. Analysis of the rainfall distribution process that occurs in the tree canopy is performed by calculating the increase in the volume of water that wets the canopy [7]. Water depth below the canopy (\( I_v \)) can be written down as:

$$I_v(t) = \int_0^t \Delta I_v(t)dt = R.L.A.I. \int_0^t f(\beta)dt$$

(3)
Or the canopy wetness index ratio $\beta$:

$$\beta = \frac{\int_{0}^{t} \Delta Iv(t) \, dt}{C_t \cdot R \cdot LAI}$$  \hspace{1cm} (4)$$

$C_t$ is the amount of water in the canopy at time $t$ (gr.mm$^{-1}$). The canopy wetting process starts with dry conditions ($\beta = 0$) up until the entire canopy becomes saturated ($\beta = 1$). The wetting duration ($t$) occurs from the first contact of raindrops on the canopy surface up to $T_i$ ($0 < t \leq T_i$).

One of the causes of water retention on the surface of the canopy is the shear stress ($\tau$) between the lamina plane and water drops. If it is assumed that the water drops on the lamina plane are at a depth that is spread evenly across the entire leaf area ($\bar{y}$) with a water droplet weight of $\rho_w$, then the shear stress can be written in the form of the following equation [24]:

$$\tau = \rho_w \cdot g \cdot \bar{y} \cdot \cos \theta$$  \hspace{1cm} (5)$$

Leaves that are deformed at the inclination angle will cause changes in shear stress between the leaves and water droplets. Leaves that have a gentle angle to the horizontal line will make it increasingly difficult for water to drain into the canopy reservoir. However, the process of forming canals to the reservoir canopy is not only dependent on the canopy wetness index [4] [24]. The structure of leaf stalks and leaf tip interactions influence the flow pattern of water filling the canopy storage.

2.4. Method

In this study, an increase in the canopy wetness ratio was assessed based on the $Iv(t)$ in each section. $Iv(t)$ was measured after the minimum canopy capacity is reached. If $Iv(t)$ had occurred throughout the canopy, the canopy was assumed to be completely wet or $\beta = 1$. After the entire canopy became wet, the process of rainfall redistribution continued. The value of $Iv(t)$ was measured until the throughfall finished and water loss was estimated based on the amount of water retained in the canopy.

The determined depth of intercepted rainfall in trees can be analysed using graphical methods [25]. This method is commonly applied to the modelling of rainfall interception by the forest canopy. In this study, the graphical method was utilized to determine the value of the canopy storage ($S$). The $S$ value of the Artocarpus heterophyllus sample tree was 2.50 mm.

The amount of water retained in the canopy ($C$) can be divided into 2 conditions [26]. $C_{max}$ is the maximum amount of water retained in the canopy. $C_{max}$ is reached as soon as the peak rainfall ceased and water drainage still occurred, while $C_{min}$ is the amount of water retained in the canopy immediately after the drainage process finished. For this condition, then the ratio is $C_t \leq C_{min}$ to $\beta \leq 1$.

The $C_{min}$ value for each unit of leaf area can be calculated using the following equation [11]:

$$C_{min} = \frac{(W_r - W_0)}{1}$$  \hspace{1cm} (6)$$

$W_0$ (gr) is the weight of the leaf unit area before spraying and $W_r$ (gr) is the weight of the leaf after spraying. Empirically, the process of redistribution in the canopy section with similar canopy characteristics and uniform leaf angle distribution per unit area can be explained as the following:

| $0 < Iv(t) \leq \% \Delta \beta(t) C_{min}$ | $\% \Delta \beta(t) C_{min} \leq Iv(t) < \% \Delta \beta(t) (1 - C_{min})$ | $Iv(t) \leq \% \Delta \beta(t) (1 - C_{max})$ |
|------------------------------------------|-------------------------------------------------|--------------------------------------------------|
| $C_{min} > 0$                            | $C_{min} < C_t \leq C_{max}$                    | $C_t \leq C_{max}$                                |

![Figure 7. Rainfall redistribution by a canopy](image)

The $C_{min}$ depth is assumed to be the evaporation that occurs during interception. The $C_{min}$ value becomes the control of $Tf$ measurement. The increase in the amount of water retained in the leaf is affected by the inclination that occurs due to an increase in $\Delta R$, so the amount of water held above the leaf surface increases until it reaches $C_{max}$. If the water depth above the leaf ($\bar{y}$) in Equation 5 is considered to be the same as the $C_{min}$, then

$$\tau = \rho_w \cdot g \cdot \frac{(W_r - W_0)}{1} \cdot \cos \theta$$  \hspace{1cm} (7)$$
The leaf inclination angle affects the canalization process of raindrops on the lamina surface and the canopy surface. If the shear stress between the lamina surface and water drops is large, then it becomes more difficult for raindrops to be canalized and then to flow into the reservoir canopy. In this research, a positive value indicates the concentration of water flowing into the canopy reservoir through the leaf base and twigs, while a negative value indicates that water flows through the lamina to drip directly as $T_f$.

3. Results and Discussion

Increased canopy wetness influences the $T_f$ distribution. Leaf inclination in each section influences the flow concentration on the canopy surface. In the Artocarpus heterophyllus canopy, the process of rainfall redistribution continues even though the rainfall has stopped and the flow from the canopy has ceased.

3.1. Results

3.1.1 Throughfall distribution

In a conical and dome canopy, the difference in thickness of each section does not significantly affect the flow of water to the canopy storage. Leaf inclination in section 1 is more acute-angled and dense. The difference in the inclination angle of the leaves will have a significant influence on the channelization of flow to the canopy storage.

Figure 8 shows the process of rainfall redistribution in the canopy with a chart. Based on the measurements, the average area of the Artocarpus heterophyllus leaf is 7.68 cm$^2$. The weight of water held above the leaves is 5.98 g ($C_{\text{min}} = 0.59$ mm). $I_v(t)$ cannot be measured before the point when $\Delta R > 0.59$ mm.min$^{-1}$.

$I_v(t)$ on Artocarpus heterophyllus does not fall evenly on the entire lower part of the canopy. The outer side of the canopy (section 3) shows a higher trend in the intensity of $I_v(t)$ than the other sections. The canopy wetness ratio increased even when the rainfall intensity is less than 4 mm.min$^{-1}$. The measured $I_v(t)$ value in section 1 is smaller compared to other sections. The $I_v(t)$ process has a significant correlation with increasing $\beta$. Figure 9 shows the increase in the value of $\beta$ based on Equation 4.

Figure 9 shows the initial conditions of the canopy wetting process. In this phase, the canopy is not completely wet ($\beta < 1$) when measurement of $I_v(t)$ started, although $\Delta R = 1.86$ mm.min$^{-1}$. Based on Equation 4, the canopy wetting process started when $\Delta R \geq 0.59$ mm.min$^{-1}$ (equal to the $C_{\text{min}}$), but the water could not hold above the lamina for time $t$. Before $\Delta R \geq 0.59$ mm.min$^{-1}$, water in the canopy completely evaporated and the canopy became dry. This proves that the values obtained empirically and graphically in this study are the same. Figure 8 and Figure 9 show that $I_v(t)$ can occur even though the tree canopy is not entirely wet. The increase in $\beta$ occurs constantly when $\Delta R = 2.50$ mm.min$^{-1}$.

![Figure 8. $I_v(t)$ distribution based on $\Delta R$](image1)

![Figure 9. Canopy wetness index ($\beta$) and rainfall intensity ($\Delta R$) in the initial saturation phase](image2)
The effect of leaves on increasing the $\beta$ ratio can occur due to changes in inclination due to energy caused by rainfall drops. Also, leaf morphology influences the direction of water flow that is concentrated on the surface of leaf strands. The increase in $\beta$ and $I_v(t)$ of each section based on rainfall intensity is presented in Figure 10. The increase in the ratio of $\beta$ in section 3 has a different pattern from section 1 and section 2. Improved wetting is faster compared to section 1 and section 2.

![Figure 10. Canopy wetness ratio ($\beta$) and measured throughfall ($I_v(t)$) with rainfall intensity ($\Delta R$) in each section](image)

Figure 10 shows that at $\Delta R \leq 1.24$ mm.min$^{-1}$, all the water was held at the canopy surface and was not measured as $I_v(t)$. Compared with Figure 9 and Figure 8, all sections will experience an increase in the value of $\beta$ along with an increase in the value of $I_v(t)$ after $\Delta R \geq 1.89$ mm.min$^{-1}$. The flow of water that occurs above the leaf blade flows through the strands or drips by gravity [24] [27]. Using Equation 7, flow conditions on the canopy surface are presented as in the form in Figure 11.

![Figure 11. Water shear stress distribution above the lamina based on leaf inclination in each section](image)

In this study, a positive value is shown if the water flows through the lamina. Water dripping directly to ground is assumed with a negative value. Figure 11 shows that 50% of the leaf clusters in section 3 will drip if $1.24$ mm.min$^{-1} \leq \Delta R \leq 1.89$ mm.min$^{-1}$. Meanwhile in section 1 and section 2, water flows down the leaf blade after the $C_{min}$ capacity has been exceeded.

An increase in the amount of water that drips compared to flowing water occurs due to changes in leaf inclination. An increase in the amount of water that drips will occur along with an increase in rainfall intensity [28] and interactions between leaves. In leaves that have a more flexible structure, the interaction between leaves is better than that of stiff leaves. In trees with stiff leaves (such as *Artocarpus heterophyllus*), differences between the leaves can occur due to vegetative factors. Leaves that are on the upper side and in the growth phase tend to be more flexible compared to leaves that have been fixed.
3.2. Discussion
Rainfall falling on the tree canopy will flow to fill the canopy storage. Interaction between canopy components gives a significant influence on the process of rain redistribution in the canopy. In the tree canopy of *Artocarpus heterophyllus*, rainfall makes contact and wets the canopy surface of each section simultaneously. However, the wetting ratio of the canopy is not uniform even in the same species. At the same rainfall intensity, the difference in measured $I_v(t)$ or $T_f$ occurs due to the shape and structure of the canopy. Figure 8 and Figure 9 illustrate the process of increased canopy wetness index due to increased rainfall intensity.

In *Acer mono maxim*, the increase in $\beta$ is strongly influenced by the characteristics of the leaves and canopy [7]. In Figure 10, an increase in rainfall intensity does not cause a uniform increase in $\beta$ throughout the canopy section. The ability of the canopy to intercept rain does not always increase during rainfall. The maximum intercepted rainfall per unit area decreases with increasing rainfall intensity.

Increased rainfall intensity will change the inclination of the leaf strands to the point of falling. The concentration of droplets to water flow on the canopy surface is largely determined by the characteristics of the leaves. The channelling process by the concentration of water droplets in needle-leaved trees is very different when compared to broadleaf trees. In *Artocarpus heterophyllus*, the inclination of leaves forms a channel that directs the flow towards the branches. However, this does not always happen. In the outer section of the canopy, the structure of the canopy is more flexible than the section near the stem. This results in the concentration of flow in the section on the outer side of the canopy becoming more dominant to direct dripping (Figure 11).

This study showed that leaf inclination is more significant to the canopy wetting process than rainfall intensity. Parts of the canopy which have a higher crown density require a longer wetting duration. In a canopy with conical or dome shape, leaf inclination leading to the branches, and the concentration of flow to the dominant canopy storage occurs near the stem. In a canopy which has a structured leaf structure, the interaction between leaf groups concentrates the flow when compared to other leaf structures.

Channels on the surface of the canopy formed by the flow concentration are closely related to the dimensions and shape of water droplets to the ground level. The flow of water concentrated on the surface of the canopy is formed due to the inclination that occurs when the water flows [27]. Redistribution of rainfall by the canopy is largely determined by the dimensions and shape of the droplets from rainfall. The flow of water on the surface of the canopy is dependent on the ecophysiological nature. In addition, the location of the habitat influences the surface morphology of the canopy [2].

4. Conclusion
Leaf surface characteristics have many variations. Variations occur in different species or the same species. In different species, variations in leaf surfaces are seen in the relatively smooth surface layers of amorphous wax (such as grapes) to very rough surfaces, while the wetting ratio will vary according to the surface characteristics of the surface layer. The greatest effect on leaf surface wettability is the surface structure.

The rainfall redistribution process is strongly influenced by leaf characteristics, rainfall depth, and duration. The ratio of leaf shape and inclination affects the process of canopy wetting and canopy saturation. In a canopy which has heterogeneous leaf inclination distribution, the entire canopy wetting does not take place simultaneously.

The measured throughfall in a part of the canopy does not indicate that the entire canopy is wet. Throughfall in some canopies can be an indicator that the canopy surface wetting process is ongoing. Increased rainfall intensity to wet the entire canopy must be greater than the $C_{max}$ depth. The entire canopy can be considered wet if all parts of the canopy have distributed throughfall and stemflow has been measured.

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