Stemflow and throughfall on several tree architectural models

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Abstract. The aim of developing urban forests for steep areas is to prevent erosion. Erosion can be caused by stemflow and throughfall. The difference in stemflow and throughfall is thought to be due to differences in the tree architecture model. The study investigates the effects of several tree architectural models on the amount of stemflow and throughfall. It is hoped that data and information of this research can be taken into consideration in selecting tree species for the benefit of soil and water conservation in urban forest areas that have the potential for erosion and sedimentation. The collection and processing of data comprised the rainfall data obtained from Meteorological Climatological and Geophysical Agency, measurement of leaf area index using a hemispherical photograph and Hemiview 2.1 software, measurement of stemflow and throughfall in five tree architectural models (Massart, Aubreville, Koriba, Rauh, and Troll). Afterward, the relationship between the dependent and independent variables is known through multiple linear regression analysis using Minitab 16 software. The result showed that the tree architectural model influences stemflow and throughfall. The tree architectural model with the highest stemflow and throughfall is Rauh, and the lowest belongs to the Massart architectural model. The tree architectural model that can be used for land and water conservation is Massart; the species is Diospyros discolor Willd.

1. Introduction

City development brings negative impacts due to development that does not pay attention to the environment, and this affects the damage to the hydrological system, which will cause flooding and erosion. One of the most critical factors causing flooding in urban areas is a poor hydrological system [1]. Large surface flow causes flooding, and this condition gets worse if it occurs on sloping areas or land, surface runoff that carries mud erodes the soil and causes erosion [2].

Erosion is the process in which earthen materials are worn away and transported by the action of wind, water or other natural forces. The vegetation, soil characteristics, climate, and topography are such as the factors influencing soil erosion [3]. The effect of vegetation on erosion is caused by the amount of rain interception by the plant canopy, the speed of surface runoff, and the destructive power of water by undergrowth/forest floor vegetation, as well as roots and biological activities that affect soil porosity. Therefore, to overcome hydrological problems in urban areas, it is necessary to build urban forests with soil and water conservation functions. Urban forests consist of trees that can intercept rainfall, reducing the amount of water that falls to the surface. The amount of rain interception by vegetation is influenced by the tree architecture model.

A tree architecture model is a three-dimensional form of a tree building that reduces the kinetic energy and potential energy of rainwater and affects the stemflow and throughfall [4, 5]. The tree...
architecture model is based on plant parts that are above the ground such as stem growth patterns, branching, size, shape and position of leaves and flowers. The tree architecture model is thought to affect the amount of stemflow and throughfall, which will ultimately affect the amount of erosion and sedimentation [6, 7, 8]. Many studies on tree architectural models have been carried out [9, 10, 11, 12, 13, 14, 15]. The results of research in the educational forest area of Mount Walat, Sukabumi, showed that the percentage of throughfall on the Massart architectural model represented by the *Agathis dammara* plant was 87.23%, greater than the Rauh tree architectural model represented by the *Schima wallichii* plant of 77.97% [16]. The type of oil palm tree (*Elaeis guineensis* Jacq) is able to produce 57.32% throughfall from 1015.5 mm of rainfall. However, to enrich the data and information, it is necessary to research other tree architecture models with different environmental conditions. Knowledge of the right tree architecture model in soil and water conservation efforts is needed to facilitate the selection of tree species for urban forest development in steep areas.

This study aimed to examine the effect of several architectural tree models on the amount of stemflow and throughfall. This research is expected to provide benefits in the form of data and information available regarding the role of several tree architecture models on the amount of stemflow and throughfall. It is hoped that this data and information can be taken into consideration in selecting tree species for the benefit of soil and water conservation in urban forest areas that have the potential for erosion and sedimentation.

2. Method

The data used in the study are primary data and secondary data which are processed qualitatively and quantitatively and then interpreted descriptively. Primary data is obtained through direct observation and measurement by researchers in the field, while secondary data is obtained through literature review in the form of books, theses, dissertations, journals and other scientific works that can be justified as well as data obtained from relevant agencies.

2.1. Time and location of the research

This research was conducted during March-May 2020. The research location was on the Campus of IPB University, Dramaga, Bogor, West Java.

2.2. Materials and equipments

The tools used in this study were the Garmin Global Positioning System (GPS) Map 78s, roll meter, beaker glass, hoses, funnels, jerrycans, Digital Single Lens Reflex (DSLR) cameras, fisheye lenses, tripod, and stationery. The materials used are plastic sheets, labels, raffia rope, wooden stakes, nails, and wood glue.

2.3. Data collection and processing

2.3.1. Identify the tree architecture model. Determination of the tree architecture model is done by first noting the characteristics of the tree, then identifying it [17]. The key to identifying the tree architecture model pays attention to several parameters, namely stem growth patterns, branching forms, and inflorescence types. The trees that became the object of the research were *Cerbera manghas* Hochr, *Terminalia catappa* Hassk, *Diospyros discolor* Willd, *Artocarpus heterophyllus* Lam, *Pterocarpus indicus* Pers. There are several conditions in the selection of trees, namely the tree is an individual that grows alone in a location (not in clusters), tree morphology such as flowers, branches, leaves are fully arranged, and the tree is in a healthy condition.

2.3.2. Leaf area index. Leaf Area Index (LAI) is the ratio of the total leaf area to the projection area of the canopy, hereinafter referred to as canopy density. Determination of LAI was done by taking a photo of the crown from below using the hemispherical photograph technique. The DSLR camera and tripod were positioned parallel to the ground with a height of ± 1 m. A fisheye lens was attached to a DSLR camera to take a close-up image by pointing the camera towards the sky [18].

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The results of the tree canopy photos were processed using Hemiview 2.1 software. Processing is carried out using the threshold method on the canopy cover image [18]. The average LAI value is calculated by the following equation (1).

\[
\text{Average of LAI} = \frac{\text{Li}}{N}
\]

where:
Li = LAI value of \(i^{th}\) point
N = Number of camera placement points on one tree

2.3.3. **Stem diameter.** Stem diameter was measured at the height of 1.3 m from the ground or at breast height. Measurements were made by wrapping a measuring tape on the trunk of the tree so that the circumference data of the trunk was obtained, which will then be processed into stem diameter data. Stem diameter data is generated using the following equation (2).

\[
D = K \pi
\]

where:
D = Diameter (cm)
K = Circumference (cm)
\(\pi\) = 3.14

2.3.4. **Tree canopy area.** The area of the canopy was obtained by measuring the shortest diameter and the longest diameter of the crown which was then processed to obtain data on the area of the canopy, with the following equation (3).

\[
L = \frac{1}{4} \pi \left[ \frac{d1+d2}{2} \right]
\]

where:
L = tree canopy area (\(m^2\))
d1 = shortest canopy diameter (m)
d2 = longest canopy diameter (m)
\(\pi\) = 3.14

2.3.5. **Stemflow.** The stemflow was accommodated by attaching a plastic hose around the surface of the stem as high as 130 cm, and one end was placed lower towards the storage (jerrycan) [19]. The stemflow container is presented in figure 1. Measurements were carried out at 07.00 WIB the day after the rain, with ten rainy days repeated.

Figure 1. Stemflow container.
The volume of stemflow (cm$^3$) that is accommodated is converted into units of water column height (mm) with the following equation (4).

$$ S_f = \frac{V}{L} \times 10 $$

where:
- $S_f$ = Stemflow (mm)
- $V$ = Volume of water collected (cm$^3$)
- $L$ = Tree canopy area (cm$^2$).

2.3.6. Throughfall. The throughfall was collected using a plastic sheet measuring 1 m x 1 m which was given a wooden frame with a height of 1.3 m, then placed under the tree canopy. The plastic sheet is perforated and given a connecting hose to drain water into the reservoir (jerrycan). The throughfall container can be seen in figure 2. Measurements were made at 07.00 WIB, the calculation of the amount of throughfall was measured based on the volume of water that was accommodated in the storage tank (jerrycan) per unit area of storage (mm) [16].

![Figure 2. Throughfall container.](image)

The volume of the accommodated throughfall (cm$^3$) is converted into units of water column height (mm) with the following equation (5).

$$ T_f = \frac{V}{L} \times 10 $$

where:
- $T_f$ = Throughfall (mm)
- $V$ = Volume of water collected (cm$^3$)
- $L$ = Storage area (cm$^2$).

2.3.7. Rain interception. The amount of rainfall in this study is divided into 3 parts, namely stemflow, throughfall, and rain interception, assuming that evaporation does not occur. The formula for calculating rain interception as follows [20], with the following equation (6).

$$ R_i = R_f - (T_f + S_f) $$

where:
- $R_i$ = Rain interception (mm)
- $R_f$ = Rainfall (mm)
- $T_f$ = Throughfall (mm)
- $S_f$ = Stemflow (mm)
2.4. Data analysis

Data collected from the field was processed using the Excel 2016 program to determine the relationship between rainfall with stemflow and throughfall as well as the relationship between leaf area index with stemflow and throughfall, multiple linear regression analysis was performed using Minitab 16 software. A negative or positive relationship between independent variables with the dependent variable can be seen in the resulting equation. To know, the influence contribution of the independent variable on the dependent variable can be seen in the value of the coefficient of multiple determination or the resulting $R^2$ value.

3. Result and discussion

3.1. Tree architecture models

Based on the identification of tree morphological characteristics [17] five different architectural models were obtained for each tree species. The architectural model of each tree and its characteristics are presented in table 1.

| Species       | Growth in height       | Branches                      | Inflorescences | Architecture model |
|---------------|------------------------|-------------------------------|----------------|-------------------|
| C. manghas    | Sympodial              | Plagiotropic                  | Terminal       | Koriba            |
| T. catappa    | Monopodial, rhythmic   | Plagiotropic, rhythmic        | Lateral        | Aubreville        |
| D. discolor   | Monopodial, rhythmic   | Plagiotropic, rhythmic        | Lateral        | Massart           |
| A. heterophyllus | Monopodial, rhythmic | Orthotropic, monopodial      | Lateral        | Rauh              |
| P. indicus    | Sympodial              | Plagiotropic                  | Lateral        | Troll             |

Apart from identifying tree morphology, measurements of the canopy area and canopy density were also carried out. Data on stem diameter, canopy diameter, canopy area, and leaf area index are presented in table 2.

| Species       | Stem diameter (cm) | Canopy diameter (m) | Canopy area (m²) | Leaf area index |
|---------------|--------------------|---------------------|-----------------|---------------|
| C. manghas    | 42                 | 10,15               | 80,87           | 3,55          |
| T. catappa    | 18                 | 9,85                | 76,16           | 2,19          |
| D. discolor   | 19                 | 8,45                | 56,05           | 4,22          |
| A. heterophyllus | 19               | 6,75                | 35,77           | 2,27          |
| P. indicus    | 53                 | 11,8                | 109,30          | 2,33          |

The architectural model of Troll type $P. indicus$ has the largest trunk diameter, while the shortest diameter is the architectural model of Aubreville ($T. catappa$). The stem diameter data were not included in the research variable because it was considered not to affect the amount of stemflow and throughfall. The amount of stemflow is influenced by the smoothness of the bark and the angle of the trunk and branches [21]. Smooth stems have fast stemflow, while in rough and cracked stems, the stemflow is slow [22]. The canopy area data was used to calculate the stemflow. The largest canopy area was owned by $P. indicus$ with the Troll architectural model, while the smallest canopy area was owned by $A. heterophyllus$ with the Rauh architectural model. The canopy density is one of the independent variables that will be tested. The species with the densest canopy was $D. discolor$ with the Massart architectural model, while the lowest canopy density was owned by $T. catappa$ with the Aubreville architectural model.

3.2. Stemflow analysis

The relationship or influence between rainfall and leaf area index on stemflow is known by performing multiple linear regression analysis. The results of multiple linear regression analysis show the following equations (7):
\[ Y = 0.05665 + 0.0241X_1 - 0.0291X_2 \]  
\[ R^2 = 60.7\% \]  

where: \( y \) stemflow, \( x_1 \) rainfall, \( x_2 \) leaf area index

Rainfall has a positive relationship to stemflow, whereas the leaf area index has a negative relationship. The \( R^2 \) value of 60.7\% indicates that rainfall and leaf area index affects the amount of stemflow by 60.7\%, while the remaining 39.3\% is influenced by other variables outside the model not studied. Simultaneous test/F test showed \( p \)-value < 0.05, so it can be concluded that together rainfall and leaf area index significantly affect the amount of stemflow.

### 3.3. Throughfall analysis

The relationship or influence between rainfall and leaf area index on throughfall is known by performing multiple linear regression analysis. The results of multiple linear regression analysis show the following equations (8):

\[ Y = -0.05 + 0.880X_1 - 0.413X_2 \]  
\[ R^2 = 77.8\% \]  

where: \( y \) = throughfall, \( x_1 \) = rainfall, \( x_2 \) = leaf area index

Rainfall has a positive relationship with throughfall, whereas the leaf area index has a negative relationship. The \( R^2 \) value of 77.8\% indicates that rainfall and leaf area index affects the amount of throughfall by 77.8\%, while the remaining 22.2\% is influenced by other variables outside the model not studied. Simultaneous test/F test showed \( p \)-value < 0.05, so it can be concluded that together rainfall and leaf area index significantly affect the amount of throughfall.

### 3.4. Stemflow based on the tree architecture model

The results of stemflow measurements show the amount of stemflow measured in the five tree species of the research object ranging from 0.078 – 0.251 mm. Data on the amount of stemflow for each tree species can be seen in figure 3.

![Figure 3. Amount of stemflow.](image)

The lowest stemflow is owned by *D. discolor* with the Massart type, and this is because this species has the highest leaf area index. The canopy density influences the amount of stemflow [23]. The condition of the canopy is tight, causing more rainwater to be held in the canopy and evaporated back into the air. Data on the value of leaf area index for each tree species observed are presented in figure 4. The Rauh model of *A. heterophyllus* species has the highest stemflow. This type has branches that grow orthotopically so that the branching angle is small. Architectural models with orthotropic branches have greater stemflow than plagiotropic [16]. The amount of stemflow is influenced by the bark (stem surface) and the angle of branching, for smooth stems the stemflow is fast, while in rough and cracked stems, the stemflow is slow [21,22,24]. In addition to the above factors, factors that affect stemflow include tree...
architecture, bark, stand structure, presence or absence of epiphytes, tree species composition, rainfall incidence (frequency, duration of rain, rainfall intensity, and leaf position) [6].

3.5. Throughfall based on the tree architecture model
The results of the throughfall measurement show that the amount of throughfall measured on the five tree species of the research object ranges from 4.064 to 5.535 mm. Data on the amount of rainfall per tree species are presented in figure 5.

![Figure 5. Amount of throughfall.](image)

The lowest throughfall was owned by the Massart architectural model (D. discolor), the highest was Rauh with species A. heterophyllus. The difference in the amount of throughfall is caused by the density of the canopy, a canopy that is not tight will cause cracks in the canopy because it is not covered by leaves. Through these gaps the rainwater that falls does not have time to be stuck in the canopy and falls directly to the surface. Escaped water (canopy escape) will decrease in line with the increasing density of the vegetation canopy or forest stands [25].

3.6. Canopy interception based on the tree architecture model
The process of holding rainwater on the surface of the vegetation before it is evaporated back into the atmosphere is called interception. This study divides the amount of rainfall into three parts, namely stemflow, throughfall, and an interception. The magnitudes and percentages of stemflow, throughfall, and interceptions are presented in table 3.

| Species         | Stemflow (mm) | Throughfall (mm) | Interception (mm) | Leaf area index |
|-----------------|---------------|------------------|-------------------|----------------|
| C. manghas      | 0.15          | 4.76             | 1.94              | 3.59           |
| T. catappa      | 0.08          | 4.85             | 1.91              | 2.78           |
| D. discolor     | 0.08          | 4.06             | 2.70              | 4.22           |
| A. heterophyllus| 0.25          | 5.53             | 1.05              | 2.27           |
| P. indicus      | 0.12          | 4.63             | 2.09              | 2.34           |

Dominant factors that influence rain interception are rain depth and canopy density [26]. The denser the tree canopy, the greater the interception. This is because more rainwater is retained by the canopy, which will then be intercepted [27]. The canopy density values for T. catappa, A. heterophyllus, and P.
indicus were not much different. However, the intercepts of A. heterophyllus were much different for T. catappa and P. indicus. This proves that canopy density is not the only vegetation character factor that affects rain interception by plants. Factors that affect the amount of interception include rain intensity, duration of rain, rain distribution according to time and type of stand/vegetation (canopy size, leaf type, stem type) [28].

3.7. Directives for development of urban forest

Urban forest development is done by developing vegetation to be planted by selecting a tree architectural model. There are criteria for selecting vegetation types in urban forests, one of which is unique plants planted with a specific purpose [29]. The selection of vegetation types is carried out based on the primary function of the urban forest. In this case, the main function in question is soil and water conservation [30]. Massart's architectural model is the most suitable for planting in urban forests. This architectural model has the lowest amount of stemflow and throughfall compared to the other four models. The model that should be avoided for planting in urban forests is Rauh. The results of this study are in line with research conducted by [11] which states that the Massart architectural model transforms the amount of rainfall into less throughfall than the Rauh model.

The thickness of the tree canopy strata of the Massart model causes rainfall to pass through many canopy strata before touching the ground. Trees with Massart's architectural models include Diospyros discolor, Agathis dammara, Myristica fragrans, Syzygium polyanthum, and Syzygium aromaticum [17]. The development of urban forests and the selection of urban forest vegetation must also be made with many strata. Multistory urban forests (A – E) are more effective in dealing with urban environmental problems than those with only two strata (trees and grass). The effect of vegetation on soil and water conservation is caused by the amount of rain interception by the canopy, the velocity of surface runoff and the destructive power of water by undergrowth/forest floor vegetation, shrubs, shrubs, as well as roots and biological activities that affect soil porosity.

4. Conclusion

The lowest stemflow and throughfall is owned by Massart, and the highest was Rauh. Differences in tree architecture models cause differences in the amount of stemflow and throughfall. Rainfall has a positive relationship to stemflow and throughfall, whereas leaf area index (LAI) has a negative relationship to both. This means that the greater the rainfall value, the greater the value of stemflow and throughfall, while the negative relationship between leaf area index and stemflow means that an increase in the value of canopy density will reduce the amount of stemflow and throughfall.

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