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STEMFLOW, THROUGHFALL AND RAINWATER INTERCEPTION OF EIGHT INDONESIAN TREE SPECIES

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ABSTRACT

Tree architecture affects how rainwater is partitioned into canopy interception, throughfall and stemflow. The canopy shape and bark/leaf surface morphology affects the plants' ability to intercept and redistribute the rainwater. Hence, the tree structure plays a key role in soil and water conservation, especially in erosion runoff. This research was conducted to predict the most suitable tree species for soil and water conservation, and recorded 32 rainfall events during the rainy season in January 2014-March 2015 in Purwodadi-LIPI, Indonesia. The stemflow, throughfall, individual tree architectural characteristics, and leaf morphology were measured for eight selected local tree species namely: *Sterculia cordata*, *Aleurites moluccanus*, *Buchanania arborescens*, *Calophyllum inophyllum*, *Dysoxylum gaudichaudianum*, *Peltophorum pterocarpum*, *Alstonia scholaris* and *Pometia pinnata*. The species which held the greatest amount of interception was *Aleurites moluccanus* at 68.1% of rainfall. Special characteristics of the leaves (like fine hairs), globose stem and long, grooved bark, probably resulted in an increased relative interception of the rain water that was higher than those of other trees. The throughfall and stemflow for each species were closely related to rainfall amount, but not related to rainfall intensity.

Keywords: canopy interception, rainfall partitioning, stemflow, throughfall, tree architecture

INTRODUCTION

Forest canopies are capable of intercepting large quantities of precipitation, altering the spatial and temporal inputs of precipitation to forested landscapes (Levia *et al.* 2011). The distribution of rain water across and through plant canopies is therefore, a heterogeneous aspect of the various processes comprising throughfall, stemflow, and the water retained by the canopy as interception. Throughfall is the portion of rain that reaches soils by dripping from canopy surfaces or through gaps. Temporally-persistent canopy structures can result in capable of creating storm-based pulses in soil moisture (Coenders-Gerrits *et al.* 2013), soil microbial community structure (Rosier *et al.* 2015) and function (Moore *et al.* 2016). Stemflow is the portion of rain water that drains down the stem. Despite being a small percentage of rainfall across the canopy area, it has a considerable influence on the spatial variability of soil biogeochemical processes. Stemflow often moves to the soil layers along the path of the roots indicating that the stemflow does not only contribute to the dynamics of water on the forest floor, but also the flow of water infiltration in the root zone (Li Liang *et al.* 2011).

The amount of rainwater retained by the tree, before it goes into the ground, depends on the leaf size, leaf shape, canopy density and canopy shape, roughness and straightness of bark (Darmayanti & Fiqa 2017). Water entering into the soil will undergo several processes. Some will be absorbed into the ground, partly filling a layer of water-saturated soil, and some will detach as runoff (Schelemmer *et al.* 2018). In this way, interception by plants indirectly affects infiltration and surface water runoff. Plant

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canopies also indirectly affect soil erosion as they can reduce the kinetic energy of the collision on the surface of the soil, so the soil structure and aggregation are not damaged.

This study aimed to evaluate the influence of plant canopy architecture model of the eight plant species to rainfall factors, such as throughfall, stemflow, and interception in the Purwodadi Botanic Garden. The tree species were selected from among local plants that have known potential soil and water conservation properties, such as those often found in springs, and also have economic value. Furthermore, the results can be used as reference for trees recommended to rehabilitating degraded areas, particularly due to soil erosion. Tree species selection for restoration or rehabilitation of degradation areas is critical in formulating programs that are effective and efficient in reducing the rate of degradation.

MATERIALS AND METHODS

The experiment was conducted at Purwodadi-LIPI in February 2014 to March 2015. The hydrological parameters (throughfall, stemflow and rainfall interception) were measured for 20-30 rain events for each species. Observations were made every morning at 07.00 am and the average daily rainfall, stemflow data and throughfall were recorded. Rainfall was measured by installing an ombrometer at the open area. Throughfall was estimated by measuring the volume of rainwater passing through the canopy of each species and were gathered in a plastic bucket. Stemflow was measured by using small water hose, wax, rubber tires and jerry cans. The water hose was cut to fit the trunk circumference and then mounted circularly at a height of about 1.3 m. The lower part of the hose was tied with rubber installed to the jerry can to collect the rainwater flowing through the tree trunk, the volume of which is the stemflow. Eight tree species were observed including *Sterculia cordata*, *Aleurites moluccanus*, *Buchanania arborescens*, *Calophyllum inophyllum*, *Dysoxylum gaudichaudianum*, *Peltophorum pterocarpum*, *Alstonia scholaris* and *Pometia pinnata.* The stemflow was gathered by spliting plastic hose stapled around the tree using galvanized staple pins with one of its ends tapering downwards to discharge water into a graduated jar (Venkatraman & Ashwat 2016). The results of stemflow and throughfall were incorporated into the equation to estimate the value of rainwater interception by plants as follows:

$$\text{Interception (mm)} = \text{Rainfall} - (\text{throughfall} + \text{stemflow})$$

The size of leaves, as well as the architectural dimensions of the tree were measured to enable evaluation of their effects on throughfall, stemflow and interception. Eight local tree species were sampled with two replications. Tree height, crown height, crown diameter and diameter at breast height (DBH) were also measured. The other characters such as bark surface, leaf surface area, leaf width, and crown gap were directly measured after the experiment ended. Finally, all of the quantitative data were analyzed using MINITAB 16, to evaluate the different species performance. Regression of the hourly canopy interception was analyzed using Microsoft Excel to show a linear relationship for each rainfall event.

RESULTS AND DISCUSSION

The tree species which has the highest canopy interception was *Aleurites moluccanus* (13.4 mm), followed by *Sterculia cordata* (5.8 mm) and *Dysoxylum gaudichaudianum* (5.6 mm) (Fig.1).

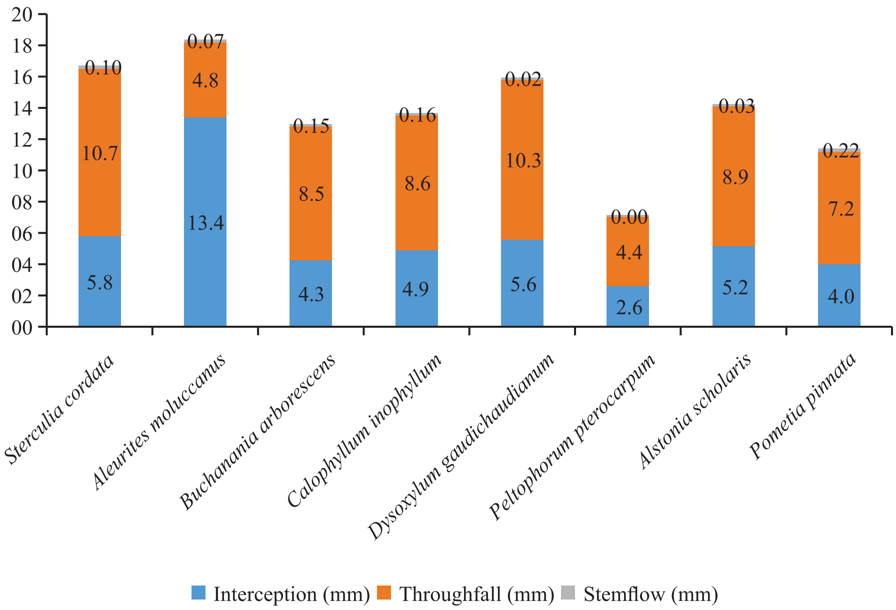


Figure 1 Interception, throughfall and stemflow of eight trees selected

Sterculia cordata has the highest throughfall, (10.7 mm), followed by *Dysoxylum gaudichaudianum* (10.3 mm), and *Alstonia scholaris* (8.9 mm). *Pometia pinnata* has the highest stemflow value (0.22 mm), followed by *Calophyllum inophyllum* (0.16 mm) and *Buchanania arborescens* (0.15 mm). Stemflow is only a small part of gross rainfall, but plays an important role in the ecology and biogeochemistry of soil (Levia & Germer 2015; Van Stan & Gordon 2018). Water from the stemflow is the concentration of nutrients that will fall to the forest floor and into the ground, infiltrate into the preferential soil and the hydrology and biogeochemistry of wooded ecosystems (Levia & Germer 2015).

Based on the rainfall percentage, *Aleurites moluccanus* has the highest canopy interception (68.1%), followed by *Peltophorum pterocarpum* (53.8%) and *Calophyllum inophyllum* (48.9%) (Fig. 2). Generally, plants that have high canopy interception rate have low stemflow values because rainfall is mostly clean and distributed and retained on the header section. Plants with low canopy interception values has stemflow values that are considerably higher than the other plants.

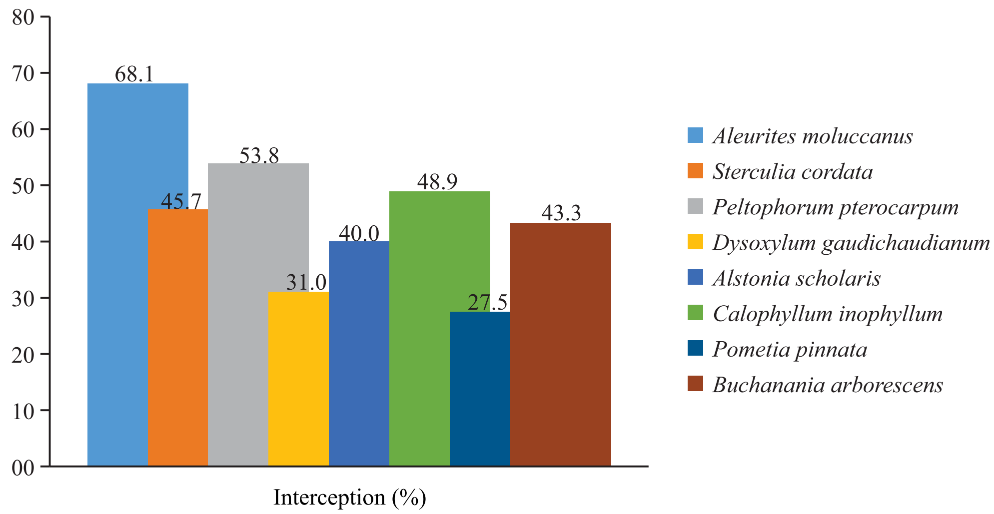
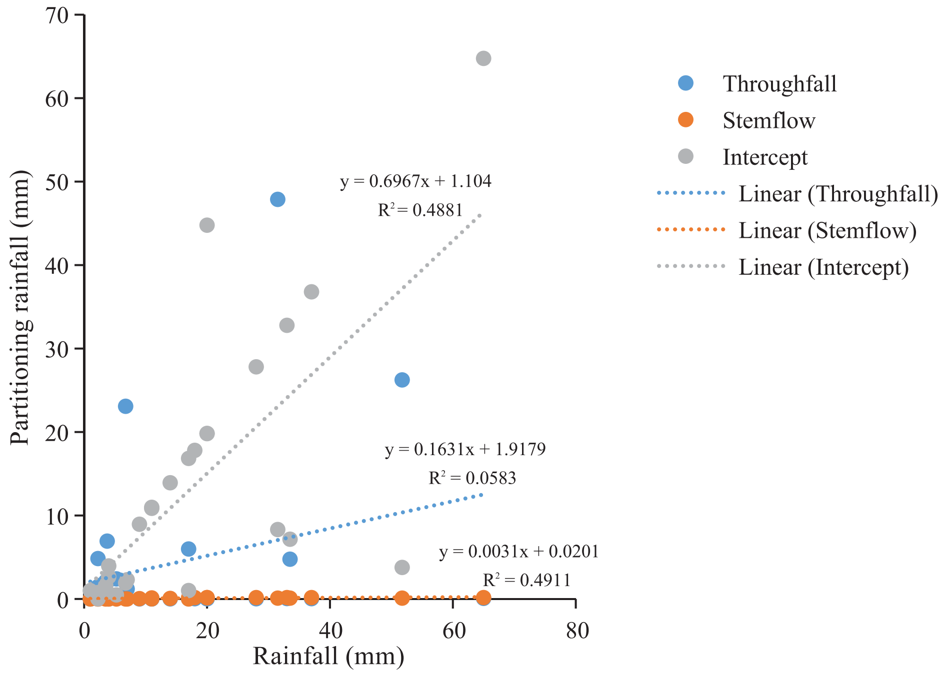


Figure 2 Interception percentage of several plants at Purwodadi Botanical Garden

The canopy interception showed a linear relationship with rainfall in each rain event (Fig. 3). The regression lines indicated a positive correlation between rainfall and throughfall or rainfall and stemflow for each tree.

Throughfall is closely related to rainfall; the higher the rainfall, the higher the throughfall. All species also showed that the increasing rainfall intensity resulted in the increasing interception percentage. Such a very strong positive relationship was observed in *B. arborescens* ($R^2 > 0.9$) (Fig. 3), and strong positive relationship was observed in *S. cordata* and *C. inophyllum* (R^2 close to 0.9). Stemflow was not correlated with rainfall intensity.

A



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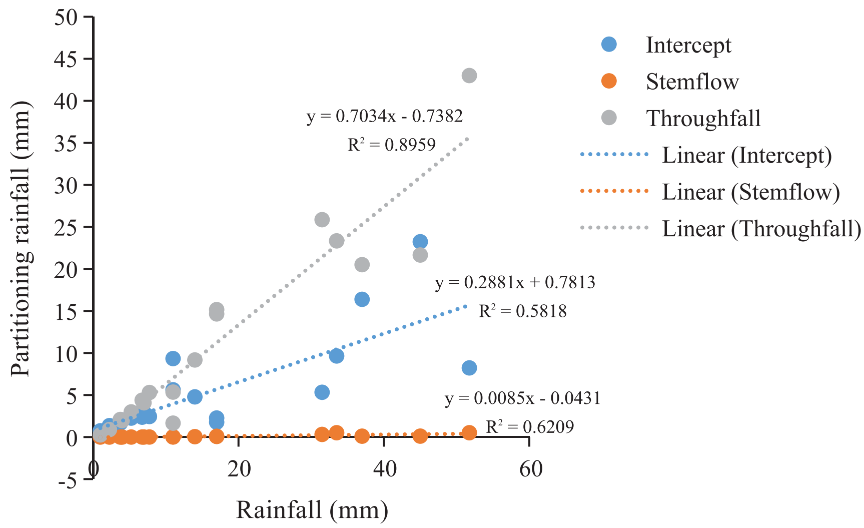
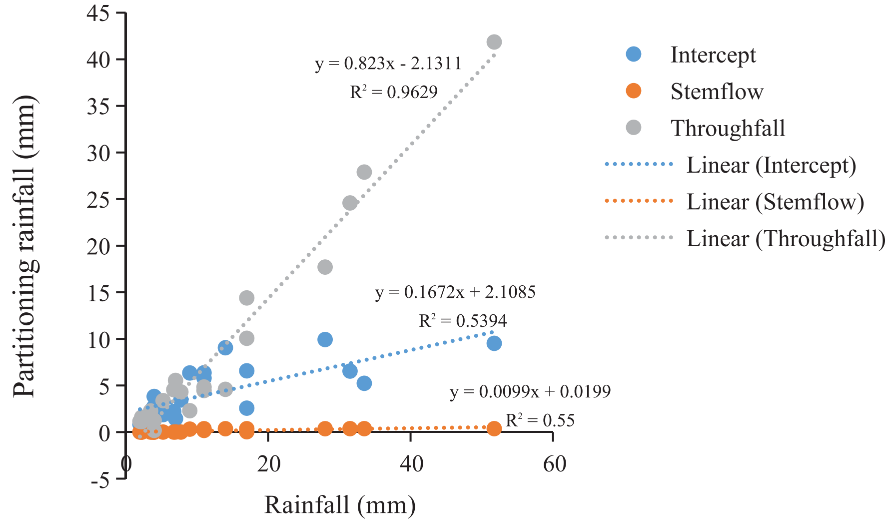
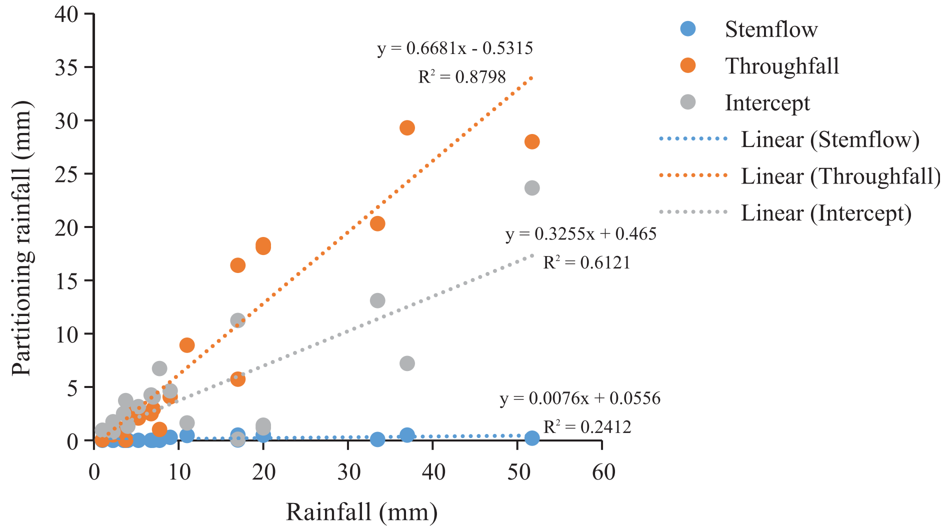
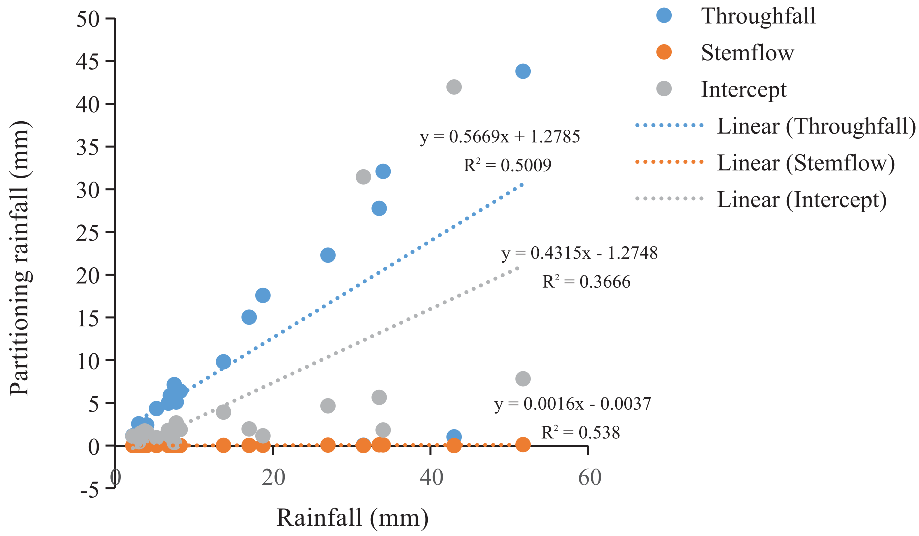



Partitioning rainfall (mm)
Rainfall (mm)
y = 0.823x - 2.1311
R² = 0.9629
y = 0.1672x + 2.1085
R² = 0.5394
y = 0.0099x + 0.0199
R² = 0.55
Intercept
Stemflow
Throughfall
Linear (Intercept)
Linear (Stemflow)
Linear (Throughfall)

C


Partitioning rainfall (mm)
Rainfall (mm)
y = 0.6681x - 0.5315
R² = 0.8798
y = 0.3255x + 0.465
R² = 0.6121
y = 0.0076x + 0.0556
R² = 0.2412
Stemflow
Throughfall
Intercept
Linear (Stemflow)
Linear (Throughfall)
Linear (Intercept)

D


Partitioning rainfall (mm)
Rainfall (mm)
y = 0.5669x + 1.2785
R² = 0.5009
y = 0.4315x - 1.2748
R² = 0.3666
y = 0.0016x - 0.0037
R² = 0.538
Throughfall
Stemflow
Intercept
Linear (Throughfall)
Linear (Stemflow)
Linear (Intercept)

E

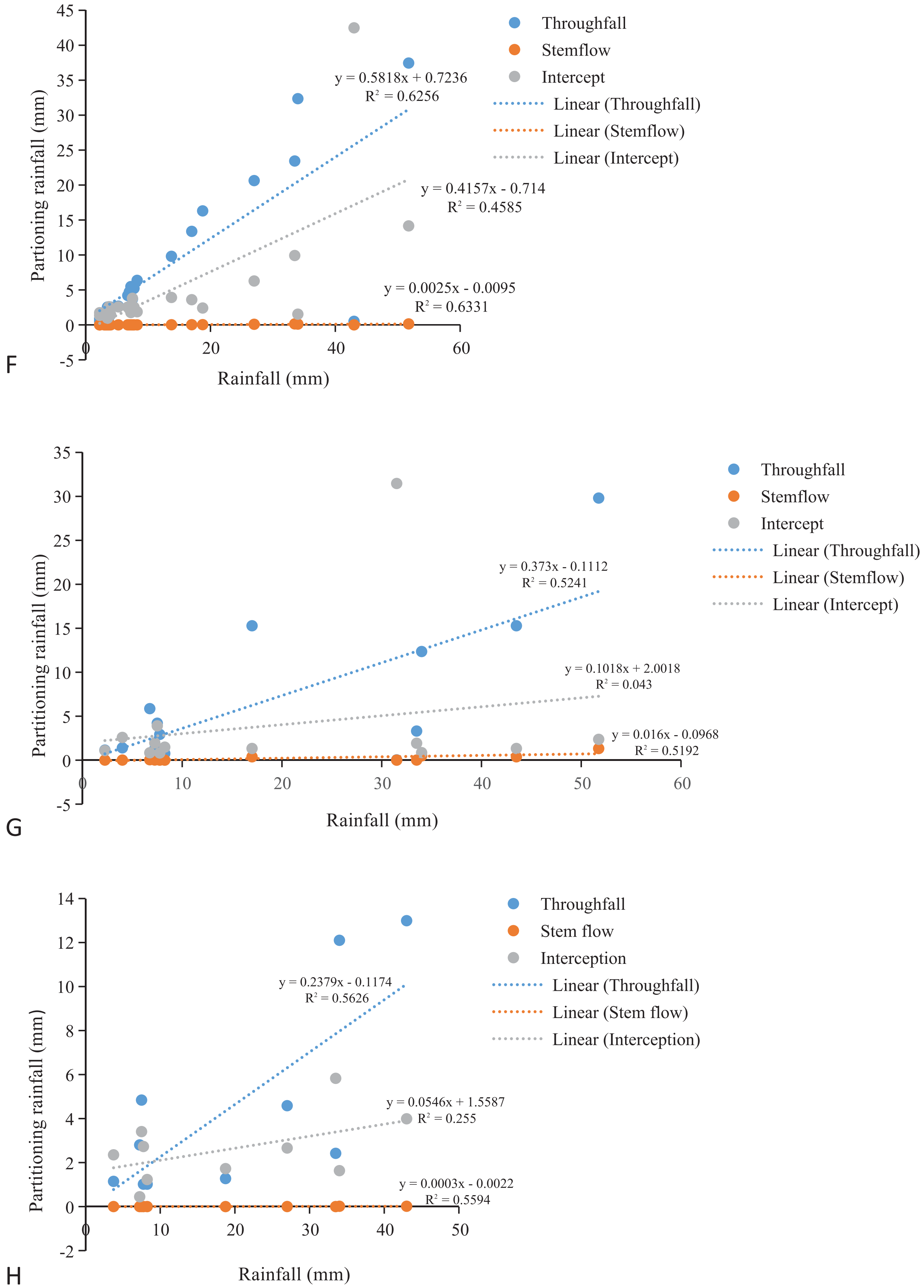


Figure 3 Rainfall average and partitioning rainfall patterns of canopy interception, throughfall and stemflow of: (a) *Aleurites moluccanus*, (b) *Sterculia cordata*, (c) *Buchanania arborescens*, (d) *Calophyllum inophyllum*, (e) *Disoxylum gaudichaudianum*, (f) *Alstonia scholaris*, (g) *Pometia pinnata* and (h) *Peltophorum pterocarpum*

The process of canopy interception is influenced by three main factors namely 1) the type of rainfall event (magnitude, intensity and duration), 2) the species and canopy structure (Jian *et al.* 2015), and 3) the antecedent weather (Livesley *et al.* 2014). The interception rate, capacity and losses depend on many factors including vegetation characteristics (Darmayanti & Fiqa 2017). The amount of rainfall affects the hydrological performance of the eight selected species in terms of stemflow, throughfall and interception processes during a heavy rain (>3 mm) (Table 1). *A. moluccanus* has the highest interception percentage, but has significantly stemflow is quite high, but relatively low throughfall values among the other species. However, no morphological character of *A. moluccanus* significantly differed from other plants (Table 2). The leaves have positively affected the amount of stemflow (Levia *et al.* 2011). The leaf of *A. moluccanus* is long and ovally elongated (Fig. 6), so it can retain water drop down to the soil. The amount of stemflow is determined by leaf shape and stem and branch architecture. *A. moluccanus* has smooth bark (Fig. 4), but it is a tree species, with a rounded canopy (Fig. 5b), large leaves with fine hairs on the surface. These morphological structures resulted in *A. moluccanus* having an interception rate higher than other plants. Rounded canopy can intercept more water than other canopy shape. Crown structure and architecture directly affect resource acquisition, mechanical support, reproduction and competitive ability (Messier *et al.* 2017). The trunk is straight and round, and grooved lengthwise, affecting the rate of stemflow before it touches the ground. The stemflow infiltration area could receive 2-7 times more precipitation than open areas in semi-arid shrubs (Návar 2011). Generally, stemflow also varied between species, but its overall contribution to site water balance was only 4.5% of the total rainfall received (Venkatraman & Ashwat 2016).

D. gaudichaudianum has a significantly different interception value than other trees, although it is not included in the highest three (Table 1). It has a significantly different crown area and crown height among other trees (Table 2), so it can temporarily hold the rainwater in its canopy and branches, before the rain falls to the ground as throughfall. Canopy interception and storage capacity varies considerably among tree species which lead to different reductions in net precipitation (Venkatraman & Ashwat 2016).

Table 1 Summary of throughfall, stemflow and intereption of eight trees based on rainfall intensity

Species	*Peltophorum pterocarpum*		*Aleurites moluccanus*		*Alstonia scholaris*		*Calophyllum inophyllum*		*Buchanania arborescens*		*Dysoxylum gaudichaudianum*		*Sterculia cordata*		*Pometia pinnata*	
Throughfall (mm)	3.8	(ab)	4.8	(b)	9.3	(a)	9.1	(a)	8.9	(a)	10.6	(a)	11.9	(a)	7.2	(a)
Stemflow (mm)	0.003	(b)	0.07	(b)	0.03	(ab)	0.17	(b)	0.16	(b)	5.8	(ab)	0.1	(b)	0.22	(b)
Interception* (mm)	8.24	(ab)	13.4	(a)	5.32	(ab)	5.14	(ab)	4.5	(ab)	0.02	(b)	5.9	(ab)	4	(ab)

Notes: Means followed by different letters are significantly different (least significant difference (LSD) $p \leq 0.05$).
*Interception was calculated only for rain events in which both throughfall and stemflow was occurred.

Figure 4 (left to right-clockwise) Tree bark characteristics of *Peltophorum pterocarpum, Aleurites moluccanus, Alstonia scholaris, Calophyllum inophyllum*, *Buchanania arborescens*, *Dysoxylum gaudichaudianum*, *Sterculia cordata* and *Pometia pinnata*

Tree architecture and bark properties greatly influence the proportion of intercepted rainfall that becomes stemflow that is directed to the base of the stem (Inkiläinen *et al.* 2013). Canopy and tree bark characteristics affect water availability, soil water recharge or runoff (Livesley *et al.* 2016) through stemflow, throughfall and interception process. Moreover, stemflow quantity is affected by the bark roughness (Nasiri *et al.* 2012). In this study, the trees with significantly different stemflow values than others have rough barks (i.e., *C. inophyllum)* (Table 1). *P. pinnata* shows a tree architecture pattern of Koriba (Ferdy 2013). Trees with Koriba pattern have orthotropic branch units and bear new branches near their ends. *S. cordata has* the highest throughfall (Fig. 1), has a strong positive relationship with rainfall (Fig. 3), and has a significantly different crown area and crown diameter (Table 2). Furthermore, *S. cordata* has interception and throughfall values ranking in the first three highest. Thus, *S. cordata* is quite suitable for soil and water conservation.

Several soft functional traits of vegetation (leaf size, leaf phenology, bark thickness, seed mass) have been associated with species response to water as a resource or as a disturbance agent (e.g., resprouting ability, plant height) (Kukowski *et al.* 2013). Hence, species differ from each other in leaf length, width, tree height, DBH, and other characters (Table 2). As these characters affect the trees performance of its hydrological role. *P. pterocarpum* is a large tree with a big stem diameter (104.6 cm DBH), and a wide (281.6 cm^2 crown area and 22 m crown diameter) and high canopy (21 m height). *P. pterocarpum* has small leaves (3.3 cm wide and 14.7 cm) which also contributed to its highest throughfall value.

Table 2 Characteristics of *Sterculia cordata*, *Aleurites moluccanus*, *Buchanania arborescens*, *Calophyllum inophyllum*, *Dysoxylum gaudichaudianum*, *Peltophorum pterocarpum*, *Alstonia scholaris* and *Pometia pinnata*

Species	*Peltophorum pterocarpum*	*Aleurites moluccanus*	*Alstonia scholaris*	*Calophyllum inophyllum*	*Buchanania arborescens*	*Dysoxylum gaudichaudianum*	*Sterculia cordata*	*Pometia pinnata*
Leaves length (cm)	14.7 (b)	21.7 (ab)	16.7 (ab)	14.3 (b)	25.4 (a)	19.7 (ab)	13.1 (b)	14.3 (b)
Width (cm)	3.3 (a)	12.1 (a)	6.2 (a)	5.1 (a)	5.7 (a)	6 (a)	10 (a)	12.5 (a)
Height (m^2)	21 (a)	18 (a)	20 (a)	20 (a)	22.5 (a)	11 (a)	22.1 (a)	13.5 (a)
Branch free stem height	16.3 (a)	6.8 (ab)	7.5 (ab)	17 (a)	9 (ab)	6.5 (ab)	4.5 (b)	8 (ab)
Crown height (m)	2.3 (b)	11 (ab)	7.5 (b)	17.1 (a)	4.3 (b)	3 (b)	2.5 (b)	3.5 (b)
Crown diameter (m)	22 (a)	18.4 (ab)	14 (abc)	12.9 (abc)	10.8 (bc)	9.5 (bc)	7.2 (c)	9 (bc)
Crown area (cm^2)	281.6 (a)	271.5 (a)	199.4 (a)	141.9 (a)	91.6 (a)	117 (a)	53.2(a)	42 (a)
DBH (cm)	104.6 (a)	64.3 (a)	68.6 (a)	100.3 (a)	76.9 (a)	56.9 (a)	56.9 (a)	25.9(a)

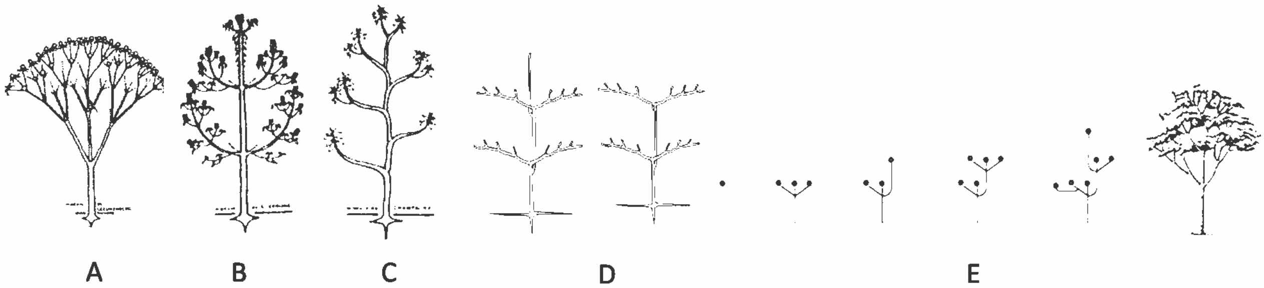


Figure 5 Canopy architecture of the species: (A) Leuwenberg's model: *Calophyllum inophyllum*; (B) Scarrone's model: *Aleurites moluccanus*, *Peltophorum pterocarpum, Buchanania arborescens*; (C) Champagnat's model: *Dysoxylum gaudichaudianum*; (D) Prevost's model: *Alstonia scholaris*; (E) Koriba's model: *Sterculia cordata, Pometia pinnata*
Note: Trees and leaves are drawn approximately to scale relative to each other.

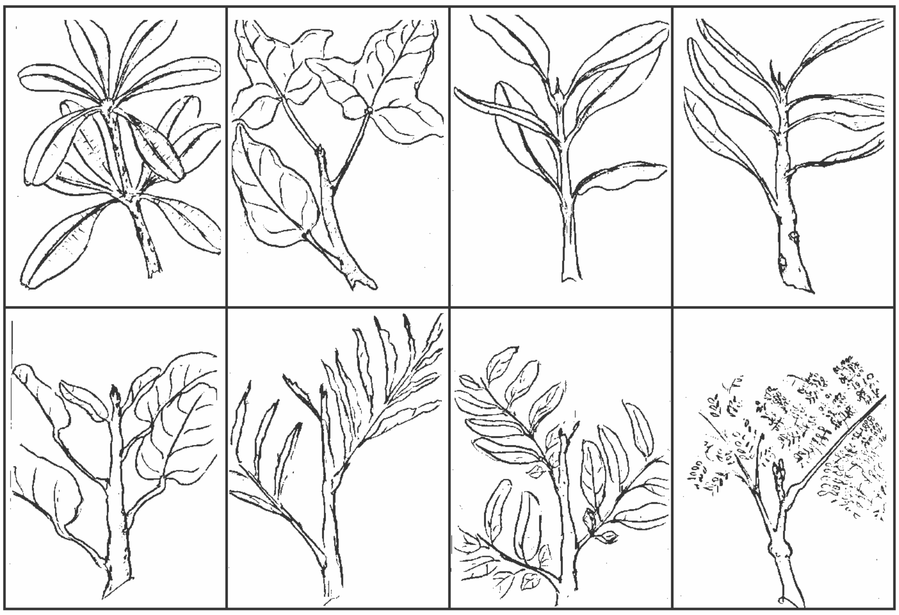


Figure 6 Leaf characteristic of the species (clockwise): *Alstonia scholaris, Aleurites moluccanus, Calophyllum inophyllum, Buchanania arborescens, Sterculia cordata, Dysoxylum gaudichaudianum, Pometia pinnata* and *Peltophorum pterocarpum*

Table 3 Tree morphology forming their architecture

Species	Family	Leaves	Crown gap	Stems and branches	Architecture
Peltophorum pterocarpum	Fabaceae	Alternate, bipinnately compound, even pinnately compound, oblong	Large	Single stem, monopodial, orthotropic, have a sympodial structure	Scarrone
Aleurites moluccanus	Euphorbiaceae	Leaves simple, variable in shape, young leaves large, up to 30 cm long, palmate	Large	Single stem, monopodial, orthotropic, have a sympodial structure	Scarrone
Alstonia scholaris	Apocynaceae	Dorsiventral, the leathery leaves are narrowly obovate to very narrowly spathulate, base cuneate, apex	Medium	Single stem, plagiotropic	Prevost
Callophylum inophyllum	Clusiaceae	Opposite, arrangements with thick shiny parallel vasculatures	Medium	Single stem, monocarpic	Leeuwenberg
Buchanania arborescens	Anacardiaceae	Leaves are simple, oblong, narrowly ovate, spirally arranged	Large	Single stem, monopodial with rhythmic branching, orthotropic, have a sympodial structure	Scarrone
Dysoxylum gaudichaudianum	Meliaceae	Opposite to alternate toward the base, very unequal size and shape	Medium	Single stem, sympodial, orthotropic branches	Champagnat
Sterculia cordata	Sterculiaceae	Alternate, simple, tripli- to penni-veined, lower surface hairy and yellow-whitish coloured, leaf base usually cordate	Medium	Single stem, sympodial, plagiothropic	Koriba
Pometia pinnata	Sapindaceae	Alternate, compound, leaflets penni-veined, glabrous to densely hairy, margin entire to toothed	Medium	Single stem, sympodial, plagiothropic	Koriba

Branch architecture, leaf structure, orientation and size, canopy volume and area and bark surface roughness (or smoothness) are known to have an influence on the partitioning of rainfall into stemflow and throughfall (Baptista *et al.* 2018). Tree architecture is also a morphological description of certain phases of tree growth that is observable at any time. Though the architecture of a young tree growing well is due to its genes, the architecture of the tree is also influenced by environmental factors such as light, temperature, humidity and availability of nutrients in the soil (Charrier *et al.* 2015). *A. moluccanus* has Scarrone tree architecture. Its main stem is monopodial with rhythmic branching forming a canopy that is hemispherical in the early (first two) years of growth. The widest part of the canopy is located in the midst of a long canopy length. This long canopy length is almost the same as the width (Murniati 2010). *A. moluccanus* is one of the trees that have a dense canopy. The average light intensity that went into the forest floor irregularly reaches 7.5% with the forest floor temperature between 24-29 °C and a humidity of 88.2% to 92.8% (Suryanto & Suryawan 2015). *A. moluccanus,* also has a high level of adaptation to degraded land (Sumarhani 2015). Hence, it can be one of those trees recommended for the rehabilitation of the region. In addition, these trees have economic benefits, an added value, especially for the local communities or the farmers.

P. pterocarpum follows the Scarrone pattern, so does *B. arborescens*. Scarrone model as distinguished from other architectural models has a special feature in the form of meristematic terminal bud that grows orthotropic rhythmic, and involves a monopodial trunk and sympodial branch modules, both orthotropic and branching rhythmically (Chomicki *et al.* 2017). The composition of multiple pinnately compound small leaves with acuminate form, enables *P. pterocarpum* as a good rainwater interceptor. This tree is a potential ornamental tree because of its beautiful flowers (Babu *et al.* 2016) that are yellow green lit so often referred to as the golden power. In addition, its leaves can be used as fodder (Danarto 2015). The tree has deep roots and rounded canopy implying its good quality for soil and water conservation. In agroforestry systems, the tree serves as a windbreaker, a shade, a nitrogen-fixer, and a green manure. *P. pterocarpum* has a fairly strong stem due to the growth of branch diameter that often times do not grow half of the main stem diameter, therefore, making it good against the wind. In addition, the tree is a good natural dye for batik. *B. arborescens* follows the Scarrone pattern. These trees are generally located in dry areas with low humidity (Rosleine & Suzuki 2012).

Vegetation helps in the improvement of soil physical and chemical properties. Litter produced by tree foliage can increase the content of organic material on the soil surface. Lush canopy also plays a role in reducing the amount of kinetic energy of rain falling to the ground. Tree selection in rehabilitating degraded areas is therefore, very important. However, it requires considerations in accordance with the conservation objectives. In dry area, the preferred trees should have high intercept values. *A. scholaris* follows the Prevost architecture. These models involve determinate trunk modules producing branch modules (Chomicki *et al.* 2017). Theoretically, plagiotropic branching results in a wider crown diameter. The lateral meristem growth in plagiotropic branching trees contributed to the development of the stem diameter. Bark characteristics of Prevost model are characterized by roughness. *A. scholaris* has a relatively smooth bark surface except the protrusion of lenticels that spread evenly (Silalahi 2019). This lenticels bulge can produce frictional force against the rainwater through. Characters of bark, thus, affect the value of stemflow.

C. inophyllum follows the Leeuwenberg architecture model while *P. pinnata* and *S. cordata* are those of the Koriba model. These architecture models possess a sympodium characteristic tree trunk. Terminal buds are stopped due to apical meristem tissue differentiating the parenchyma. Axillary buds growing close underneath and forming columnar form. One bud becomes a columnar rod and the other becomes columnar branches. *D. gaudichaudianum* follows that of Champagnat model that has a characteristic form of sympodium rods and each column is curved due to being too heavy and not supported by tree tissue. Spiral phyllotax is contained in the axis which is not much different from the tip and base morphology (Hasanuddin 2013). Hence, the tree architecture shows the pattern of the structure and growth of the tree canopy.

The difference in the distribution of rainwater among trees is affected by several factors including, branching growth pattern, leaf surface area, stem surface pattern and soil density. The branching pattern will form the shape of the tree canopy, while soil density will influence the hydraulic conductance. Branches function in the mechanism of movement of the water system in trees, in the process of transpiration and photosynthesis (He & Deane 2016). The distribution points around the straight line indicate that the amount of rainfalls affect the amount of intercepted rainwater in the vegetation. However, interception of rainwater can be ignored at a very high rainfall since the trees ability to pass water is also very high, so high that almost all of the water can be dropped quickly toward the ground and not get stuck in the canopy. Thus, tree branching patterns are influential in anatomical property system such as biomechanics and hydraulic functions.

Dimensions of tree architecture are influential in the input process of rainwater. When the precipitation is retained as interception by the canopy, it will then spread and enter as throughfall and stemflow (Mali *et al.* 2020). Tree architectural patterns are also influential in the process of kinetic rainfall toward the ground. The height of the first branch from ground level is one factor among others. Tree architecture and characteristics of stems play important roles in the interception of rainwater by trees, which will flow on the stem as the stemflow to the bottom of the trunk (Ahmed *et al.* 2015). The interception process by the canopy is influenced by the type of rainfall events (heaviness, intensity and duration); tree species and its canopy structure as well as the previous weather (Livesley *et al.* 2014). Wind direction and speed affect the process of rainwater interception by trees (Nytch *et al.* 2019).

CONCLUSION

Partitioning of rainfall into throughfall, stemflow and interception varied among the species. The highest value of tree interception was exhibited by *Aleurites moluccanus* (68.1%), followed by *Peltophorum pterocarpum* (53.8%) and *Calophyllum inophyllum* (48.9%). Tree architecture significantly influenced the transformation of rainwater into stemflow, throughfall and canopy interception. However, the interception of rainwater can be ignored at very high rainfall intensities rates. *Aleurites moluccanus* is the one that has the highest value of interception (68.1%), but both throughfall and stemflow did not significantly correlate to rainfall intensity. Throughfall, however, was found to be closely related to rainfall events in *Buchanania arborescens*, *Sterculia cordata* and *Calophyllum inophyllum*.

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