Predictive models for stemflow and throughfall estimation in four fruit tree species under hot and sub-humid climatic region

S. S. Mali, P. K. Sarkar, S. K. Naik, A. K. Singh and B. P. Bhatt

ABSTRACT

Inclusion of stemflow and throughfall processes in rainfall-runoff modelling requires reliable models for their estimation. In the present paper, stemflow and throughfall generation processes were investigated in relation to rainfall, and morphological properties of four major fruit species grown in hot and sub-humid climatic region. Two types of models, rainfall-based and morphology-based, were developed and validated using observed data. Morphology-based models included relative roughness of branch (RR), leaf area index (LAI), canopy length (CL), tree height (TH) and diameter at breast height (DBH) as input variables. Rainfall-based stemflow prediction models, namely, Weibull, Logistic, Allometric and Exponential ($R^2 = 0.74$ to 0.82) and throughfall prediction models, namely, Weibull, Allometric, Linear and Linear ($R^2 = 0.94$ to 0.99) provided the best goodness-of-fit statistics for mango, litchi, guava and jackfruit, respectively. The parameters RR and LAI affected stemflow irrespective of rainfall depth. However, different sets of variables, namely, CL-LAI, CL-LAI-TH, CL-LAI-TH and DBH-CL-LAI affected throughfall in rainfall ranges <5, 5–10, 10–20 and >20 mm, respectively. The higher range of interception loss (6.5% for guava to 21.3% for jackfruit) indicated that interception loss from fruit trees needs to be considered in the water balance modelling of watersheds having larger areas under orchards.

Key words | interception loss, predictive modelling, stemflow, throughfall, tree morphology

S. S. Mali (corresponding author)
P. K. Sarkar
S. K. Naik
A. K. Singh
ICAR Research Complex for Eastern Region, Research Centre,
Plandu, Ranchi 834010, Jharkhand,
India
E-mail: *santosh.icar@gmail.com*

B. P. Bhatt
ICAR Research Complex for Eastern Region,
Patna 814014, Bihar,
India

INTRODUCTION

Tree canopies modify rainfall trajectory by partitioning it into stemflow and throughfall, affecting the vertical and horizontal spatial distribution of rainwater (Zheng *et al.* 2018). The proportion of rain that falls from foliage as 'leaf-drip' or passes directly through small gaps in the canopy is termed 'throughfall'. Stemflow is the portion of rainfall which is drained from the branches and leaves of a tree and runs down towards the bole or stem of the tree (Ahmed *et al.* 2015). Rainfall is intercepted and retained temporarily on leaf surfaces, branches and stems. Some of this intercepted rainfall subsequently evaporates and is lost to the atmosphere. This evaporated portion of rainfall is termed 'interception-loss' (IL). These interception losses are an important component of the hydrological budget. The relationship between rainfall (R), stemflow (SF), throughfall (TF) and interception loss is represented as (Krusche *et al.* 2011):

$$R = TF + SF + IL \quad (1)$$

The generation of stemflow has been studied in recent decades for diverse forest types in various climatic regions

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(Zhang et al. 2015; Su et al. 2019) and the factors affecting the stemflow and throughfall generation process are well identified. Stemflow and throughfall have major consequences on groundwater (Levia et al. 2011), dry season water flows (Scott et al. 2005) and raindrop erosivity (Goebes et al. 2015). These studies highlighted the significance of stemflow and throughfall in hydrology of the vadose zone water balance, and its biotic and abiotic influencing factors. Knowledge about partitioning of rainfall into throughfall and stemflow by the tree species is important in assessing the effects of rainfall on runoff and soil erosion processes.

An essential aspect of hydrological studies is the quick and accurate estimation of stemflow and throughfall using the least amount of measurements. Accurate and reliable models are needed for estimation of these parameters. Previous researchers (Ahmed et al. 2015; Darmayanti & Fiqa 2017) developed rainfall-based regression models to predict stemflow and throughfall from forest tree species. Most of these empirical models, however, do not explain physical processes of stemflow and throughfall generation. Although rainfall is the principal source of variability in stemflow and throughfall estimates, models developed as a function of rainfall may not be better predictors as other variables affecting tree morphology may also significantly influence the throughfall (Lima et al. 2018). Park & Cameron (2008) used canopy traits like leaf area index (LAI), per cent crown openness and live crown depth as inputs in regression models to assess the throughfall in five tropical trees. However, other tree morphological properties like 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). Therefore, inclusion of these parameters in model development can improve the accuracy and reliability of estimations. As the plant architecture of fruit trees varies considerably from forest trees, the application of such regression-based models developed for agroforestry species may not yield accurate estimation of stemflow and throughfall for fruit trees.

Previous works on partitioning of rainfall into stemflow and throughfall and their estimation were mainly focused on forestry (Park & Cameron 2008; Li et al. 2016). Throughfall has received more attention than stemflow because of the scarce hydrological significance of the latter (Marin et al. 2000). Further, estimation of stemflow and throughfall from horticultural plants, particularly fruit tree species, is poorly studied. Fruit trees cover a larger proportion of the cultivated areas (1.99 million hectare) in the eastern states of India under hot and sub-humid climatic conditions. Studying throughfall and stemflow dynamics in diverse climatic conditions is a measurement challenge and many times measurements are not possible due to adverse biophysical conditions. Also, the stemflow and throughfall fluxes are typical responses of the complex interaction between climate, rainfall and plant morphology. In such situations, physically based analytical or semi-analytical models can be developed to predict these parameters (Zeng et al. 2000).

Keeping in view that quantifying and analysing the species-wise variation of stemflow and throughfall production from tree crops could help in accurate estimation of hydrological water budget components, this study aims to characterize the canopy-specific morphological parameters of fruit trees and evaluate their influence on throughfall and stemflow generation at variable rainfall depths. The main objective of the study was to develop prediction models using two distinct modelling approaches, namely, rainfall-based models and tree morphology-based models, for estimation of stemflow and throughfall from fruit tree species. The modelling exercise provides insight into the stemflow and throughfall generation processes, and the most influential factors affecting the stemflow and throughfall from these tree species.

Study area

The study was conducted in Ranchi district, located in the central part of the East Indian plateau (Figure 1) at about 651 m above the mean sea level (latitude: 23°16′ N, longitude: 85°50′ E). The climate is classified as hot-dry, sub-humid with monsoon type of rainfall pattern. The average annual precipitation and evaporation is 1,316 and 1,725 mm, respectively. The major portion of the annual rainfall (>80%) is received during the monsoon months of June to September, while less than 20% of annual rainfall is received during the winter season (October to December). Most rain events are short (less than 30 min duration) but

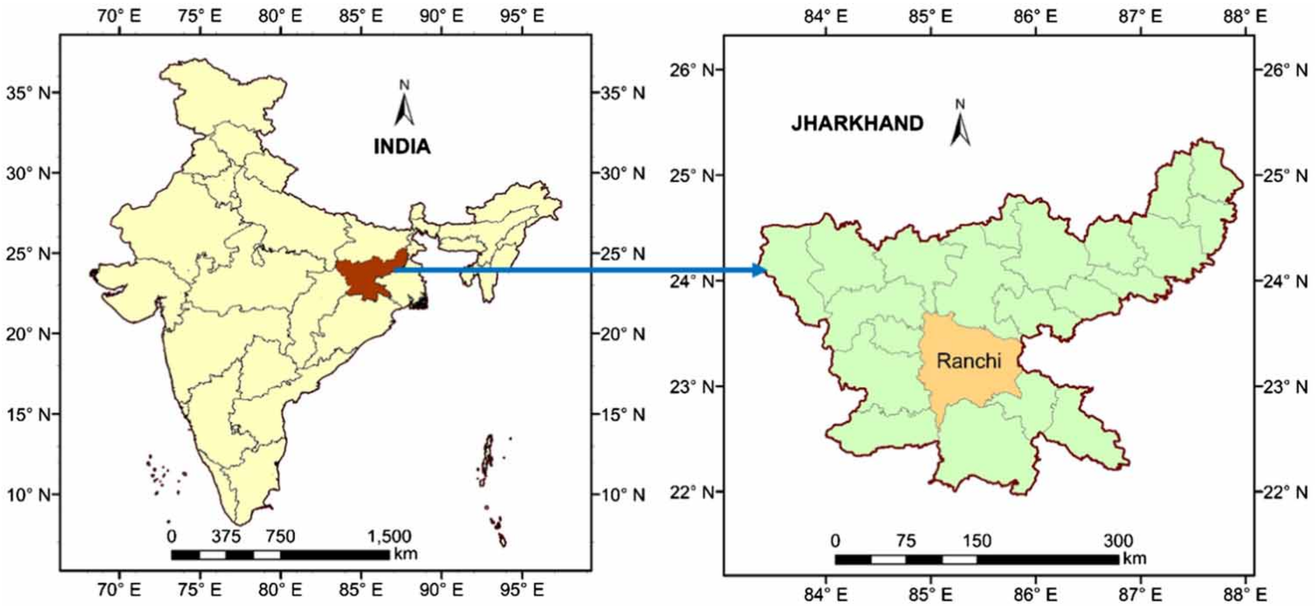

Figure 1 | Location map of the study area Ranchi in eastern plateau region of India.

there are severe storms with an intensity of 8–10 mm/h, with occasional longer events of moderate intensity. Average annual temperature of the region is 23.7 °C with long-term average maximum and minimum temperatures of 18.0 and 29.5 °C. Relative humidity ranges between 55% (winter) and 88% (rainy season). The soils of the area belong to the order alfisols and are highly acidic (pH 4.5–5.5) in reaction. The topography of the planted orchards is flat lands with a moderate slope of 1–2%. The selected research sites are permanent undisturbed orchard plots of the ICAR-Research Complex for Eastern Region, located at Ranchi. Mature plants (10–25 years old) of mango, litchi, guava and jackfruit were selected for this study, as they are the major fruit crops of the region. These four species have discriminant canopy architecture, leaf size and branch orientation. The mango, litchi, jackfruit were planted at 10×10 m while guava was planted at 5×5 m spacing.

METHODS

Tree measurements

Tree species chosen for the measurement of throughfall and interception were selected on the basis of obvious differences in crown architecture, leaf size and arrangement and stem morphology. Quantitative measurements and comparisons were made for stemflow, throughfall and interception losses from four largely grown fruit species, namely, mango, litchi, guava and jackfruit in East Indian plateau. The plots were randomly selected within the orchards, such that, the selected plants represent the average canopy morphology for the respective fruit species. Each species was represented by a sample of five individual trees selected from these plots. Tree height (TH), canopy area (CA), live crown length (CL), crown width (CW) and diameter at breast height (DBH) of the individual trees were recorded at the beginning of the study. Measurements on horizontal spread of canopy (average of east–west and south–north canopy spread on ground) were used to work out the canopy area (CA). The projected canopy area on ground surface was estimated using the equation for area of a circle. The branch angles were measured with respect to horizontal using the methodology described by King (1998). We used a plant canopy analyser to obtain the LAI of the selected fruit species. Bark surface roughness metrics, roughness ratio (RR), was calculated using the methodology suggested by Holley *et al.* (2015). The minimum and maximum bark thickness were measured with a digital calliper and the surface roughness ratio was estimated as the ratio between minimum and maximum thickness. Higher roughness ratio indicated smoother branch surface.

Rainfall

The study was conducted during the monsoon season (June to September) of 2016, covering 49 rainfall events. The daily rainfall data were obtained from the field meteorological observatory located within 100 m of the experimental plots. A standard tipping bucket type of rain gauge was used to record the daily rainfall. A rainfall event occurring 1 hour after the previous event was considered as a separate rainfall event for data collection and analysis (Ahmed et al. 2017). At the end of each rainfall event, rainfall depth and stemflow volume were recorded.

Stemflow measurement

To measure stemflow volumes, five plants were randomly selected from the blocks of four fruit species. These sample sizes were based on the equation of Freese (1962) using 95% confidence limits from preliminary sampling. Trees were fitted with stemflow collars and pipe connections were made to collect the stemflow into calibrated black 20-litre plastic cans. Stemflow collars were constructed at the base of the stem using high quality cement mortar. The collar was 50 mm wide and 40 mm deep, with inert silicon sealant applied at the stem–mortar interface. Stemflow volume (L) was divided by crown area (m^2) to convert the volume units of stemflow into depth units (mm). Per cent stemflow (%SF) and per cent throughfall (%TF) were determined as:

$$\%SF = \frac{SF}{P} \times 100 \quad (2)$$

$$\%TF = \frac{TF}{P} \times 100 \quad (3)$$

Throughfall measurement

For the measurement of throughfall, four collectors were placed under each of the selected trees in a predefined grid. To reduce the standard error of measurement, each collector was relocated randomly within the grid after one set of data were collected (Lloyd & Marques Filho 1988). The throughfall collectors consisted of graduated plastic collectors of 20 L capacity with opening diameter of 24.5 cm and standing on the orchard floor. The rims of the collectors were 25 cm above the ground to prevent water droplets and soil particles splashing in from the orchard floor. The square shape and size of the blocks allowed the inclusion of whole crowns. The analysis of variance (ANOVA) in SPSS (version 19.0) was applied to assess the significance of interspecific differences in throughfall and stemflow.

Model fitting

Many recent studies have reported rainfall-based predictive models for stemflow and throughfall, mainly for forest species (Darmayanti & Fiqa 2017; Lima et al. 2018), implying that rainfall can be a reliable predictor of stemflow and throughfall. Rainfall records are generally available for many watersheds (NIH 2001) and can be used in developing predictive models for estimating the stemflow and throughfall. In the present study, different models were fitted to establish the functional relationship between rainfall (mm) vs stemflow (mm) and rainfall (mm) vs throughfall (mm). Six types of models, namely, Linear, Allometric, Logistic, Exponential, Mitscherlich and Weibull were tested to predict the stemflow and throughfall for each of the fruit tree species using rainfall as the explanatory variable. Since coefficient of determination (R^2) value alone is not a sufficient criterion to judge the best fitting model, the Akaike information criterion (AIC) (Akaike 1973) was used to select the best fitting model for each tree species. The AIC is a measure of the relative quality of statistical models for a given set of data (Burnham & David 1998). It tends to penalize over-fitting models, and is a widely used criterion for model selection (Westra et al. 2014). The root mean squared error (RMSE) which defines the absolute error between observed and predicted parameters was also applied to evaluate the model performance. XLSTAT (2018.6) software was used for fitting different models (estimates of model parameters, asymptotic standard error of estimate, confidence interval, adjusted R^2, AIC, RMSE) and plotting of graphs between response and explanatory variates and plotting of residuals against their predicted variates.

Variation in stemflow and throughfall among various tree species reflects characteristics of canopy architecture and morphological properties of the species (Park & Cameron 2008). To evaluate which parameters provide the best description of the relationship between morphological parameters and throughfall, statistical models representing the relations between response (stemflow or throughfall) and explanatory variables (morphological properties) were fitted. Morphological properties (namely TH, DBH, CL, CA, RR and LAI) of 20 plants (four species × five replications) were used in developing models for estimating the stemflow and throughfall. Rain events with different depths are likely to vary in the ways that they interact with canopy traits (Siles *et al.* 2010). To account for the rainfall effects, models were formulated for four rainfall classes (<5, 5–10, 10–20 and >20 mm). Different combinations of morphological parameters were used as inputs in developing candidate solutions in each rainfall class. The minimum number of variables for each candidate model was specified as two, while the maximum variables were restricted to six. Altogether, five models with different combinations of morphological parameters as inputs, were developed for each rainfall class and the best performing model was selected using lowest values of AIC. The coefficient of determination (R^2) was interpreted as the proportion of variation in the observed values of stemflow and throughfall that is explained by the variables in the fitted model. As a requisite for regression modelling, the residual values (observed minus predicted) should be independently and normally distributed with mean zero. The normality of the residuals was tested using Anderson–Darling tests (Das & Imon 2016).

RESULTS AND DISCUSSION

Canopy architecture and leaf morphology

Tree height, crown length, DBH, canopy area, leaf area, LAI and bark roughness varied significantly among the tree species (Table 1). The average height and DBH of mango plants was 8.21 m and 39.32 cm, respectively. Among the selected plant species, jackfruit was the tallest plant (mean height 10.53 m) while guava was the shortest plant (mean height 2.11 m). Mean crown length of mango, litchi, guava and jackfruit was 5.52, 4.56, 1.26 and 7.23 m, respectively. Matured jackfruit plant had the largest crown area of 84.5 m^2 while the guava had the smallest (4.52 m^2). Leaf area of the jackfruit was about two and three times larger as compared to mango and litchi leaves, respectively. Figure 2 shows the canopy architecture and leaf orientation of selected fruit plants. Jackfruit had an average canopy area of 85.0 m^2, which is significantly higher than small (guava) and medium (mango and litchi) crowned plant species. The other important morphological characteristics of sampled plants are presented in Table 2. On the basis of roughness ratio, the guava bark surface was relatively smoother (roughness ratio 0.99) as compared to mango (0.83) (Table 1). The bark roughness of litchi and jackfruit did not differ significantly ($P \leq 0.05$).

Average angle of inclination of primary, secondary and tertiary branches of mango, litchi, guava and jackfruit are presented in Figure 3. The primary branches in litchi plants have higher upward inclination with respect to horizontal (steep angles) with angles ranging from 48° to 72°, while the steepest angles of secondary branches were observed in the case of guava, where the branching angles ranged from 62° to 85°. Guava plant had near-to-vertical

Table 1 | Morphological metrics of the experimental plant species

Sl No.	Species	DBH, cm	Crown length, cm	Canopy area, m^2	Roughness ratio [–]	Leaf area, cm^2	LAI
1	Mango	39.32 ± 6.4 b*	5.52 ± 1.0 b	55.4 ± 8.3 b	0.828 c	54.7 ± 8.2 b	16.5 ± 1.98 b
2	Litchi	33.15 ± 5.2 c	4.56 ± 0.7 c	47.8 ± 7.5 b	0.915 b	34.7 ± 2.8 c	13.5 ± 2.02 c
3	Guava	17.21 ± 4.1 d	1.26 ± 0.3 d	4.5 ± 1.1 c	0.991 a	50.4 ± 6.1 b	3.1 ± 0.55 d
4	Jackfruit	45.12 ± 7.2 a	7.83 ± 1.4 a	85.0 ± 14.6 a	0.905 b	109.0 ± 18.5 a	21.2 ± 3.02 a

DBH: diameter at breast height, LAI: leaf area index.
*Means followed by different letters are significantly different ($P \leq 0.05$).

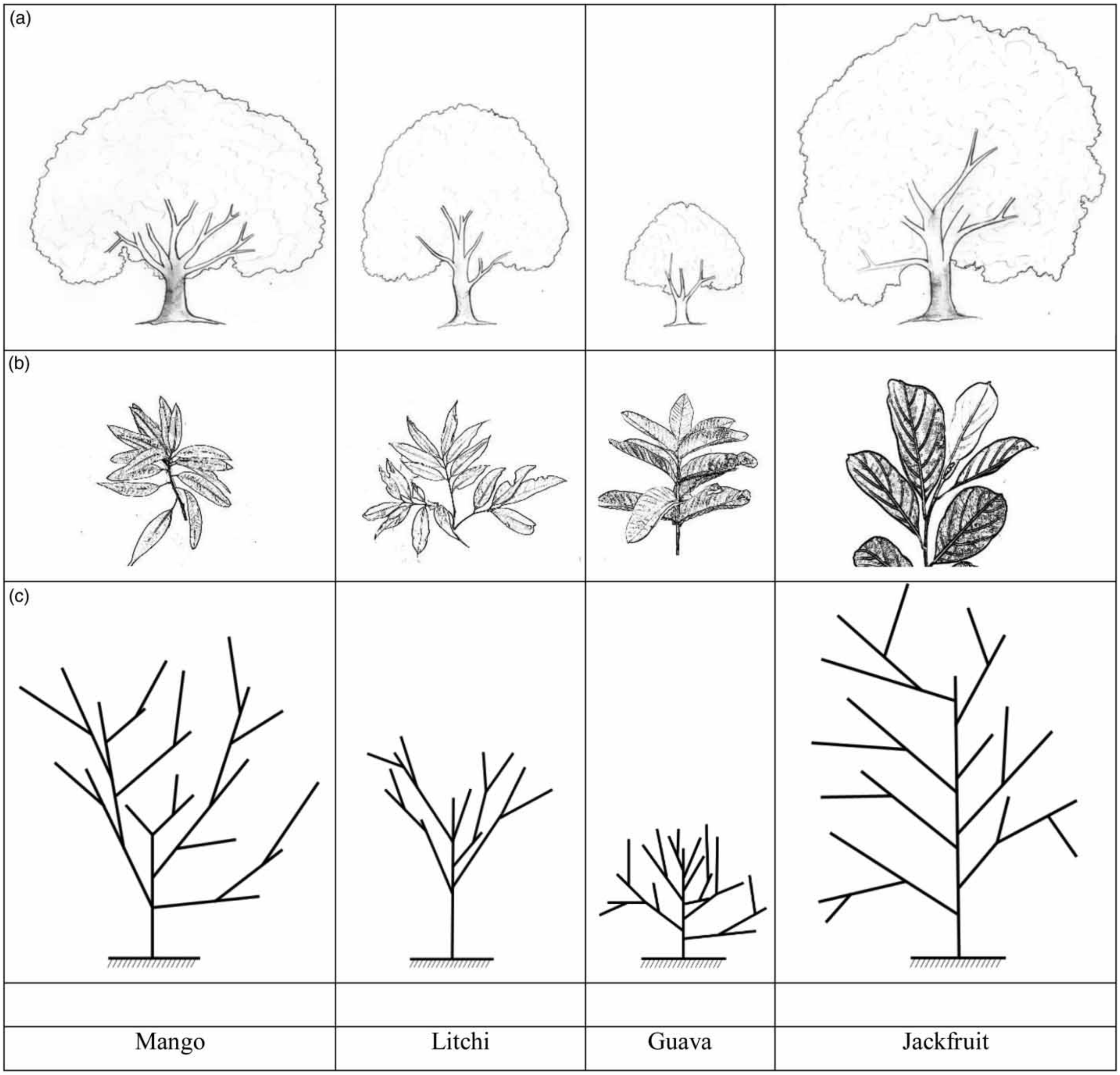

Figure 2 | Crown morphology (a), leaf structure (b) and branching patterns (c) of matured fruit species (figures are drawn to an approximate relative scale).

tertiary branches (angle 56–90°), whereas in the case of jackfruit, the tertiary branches showed negative inclination (7° to −53°), i.e., after branching point, the branch inclined towards the ground instead of inclining upward.

Rainfall

During the study period, 49 and 33 rainfall events were available for the stemflow and throughfall analysis, respectively. Rainfall received during these events was 661.3 and 477.0 mm with an average depth of 13.5 and 14.4 mm, respectively. The smallest and largest events recorded rainfall of 1 and 53 mm, respectively (Figure 4).

Canopy traits and stemflow

Average total stemflow varied from 0.45% (jackfruit) to 2.32% (guava) (Table 3). The differences in total stemflow

Table 2 | Tree morphological characteristics of fruit species

Species	Crown shape	Leaf orientation	Leaf shape	Stems and branches
Mango	Round, symmetrical, dense, coarse texture	Inclined to horizontal	Lanceolate, oblong	Sympodially branched, branching from 60 to 80 cm above ground
Litchi	Round dome-shaped, dense, coarse to uniform texture	Alternate, glossy textured, oblique leaves	Lanceolate, oblong, elliptical (ovate)	Low-hanging and spreading, 3–4 lateral shoots 50–60 cm above ground
Guava	Oval, very less dense, medium texture	Opposite, rough textured, droop outside	Obovate, concave	Wide spreading branches and downy twigs
Jackfruit	Round, symmetrical, dense, coarse texture	Inclined to vertical	Oval at matured stage and lobed at young stage	Straight trunk, branching out from the base at an angle of 32–88°

among the monitored tree species were significant ($P \leq 0.05$). Fewer datasets in the case of throughfall indicates that rainfall during some events was just enough to wet the tree canopy but did not generate any throughfall. Lowest stemflow percentage (0.45%) was recorded in jackfruit, with the highest in guava (2.32%) (Table 3).

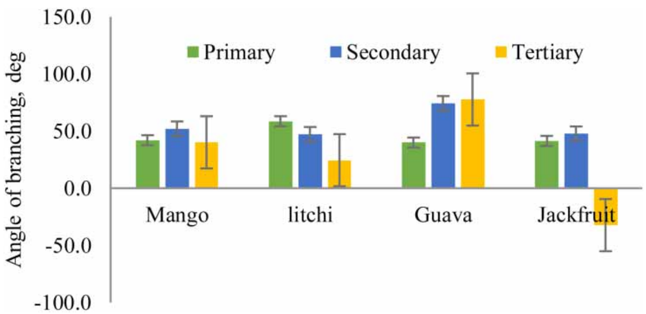

Figure 3 | Average branching angles measured with respect to horizontal.

Table 3 | Summary of total rainfall, throughfall, stemflow and interception for selected fruit tree species

Parameter measured	Mango	Litchi	Guava	Jackfruit
Stemflow[a]				
Rainfall (mm)	645.3	645.3	645.3	645.3
Stemflow (mm)	7.19b	5.22c	15.00a	2.91d
Percent stemflow	1.11	0.81	2.32	0.45
Throughfall[a]				
Rainfall (mm)	477.0	477.0	477.0	477.0
Throughfall (mm)	399.7b	389.0b	440.7a	378.1c
Percent throughfall	83.8	81.5	92.4	79.3
Interception loss (mm)[b]	72.4	80.4	27.9	91.6
Interception loss (%)	16.8	18.7	6.5	21.3

Stemflow and throughfall figures separated by different letters are significantly different (LSD, $P \leq 0.05$).
[a]Stemflow and throughfall calculated for 49 and 33 rain events.
[b]Interception calculated only for rain events in which both throughfall and stemflow occurred.

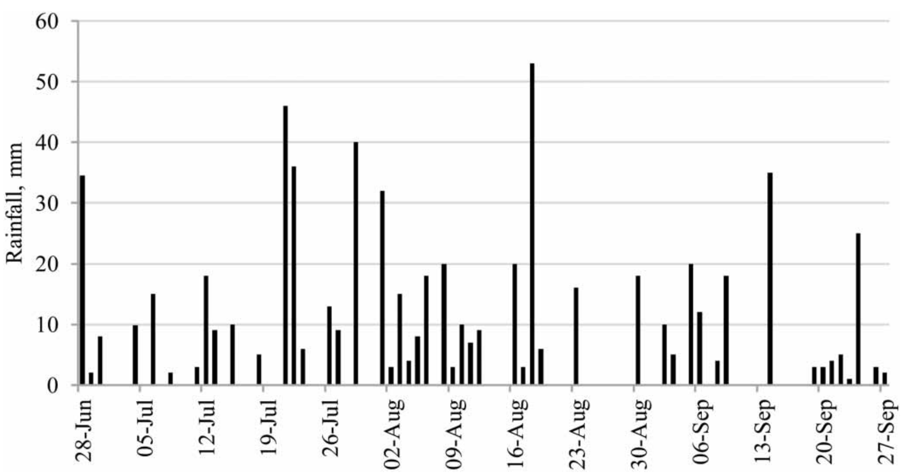

Figure 4 | Rainfall depths arranged by date of occurrence.

Measurements made for four species of fruit plants in this study showed that a relatively smaller proportion (0.45 to 2.32%) of rainfall contributes to stemflow. These measurements compared well with the reported stemflow observed in other fruit trees. Xiao *et al.* (2007) reported 2.0% of rainfall as stemflow for lemon, whereas Dietz *et al.* (2006) reported it as 1.0% for cocoa. Important morphological characteristics affecting partitioning of rainfall into stemflow and throughfall include specific surface roughness of branches and bark and leaf morphological characteristics, such as shape, size and convexity or concavity (Chuyong *et al.* 2004). Plant species with smooth bark such as guava (roughness ratio = 0.991) generated stemflow at lower precipitation in comparison to species with rough bark such as mango (roughness ratio = 0.82) and jackfruit (roughness ratio = 0.91). Lower stemflow percentage as observed in the case of rough barked plants may be due to stem dripping (Ahmed *et al.* 2015). In stem dripping, part of the stemflow falls on the ground, while flowing down the stem, which is further increased by the rough surface (Levia *et al.* 2011).

Concave orientation of leaves led to higher stemflow, as evident from the concave shape of guava leaves (Table 2). The concave shape of leaves directed a considerable part of the precipitation to their petiole and subsequently to the stems, leading to increased stemflow. Plant branches with lower inclination angle generated less stemflow as compared to the species having higher inclination angle (e.g., guava). Stemflow was significantly negatively correlated with tree size, canopy area and canopy length and DBH, indicating that increase in the value of these parameters will lead to reduced stemflow. Schroth *et al.* (1999) also reported similar results for peach palm, where stemflow was negatively related to tree size, i.e., thinner trees had higher stemflow than thicker trees. Similarly, higher trunk surface roughness (i.e., lower roughness ratio), as in the case of jackfruit (0.90) and mango (0.82), resulted in less stemflow. This may be due to increased storage capacity of branches as shown previously by Levia & Frost (2003).

Canopy traits and throughfall

Seasonal throughfall varied from 378.8 mm (79.3% of total rainfall) for jackfruit to 440.7 mm (92.4% of total rainfall) for guava. Observed throughfall from the selected fruit species ranging from 79.3 to 83.8% is within the range of reported values of throughfall of 66% (lemon) (Xiao *et al.* 2007) and 96% (cocoa) (Poppenborg & Holscher 2009). Although the differences in throughfall observed for four fruit species were relatively small, total throughfall was significantly lower in jackfruit (79.3%) than that in the other three species. Jackfruit plant has a comparatively extensive canopy cover and has a relatively high leaf area that restricted the throughfall. Also, compared to other fruit species, jackfruit was the tallest plant with longer canopy (7.3 m). The presence of multiple layers of comparatively larger leaves intercepted the raindrops effectively and evaporated back to the atmosphere, reducing throughfall from jackfruit plants. Poppenborg & Holscher (2009) also showed that, while estimating the throughfall from cacao-based agroforestry, the tree height was much more influential than the leaf area.

Although the mango plant is taller than the litchi plant, its leaves are more inclined to horizontal, promoting dripping of water from the tips of the leaf. This type of leaf arrangement increased throughfall (83.8%) from the mango trees. Highest throughfall in the case of guava was related more to its leaf and branch configuration. The leaf orientation of guava is such that the leaves droop to the outside. The drooping of leaves to the outward side contributes more to throughfall (Ahmed *et al.* 2015). Also, low density canopy of guava plant (Table 2) allowed rain to fall directly through the canopy without coming into contact with leaf, leading to increased throughfall. The presence of higher numbers of primary branches, as in the case of mango and jackfruit, led to enhanced canopy storage, ultimately reducing the throughfall. Herwitz (1985) also reported that in the case of tropical rain forests, the higher number of primary branches of long crowns enhanced the water storage, especially in heavy rains. The longer canopy of jackfruit and mango also implies that a droplet travelling through its canopy has the lower kinetic energy and lower distance to fall from the canopy to the ground, and can cause less erosion. The difference between throughfall recorded for mango and litchi was statistically non-significant ($P \geq 0.05$). The amount of throughfall varied significantly ($P \leq 0.05$) among the species. Throughfall observed for mango and litchi was 9.3 and 11.7% less than that observed for guava, respectively.

Interception loss

The interception loss in the selected fruit species varied from 6.5% (guava) to 21.3% (jackfruit). Actually, very few data on interception loss are available from tropical fruit crop plantations. Comparatively lower (1%) interception loss has been reported for cupuacu (*Theobroma grandiflorum*) monoculture in central Amazonia by Schroth *et al.* (1999) and 4% and 16% for cocoa canopies and cocoa plus tree plots, respectively (Poppenborg & Holscher 2009). Siles *et al.* (2010) found that for events with less than 30 mm rainfall, interception loss was greater than 11.2 ± 3.8% in coffee, planted as monoculture or in an agroforestry system, while it decreased to 7.0 ± 3.3% for events with rainfall amount of more than 40 mm. Interception loss is mainly governed by the canopy retention, rainfall characteristics. Cheng *et al.* (2008) showed that for the betel nut plantations in central Taiwan, the interception loss was 8.25% of the total storm rainfall. It is obvious that the higher interception loss was in the case of lighter rains. Dietz *et al.* (2006) suggested that high evaporation rate of intercepted rainfall from tall trees leads to low throughfall. The event-wise analysis in our study revealed that the percentage of stemflow from jackfruit, mango and litchi was lower during the light showers. These trees, because of their taller and denser canopies, absorbed more water and evaporated much of it before it fell through or ran down the stems, leading to increased interception loss. In the present study, the interception loss was higher (21.3%) in the case of jackfruit, presumably due to its higher leaf area per unit of the ground area (higher LAI), and denser and longer canopy. High rainfall interception by forest canopies is frequently associated with high LAIs (Marin *et al.* 2000) and canopy architecture (Pypker *et al.* 2005).

Rainfall-based models for stemflow estimation

Different models, namely, Linear, Allometric, Logistic, Exponential, Mitscherlich and Weibull were fitted to derive the relationship between stemflow and rainfall. A preliminary screening, using a scatter plot of stemflow vs rainfall, of different functions revealed that the candidate functions, namely, Linear, Allometric, Logistic, Exponential, Mitscherlich and Weibull are the better models to describe the observed dataset. Hence, these six models were fitted for the observed stemflow data from mango, litchi, guava and jackfruit. The best performing model was selected on the basis of higher R^2 and lowest AIC values. The functional form and parameter estimates for the best performing models for each tree species along with other related statistics fitted on the estimation datasets are presented in Table 4. The adjusted R^2 value (observed vs predicted) of the given dataset was more than 0.74 for best functions fitted to all tree species.

The best fitting model curves and plots between observed and predicted values of stemflow are presented in Figure 5. Out of six prediction models, the non-linear models, namely, Weibull, Logistic, Allometric and Exponential fitted well for mango ($R^2 = 0.774$), litchi ($R^2 = 0.819$), guava ($R^2 = 0.743$) and jackfruit ($R^2 = 0.812$), respectively (Figure 5(a)–5(d)). The 1:1 plots between explanatory and predicted variates showed a good degree of agreement between observed and predicted stemflow values

Table 4 | Parameter estimates for the rainfall based best fitted candidate function for stemflow

Tree species	Name of the function	Functional form	Parameter estimates a	b	c	Adjusted R^2	RMSE, mm	AIC
Mango	Weibull	$Y = [a–b \times \exp(-c \times X)] + \varepsilon$	0.521	0.542	−0.032	0.774	0.065	−74.47
Litchi	Logistic	$Y = a/1 + \exp(c–b \times X) + \varepsilon$	0.247	2.910	−0.219	0.819	0.040	−121.7
Guava	Allometric	$Y = a \times X^b + \varepsilon$	0.045	0.765	–	0.743	0.132	−5.55
Jackfruit	Exponential	$Y = a \times [1 - \exp(-b \times X)] + \varepsilon$	0.420	−0.012	–	0.812	0.025	−168.6

Y, Dependent growth variable; X, independent growth variable; a, b and c are parameter estimates and ε is the additive error term.
AIC, Akaike information criteria; RMSE, root mean squared error.

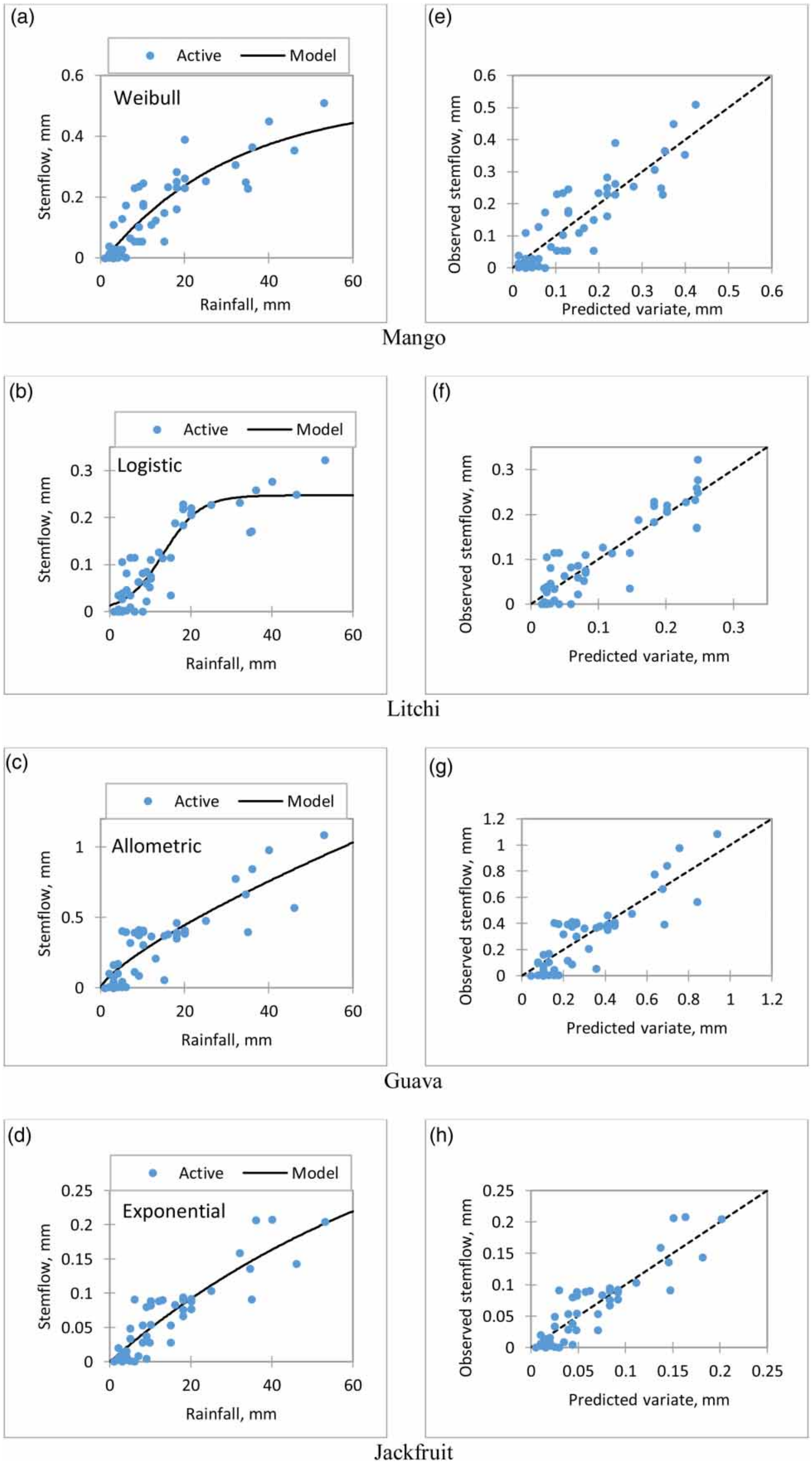

Figure 5 | Fitted model curves (a), (c), (e), (g) to the observed dataset of the stemflow vs rainfall for mango, litchi, guava and jackfruit plantations and corresponding 1:1 plots (b), (d), (f), (h) between observed data and predicted variate.

for all the fruit crops (Figure 5(e)–5(h)). The low RMSE (0.025–0.132 mm) values indicated that the models are capable of estimating the stemflow with a higher degree of precision. The fitted models showed that stemflow increased with increased rainfall amount, which is in agreement with the results presented by Ahmed *et al.* (2015). The fitted model curves, scatter plots and plots of residuals of the models developed for stemflow prediction are provided in the Supplementary material (Online resource 1).

Rainfall-based models for throughfall estimation

Similar to stemflow, six models were also fitted for throughfall to derive the relationship between throughfall and rainfall for the four tree species. The functional form and the parameter estimates for the best fitting models are presented in Table 5. The adjusted R^2 value (observed vs predicted) was more than 0.94 for all the best fitting functions to throughfall data of all tree species. The non-linear models, namely, Weibull ($R^2 = 0.99$) and Allometric ($R^2 = 0.94$) fitted well for mango and litchi (Figure 6(a) and 6(b)) trees, respectively. In the case of guava and jackfruit, the linear models outperformed (AIC 207.6 and 220.0; $R^2 > 0.98$) other non-linear models (Figure 6(c) and 6(d)). Previous studies also reported linear or power functions relationships between throughfall and rainfall (Ahmadi *et al.* 2009).

Low values of RMSE (1.078–3.087) implies that the models have a higher precision of prediction. Details of all the fitted models to throughfall data from all four tree species and the corresponding scatter plots are provided in the Supplementary material (Online resource 2). Higher values of R^2 (>0.94), in the case of throughfall indicated that rainfall is a better predictor of throughfall than stemflow (R^2 0.743–0.819). Rainfall needed to saturate the canopy before throughfall could start, which was estimated by using back-transformation of the data (Carlyle-Moses & Price 1999) with the developed models as 2.1, 2.3, 1.1 and 1.8 mm for mango, litchi, guava and jackfruit, respectively.

Morphology-based stemflow prediction

The potential influence of morphological parameters on stemflow and throughfall was tested with multiple linear regressions on the pooled tree population. Multiple regressions were performed on untransformed data, since exploratory analyses showed residuals to be normally distributed. The best performing model for each rainfall class was selected on the basis of AIC. Readers may refer to the Supplementary material (Online resource 3) for the summary of variable selection and performance statistics of each of the candidate solutions evaluated for stemflow prediction. The model variables, their coefficients and intercepts of the best fitting models are presented in Table 6. All the regressions were highly significant ($P < 0.001$) and performed well with adjusted R^2 varying from 0.856 to 0.944 and RMSE in the range of 0.141 to 0.492 (Table 6). The number of variables in the best performing models varied from 2 (RR and LAI), in the case of low rainfall depths (<5 mm) to 4 (RR, LAI, TH, CA), in the 10–20 mm rainfall class. Park & Cameron (2008) also observed that the relative importance of different

Table 5 | Parameter estimates for the rainfall-based best fitted candidate function for throughfall

Tree species	Name of the function	Functional form	Parameter estimates a	b	c	R^2	RMSE, mm	AIC
Mango	Weibull	$Y = [a - b \times \exp(-c \times X)] + \varepsilon$	−213.278	211.674	0.0041	0.993	1.078	178.3
Litchi	Allometric	$Y = a \times X^b + \varepsilon$	0.462	1.193	–	0.943	3.087	281.1
Guava	Linear	$Y = a + b \times X + \varepsilon$	−1.221	1.004	–	0.987	1.459	207.6
Jackfruit	Linear	$Y = a + b \times X + \varepsilon$	−1.691	0.904	–	0.980	1.683	220.0

Y, Dependent growth variable; X, independent growth variable; a, b and c are parameter estimates and ε is the additive error term.
AIC, Akaike information criteria; RMSE, root mean squared error.

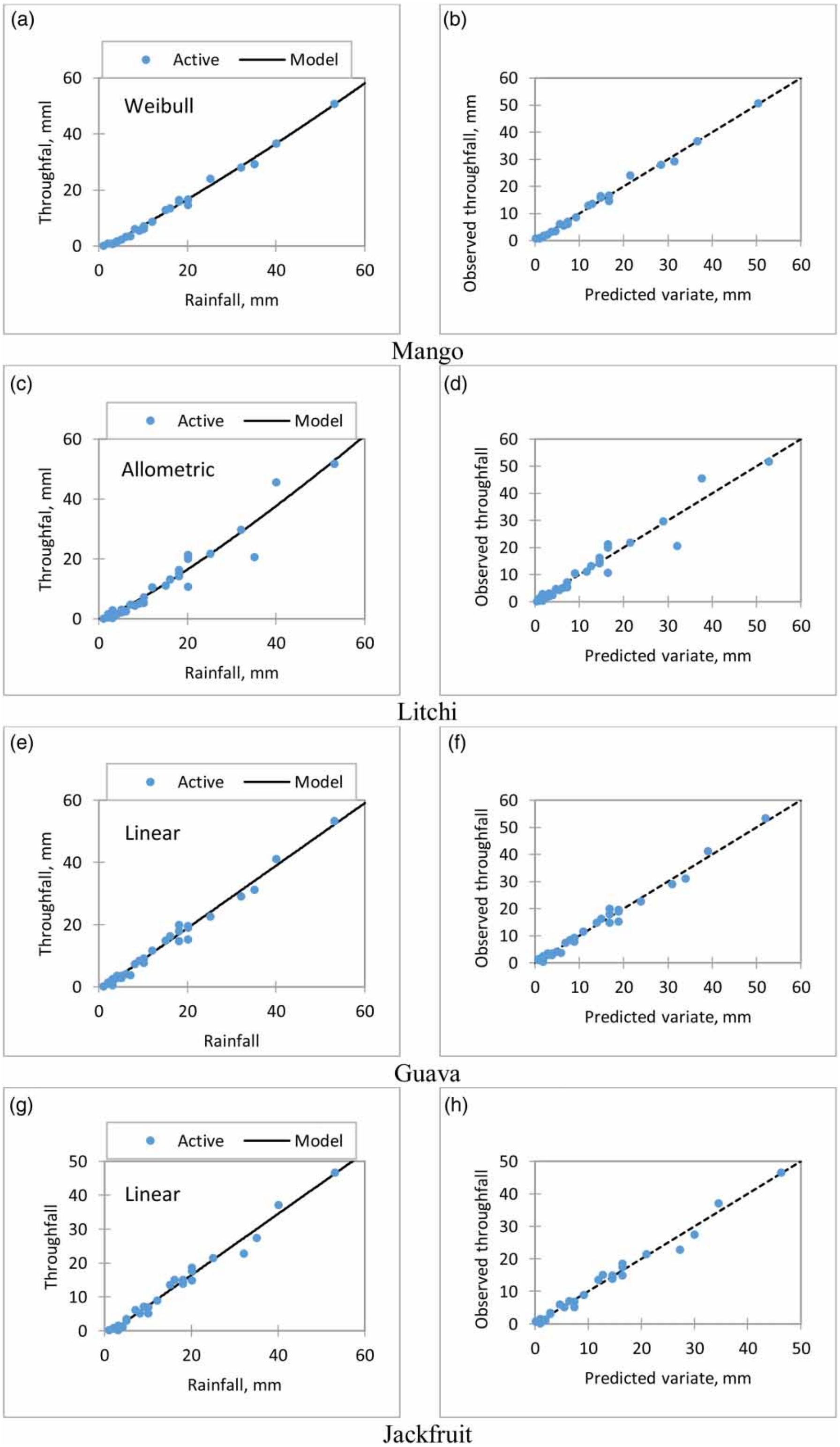

Figure 6 | Fitted model curves (a), (c), (e), (g) to the observed dataset of the throughfall vs rainfall for mango, litchi, guava and jackfruit plantations and corresponding 1:1 plots (b), (d), (f), (h) between observed data and predicted variate.

Table 6 | Coefficient and intercepts of the morphology-based stemflow prediction models for different classes of rainfall depths

Rainfall class	Number of variables	Variables entered in equation	Coefficient	SE	RMSE, mm	Adjusted R²	AIC	F	Pr > F
< 5 mm	2	RR	−8.768	6.390	0.492	0.856	– 14.46	33.56	<0.0001
		LAI	−0.203	0.037					
		Intercept	12.53	6.266					
5–10 mm	2	RR	5.602	3.036	0.313	0.934	– 25.36	92.90	<0.0001
		LAI	−0.143	0.013					
		Intercept	−1.086	2.915					
10–20 mm	4	RR	5.117	1.829	0.141	0.944	– 43.57	47.08	<0.0001
		LAI	0.093	0.036					
		TH	0.251	0.095					
		CA	−0.055	0.013					
		Intercept	−3.779	1.829					
> 20 mm	3	RR	7.207	2.547	0.192	0.896	– 36.44	32.61	<0.0001
		LAI	−0.067	0.023					
		DBH	0.020	0.014					
		Intercept	−5.242	2.540					

RR, roughness ratio; LAI, leaf area index; DBH, diameter at breast height; CA, canopy area; TH, tree height; CL, canopy length; R^2, coefficient of determination; F, F value; Pr, significance probability; SE, standard error; AIC, Akaike information criteria; RMSE, root mean squared error.

morphological parameters as predictors of stemflow depended on rainfall depth. At rainfall depths less than 10 mm, only RR and LAI were statistically significant variables entering the model. At rainfall >20 mm, DBH, in addition to RR and LAI, was also statistically significant, implying that DBH has considerable influence on stemflow generation at higher rainfall depths. The parameters RR and LAI were significant and appeared in the best models for all rainfall classes. Zhang *et al.* (2015) used nine biological parameters of trees and showed that rainfall and above-ground biomass were the best variables for modelling and predicting stemflow. The major disadvantage of models developed by Zhang *et al.* (2015) is that they require estimation of tree biomass using a destructive method of sampling. Since the models developed in the present study do not require destructive sampling of trees, these models can be considered as an improvement over the types of models presented in Zhang *et al.* (2015).

The graphic plots of stemflow vs rainfall with upper and lower bounds of predicted variable for various rainfall depth classes are presented in Figure 7(a)–7(d). The Anderson–Darling tests confirmed that, for all the morphology-based throughfall estimation models, the residuals were normally distributed. The plots (Figure 7(e)–7(h)) ensured that the residuals are not continuously over/underestimating stemflow.

Morphology-based throughfall prediction

The model variables, coefficients of variables and intercepts of the best performing throughfall prediction models are presented in Table 7. Details on variable selection and performance statistics of each of the candidate solutions is provided in the Supplementary material (Online resource 4). In the case of throughfall, the developed models performed well with adjusted R^2 and RMSE within the acceptable ranges of 0.815–0.949 and 1.522–5.028, respectively. In each rainfall class, the number of morphological parameter in the best-fit models varied with their relative importance as predictors of throughfall. Canopy length and LAI were the most significant parameters for all the rainfall classes. Canopy coverage (live crown length and area) is an important parameter in analytical models, and many model parameters have a linear relationship with the canopy coverage (Gash *et al.* 1995). At low rainfall depths, the LAI and CL governed the process of throughfall generation. Tree height (TH) had a significant influence on throughfall for rainfall depths ranging from 5 to 20 mm. In the assessment of throughfall, the role of LAI was statistically significant and this parameter appeared in the best performing models for all the rainfall classes. This is mainly because leaf area significantly influences the canopy water storage capacity, consequently increasing the

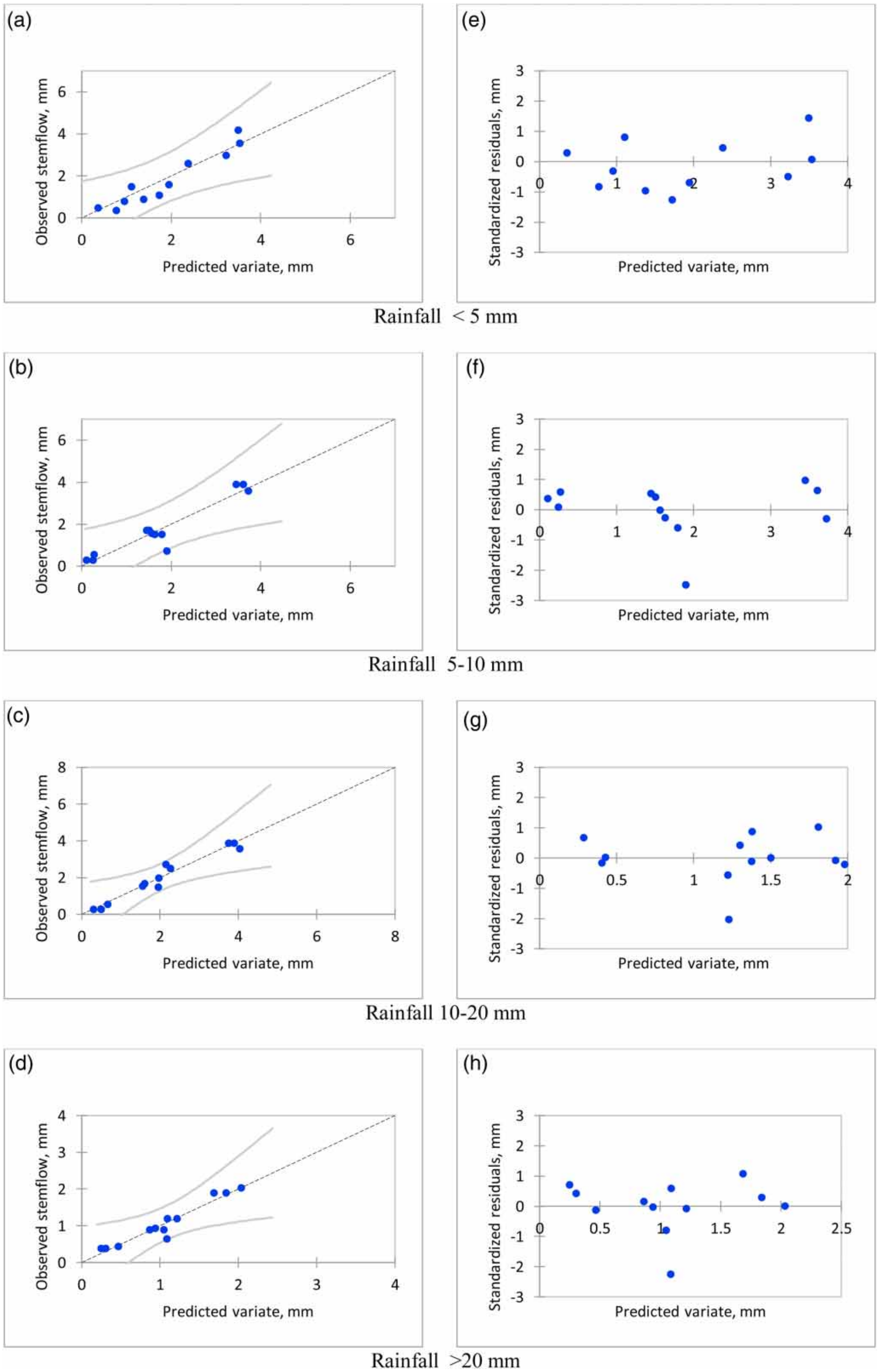

Figure 7 | Comparison of observed and predicted stemflow (1:1 plots) in different rainfall classes (a), (c), (e), (g) and corresponding standardized residuals against predicted variate (b, (d), (f), (h).

interception loss (Deguchi *et al.* 2006). The fitted models for throughfall estimation for various rainfall depth classes are presented in Figure 8(a)–8(d). The residual values plotted against the predicted variates (Figure 8(e)–8(h)) showed that the model estimated the throughfall with a good degree of precision. The Anderson–Darling test for

Table 7 | Coefficient and intercepts of the morphology-based throughfall prediction models for different classes of rainfall depths

Rainfall class	Number of variables	Variables entered in equation	Coefficient	SE	RMSE, mm	Adjusted R^2	AIC	F	Pr > F
<5 mm	2	CL	−3.770	0.637	2.748	0.949	26.81	104.17	<0.0001
		LAI	−0.647	0.144					
		Intercept	75.204	2.465					
5–10 mm	3	TH	4.851	2.347	5.028	0.815	41.89	17.14	<0.001
		CL	−7.453	2.189					
		LAI	−1.599	0.899					
		Intercept	84.681	4.668					
10–20 mm	3	TH	−3.145	0.968	2.073	0.917	20.63	41.44	<0.0001
		CL	4.215	0.903					
		LAI	−0.483	0.371					
		Intercept	94.792	1.925					
>20 mm	3	DBH	−0.182	0.064	1.522	0.934	13.21	52.72	<0.0001
		CL	−0.781	0.266					
		LAI	−0.299	0.140					
		Intercept	106.926	1.616					

RR, roughness ratio; LAI, leaf area index; DBH, diameter at breast height; CA, canopy area; TH, tree height; CL, canopy length; R^2, coefficient of determination; F, F value; Pr, significance probability; SE, standard error; AIC, Akaike information criteria; RMSE, root mean squared error.

normality showed that the residuals were normally distributed and the developed models are acceptable for estimating throughfall with a reasonable degree of accuracy.

From this study it can be inferred that, among the four species studied, jackfruit is the best species to plant, if the aim of the plantation is to reduce soil erosion from the degraded uplands of the East Indian plateau region. Jackfruit, having a comparatively longer canopy and higher LAI, intercepted more rainfall (21.2%). Although mango had a higher LAI, litchi plant also showed comparatively a lower throughfall and higher interception loss (18.7%), mainly because of its dense canopy. The higher the ability of the plant to reduce throughfall, the greater is the potential to reduce throughfall kinetic energy, consequently reducing the potential for rill initiation (Keim & Skaugset 2003). However, these protective functions of fruit tree species must be balanced against interception losses (Wallace *et al.* 2005) and the large amount of water transpired by such trees (Scott *et al.* 2005).

CONCLUSIONS

The partitioning of rainfall into stemflow, throughfall and the resulting interception loss by the major fruit crops of the East Indian plateau was analysed, considering the rainfall and canopy traits. Stemflow, throughfall and interception loss were strongly influenced by canopy architecture and tree morphological characteristics. Among the studied fruit species, jackfruit has the highest per cent of interception loss relative to gross rainfall and the guava plant has the least per cent of interception loss. Among rainfall-based models, Weibull, Logistic, Allometric and Exponential model were found as the best fit models for stemflow estimation for mango, litchi, guava and jackfruit, respectively, whereas Weibull, Allometric, Linear and Linear were the best fit models for throughfall estimation from mango, litchi, guava and jackfruit, respectively. The morphology-based models can only be used over the range of tree morphological parameters considered in this study, because these models do not consider other sources of variation. The models clearly identified the specific set of morphological parameters that are affecting the stemflow and throughfall generation process at different rainfall depths. We found that these static models are capable of describing rainfall partitioning from the fruit tree species. Although the developed models did not explain the stemflow and throughfall generation processes at canopy level, the models clearly identified the extent to which rainfall partitioning is controlled by the morphological parameters. Rainfall- and tree morphology-based models developed in this study will be useful to hydrologists in modelling runoff

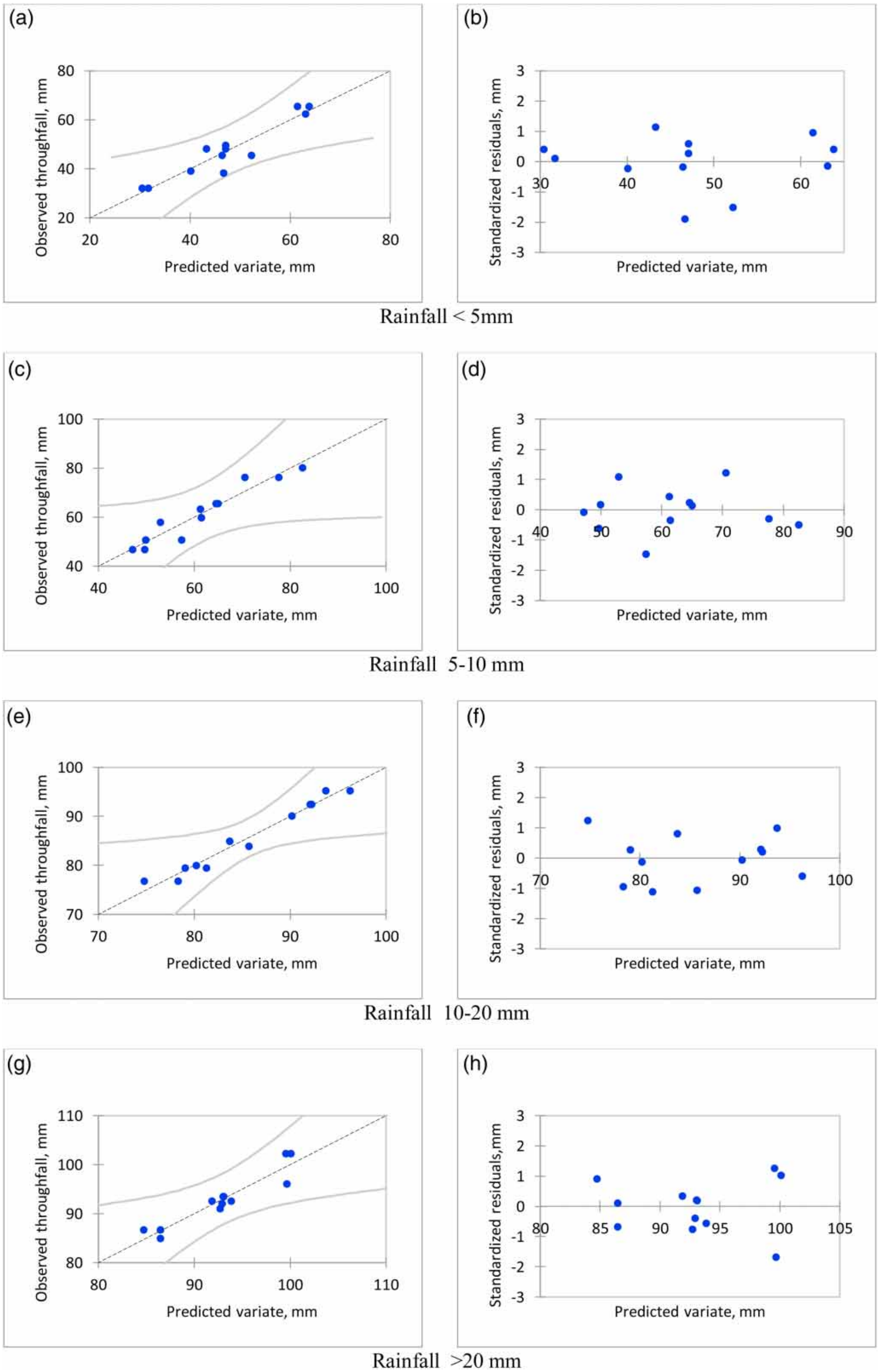

Figure 8 | Comparison of observed and predicted throughfall (1:1 plots) in different rainfall classes (a), (c), (e), (g) and corresponding standardized residuals against predicted variate (b), (d), (f), (h).

and soil erosion processes. Although the study presents quantitative results of stemflow and throughfall from four important fruit species of the East India plateau region, future studies should also focus on assessment of spatial variations in the soil hydraulic and physical properties as triggered by stemflow and throughfall patterns.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/nh.2019.052.

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