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Modeling and measurement of two-layer-canopy interception losses in a subtropical mixed forest of central-south China

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Abstract

The original Gash analytical model and the sparse Gash's model have been applied to simulate rainfall interception losses from the two canopy layers in Shaoshan forest of central-south China during 2003. The total estimated interception loss from the two canopy layers is 478.4 mm with an error of 12.4 mm or 2.7% of total measured interception loss (466.0 mm). Both the original Gash model for top-canopy interception loss and the sparse model for sub-canopy loss overestimate interception losses. The simulated results show that the interception losses in top-canopy is 182.6 mm with an overestimation of 4.9% of measured losses and that in sub-canopy is 295.8 mm with an overestimation of 1.3%. The simulated values of the top-canopy suggest that 47% of the simulated interception losses are evaporated in the stage of "during storms" and 38% in "after storms", which is similar to the published results in temperate and tropical forests. However, the modelled losses from the sub-canopy show that 17% of interception losses are evaporated in "during storms" and 70% in "after storms", which is deviated from the reported results. The simulated results of two canopy interception losses in Shaoshan forest indicate that canopy structures may strongly impact hydrological fluxes in forested ecosystems.

1. Introduction

Canopy interception loss, the proportion of incident precipitation that is intercepted, stored and subsequently evaporated from the leaves, branches and stems of vegetation, is a significant and sometimes a dominant component of evapotranspiration from forest stand (Gash, 1979; Dolman, 1988; Tiktak and Bouten, 1994; Gärdenäs and Jansson, 1995; Hörmann et al., 1996), which is approximated to the differences between incident precipitations measured above canopy, the sum of throughfall and stemflow below canopy (Turner and Lambert, 1987; Lloyd et al., 1988; Mahendrappa, 1990; Liu, 1997; Tobón et al., 2000). Many forest researches on canopy interception showed that forest canopy interception accounted for 10∼35% of gross precipitation (Wright et al., 1990; Whitehead and Kelliher, 1991; Thimonier, 1998; Zeng et al., 2005). But interception varies greatly among tree species, forest density, canopy structure, vegetation physiology and different climatic conditions. Interception can be as high as 50% of rainfall in some areas (Calder, 1990; Lankreijer et al., 1993).

Gash (1979) proposed a rainfall interception model, which was essentially an analytical form of Rutter model (Rutter et al., 1975; Gash et al., 1995). The Gash model retains some of the simplicity of the empirical approach, while also preserving much of the fundamental physical reasoning explicit in the Rutter model. According to the weakness in application of the Gash's model, Gash et al. (1995) and Valente et al. (1997) also revised the Gash's model for sparse forests. The analytical model has been used with considerable success to predict or simulate interception in a wide range of environments, including temperate coniferous and broadleaf forests, tropical rainforests, and semi-arid forests (Leyton et al., 1967; Lloyd et al., 1988; Hutjes et al., 1990; Dykes, 1997; Valente et al., 1997; Jackson, 2000; Price and Carlyle-Moses, 2003).

The quantitative effects of woodland on water resources are largely dependent on interception loss (Jetten, 1996), since tree canopies typically intercepted the majority of rainfall, and control its subsequent evaporation and drainage (Carlyle-Moses and Price, 1999; Barbour et al., 2005). The availability of water directly influences the vitality and growth of forest ecosystems by limiting the transpiration (Price and Carlyle-Moses, 2003; Cui et al., 2005). If the conceptual interception loss models such as the Gash analytical models can be applied to the subtropical mixed forests in central-south China, this would provide watershed managers with a valuable tool for evaluation of the hydrologic impacts on the forest ecosystem.

Neither the original Gash model (Gash, 1979) nor the reformulated versions (Gash et al., 1995; Valente et al., 1997) have been applied to subtropical mixed forest in China. Shaoshan forest is with two-layer canopy structure, i.e. top-canopy with 10–30 m height and sub-canopy with 0.8–4.5 m height. It is difficult to predict the canopy interception losses by using one time of Gash analytical model owing to the special canopy structures in Shaoshan forest. Therefore, authors, considering the nature of Gash analytical models and the height and the coverage of canopies, tend to use the original Gash model to simulate top-canopy interception losses and the sparse model to predict the sub-canopy losses).

The study objectives are, in a conifer-deciduous mixed stand, to: (i) estimate the various climatological and stand parameters required for the original Gash model and the sparse Gash model in top- and sub-canopy layer, respectively, (ii) assess the appropriateness of the two types of models, and (iii) determine whether the model provides the better estimates of canopy interception losses relative to the measurements.

2. Materials and methods

2.1. Site description

The experimental site of Shaoshan forest is located in the hills in central Hunan Province (27°87′ N, 112°91′ E, 292.4 m a.s.l.), which is in Central-south China. The forest is 30 km away from the nearest town Xiangtan City (600 thousand inhabitants) (Fig. 1).

2.2. Climate

Owing to the effect of the monsoon from the Pacific and Indian Oceans, the climate of Hunan is the humid subtropics monsoon type, which is symbolized by warm in winter and hot in summer, abundant but unevenly distributed rainfall and high humidity. The site is with distinct four seasons in a year, i.e. spring (January to March), summer (April to June), autumn (July to September) and winter (October to December). About 20% of the annual rainfall is assigned to spring and 70% to summer. The highest humidity of 90% is in summer. Autumn and winter are of dry and short period of raining (~15% of annual rain duration). Annual mean precipitation is 1200–1700 mm and annual mean temperature is 17.0°C, an absolute maximum of 39°C in summer and an absolute minimum of −2.0°C in winter.

2.3. Vegetation

The projected top-canopy coverage of the stand is about 82% and sub-canopy coverage of the stand is 91%. The forest trees are generally 20∼40 year-old. The dominant tree species (diameter at breast height (DBH) ≥10 cm) in top-canopy layer within the study plots are China fir (*Cunninghamia Canceolata*), massoniana (*Pinus Massoniana*), camphor wood (*Cinmamomum camphora*), and bamboos (*Phyllostachys pubescens*). The four species make up approximate 98% of the density and 96% of the relative dominance of the top-canopy layer in the study stand (Table 1). The sub-canopy is dominated by camellia (*Camellia japonica*), oleander (*Nerium indicum*) and holly (*Euonumus japhonicus*), Ternstroemia (*Ternstroemia gymnanthera*). The vegetation forms the obvious two-layer canopy, i.e. the tall arbor canopy and the lower shrub canopy layers due the effects of local climate (Fig. 2). The top-canopy layer, with an approximate height of 10–30 m, is dominated by the four species crowns, while the sub-canopy layer, which ranges from approximately 0.8–4.5 m in height, is comprised of the crowns of all tree species found within the plot.

2.4. Sampling design

Data were generated from ten 30×30 m^2 sample plots in a 2.5 ha subtropical deciduous-conifer mixed forest in central Hunan. A wet-only collector from MISU was placed on the tower (25 m height) within the studied forest adjacent to canopy covered throughfall plots. For the 10 plots in the studied forest stand, 3 plots were located in the lower parts of the catchment with water saturation, 5 in the middle of the catchment and 2 in the upper parts (Fig. 1). At each studied plot, 12 canopy throughfall collectors were randomly placed 1.0 m above forest ground within the selected area and 4 sub-canopy throughfall collectors were placed beneath the sub-canopy and 0.20 m above the floor. Each collector consists of two connected parts, a polyethylene funnel (18 cm diameter) and a white polyethylene bottle (5 liter capacity). A meteorological station was established for the parameters of wind speed, main wind direction, radiation, humidity, and vapor pressure in the open field in vicinity of the experimental plots in the forest during the observed years. Halved plastic corrugated tubing (∼2.5 cm wide) was stapled and sealed with caulking around the circumference of 8 trees at a mean height of ∼1.5 m. Stemflow from each tree was diverted from the corrugated collar to a collection container at base of each tree. The stemflow (mm) was derived employing the equation (Price and Carlyle-Moses 2003):

$$SF = \frac{n \cdot SF(a)}{FA} \quad (1)$$

where SF is the estimated stemflow for a given area of forest (FA) (m^2) with n number of trees (n=8) and $SF(a)$ is the average stemflow volume from sampled trees.

3. Model descriptions

3.1. The original Gash model

The original model of Gash (1979) considers rainfall to occurs as a series of discrete events, during which three phases can be distinguished: (i) a wetting phase during which rainfall, P_G, (mm) is less than the value required to saturate the canopy, P'_G, (mm); (ii) a saturation phase (provided rainfall intensity, R, exceeds evaporation from the wet canopy, E), and (iii) a drying phase after rainfall has ceased. The canopy is assumed to have sufficient time to dry between storms. Therefore, the model was not intended to use in short vegetation types in temperature latitudes, which may stay wet for prolonged periods (van Dijk and Bruijnzeel, 2001). The original Gash model has been successfully applied to simulate interception loss in relatively closed canopies (with canopy covers ranging from 40% to 100%), particularly for the evaporative process, through the assumption that the canopy and trunk storages extend to the whole plot area (Gash and Morton, 1978; Gash et al., 1980; Pearce and Rowe 1981; Lloyd et al., 1988; van Dijk and Bruijnzeel, 2001). But the results from some other studies suggested that these models should not be applied to sparse forests, as they significantly overestimated the interception loss (Lankreijer et al., 1993; Gash et al., 1995).

The forest structure is described in terms of a canopy storage capacity, S, which is defined as the amount of water left on the canopy in zero evaporation conditions when rainfall and throughfall have ceased (Gash and Morton, 1978), and a free throughfall coefficient, p, which determines the amount of rain which falls directly to the forest floor without hitting the canopy (p is often assumed equal to one minus the canopy cover, c). More often $(1-p-p_t)$ is considered equal to canopy cover. Furthermore, there is a fraction p_t of incident rainfall that is diverted to the trunks, which represents a storage capacity, S_t (mm). The mean evaporation rate during rainfall, $\bar{E}$ (mm h^{-1}), and the mean rainfall intensity, $\bar{R}$ (mm h^{-1}), for saturated canopy conditions, are also required. The separate components of the interception loss are calculated as shown in Table 2. The model is usually calculated from daily rainfall totals assuming one storm per day (Gash, 1979).

3.2. The sparse Gash model

Addressing both a conceptual error in the original model and the inadequate performance in forests with sparse canopies (Teklehaimonot and Jarvis, 1991), Gash et al. (1995) proposed a revised version. The improved Gash model by Valente et al. (1997) takes the sparseness of a canopy into consideration by scaling the mean evaporation rate during a storm event and other model parameters to the proportion of canopy cover present at the community of interest. Two distinct sub-areas (open area and covered area) are also considered, each having the same gross rainfall input. Average evaporation ($\bar{E}$) from the saturated canopy is calculated, as in the original version of the model, through the Penman – Monteith equation. The reformulated model also considers that no rainfall enters trunk storage until canopy saturation is reached. Although some modifications were made in the revised Gash model (Gash et al., 1995), additional modifications to the model were also described by Valente et al. (1997). Valente et al. (1997) replaced the evaporation from the canopy term ($\bar{E}_c$) with a term that includes both evaporation from the canopy and trunks, $(1-\varepsilon)\bar{E}_c$, where ε is a model constant relating trunk evaporation to canopy evaporation (Table 2).

3.3. Estimation of canopy-structure parameters

3.3.1. Canopy storage capacity in each canopy layer

The canopy storage capacity (S) was calculated from a plot of throughfall plus stemflow versus gross precipitation (Aboal et al., 1999). Valente et al. (1997) suggest that the trunks storage capacity (S_t) of the site may be estimated as the negative interception of linear regression with stemflow as the dependent variable and $(TF-(1-c)P_G)$ as the independent variable. While the drainage portioning coefficient (p_d) is equated with the slope of this linear equation divided by (1 + the slope). The parameters $\bar{E}$, S, and S_t are all scaled to the fractional cover (c):$\bar{E}_c$, S_c, and $S_{t,c}$.

3.3.2. Evaporation rate

Potential evaporation (E_p) is calculated using the Penman-Monteith equation (Rutter et al., 1971), which is equivalent to the Penman-Monteith equation with r_s set to zero. Evaporation rate (E) for the saturated canopy of a sparse forest can be estimated as E_p when $C>S$, or as $E=E_p \cdot C/S$, when $C<S$ (C is the actual canopy storage and S is canopy storage capacity) (Teklehaimonot and Jarvis, 1991). $\bar{E}_c$, the corrected average evaporation rate over the hours of rainfall in one day equals to $\bar{E} \cdot c$ (mmh^{-1}). R is calculated for all hours when the rainfall exceeds the threshold to give an estimate of the mean rainfall rate onto a saturated canopy (Gash et al., 1999).

3.4. Coefficient of free throughfall (p) and model constant (ε)

The coefficient was estimated by the method of Leyton et al. (1967), as the slope of the regression of single-event throughfall on single event rainfall, in this case considering events amount necessary exceed canopy storage capacity. The model constant (ε) that relates the evaporation rate from trunks to that of saturated canopies was not determined experimentally. Rather the value of this constant was estimated as 0.023 with little expected error based on the findings of Valente et al. (1997). The constant (ε) was similar in two contrasting stands in central Portugal, ε=0.024 in a *Pinus pinaster* stand and ε=0.022 in a stand of *Eucalyptus globulus*, suggesting that the value of ε does not vary significantly between forest stands (Valente et al., 1997).

In applying the analytical model, saturated conditions are assumed to occur when the hourly rainfall exceeds a certain threshold. Often a threshold of 0.5 mm h^{-1} is used (Gash, 1979; Gash et al., 1995; Valente et al., 1997).

4. Results

4.1. Incident precipitation

During the observed year of 2003 in Shaoshan forest, a total of 75 events were measured and with a cumulative precipitation quantity 1226±15.6 mm, daily rainfall varying from 0.9 mm to 55 mm. Mean rainfall intensity as 5.3 mm h^{-1}, ranging from 1.8 mm h^{-1} to 14.0 mm h^{-1}. As can be seen from Fig. 3, 60% of annual precipitation was distributed to the period of mid-March to start of July.

Cumulative incident precipitation, measured throughfall and sub-throughfall and stemflow in 2003 are presented in Figs. 4a and 4b. Cumulative throughfall of top-canopy layer is 1052±9.6 mm or 85.8±2.0% of total precipitation. Cumulative stemflow is 5.3±0.8 mm or 0.4±0.5% of total precipitation in top-canopy during the studied period. The stemflow in sub-canopy was not measured for the practical reasons. The input of rainfall into sub-canopy layer should be $P_G - TF - SF$, which was 1046.7 mm (85.4% of total rainfall). Cumulative sub-throughfall in sub-canopy layer is 760±6.3 mm or 72.6±1.5% of sub-precipitation or 62.0±0.8% of total precipitation.

4.2. Derived values of parameters for the Gash models in each canopy layer

The values of parameters derived for the Gash model versions are presented in Table 3. The value of canopy storage capacity (S) appeared to be related to season, increasing from an average of 1.1 mm in spring and winter to a maximum of 1.7 mm (a 54.5% increase) in the summer, with a mean of 1.4 mm of S and a 1.71 mm of S_c for the original Gash model in top-canopy layer (Table 3). The sub-canopy storage capacity, S, is estimated to be 0.7 mm with a 0.8 mm for S_c.

The mean evaporation rate per unit ground, $\bar{E}$, during rainfall was calculated to be 0.79 mm h^{-1} for the original Gash model. $\bar{E}$ from sub-canopy layer was 0.84 mm h^{-1} for the sparse Gash model, and the $\bar{E}_c$ for the sparse Gash model is 0.77 mm h^{-1}.

Free throughfall coefficient (p) for the original Gash model is 0.15 in top-canopy layer by the method of Leyton et al. (1967) (Fig. 5) and 0.27 for the sparse Gash model in the sub-canopy (Fig. 6), respectively. The stemflow coefficient (p_t) in top-canopy layer was estimated to be 0.03, but the p_t in sub-canopy layer was not estimated for experimental difficulties.

4.3. Components of canopy interception loss

Measured and modeled interception loss components are presented in Table 4. Annual canopy interception loss in top-canopy layer was measured to be 174.0±5.1 mm or 14.2±2.1% of incident precipitation during the studied year of 2003. The annual interception loss in understory was measured to be 292.0±5.5 mm or 27.8±3.4% of sub-precipitation or 23.8±3.6% of precipitation.

Modeled interception loss from the top-canopy by the original Gash model was 182.6 mm (14.9% of precipitation) with an overestimation of 4.9% relative to the measured loss. Modeled interception loss in sub-canopy layer by the sparse Gash model is 295.8 mm, with an overestimation of 1.3% of the measured loss. The total measured interception loss was 466.0 mm (38% of precipitation). The total modelled loss was 478.4 mm, indicating a 2.7% overestimation relative to total measured loss.

The predicted top-canopy interception loss by the original Gash model suggested that 47.1% and 37.6% of losses were evaporated from the stages of "during storms" and "after storms", respectively (Table 4). While the simulated sub-canopy interception loss by the sparse model indicated 17.4% and 70.1% of losses were evaporated from the stages of "during storms" and "after storms", respectively. Additional components of interception (including evaporation from trunks for storms that saturate trunk store and from trunks for storms that do not saturate the trunk store) accounted for 8.0% (top-canopy), 3.9% (sub-canopy) of the modeled trunk interception loss.

5. Discussion

5.1. Canopy storage capacity in each canopy layer

The derived values of parameters for Gash models in top- and sub-canopy layer are similar to those derived by other workers. Canopy storage capacity, for example, the calculated S_c value falls within the typically range of ~0.6 mm to ~1.8 mm for forest communities (Whitehead and Kelliher, 1991; Návar and Bryan, 1994; van Dijk and Bruijnzeel, 2001). van Dijk and Bruijnzeel (2001) also reviewed the interception loss literatures and suggested that S for deciduous canopies is generally between 0.5 mm and 2.5 mm (Bruijnzeel and Wiersum, 1987), for coniferous canopies is between 0.3 mm and 2.4 mm (Klaassen et al., 1998; Waterloo et al., 1999). The storage capacity is assumed to be constant during a single storm, but is probably variable between events (Robin, 2003). Storage capacity tends to increase with smaller drops and lower rainfall rate (Calder, 1990; 1996). The canopy storage capacity in current study was assumed to be relatively constant because the mean rainfall density was measured to be

5.3 mm h^{-1} and 80% of annual precipitation derived from widespread rain. Raindrop size in sub-canopy layer did not vary significantly because the deep canopy may reduce the dependence of S on rainfall intensity by homogenizing the size distribution of raindrops in the upper layers of the canopy prior to contact the lower layers (Link et al., 2004).

Gash et al. (1995) assumed canopy capacity, S, to be linearly related to canopy cover capacity, c. Leonard (1961) concluded that canopy capacity may be expected to be linearly related to leaf area index, rather than to canopy cover, in a given vegetation type of constant physiognomy and configuration. A sensitivity analysis of the sparse Gash model for parameters showed that the simulated interception loss is the most sensitive to the value of the canopy cover (c), followed by a lower sensitivity to the canopy storage capacity (S), however, the modelled interception loss was fairly insensitive to the stemflow parameters, S_t, p_d and ϵ (Gash et al., 1995). The sensitivity of c and S in our study is similar to the analysis, but the p_d and ϵ of the sparse model improve the simulating accuracy over the original version.

In deciduous forests, wind speed was demonstrated to reduce S by the mechanical shaking of the canopy elements (Hörmann et al., 1996), while Link et al. (2004) found no relationship between S and wind speed during an event study in an old-growth Douglas-fir-western hemlock ecosystem. In some conifer forests, Calder (1996) found that canopy storage capacity (S), varied dynamically with rainfall intensity and suggested that S_c is a function of raindrop size and thus rainfall intensity, with S_c being reduced when raindrop volumes and associated kinetic energies are large. However, Link et al. (2004) suggested that S was not strongly related to rainfall intensity in an old-growth Douglas-fir canopy, because the homogenization of the size distribution of raindrops in the upper canopy layers prior to contact the lower layers. S in Shaoshan, deciduous-conifer mixed forest, is more variable in top-canopy layer than sub-canopy layer. Moreover, the S in top-canopy is two times higher than that in sub-canopy layer.

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5.2. Evaporation rate from canopy in each canopy layer

The values of $\bar{E}$ and $\bar{E}_c$ are in agreement with those in other studies which typically ranged from 0.15 mm h^{-1} (Lousteau et al., 1992) to 0.65 mm h^{-1} (Valente et al., 1997). Gash et al. (1995) assumed that the wet canopy evaporation rate is directly related to the canopy fraction, and van Dijk and Bruijnzeel (2001) found that evaporation from wetted stems during a storm have a significant impact on the relative magnitude of the interception loss and assumed that evaporation rates from wetted stems equal those from the wet canopy. However, Rutter and Morton (1975) suggested the evaporation from stems (on a projected area basis) to be only 2% of wet canopy evaporation rate. Evaporation from stem and trunks in Shaoshan study was slight, accounting for 8.0 and 3.9% of estimated interception loss in top- and sub-canopy, respectively.

5.3. Canopy interception loss

With regard to the interception losses from the two canopy layers, the original Gash model overestimated top-canopy loss (4.9% of measured loss) relative to the sparse Gash model for sub-canopy (1.3 % of measured loss) (Table 4), which was within the errors of reported interception studies by using Gash's models.

Comparison of the results of these studies as regards the partitioning of interception losses among the different modelled stages of rainfall events by the original Gash model or revised sparse model (Table 5) shows that in all previous studies major interception losses occurred during the stages of "after storms" (10~54% of the calculated interception loss estimated by the original Gash model and 8~60% by the sparse model) and "during storms" (27~82% by the original model and 27~84% by the sparse model). The modelled losses by the original Gash model from top-canopy in "during storms" (47% of the estimated interception loss) and "after storms" (38% of the estimated loss) phases were within the previous results (Table 5). However, the modelled losses by the sparse Gash model for sub-canopy layer in "during storms" (17% of the estimated interception loss) and "after storms" (70% of the estimated loss) phases were slightly lower or higher than the reported results (Table 5).

There are steadily growing number of studies that report wet canopy evaporation rates inferred from throughfall measurements to be much higher than suggested by Penman-Monteith theory, particularly under wet maritime climatic conditions (Rowe, 1983). The overestimates of the interception of storms around the saturation point (when P_G is close to P_G) by the Gash models can be explained by the use of the water box concept. When the shower is too small to saturate the canopy ($P_G < P_G$), estimated interception is dependent on E and linear with rainfall, and canopy drip is neglected.

Gash and Morton (1978), using the original analytical model in England, found that interception loss was overestimated by 6.9%. Moreover, Gash et al. (1980) found great deficit between observed and modelled values for three coniferous forests in UK, although the value for the mean evaporation rate was within the 20% level of confidence. Rowe (1983) found the Gash model overestimated interception loss by 3.4% in a evergreen mixed forest in New Zealand, while Hörmann et al. (1996) concluded, introducing a wind dependent storage capacity, that the Gash model overestimated observed interception loss by 5.4% in beech forests in northern Germany. In Shaoshan forest study, the total estimated interception loss by combing of the original Gash model and the sparse model provided the accurate estimate with an overestimation of 2.7% of total measured loss, which was relatively low in comparison with the reported results of interception loss and the combination also utilized the respective advantages of the Gash models.

5.4. Application of the groups of the Gash models

The original and revised Gash models will tend in theory to overestimate the interception loss from sparse forests as they assume that the evaporation area (canopy and trunks) extends to the whole plot area, whereas the actual evaporating area (canopy and trunks) is much reduced in these types of forests (Teklehaimonot and Jarvis, 1991).

The main weakness of the reformulated versions is probably the assumption that the evaporation for the saturated canopy of a sparse forest can be estimated adequately

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by the Penman-Monteith equation. Application of the Penman-Monteith equation to simulate the evaporation rate requires good description of the internal layer resistance of the canopy. In addition, the stability correction for aerodynamic resistance above forests cannot be neglected, as is usually assumed. Valente et al. (1997) has found that the interception loss in *pine* stand was usually higher that that in *eucalypt* forests, as the higher interception loss from pine forest can be attributed to its larger canopy storage and to the larger aerodynamic conductance resulting from its greater height.

The method used to derive the value of $\bar{R}$ should be chosen carefully, whereas the value of $\bar{E}_c$ seems to be relatively stable. For short time-steps a smaller bucket size should probably be used (Gash et al., 1995; 1999; Valente et al., 1997; Jackson, 2000).

6. Conclusions

The original Gash analytical model and the sparse Gash's models have been combined to simulate rainfall interception loss from top- and sub-canopy layers in Shaoshan forest, Central-south China during the year of 2003. The total estimated interception loss from the two canopy layers is 478.4 mm with an error of 12.4 mm or 2.7% of total measured interception loss (466.0 mm). Both the two models overestimate the canopy interception losses relative to the measured values. The simulated interception losses by original Gash model from top-canopy is 182.6 mm with an overestimation of 4.9% of measured losses and that estimated by sparse model in sub-canopy is 295.8 mm with an overestimation of 1.3%.

The Gash model parameters derived from the two canopy layers in this study are similar to those in other forest works. Other parameters and coefficients, such as p, p_t, S_t, and P_G calculated during this study are also within the range of estimates from other forests, especially in coniferous stands.

The simulated values of the top-canopy suggest that the simulated interception losses in the major stages of "during storms" and "after storms" are similar to the published results in forests. However, the modelled losses from the sub-canopy are slightly deviated from the literature results. The simulations of two canopy interception losses in Shaoshan forest indicate that the canopy structures strongly influence the hydrological cycles in Shaoshan ecosystems.

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References

Aboal, J. R., Jiménez, M. S., Morales, D., and Hernndez, J. M.: Rainfall interception in laurel forest in the Canary Islands, Agric. For. Meteorol., 97, 73–86, 1999.

Barbour, M. M., Hunt, J. E., Walcroft, A. S., Rogers, G. N. D., Mc Seveny, T. M., and Whitehead, D.: Components of ecosystem evaporation in a temperate coniferous rainforest, with canopy transpiration scaled using sapwood density, New Phytol., 165, 549–558, 2005.

Calder, L. R.: Evaporation in the uplands, Wiley, New York, 1990.

Calder, L. R.: Dependence of rainfall interception on drop size, 1. Development of the two-layer stochastic model, J. Hydrol., 185, 363–378, 1996.

Carlyle-Moses, D. E. and Price, A. G.: An evaluation of the Gas interception model in a northern hardwood stand, J. Hydrol., 214, 103–110, 1999.

Cui, J. B., Li, C. S., and Carl, T.: Analyzing the ecosystem carbon and hydrologic characteristics of forested wetland using a biogeochemical process model, Global Change Biol., 11, 278–289, 2005.

Dolman, A. J.: Evaporation from an oak forest, Ph.D. Thesis University of Groningen, the Netherlands, 1988.

Dykes, A. P.: Rainfall interception from a lowland tropical rainforest in Brunei, J. Hydrol., 200, 260–279, 1997.

Gash, J. H. C.: An analytical model of rainfall interception in forest, Q. J. R. Meteorol. Soc., 105, 43–55, 1979.

Gash, J. H. C., Lloyd, C. R., and Lachaud, G.: Estimating sparse forest rainfall interception with an analytical model, J. Hydrol., 170, 79–86, 1995.
Gash, J. H. C. and Morton, A. J.: An application of the Rutter model to the estimation of the interception loss from Thetford forest, J. Hydrol., 38, 49–58, 1978.
Gash, J. H. C., Wright, I. R., and Lloyd, C. R.: Comparative estimates of interception loss from three coniferous forests in Great Britain, J. Hydrol., 48, 89–105, 1980.
Gash, J. H. C., Valente, F., and David, J. S.: Esitmates and measurements of evaporation from wet, sparse pine forest in Portugal, Agric. For. Meteorol., 94, 149–158, 1999.
Gärdenäs, A. I. and Jansson, P. E.: Simulated water balance of Scots pine stands in Sweden for different climate change scenarios, J. Hydrol., 166, 107–125, 1995.
Hörmann, G., Branding, A., Clemen, T., Herbst, M., Hinrichs, A., and Thamm, F.: Calculation and simulating of wind controlled canopy interception of a beech forest in Northern Germany, Agric. For. Meteorol., 79, 131–148, 1996.
Hutjes, R. W. A., Wierda, A., and Veen, A. W. L.: Rainfall interception in the Tai forest, Ivory coast, Application of two simulation models to a humid tropical system, J. Hydrol., 114, 259–275, 1990.
Jackson, N. A.: Measured and modelled rainfall interception loss from an agroforesry system in Kenya, Agric. For. Meteorol., 100, 323–336, 2000.
Jetten, V. G.: Interception of tropical forest: performance of a canopy water balance model, Hydrol. Process., 10, 671–685, 1996.
Klaassen, W., Boseveld, F., and de Water, E.: Water storage and evaporation as constituents of rainfall interception, J. Hydrol., 212–213, 36–50, 1998.
Lankreijer, H., Lundberg, A., Grelle, A., Lindroth, A., and Seibert, J.: Evaporation and storage of interception rain analyzed by comparing two models applied to a boreal forest, Agric. For. Meteorol., 98–99, 595–604, 1999.
Lankreijer, H., Hendriks, M. J., and Klaassen, W.: A comparison of models simulating rainfall interception of forests, Agric. For. Meteorol., 64, 187–199, 1993.
Leonard, R. E.: Net precipitation in a northern hardwood forest, J. Geophys. Res., 66, 2417–2421, 1961.
Leyton, L., Reynolds, E. R. C., and Thompson, F. B.: Rainfall interception in forests and moorland, in: Forest Hydrology, edited by: Sopper, W. E. and Lull, H. W., Pergamon, Oxford, 1967.
Link, T. E., Unsworth, M., and Marks, D.: The dynamics of rainfall interception by a seasonal

temperate rainforest, Agric. For. Meteorol., 124, 171–191, 2004.
Liu, S. G.: A new model for the prediction of rainfall interception in forest canopies, Ecol. Model., 99, 151–159, 1997.
Lloyd, G. R., Gash, J. H. C., Shuttleworth, W. J., and Marquesde, A. O.: The measurement and modeling of rainfall interception by Amazonian rain forest, Agric. For. Meteorol., 43, 277–294, 1988.
Lousteau, D., Berbigier, P., and Granier, A.: Interception loss, throughfall and stemflow in a maritime pine stand, II. An application of Gash's analytical model of interception, J. Hydrol., 138, 469–485, 1992.
Mahendrappa, M. K.: Partitioning of rain water and chemicals into throughfall and stemflow in different forest stands, For. Ecol. Manag., 30, 65–72, 1990.
Návar, J. and Bryan, R. B.: Fitting the analytical model of rainfall interception of Gash to individual shrubs of semi-arid vegetation in northern Mexico, Agric. For. Meteorol., 68, 133–143, 1994.
Pearce, A. J. and Rowe, I. K.: Rainfall interception in a multistoried evergreen mixed forest: estimates using Gash's analytical model, J. Hydrol., 49, 341–353, 1981.
Price, A. G. and Carlyle-Moses, D. E.: Measurement and modeling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, south Ontario, Canada, Agric. For. Meteorol., 119, 69–85, 2003.
Robin, L. H.: Interception loss as a function of rainfall and forest types: stochastic modeling for tropical canopies revisited, J. Hydrol., 280, 1–12, 2003.
Rowe, L. K.: Rainfall interception by an evergreen beech forest Nelson, New Zealand, J. Hydrol., 66, 143–158, 1983.
Rutter, A. J., Morton, A. J., and Robins, P. C.: A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands, J. Appl. Ecol., 12, 367–384, 1975.
Rutter, A. J., Kershww, K. A., Robins P. C., and Morton, A. J.: A predictive model of rainfall interception in forests 1, derivation of the model from observations in a stand of Coriscan pine, Agric. Meteorol., 9, 367–384, 1971.
Schellekens, J., Scatena, F. N., Bruijnzeel, L. A., and Wickel, A. J.: Modelling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico, J. Hydrol., 225, 168–184, 1999.
Teklehaimonot Z. and Jarvis, P. G.: Modelling of rainfall interception loss on agroforestry sys-

tems, Agric. Sys. 14, 65–80, 1991.
Thimonier, A.: Measuring of atmospheric deposition under forest canopies: some recommendations for equipment and sampling design, Environ. Monitor. Assess., 52, 353–387, 1998.
Tiktak, A. and Bouten, W.: Soil water dynamics and long-term water balance of a Douglas fir stand and in the Netherlands, J. Hydrol., 156, 265–283, 1994.
Tobón, M., Bouten, C. W., and Serink, J.: Gross rainfall and its portioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazionia, J. Hydrol., 237, 40–57, 2000.
Turner, J. and Lambert, M. J.: Forest water usage and interactions with nutrition of Pinus radiate, Acta Ecol., 8, 37–43, 1987.
Valente, F., David, J. J. M., and Gash, J. H. C.: Modeling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models, J. Hydrol., 190, 141–162, 1997.
van Dijk, A. I. J. M. and Bruijnzeel, L. A.: Modelling rainfall interception by vegetation of variable density using an adapted analytical model, Part 1 – Model description, J. Hydrol., 247, 230–238, 2001a.
van Dijk, A. I. J. M. and Bruijnzeel, L. A.: Modelling rainfall interception by vegetation of variable density using an adapted analytical model, Part 2 – Model validation for a tropical upland mixed cropping system, J. Hydrol., 247, 239–262, 2001b.
Waterloo, M. J., Bruijnzeel, L. A., Vuggts, H. F., and Rawaqa, T. T.: Evaporation from pinus caribaea plantation on former grassland soils under maritime tropical conditions, Water Resour. Res., 35, 2133–2144, 1999.
Whitehead, D. and Kelliher, F. M.: A canopy water balance model for a Pinus adiata stand before and after thinning, Agric. For. Meteorol., 55, 109–123, 1991.
Wright, R. F., Cosby, B. J., Flaten, M. B., and Reuss, J. O.: Evaluation of an acidification model with data from manipulated catchments in Norway, Nature, 343, 53–55, 1990.
Zeng, G. M., Zhang, G., Huang, G. H., Jiang, Y. M., and Liu, H. L.: Exchange of Ca^{2+}, Mg^{2+} and K^+ and the uptake of H^+, NH_4^+ for the canopies in the subtropical forest influenced by the acid rain in Shaoshan forest located in central south China, Plant Sci., 168, 259–266, 2005.

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Table 1. Density, basal area and relative dominance of tree species within the study plot.

Vegetation type	Density (trees ha^{-1})	Mean D.B.H. (cm)	Basal area ($m^2 ha^{-1}$)	Relative dominance (%)
Top-canopy layer				
China Fir	134	45.2	22.6	42.0
Massoniana	108	34.1	18.7	30.2
Camphor wood	66	76.3	4.5	18.8
Bamboos	55	20.5	3.3	5.0
Sub-canopy layer				
Camellia	45	3.5	2.1	25.1
Oleander	32	6.4	1.5	20.2
Holly	30	5.0	0.6	18.6
Ternstroemia	15	5.5	0.8	10.4

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Table 2. The original form of the Gash's analytical model compared with the form of the sparse Gash's model revised by Valente et al. (1997).

	Original Gash (1979) model	Sparse Gash model (Valente et al., 1997)
Components of interception loss		
For m storms insufficient to saturate the canopy ($P_G<P'_G$)	$(1-p-p_t)\sum_{j=1}^{m} P_{G,j}$	$c\sum_{j=1}^{m} P_{G,j}$
For n storms ($P_G \geq P'_G$)		
Wetting up canopy	$n[(1-p-p_t)P'_G - S]$	$n(cP'_G - S_c)$
Wet canopy evaporation during storms	$\frac{\bar{E}}{\bar{R}}\sum_{j=1}^{n}(P_{G,j} - P'_G)$	$\frac{c(1-\varepsilon)\bar{E}_c}{\bar{R}}\sum_{j=1}^{n}(P_{G,j} - P'_G)]$
Evaporation after storms	nS	nS_c
Evaporation from trunks for q storms ($P_G>S_t/p_t$), which saturate the trunks and in the left column for the $n+m-q$, which do not ($P_G<S_t/p_t$)	$qS_t+p_t\sum_{j=1}^{m+n-q} P_{G,j}$	$qS_t+p_d c[1-\frac{(1-\varepsilon)\bar{E}_c}{\bar{R}}]\sum_{j=1}^{n-q}(P_{G,j} - P'_G)$
Parameters		
Rainfall necessary to saturate the canopy (P_G')	$-\frac{\bar{R}S}{\bar{E}}\ln[1-\frac{\bar{E}}{(1-p-p_t)\bar{R}}]$	$-\frac{\bar{R}}{(1-\varepsilon)\bar{E}_c}\frac{S}{c}\ln[1-\frac{(1-\varepsilon)\bar{E}_c}{\bar{R}}]$
Mead wet canopy evaporation rate	$\bar{E}=\bar{E}_W$	$\bar{E}=c\bar{E}_c$
Canopy capacity	S	$S=cS_c$
Canopy cover fraction	$1-p$	c

Table 3. Derived parameters for the Gash models in the Shaoshan stand.

	Top-canopy layer Original model	Sub-canopy layer Sparse model
Total precipitation, P_G(mm yr^{-1})	1226	1046.7
Necessary to saturate canopy, P'_G (mm)	1.85	1.10
Free throughfall coefficient, p	0.15	0.27
Stemflow partitioning coefficient, p_t	0.031	–
Canopy storage capacity, S (mm)	1.4	0.72
Canopy storage scaling by canopy cover, S_c (mm)	1.71	0.79
Trunk storage capacity, S_t (mm)	0.16	0.09
Canopy cover, c	0.82	0.71
Average evaporation rate, $\bar{E}$ (mm h^{-1})	0.79	0.84
Average evaporation rate scaling by canopy cover, $\bar{E}_c$ (mm h^{-1})	–	0.77
Average rainfall intensity, $\bar{R}$ (mm h^{-1})	5.3	3.8
Number of rainfall sufficient to saturate the canopy, n	41	35
Number of rainfall insufficient to saturate the canopy, m	8	14
Number of rainfall sufficient to saturate the stems and trunks, q	26	15
Constant, ε	–	0.023
Drainage partitioning coefficient, p_d	–	0.037

Table 4. Measured and modelled results of the canopy interception loss components in the studied forest during 2003 (in mm and as% of total estimated interception loss).

	Top-canopy Original model	Sub-canopy Sparse model
For storms $P_G < P'_G$		
Evaporation from canopy	3.7 (2.0%)	5.0 (1.7%)
For storms $P_G \geq P'_G$ (mm)		
Wetting up of canopy	9.7 (5.3%)	20.4 (6.9%)
Evaporation from canopy during storms	86.0 (47.1%)	54.4 (17.4%)
Evaporation after storms	68.7 (37.6%)	207.4 (70.1%)
Evaporation from trunks and stems	14.6 (8.0%)	11.5 (3.9%)
Estimated interception loss in each canopy layer(mm)	182.6	295.8
Measured interception loss in each canopy layer(mm)	174.0	292.0
Deviation (%)	4.9	1.3
Total estimated interception loss of two layers(mm)	478.4	
Total measured interception loss of two layers(mm)	466.0	
Deviation (%)	2.7	

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Table 5. Partitioning of interception losses among the different modelled stages of rainfall events in the Gash models. The results shown for the present study refer to the estimates from the original and sparse Gash's models. A-stage: Evaporation from events in which rainfall was insufficient to saturate the canopy; B-stage: Wetting up of canopy; C-stage: Evaporation from canopy during storms; D-stage: Evaporation from canopy after storms; E-stage: Evaporation from trunks and stems.

Canopy interception losses (%)	A-stage	B-stage	C-stage	D-stage	E-stage
Original Gash model					
Gash (1979)	19	5	34	41	1
Gash et al. (1980)	10	3	27	49	11
Pearce and Rowe (1981)	3	4	69	23	1
Lloyd et al. (1988)	7	1	34	49	9
Návar and Bryan (1994)	0	4	71	22	3
Carlyle-Moses and Price (1999)	4	3	34	54	5
Schellekens et al. (1999)	0	8	82	10	0
Present study for top-canopy	2	5	47	38	8
Sparse Gash's model					
Carlyle-Moses and Price (1999)	5	3	27	60	5
van Dijk and Bruijnzeel (2001)	0	8	84	8	0
Present study for sub-canopy	2	7	17	70	4

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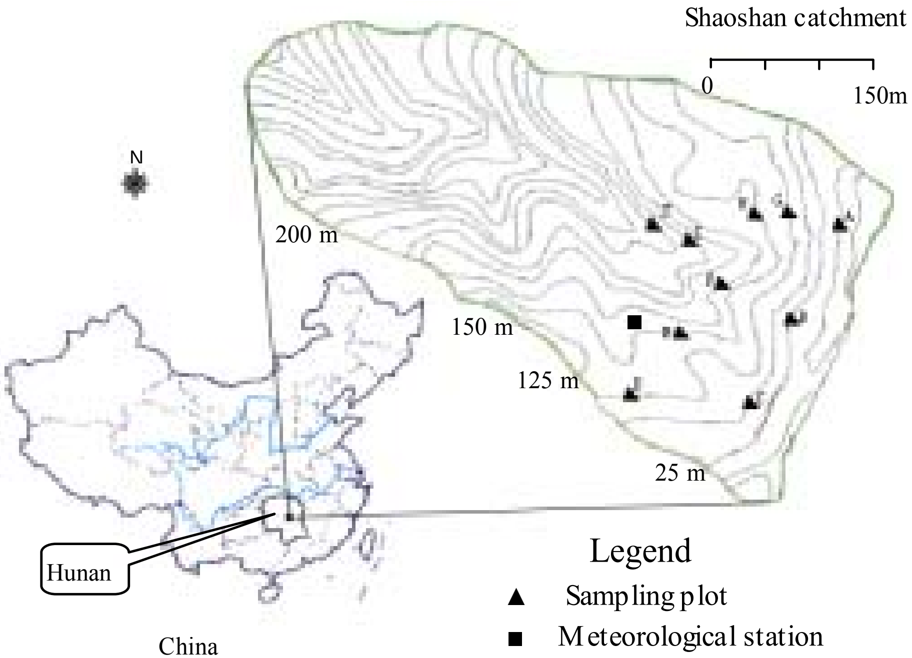

Fig. 1. Location of the studied site and distribution of 10 plots.

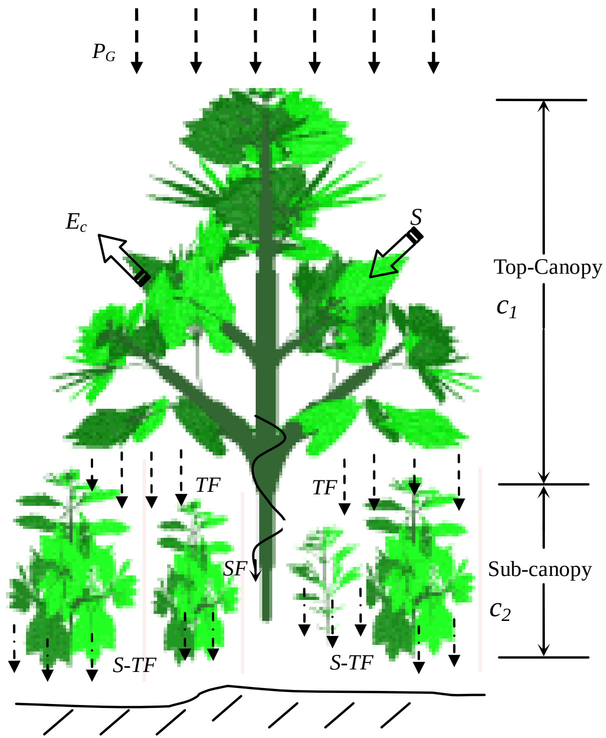

Fig. 2. Schematic diagram of the two-layer structure canopy and canopy water components in Shaoshan forest. (P_G is the bulk precipitation above the forest canopies; E_c is the wet canopy evaporation; S denotes the canopy storage capacity; SF is the stemflow; TF is the throughfall passed top-canopy layer; c_1 is the top-canopy cover fraction; $S\text{−}TF$ is the sub-throughfall passed sub-canopy layer; c_2 is the sub-canopy cover fraction).

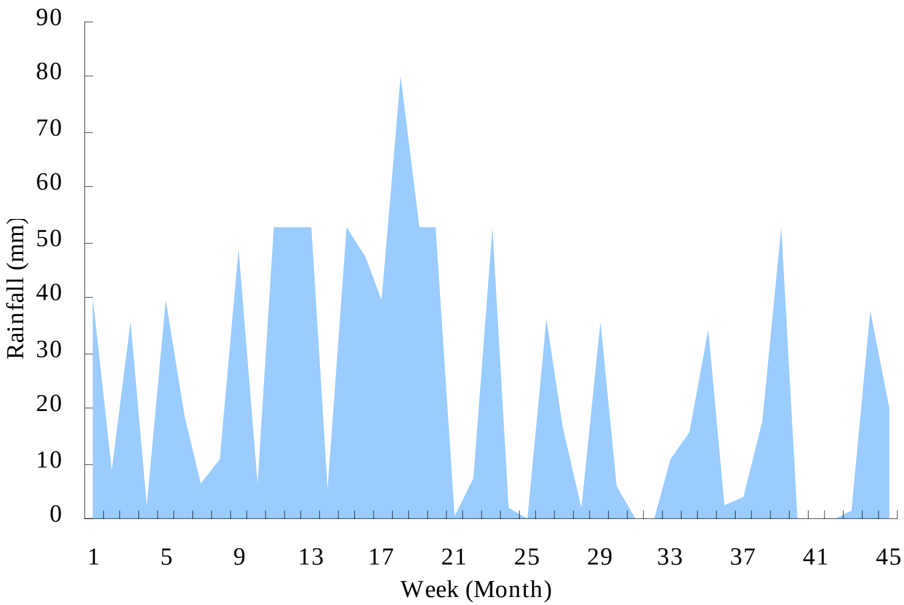

Fig. 3. Weekly (or monthly) distribution of rainfall in Shaoshan forest during the observed year of 2003.

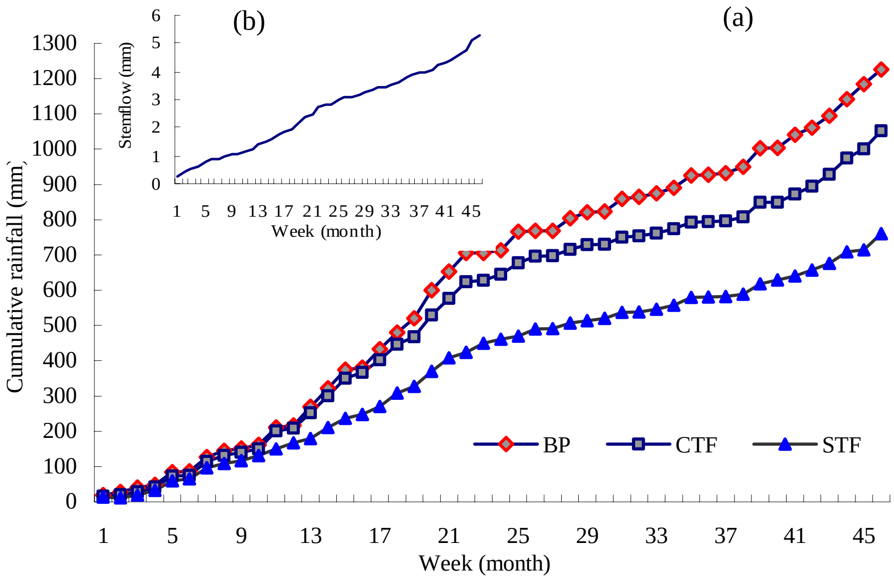

Fig. 4. Cumulative measured precipitation, throughfall and sub-throughfall **(a)**, and stemflow **(b)** during 2003. (BP denotes the precipitation; CTF denotes the throughfall in top-canopy and STF the throughfall in sub-canopy; Stemflow is in the top-canopy layer).

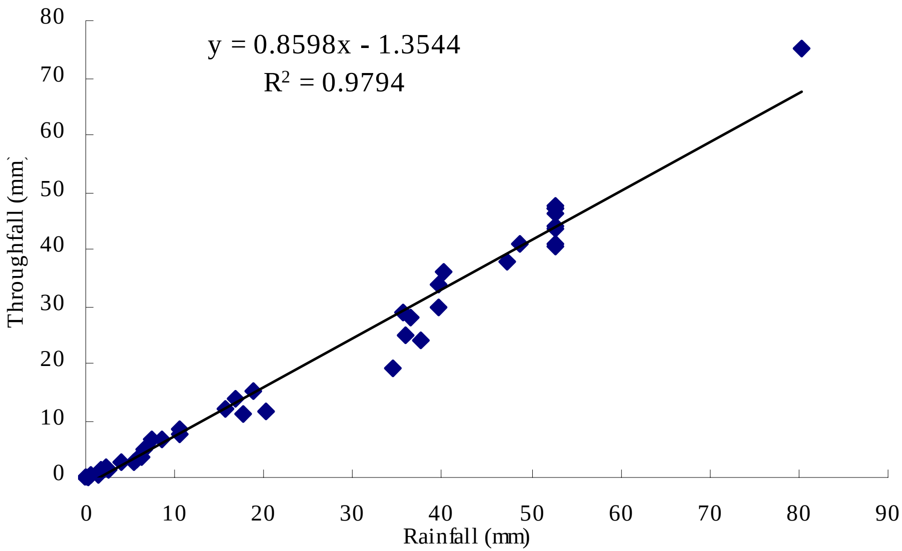

Fig. 5. Single event versus throughfall in top-canopy layer.

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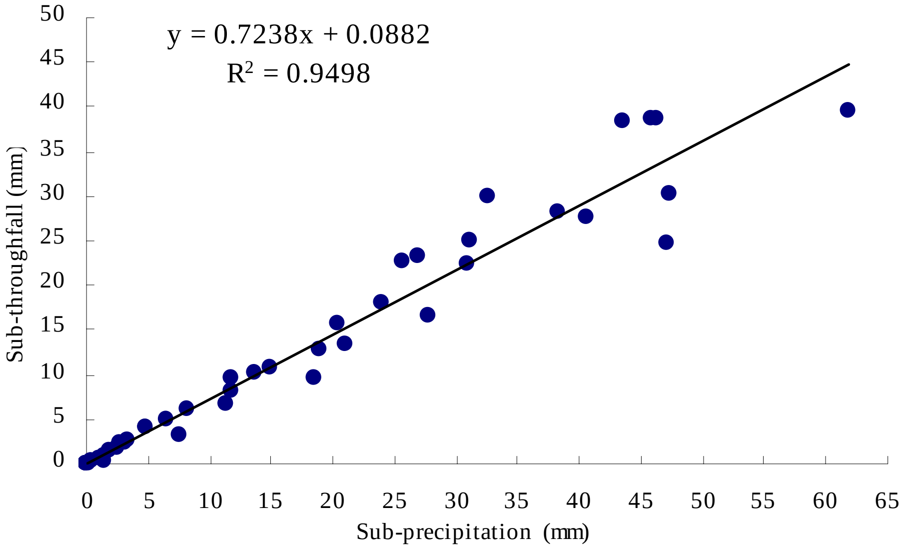

Fig. 6. Single event versus sub-throughfall in sub-canopy layer. Sub-precipitation (mm) is the input of rainfall to sub-canopy layer, which equals to $P_G - TF - SF$ of top-canopy layer.