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Modelling rainfall interception in unlogged and logged forest areas of Central Kalimantan, Indonesia

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Abstract

Rainfall interception losses were monitored for twelve months and related to vegetation and rainfall characteristics at the Wanariset Sangai on the upper reaches of the Mentaya river, Central Kalimantan. The rainfall interception losses were quantified for one hectare each of unlogged and logged humid tropical rainforests. The results show that interception loss is higher in the unlogged forest (11% of total gross rainfall) than in the logged forest (6%). Interception loss was also simulated by the modified Rutter model and Gash's *original* and *revised* models. Both the Rutter and revised Gash models predicted total interception loss over a long period adequately, and resulted in estimates of the interception loss that deviated by 6 to 14% of the measured values, for both the unlogged and logged plots.

Introduction

Most investigations of rainfall interception loss have been confined to comparisons of the magnitude of interception loss from closed canopies of different species of trees, in temperate as well as tropical forests, usually with little variation in tree spacing or with forest gaps resulting from forest logging. There have been just a few studies to ascertain the effects of different intensities of thinning and pruning on interception loss in temperate forests (e.g. Teklehaimanot and Jarvis, 1991; Whitehead and Kelliher, 1991); as far as the authors are aware, there has been no previous investigation of the effects of logging practices on interception loss in tropical rainforest.

Many previous studies of the interception and evaporation of rainfall have been expressed in the form of empirical regression equations between interception loss (I) and gross rainfall (P_g). Such an equation or model can be used either to describe sets of storm data or, if it is assumed that there is only one rainfall event per day, to describe daily interception loss as a function of daily gross rainfall (Gash, 1979). This assumption may contribute a large part of the error in the simulated interception loss (Lloyd *et al.*, 1988; Hutjes *et al.*, 1990). The empirical regression model has also been criticised for taking no account of such variables as rainfall intensity and duration (e.g. Jackson, 1975) and drop size (Calder, 1996).

In contrast to the empirical regression approach, Rutter *et al.* (1971, 1975) developed a process-based model which uses inputs of rainfall and the meteorological variables controlling evaporation to calculate a running water balance of a forest canopy, including an estimate of the interception loss. This approach led to the development of an analytical model by Gash (1979), a numerical model by Whitehead and Kelliher (1991), and a stochastic model by Calder (1996). One computerised representation of the Rutter model, known as WATMOD, has been used successfully to investigate the effects of thinning (Whitehead and Kelliher, 1991) and tree spacing (Teklehaimanot and Jarvis, 1991) on interception loss of temperate forests. In this study, WATMOD and the *original* and *revised* versions of the analytical model by Gash *et al.* (1995) were tested and adapted to predict interception loss in both unlogged and logged-over tropical rainforest areas in Central Kalimantan, Indonesia.

Study site

The study site is located in the rainforest area of Central Kalimantan, Indonesia (1° 17′ 46″ S and 112° 22′ 42″ E) and lies in the headwaters of the Mentaya river in a hilly area with altitude ranging from 100 to 300 m above sea level. Slopes are variable but can be as steep as 35°. The climate of this region is determined primarily by the East and West monsoons and by movement of the intertropical convergence zone. The site is *ca* 250 km from the sea so

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that there is little oceanic influence on the climate (cf. Dykes, 1997, 25 km from the sea). The average monthly rainfall collected during the study period from November 1993 to June 1995 was 239 mm with annual rainfall of 3563 mm. At this research site, rainfall is seasonally distributed, with the maximum mean monthly rainfall of 305 mm occurring in November and the minimum of 154 mm in July. Most of the rain is convectional in origin with storm sizes that can exceed 100 mm on occasion, and intensities that can average 20 to 25 mm per hour for considerable periods.

The research area is a typical lowland dipterocarp rainforest, which contains a large number of species. Kartawinata *et al.* (1981) reported that a typical lowland rainforest of Kalimantan contains between 138 to 180 tree species per hectare. The average height of the topmost tree layer is between 40 to 55 m and there is an understorey that usually consists of shrubs of 2 to 8 m in height. The average depth of canopy is about 10 m. The density of trees (diameter at breast height (dbh) over 10 cm) in the unlogged forest is 581 trees per hectare, while in the logged forest the number of trees remaining with dbh over 10 cm is 278 trees per hectare. The basal areas per hectare in the unlogged and logged-over areas are 38.6 and 13.8 $m^2\ ha^{-1}$, respectively. Logging resulted in canopy gaps of about 38% of the total coverage per hectare and reduced the average height of the topmost tree layer to about 20 m.

Modelling

THE RUTTER MODEL

The Rutter model (Rutter *et al.*, 1971, 1975) calculates a running balance of the amount of water on the canopy and tree trunks, with inputs of hourly rainfall and the hourly meteorological variables of net radiation, windspeed, air temperature and water vapour pressure, that control evaporation. These meteorological variables are used to calculate the boundary layer conductance, g_a, and evaporation of intercepted rainfall when the canopy is saturated, E_c, using the Penman equation (see Monteith and Unsworth, 1990 pp 186–187) (Asdak *et al.*, 1998).

The model requires the following parameters: canopy storage capacity, S, which is the depth of water left on the canopy in conditions of zero evaporation when rain and throughfall have ceased; free throughfall coefficient, p, the proportion of rain which falls to the ground without striking the canopy; trunk water storage capacity, S_t; and the proportion of rain diverted to the trunks, p_t.

Components of the water balance model are rainfall rate, P_g; throughfall rate, T; stemflow rate, F; drainage rate D; and evaporation rates, E: ΣP_g, ΣT, ΣF, ΣD and ΣE are the summed total amounts of each of these component rates at a given time. The interception loss, I, in a storm, i.e. the water intercepted and evaporated between the time when rain begins to fall on a dry canopy and the end of the rainfall event when the canopy is again dry, is (Rutter *et al.*, 1971, 1975):

$$I = \Sigma E = \Sigma P_g - \Sigma T - \Sigma F. \qquad (1)$$

The water balance of the canopy for any period within a storm may then be written as:

$$(1 - p - p_t)\Sigma P_g = \Sigma E + \Sigma D \pm \Delta C\ ; \qquad (2)$$

where ΔC is the change in the amount of water stored on the canopy, C.

Similarly the water balance for the trunks (subscript t) may be written as:

$$p_t \Sigma P_g = \Sigma E_t + \Sigma F \pm \Delta C_t\,. \qquad (3)$$

It is assumed that there is a minimum quantity of water required to wet all the canopy surface. This corresponds to the canopy storage capacity, S, of Leyton *et al.* (1967). The amount of water stored on the canopy, C, may be larger or smaller than S. The rate of drainage from the canopy is calculated when $C > S$ by:

$$D = [(1 - p - p_t)P_g - E_c + \mathrm{d}(C - S)/\mathrm{d}t]. \qquad (4)$$

unless values are negative in which case D is assumed to be zero, and summed to give ΣD (Whitehead and Kelliher, 1991).

Another assumption made in the Rutter model is that a potential evaporation rate, E_{pot}, is obtained when all canopy surfaces are wet, i.e. when $C \geq S$. The model also assumes that when $C \leq S$ (indicating a partially wet canopy with no drainage), the rate of evaporation of any rainfall intercepted by the canopy is set equal to a proportion (C/S) of the wet canopy evaporation rate, E_{pot} (Shuttleworth, 1988; Lloyd *et al.*, 1988), so that: $E_c = E_{pot} \times C/S$, where E_c is the actual evaporation rate from the wet tree canopy. The validity of this assumption was confirmed by Teklehaimanot and Jarvis (1991). As the surface temperature of the canopy is usually not measured, E_{pot} is calculated from the Penman equation for a saturated canopy.

Initially, the value of C is set to zero, appropriate for a dry canopy. The change in canopy storage through time is obtained by rewriting Eqn. 3 so that it operates as a running water balance (Rutter *et al.*, 1971, 1975):

$$\mathrm{d}C/\mathrm{d}t = P_g(1 - p - p_t) - E(C/S) - D. \qquad (5)$$

Similarly for the trunks:

$$\mathrm{d}C_t/\mathrm{d}t = P_g p_t - E_t(C_t/S_t) - F. \qquad (6)$$

THE GASH MODEL

The Gash model is a storm-based simplification of the Rutter model in which the mean evaporation rate $\bar{E}$, and the mean rainfall rate, $\bar{R}$ can be used as daily values, if it is assumed that there is only one storm per day (Gash, 1979). Consequently, daily records of rainfall data and the forest structure are sufficient to provide the inputs to the model, in contrast to the hourly inputs required by the Rutter model. If one rainfall event per day is assumed, then $\bar{E}/\bar{R}$ ratios can be applied to other sites where only rainfall data are available. Lloyd *et al.* (1988) argued that such an assumption is reasonable in the humid tropics because of the short and intense storms.

The Gash model requires the same state variables of canopy and stand structures (S, p, S_t and p_t) in addition to the predicted ratio of the mean evaporation rate to the mean rainfall rate, $\bar{E}/\bar{R}$, for hours when rain is falling on a saturated canopy. The model considers rainfall to occur in a series of discrete storms each of which comprises a period of wetting-up, a period of saturation and a period of drying-out to empty the canopy storage. In previous applications of the Gash model in tropical rainforest areas (e.g. Rao, 1987; Lloyd *et al.*, 1988; Hutjes *et al.*, 1990), saturated canopy conditions were defined arbitrarily as occurring when the hourly rainfall exceeded 0.50 mm. For this experimental site, the rainfall necessary to maintain saturation was calculated as 0.30 mm, using the formula $\bar{E}_c/(1-p-p_t)$, where $\bar{E}_c$ is the mean evaporation rate for the saturated canopy, calculated using the Penman equation for different sets of micrometeorological and weather data (Gash, 1979). As a compromise, an hourly rainfall quantity of 0.40 mm was used to define a saturated condition. The average evaporation rate and rainfall rate onto a saturated canopy were then used to estimate the total evaporation for each day and month. Evaporation from the wet canopy was assumed to occur at a fixed rate (Pearce and Rowe, 1981) equal to that calculated using the Penman equation. It was also assumed that all rainfall on a day falls in a single storm, which may or may not be large enough to saturate the forest canopy.

Later (Gash *et al.*, 1995), it was realised that the original Gash model tends to overestimate the interception loss from sparse canopy forests because of the assumption that the evaporating area extends over the whole plot area, whereas in sparse forests the actual evaporating area is much reduced to the individual tree crowns. This led to a modification of the *original* model, which now requires an estimate of the evaporation per unit area of canopy rather than per unit ground area. Thus, the parameter c is introduced to represent the fractional projected crown area relative to the total ground area of the plot, so that $S_c = S/c$ (Gash *et al.*, 1995). With the *revised* model, more open canopy structures can be taken into account, making the model more suitable for calculating evaporation of intercepted water in sparse forest stands. The stemflow submodel has also been modified so that water is diverted to the trunks only after the canopy is saturated. For a more detailed elaboration of the *revised* analytical model, see Gash *et al.* (1995) and Valente *et al.* (1997).

Measurement principles

GROSS RAINFALL, NET RAINFALL AND INTERCEPTION LOSS

Gross rainfall was measured using three 0.2 mm tipping bucket raingauges (ARG100, Campbell Scientific (UK) Ltd., Loughborough, UK) and two simple raingauges, comprising a combination of an 18.3 cm diameter funnel and a 5 dm^3 plastic container. Two tipping bucket raingauges were erected in a large gap at a height of 15 m above the ground surface to reduce effects of disturbance caused by their surrounding environment. With this raingauge arrangement, the angle between the zenith and the top of the trees nearest the gauge was greater than 45°. One tipping bucket and two simple raingauges were installed 1 m above the ground for comparison.

In the unlogged plot, the error on the measured throughfall was *ca* 0.7% of P_g and, in the logged plot, errors ranged from 0.5 to 0.9% of P_g for the closed canopy, partial canopy and canopy gap, respectively (Asdak *et al.*, 1998).

Measurement of throughfall was based on the sampling scheme of Lloyd and Marques (1988). In the unlogged plot, throughfall was measured in a 100 × 40 m plot along five parallel transects of 100 m in length separated by 10 m. Each transect contained 101 sampling positions at 1 m intervals giving a total of 505 sampling positions. Fifty throughfall gauges were distributed equally in the five transects in which, for each transect, 10 throughfall gauges (each a combination of a 5 dm^3 plastic container and an 18.3 cm diameter funnel) were relocated randomly after every rainfall event. In the logged plot, a simple stratified sampling technique was utilised, based on a grid map of canopy cover. This map was produced for a 100 × 100 m plot in which canopy cover was assessed on a three point scale of closed canopy, partial canopy and canopy gap. The grid map of the canopy was produced by dividing up the 100 × 100 m plot into 10 × 10 m sections. Each section was further divided into a 5 × 5 m grid from which a gridded map of the canopy was drawn using the three point scale. The distribution of 55 throughfall gauges was based on the proportion of the area occupied by each canopy cover in the one hectare plot. Within these three different canopy cover conditions, the throughfall gauges were relocated randomly after every rainfall event.

Stemflow for large trees was collected using composite aluminum (0.5 mm thick) building material. For small trees, a half-section plastic tube was used as a collar to channel the stemflow water down to a collector. The sampling of trees for stemflow measurement was stratified by the size class of the trees in each plot. Thus, stemflow was measured on sixteen sample trees in five diameter classes scattered within the area of the transect lines in the unlogged plot and on twenty sample trees in four diameter classes in the logged plot. The data from the sample trees were integrated up to a stand basis (one hectare) making use of the frequency distribution of basal area in each plot. Overall interception loss was calculated from the difference between gross rainfall, ΣP_g, and net rainfall, ΣP_n (= throughfall + stemflow), i.e. $I = \Sigma P_g - \Sigma P_n$. The measurement error on I was *ca* 1% of P_g.

DERIVATION OF CANOPY AND TRUNK PARAMETERS

Canopy storage capacity

The canopy storage capacity, S, is the amount of water present on the canopy in conditions of zero evaporation, when throughfall has ceased (Gash, 1979). The value of S is usually determined by plotting throughfall against gross rainfall following the method of Leyton *et al.* (1967). An outer envelope {line of slope $(1 - p_t)$} is then drawn to enclose all the points above the inflection point and the intersection of the boundary line with the yaxis is read as the value of S. The inflection point is defined as the point above which throughfall is assumed to be linearly related to gross rainfall. It is usually identified by plotting the residuals of a regression of net on gross rainfall (e.g. Hutjes *et al.*, 1990). The value of S at saturation is given by the negative intercept on the throughfall axis. This method seems to be subjective both in recognition of the inflection corresponding to the point of canopy saturation, and in fitting the upper envelope to the scattered points. A more appropriate method of determining S in tropical rainforest is to use separate linear regressions of gross rainfall versus throughfall for individual small storms (Lloyd *et al.*, 1988). The value of S is given by the slope of the linear regression for zero throughfall. In this study, values of S were calculated by both the Leyton and the Lloyd methods for comparison.

Free throughfall coefficient

The free throughfall coefficient, p, is an estimate of that fraction of gross rainfall which arrives directly at the soil surface without striking any of the vegetation. In this study, p was estimated from gap fractions derived using hemispherical photography.

Hemispherical photos were taken at 1.2 m above the forest floor, above each tipping bucket raingauge in both the unlogged and logged plots, with a camera (Nikon FM2) and 8 mm fish-eye lens (Nikkor, Nikon Co., Japan) set in a self-levelling mount borne on a tripod. The camera was pointed upwards, and levelled right above each of the tipping bucket raingauges. The top of the image was oriented to the north. Colour slide film (Kodachrome 200 ISO, Kodak Co., USA) was used and, using an electronic spot light meter, the exposure was set at the second and third f-stops below the meter reading.

For each hemispherical photograph, the gap fraction was obtained using Optimas image analysis software (Optimas Co., Washington, USA) for the five annuli between 0 and 5 degrees from the zenith. These first five zenith angles were chosen as representative, and hence the free throughfall coefficient, p, was based on the assumption that rainfall in this tropical region is mainly vertical. The average gap fraction was calculated as the average of these five values, weighted by annulus area, i.e.

$$\text{average gap fraction} = \sum_{i}^{n} G_i A_i / A_5 \qquad (7)$$

where G_i is the gap fraction and A_i the area of the ith annulus (n = 5) and A_5 is the total area of the five annuli. The mean gap fraction over the one hectare unlogged plot was derived from 10 hemispherical photographs and over the logged plot from 15 hemispherical photographs. Gap fractions estimated in the unlogged and logged plots were equated to the values of p following Dolman (1987) and Hutjes *et al.* (1990).

Tree trunk parameters

A similar method to that used for estimating canopy storage capacity was adopted for evaluating the trunk storage capacity, S_t, and the proportion of rainfall which is diverted onto the trunks, p_t. Instead of the conventional method used to estimate S_t, separate linear regressions of stemflow versus gross rainfall for each sample tree were calculated (Lloyd *et al.*, 1988). For the estimation of S_t and p_t, gross rainfall and stemflow data were extracted for all rainfall events larger than 1.5 mm (which represents canopy saturation) and were regressed against gross rainfall. The intercepts of the regressions of stemflow versus individual gross rainfall gave estimates of S_t and the gradients gave estimates of p_t.

Canopy drainage parameters

The rate of drainage from the canopy, D, when $C > S$, was determined using Eqn. 4. The value of D was assumed to be zero when $C \leq S$. When the amount of rainfall diverted to the canopy during a period Δt was larger than S, D was taken as equal to the amount of water on the canopy $[(1 - p - p_t)\, P_g - E_c]\Delta t$, that exceeds the remaining water storage capacity $(S - C_{j-1})$ (Whitehead and Kelliher, 1991).

ESTIMATION OF BOUNDARY LAYER CONDUCTANCE

The boundary layer conductance, g_a, is the most important feature of a forest canopy determining the evaporation of intercepted water (Rutter *et al.*, 1975; Teklehaimanot and Jarvis, 1991). In this study, g_a was calculated indirectly by inverting the Penman equation, given the values for evaporation of intercepted water and the micrometeorological variables measured above the forest canopy. Thus, the new parameter c is taken into account implicitly in the derivation of g_a.

Logging activities reduced g_a from 0.3 m s^{-1} in the unlogged plot to 0.2 m s^{-1} in the logged plot. This reduction of g_a is attributable to the reduction of tree basal area, and hence leaf area, per unit ground area from 38.6 to 13.8 m^2 ha^{-1}. This is similar to the finding of Teklehaimanot and Jarvis (1991) that g_a per unit ground area declined from 0.17 to 0.07 m s^{-1} as the density of trees decreased from 2600 to 180 per hectare.

The model assumption for WATMOD used in this study follows Teklehaimanot and Jarvis (1991) which allows g_a to change with canopy cover. Similarly, the measured value of c was incorporated in the Penman equation prior to its inversion, so that the values of g_a obtained were appropriate to the degree of cover.

Results and discussion

Table 1 shows the comparison of model input parameters obtained according to the procedures described in the previous sections from November 1993 to April 1994 in the unlogged plot and from June 1994 to June 1995 in the logged plot. In the logged plot, there were separate calculations of canopy and stand parameters for the areas with different canopy cover resulting from logging activities.

The spatial and temporal variability of rainfall and canopy structure in a tropical rainforest is large and this results in a wide range of rainfall interception loss. In this experiment, interception loss decreased as the area of canopy was reduced. The reduction in canopy area was caused mainly by reduction in the number of trees following logging. The logging affected the local water balance through reduction of the amount of rainfall interception from 11% of gross rainfall in the unlogged forest to 6% in the logged forest (Asdak *et al.*, 1998).

The predictions of throughfall and interception loss for each individual storm are shown in Figs. 1, 2 and 3 for WATMOD, the *original* and the *revised* Gash models, respectively. The number of storm events used in this study varied according to the availability of the meteorological data and other required model inputs. Data analysis and Fig. 1 indicate the comparison of relationships between observed and predicted throughfall and interception loss using WATMOD in both the unlogged and logged plots. The discrepancies between cumulative observed and predicted throughfall and interception loss, expressed as a percentage of observed values are comparable to similar interception studies (e.g. Lloyd *et al.*, 1988). In the unlogged plot, WATMOD underestimates the interception loss slightly. Interception loss is estimated to be 88 mm, or 9.8% of gross rainfall, an underestimate of 6 mm or 6% of the measured interception loss (94 mm). This is in good agreement with similar studies in the Amazonian forest by Lloyd *et al.* (1988) and by Ubarana (1996), where the difference between observed and predicted interception loss was within 5% of the measured value; in the logged plot, taking no account of canopy cover divisions, the model overestimates interception loss by 10% of the measured value. When WATMOD was applied separately to the three different canopy cover areas, the discrepancies between cumulative observed and predicted interception loss were increased as the canopy cover decreased to 9%, 12% and 19% for the closed canopy, partial canopy and canopy gap, respectively.

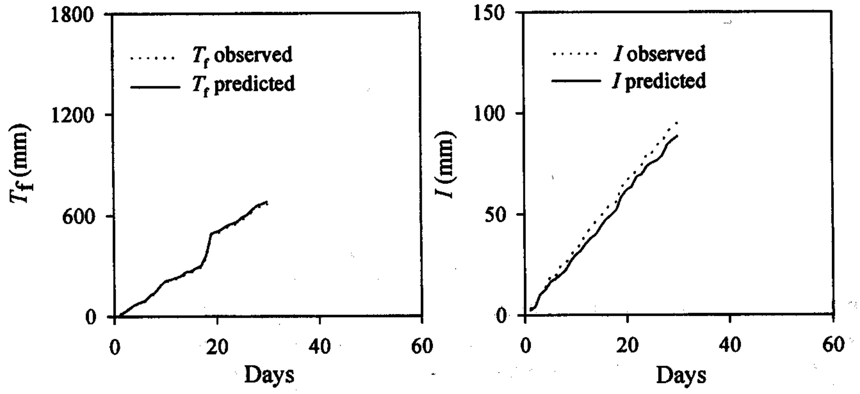
Figures 2 and 3 indicate that, in the unlogged plot, the *original* Gash model's performance is as good as the *revised* one; the differences between cumulative observed and predicted throughfall and interception loss for both models are 3 and 14% of the observed values, respectively. In the logged plot, taking no account of canopy cover divisions, the *revised* Gash model is better than that of the *original* Gash model. The differences between cumulative observed and predicted interception losses are 14 and 65%, respectively. When the one hectare plot was divided into three canopy cover areas, neither the *revised* Gash model nor the *original* one performed adequately.

Table 1. The derived stand and canopy parameters in the unlogged and logged plots: canopy storage capacity per unit ground area, S; free throughfall coefficient, p; trunk storage capacity, S_t; proportion of rainfall diverted to the trunks, p_t; canopy storage capacity per unit crown area, S_c $(= S/c)$; mean rainfall rate, $\bar{R}$; evaporation rate from the saturated canopy, $\bar{E}_c$; proportion of crown area relative to the total area, $\bar{E}_c$; and atmospheric boundary layer conductance, g_a.

Parameters	Units	Unlogged plot	Logged plot			
			Closed canopy	Partial canopy	Canopy gap	Overall[1]
S	mm	1.30	1.21	1.14	0.69	1.00
p	–	0.10	0.13	0.15	0.64	0.30
S_t	mm	0.01	0.01	0.01	0.001	0.001
p_t	–	0.001	0.001	0.001	0.0001	0.0001
S_c	mm	1.30	1.21	2.28	3.45	2.30
c	–	1.00	1.00	0.50	0.20	0.60
$\bar{R}$	mm h^{-1}	5.50	5.60	5.60	5.60	5.60
$\bar{E}$–	mm h^{-1}	0.30	0.30	0.15	0.06	0.17
g_a	m s^{-1}	0.31	0.29	0.18	0.13	0.20

[1] weighted average of the three different canopy cover areas

a) The unlogged plot



b) The logged plot (no canopy cover divisions)

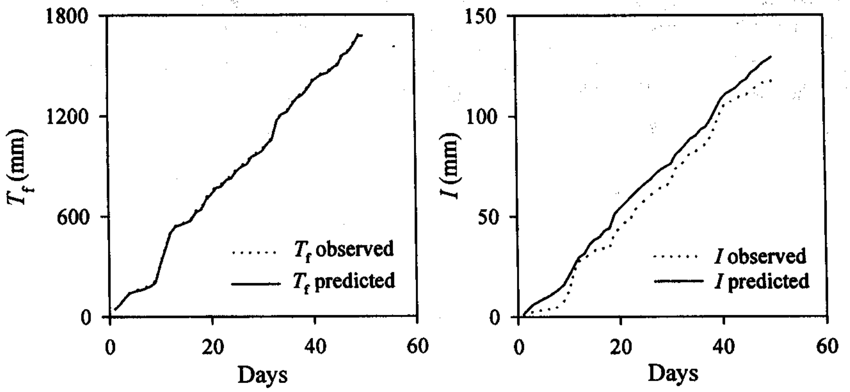


Fig. 1. *The relationship between observed and WATMOD predicted throughfall, T_f, and interception loss, I, in the unlogged and logged plots for individual storms (30 storms in the unlogged plot and 50 storms in the logged plot).*

Figure 2b indicates that, in the logged forest, the *original* Gash model overestimates the interception loss significantly. Interception loss is estimated to be 195 mm, or 7.9% of total precipitation, an overestimation of 77 mm or 65% of the measured interception loss (118 mm). This is consistent with the suspected weakness in the formulation of the *original* version of Gash's model for sparse forests (Gash *et al.*, 1995; Valente *et al.*, 1997). When the *revised* version of the model is applied to the logged forest, interception loss is estimated to be 135 mm, or 5.5% of the gross rainfall, an overestimate of 17 mm or 14% of the measured interception loss. This improvement seems to be attributable to the reformulation by which evaporation of the whole plot area is reduced in proportion to the relative size of the area covered by the tree crowns.

Figure 3, for the unlogged and logged plots, compares the cumulative observed and the predicted throughfall and interception loss using the *revised* Gash model. The discrepancies between observed and predicted throughfall and interception losses in the unlogged plot are 3 and 15% of the measured values, respectively. The model's performance improved slightly when applied in the logged plot; here the differences between cumulative observed and predicted throughfall and interception losses were 0.4 and 14%, respectively. These comparable estimates of the total interception losses in both the unlogged and logged forest areas are in line with the conclusions of Valente *et al.* (1997), that the *revised* Gash model is likely to predict interception loss from closed canopies as well as the *original* model, considering that when c tends to unity the formulation of the *revised* version approaches that of the *original* version (cf. Figs 2a and 3a), while for sparse canopies it will give better predictions than the *original* version (cf. Figs 2b, 3b).

To assess the agreement between observed and predicted throughfall and interception losses, several statistical tests were performed (Mulder, 1983). The relationships between observed and model-predicted throughfall were tested by regression analysis; the coefficients of determination, r^2, are all 0.99 (Table 2). Observed and predicted means of throughfall were also compared using the standard errors of the estimates obtained from each regression equation. The differences were not significant at $p = 0.01$. The agreements between observed and predicted totals were also assessed by calculating the ratio of predicted to observed losses and then testing the hypothesis that the

Table 2. Tests of the agreement between observed and predicted throughfall, T_f, in the unlogged and logged plots. SE is the standard error of estimate of the observed and predicted values; n is the number of observations; r^2 is the coefficient of determination; is the mean ratio of predicted to observed throughfall.

Model	Mean T_f obs.	Mean T_f pred.	n	SE	r^2	x/y
The unlogged plot						
WATMOD	25.4	25.9	30	0.5	0.99	0.98
Gash (revised)	33.3	34.3	40	0.6	0.99	0.99
The logged plot						
WATMOD	33.7	33.5	50	0.14	0.99	0.97
Gash (revised)	33.5	33.4	70	0.12	0.99	0.99

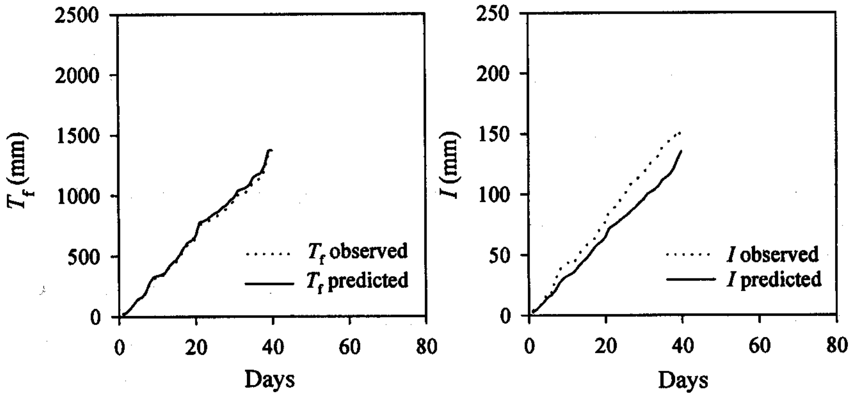
mean value of that ratio did not differ from 1.0. The results indicated no significant differences of the mean ratios from 1.0 at $p = 0.01$ (Table 2). These tests suggest that all three models simulate total throughfall over a long-period adequately.

Table 3 shows the statistical tests on the agreement between observed and predicted interception losses in the unlogged and logged plots; the regression between observed and predicted interception loss shows that model performances for interception loss are not as good as for throughfall. The values of the coefficient of determination vary from 0.27 to 0.72. However, the comparison of observed and predicted means of interception loss indicates that the differences were not significant at $p = 0.05$. The agreement between observed and predicted total interception loss indicated no significant differences of the mean ratios from 1.0, which suggests that the models predicted total interception loss adequately over a long period.

In contrast to the excellent relationship between observed and predicted throughfall as shown in this experiment and elsewhere (e.g. Ubarana, 1996), the relationship between observed and predicted interception losses is likely to be worse because interception loss is the smallest component in the water balance equation, and absolute errors in measuring gross rainfall and throughfall are additive.

The sensitivity analyses showed that prediction of interception loss by WATMOD is quite sensitive to variation

a) The unlogged plot



b) The logged plot (no canopy cover divisions)

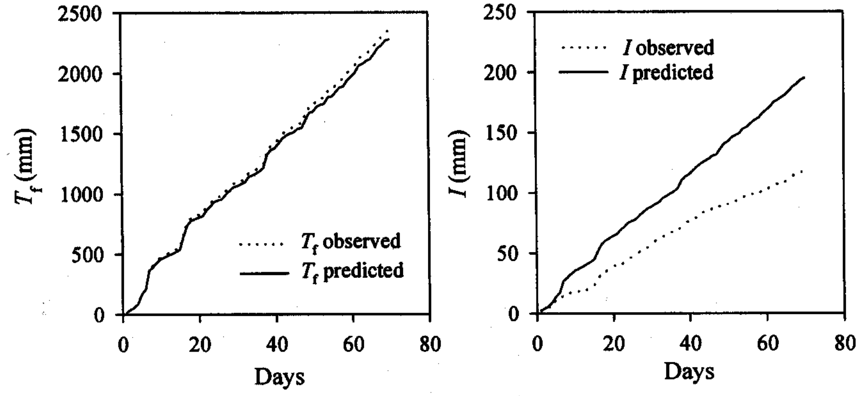
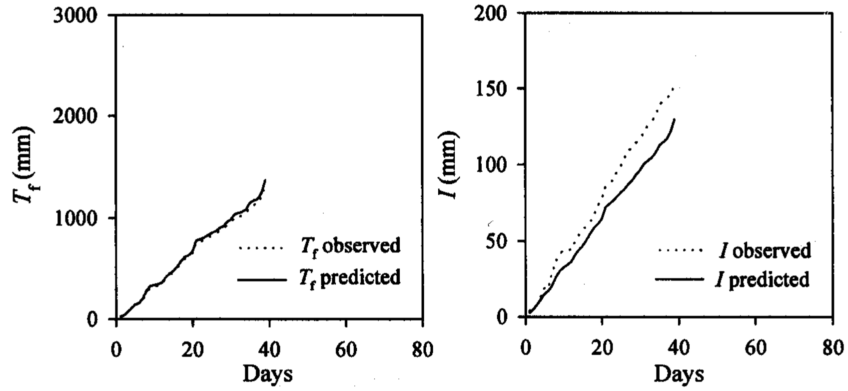


Fig. 2. *The relationship between observed and the original Gash predicted throughfall, T_f, and interception loss, I, in the unlogged and logged plots for individual storms (40 storms in the unlogged plot and 70 storms in the logged plot).*

a) The unlogged plot



b) The logged plot (no canopy cover divisions)

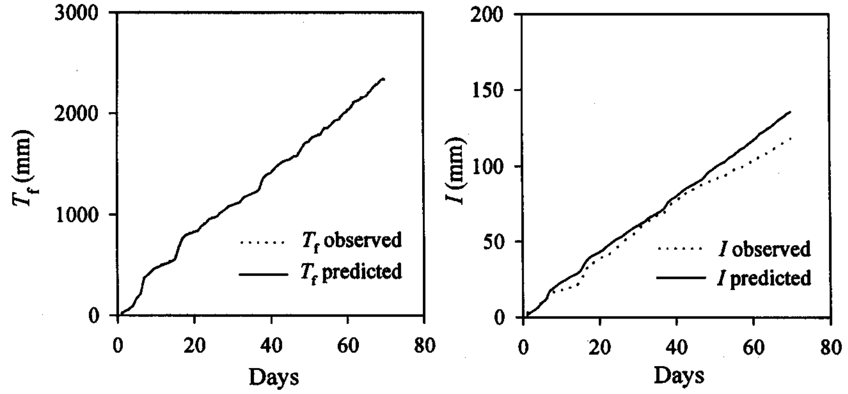


Fig. 3. *The relationship between observed and the revised Gash predicted throughfall, T_f, and interception loss, I, in the unlogged and logged plots for individual storms (40 storms in the unlogged plot and 70 storms in the logged plot).*

in the canopy storage capacity, S, whereas it is relatively insensitive to the free throughfall coefficient, p, within the range tested. A change of ±30% in S led to a change in interception loss of 15 to 17%. This is in line with other interception modelling studies (e.g. Hutjes *et al.*, 1990; Valente *et al.*, 1997) and suggest that special care should be taken in the estimation of S because of its importance in the estimation of interception. The model is also moderately sensitive to changes in the boundary layer conductance, g_a, especially in the unlogged forest, where ±30% changes in g_a led to changes in interception loss of 6 to 8%. In the logged plot, the same changes in g_a produced changes in interception loss of only 2 to 4%. The significant influence of S and, to a smaller extent, of g_a indicate the predominant role of canopy and aerodynamic properties in determining interception loss during and shortly after rainfall.

Table 3. Tests of the agreement between observed and predicted interception loss, I, in the unlogged and logged plots. SE is the standard error of estimate of observed and predicted values; n is the number of observation; r^2 is the coefficient of determination; x/y is the mean ratio of predicted to observed interception loss.

Model	Mean I obs.	Mean I pred.	n	SE	r^2	x/y
The unlogged plot						
WATMOD	3.3	3.0	30	0.36	0.55	0.96
Gash (revised)	3.9	3.4	40	0.65	0.27	0.79
The logged plot						
WATMOD	2.3	2.5	50	0.18	0.72	1.04
Gash (revised)	1.6	1.9	70	0.11	0.38	0.96

The total interception loss predicted by the Gash models is very sensitive to changes in mean rainfall rate, $\bar{R}$, and mean evaporation rate, $\bar{E}$, in both the unlogged and logged plots, where ±30% changes in $\bar{R}$ and $\bar{E}$ led to changes in interception loss of 15 and 24%, respectively. Similar model sensitivity to changes in $\bar{R}$ and $\bar{E}$ has also been reported (Hutjes *et al.*, 1990; Navar and Bryan 1994; Valente *et al.*, 1997).

It was calculated that 55% of total evaporation in the unlogged plot was lost during saturated conditions, 40% during the drying-out phase, 2% during the wetting-up phase, and the remaining 3% evaporated during small storms insufficient to saturate the canopy. For the logged plot, the corresponding figures are 47% for saturated conditions, 51% for the drying-out phase, 0.5% for the wetting-up phase, and 1.5% for small storms. As in other similar studies (e.g. Bruijnzeel and Wiersum, 1987; Lloyd *et al.*, 1988), evaporation of intercepted water occurs mainly during canopy saturated and drying-out conditions.

Conclusions

The experimental results show that interception loss is reduced from 11% of total gross rainfall to 6% following logging (Asdak *et al.*, 1998) because of the reduction in number of trees from 581 in the unlogged plot to 278 per hectare (i.e. 52%) in the logged plot with a reduction of basal area from 38.6 to 13.8 m^2 ha^{-1} (64%).

In general, both the WATMOD model and the Gash models may be strong enough conceptually to be applicable to this situation in tropical humid rainforests. The model comparison with data suggests that both models perform adequately over a long period. With both models, the differences between cumulative observed and predicted interception losses, expressed as a percentage of the measured interception loss, ranged from 6 to 14% for both the unlogged and logged plots. None the less, the models were apparently not adequate for predicting interception loss on a storm by storm basis. However, errors of measurement contribute to this assessment and these results suggest that, before the models can be improved any further, it is necessary to increase the accuracy of the observations of gross and net rainfall in tropical rainforest environments.

WATMOD performed better than the Gash models in both the unlogged and logged plots. In the unlogged plot, WATMOD estimated interception loss better than the Gash models by a factor of 8% of the measured value. In the logged plot, WATMOD estimated interception loss better than the *original* Gash model by factor of 55% and better than the *revised* Gash model by factor of 4%. In the unlogged plot, the *original* Gash model's performance was as good as the *revised* one (both models underestimated interception loss by 14%). In the logged plot, taking no account of canopy cover divisions, the *revised* Gash model was much better than the *original* (an overestimate of 14 and 65%, respectively). When the one hectare plot was divided into three canopy cover sub-areas, model performances of WATMOD, the *revised* Gash model and the *original* model were less good. It seems that interception loss in the logged plot is modelled adequately by treating the whole plot as a single unit for analysis, rather than by dividing it into three different canopy cover sub-areas.

This experiment has also demonstrated that the most important parameters in the interception loss processes are the canopy storage capacity, the boundary layer conductance, the mean rainfall rate and the mean evaporation rate, as they dictate the rate of water loss from tropical rainforest canopies. Consequently, special attention should be given to the derivation of S, g_a, $\bar{E}$, and $\bar{R}$ in any future similar studies to resolve the inconsistency in modelling interception loss using Rutter-type models, particularly over the short time periods of individual storms.

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