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Evaporation and storage of intercepted rain analysed by comparing two models applied to a boreal forest

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Abstract

Rainfall and throughfall were measured during the summer of 1995. Rainfall interception is often simulated by a version of the well-known Rutter-Gash analytical model. In this study this model was compared to a model based on an exponential saturation equation. The concept of the 'minimum method' for deriving canopy storage capacity and free throughfall coefficient by the Leyton-analysis, is compared to the concept of maximum storage capacity by reversing the models. Measured evaporation rate during rain events was found to be lower than simulated by the Penman equation using different known formulations for aerodynamic resistance. The concept of a high internal canopy resistance and decoupling of the canopy from the atmosphere should be analysed further in order to explain low evaporation during rainfall.

Keywords: Rainfall interception; Aerodynamic resistance; Coniferous forests; Penman equation; Canopy layer resistance

1. Introduction

Simulation of rainfall interception depends on correct estimation of the evaporation rate (E) and the saturated storage capacity of the canopy (S). All types of interception model use both of these parameters (e.g. Rutter et al., 1971; Gash, 1979; Mulder, 1985; Calder, 1986). Estimation of the evaporation rate by the Penman equation, using the aerodynamic resistance for momentum ($r_{a,M}$), may overestimate evaporation (Lankreijer et al., 1993; Gash et al., 1995; Klaassen et al., 1996b). By contrast, S is underestimated in many cases (Bouten et al., 1991; Klaassen et al., 1996b) and the often acceptable simulation of rainfall interception can be considered as the result of a cancellation of errors.

To improve simulation of interception, Lankreijer et al. (1993) reduced the simulated evaporation rate by assuming the roughness length for vapour to be equal to that for heat ($z_{0,H}$), but much smaller than that for momentum ($z_{0,M}$). Gash et al. (1995) reduced the simulated evaporation from sparse forests and increased the value for S by formulating those values in relation to the area of canopy cover, rather than to the unit ground area. To simulate interception and

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actual water storage in the canopy, Bouten et al. (1996) used a Rutter-based, multi-layered canopy model. They applied an empirical parameter to scale the evaporation rate of each layer, and showed that the ratio of evaporation efficiency vs. storage capacity tends to increase with height in the upper part of the canopy. Klaassen et al. (1996b) used the same measurements of actual water storage during rainfall showers (Bouten et al., 1991), and showed that the evaporation rate must be very low (0.077 mm h^{-1}) and the storage capacity higher (up to 5–10 times), than had been analysed in many other studies. They applied the exponential saturation approach (Merriam, 1960; Calder, 1986) to describe the high water storage capacity, instead of the waterbox-threshold approach of Rutter et al. (1971) and Gash (1979).

For the Norunda forest site in the NOPEX project (Halldin et al., 1999), throughfall and rainfall data were analysed by Grelle et al. (1997). For the site a value for S of 1.5 mm was found by the Leyton-analysis (Leyton et al., 1967) from the data of 1995. However, an indication of a higher value for S of 3.3 mm was found by comparing water balance components measured over a short period of 4 days.

Not only is the actual size of the storage capacity a part of the discussion of rainfall interception, but also the method of derivation of S and the free throughfall coefficient (p) from throughfall measurements. The last is the fraction of rainfall that reaches the ground without striking the canopy. The value p can be found by least-squares linear regression on the interception versus rainfall data of small showers or is estimated from the ratio of open areas in the canopy to the total area which can be measured *in situ* (Hendriks et al., 1990). The so-called minimum method or the Leyton analysis (Leyton et al., 1967) is often applied to derive the storage capacity (Mulder, 1985; Hutjes et al., 1990; Hall et al., 1992; Lankreijer et al., 1993). The method is elegant because it is easy to apply to daily rainfall and throughfall measurements, but is, however, sensitive to areal variability in the measurements. A more statistically sound method of deriving canopy characteristics is therefore needed.

In this study, two interception models were applied and compared; the Gash model (Gash, 1979; Gash et al., 1995) and the exponential model, originally proposed by Merriam (1960). The concepts of maximum storage capacity, lower evaporation rate and lower aerodynamic conductance are tested on a coniferous forest site. The study aimed at deriving the required model parameters from daily values of throughfall and precipitation and hourly meteorological measurements–without extensive or complex measurements of canopy characteristics since those data are usually available for most forest sites. Single storm data might be better for deriving storage capacities and the throughfall coefficient, but this raises the question of how to distinguish single storm events. To distinguish additional storms within a day for analysis of storage capacity, one needs to know when the canopy is dry.

2. Materials and method

2.1. Site and stands

A detailed description of the site and the measurements are given by Grelle et al. (1997) and Lundberg et al. (1996). The measurements took place at the central NOPEX site (60°5′N, 17°29′E, alt. 45 m), located about 30 km north of Uppsala, Sweden. Throughfall was measured in 50- and 100-year-old stands. The 50-year-old stand had a practically closed canopy, with few openings. Maximum stand height was 23 m. Projected leaf area index (LAI) was about 4–5. The stand consists of Norway spruce (*Picea abies* (L.) Karst.), with 66% of the stand basal area, Scots pine (*Pinus sylvestris* (L.)), with 33% of the basal area, and a few specimens of birch (*Betula spec.*). The 100-year-old stand was more open and had a LAI of 3–4. This site was mainly composed of pine (80%), with spruce (19%) and birch (1%) in the minority. Maximum tree height was 28 m.

2.2. Data

Throughfall (T) was measured by weighing throughfall gauges (In Situ, Ockelbo, Sweden), five in each stand (Lundberg et al., 1999). Each gauge consists of two 5 m long and 0.1 m wide V-shaped troughs. Precipitation (P) was recorded with a weighing gauge (In Situ), in a nearby clearing, situated ca. 300 m north of the old stand (Siebert et al., 1999). Precipitation measurements were performed with a time resolution of 1 min. Throughfall was measured with a high resolution of 6 measurements min^{-1}, but filtered to 1 min records. Stemflow was not measured, as it was considered to be negligible. Analysis by Lundberg et al. (1996) showed that the number of troughs was sufficient, although computation of the areal mean throughfall from troughs can introduce an error of 20% at the 99% confidence level.

Meteorological measurements were available with a 30 min time resolution. In this study, the measurements were summed and averaged to hourly values for both stands together.

Evaporation rate and meteorological variables were measured at a tower located ca. 20 m from the south-east edge of the 100-year-old stand and 350 m from the 50-year-old stand (Grelle and Lindroth, 1999). Vapour pressure deficit and temperature were measured at 28 m and net radiation at 68 m height on the tower. Wind speed was taken from 70 m, as the 28 m sensor was considered to be too close to the canopy. Soil heat flux was determined from heat flux plates. Evaporation rate was measured by eddy correlation at 70 m height. The eddy correlation system consists of a three-dimensional SOLENT 1012R2 sonic anemometer (Gill Instruments, Lymington, UK), a fast platinum resistance thermometer, a LI-6262 closed path infrared gas analyser (LI-COR, Lincoln, Nebraska), and inclination sensors (HL-Planar, Dortmund, Germany). The system operates with a sampling rate of 10 Hz and fluxes are calculated on the basis of 30 min average times and the raw data are stored as well. For a more detailed description of the eddy correlation system and error analysis, see Grelle and Lindroth (1996), Grelle et al. (1999), (this issue). The system, which has now been running for 4 years, showed good results in terms of energy closure. Both fluxes and energy closure during rainfall perods showed no discrepancies and were in the same range as those found during dry periods. We concluded from this that the system worked well during rainfall conditions.

Data for simulating rainfall interception were available for the period of 22 May–30 October, 1995, except for 5 June–2 July.

2.3. Model description

2.3.1. Gash's analytical model

The analytical model described by Gash (1979) is a simplification of the Rutter model (Rutter et al., 1971). The version described here is that adapted for sparse canopies by relating E and S to the fraction of canopy cover c, which can be calculated from 1-p (Gash et al., 1995; Valente et al., 1997). When the precipitation is too small to saturate the canopy, interception is given by $I = c\ P$, and canopy drip is neglected.

The amount of rainfall necessary to saturate the canopy (P'_g) is given by:

$$P'_g = -\frac{\bar{R}}{\bar{E}_c} S_c \ln\left(1 - \frac{\bar{E}_c}{\bar{R}}\right) \tag{1}$$

where S_c is the corrected storage capacity, equal to S/c (mm), $\bar{E}_c$ the corrected average evaporation rate, equal to $\bar{E} \cdot c$ (mm h^{-1}), and, $\bar{R}$ the average rainfall intensity (mm h^{-1}) during the shower. Note that $\bar{E}$ is the average evaporation rate over the hours of rainfall on one day. A shower large enough to saturate the canopy will give a total interception of:

$$I = c\left[P'_g + \frac{\bar{E}_c}{\bar{R}}(P - P'_g)\right] \tag{2}$$

2.3.2. Exponential model

The exponential model was proposed by Merriam (1960). Aston (1979) and Calder (1986) also used the exponential saturation of the canopy to describe interception. The model of Merriam is given by:

$$I = S_{\max}\{1 - \exp(-yP)\} + \left(\frac{\bar{E}}{\bar{R}}\right)P \tag{3}$$

The exponential function includes the gradual wetting of the canopy and describes throughfall by canopy drip. When $-y$ is replaced by $-k/S_{\max}$, the value of k is comparable with the cover parameter c (Calder, 1986). In the model, the first part describes the amount of water stored in the canopy, while the term $(\bar{E}/\bar{R})P$ gives evaporation during the shower. Following Rutter et al. (1971), the model is slightly adapted to correct for the evaporation rate from partly wet canopies, when E is calculated as the potential evaporation rate:

$$I = S_{\max}\{1 - \exp(-yP)\} + \left(\frac{\bar{E}}{\bar{R}}\right)\left(\frac{C}{S_{\max}}\right)P \tag{4}$$

where C is the actual water content of the canopy. In cases where the measured evaporation rate during rainfall ($\bar{E}_m$) is used to simulate the interception, Eq. (3) was applied.

2.4. Method

The canopy parameters p and S are derived from daily totals of precipitation and throughfall (T) or interception (I). The free throughfall coefficient p is found from linear regression of I versus P for small storms ($P < 1.5$ mm). For the determination of S, three different methods were used. (i) The minimum method, or Leyton analysis, calculates the storage capacity (S_{min}) by defining an upper envelope of the P versus T graph, assuming P to be large enough to saturate the canopy. In this study, the upper envelope was taken as the line found by linear regression on three selected points with the lowest interception. The total precipitation was assumed to saturate the canopy when it was larger then 1.5 mm. The value of 1.5 is taken from the I versus P graph, as the point where scatter in the graph started, following the assumption of the waterbox concept; canopy drips appears when the canopy is saturated. The mean method (ii) was also used, where S_{mean} is found by linear regression on all points of I versus P, and P was again large enough to saturate the canopy. The third method (iii) is the determination of S_{max}, found by fitting of the function $I = S_{max}(1\text{-}\exp(-yP))$, as proposed by Klaassen et al. (1996a, b).

Assuming correct measurements of rainfall, throughfall and evaporation during the storms, the models were used in reverse mode to calculate storage capacity S_{min} and S_{max}. The values found were compared with those found by the minimum, mean and fitting methods. To obtain a value for S close to the actual value, the absolute value of evaporation during the storm must be low. Therefore the totals of rainfall and interception were selected on average values of available energy larger than 0 and smaller than $30\ \mathrm{W\ m^{-2}}$ and relative humidity (h) larger than 90%, over the hours with rainfall. Available energy was calculated from net radiation (R_n) minus soil heat flux (G).

S is calculated by inverse modelling of the Gash model for precipitations totals larger than 1.5 mm, assuming completely wet canopies, and is given by

$$S = \left[I - \frac{((\bar{E}/\bar{R})P)}{c - \bar{E}/\bar{R}}\right] \frac{1}{-(\bar{R}/\bar{E})\ln(1-(\bar{E}/\bar{R}\cdot c))} \tag{5}$$

S_c is then given by S/c.

S_{max} is calculated from the days where $I > (\bar{E}/R)\cdot P$ by:

$$S_{max} = \frac{I - (\overline{E}/\overline{R})\cdot P}{1 - \exp(-yP)} \tag{6}$$

The value of $y = 0.21 \pm 0.07$ for the derivation of S_{max} was approximated by fitting $I = S_{max}(1 - \exp(-yP))$ on all points ($n = 50$, $r^2 = 0.47$).

Model runs using measured E_m were compared with the simulation runs using evaporation rate values estimated by the Penman equation (E_P). Use of the Penman equation implies that stomatal resistance is zero, which is clearly an approximation of reality by the model. Three different methods were applied by calculating different values for the aerodynamic resistance (r_a) (or its reciprocal value, aerodynamic conductance g_a). The first method for calculating E_P used the measured wind speed (u) and friction velocity: (u_*) in

$$r_{a,M} = \left(\frac{u}{u_*}\right)^2 \tag{7}$$

Here the roughness length for momentum and for heat are assumed to be equal. The method will be denoted as Method A.

In the second method (Method B) it was assumed that the roughness length for heat ($z_{0,H}$) was smaller than that for momentum (Lankreijer et al., 1993), and the relation proposed by Garrett and Francey (1978) is used. The aerodynamic resistance for latent heat was given by:

$$r_{a,H} = \frac{1}{k^2 u}\ln\left\{\frac{z-d}{z_{0,M}}\right\}\ln\left\{\frac{z-d}{z_{0,H}}\right\} \tag{8}$$

where k is the von Kármán constant (=0.4), u is the wind speed ($\mathrm{m\ s^{-1}}$), z is measuring height (m), $z_{0,M}$ is the roughness length for momentum (m) and d is zero plane displacement (m) and $z_{0,H} = z_{0,M}e^{-2}$. However, in this function the correction for stability is neglected. To correct for some extent for stability the function was replaced by:

$$r_{a,H} = \ln\frac{\{z-d/z_{0,H}\}}{k\cdot u_*} \tag{9}$$

The third value for E_P is the value used by Gash et al. (1995), sparse canopy model (denoted as Gash95).

Here E_P was calculated by using Method A, but multiplied by the fractional cover c.

The values for z, d, h_c and $z_{0,M}$ were taken from Grelle (pers. comm.) and were 70, 18, 25.5 and 2.0 m, respectively. The value for d was assumed to be 75% of canopy height and $z_{0,M}$ was derived from measured u_* in neutral conditions.

3. Results

3.1. Interception data analysis and Leyton's analysis

The simulated period had 305 h of rainfall over 50 days and the total measured precipitation was 179 mm. Measured throughfall was 133 mm, resulting in 46 mm interception (25.8% of precipitation).

The variability in the amount of rainfall interception increases as usual with rainfall (Fig. 1). The increase in variability with precipitation is partly explained by differences in evaporation rate during rain, by the rainfall intensities and the duration of the storms. Figs. 2–6 show conditions during rainfall periods. The average E_m over hours with rain was very low. Only during small storms was it somewhat higher than the average 0.04 mm h^{-1} (Fig. 2). The low evaporation rate during rainfall, measured at 70 m above the canopy, was confirmed by the low values of available energy ($R_n - G$) and high relative humidity (h), measured at 68 m and 28 m, respectively (Figs. 3 and 4).

During rainfall the atmosphere is very often neutral to stable (Fig. 5). The stability is given by the parameter $\zeta = (z - d)/L$. Here is L the Monin–Obhukov length and with $\zeta < -0.03$ the atmosphere is considered unstable, when $-0.03 < \zeta < 0.03$ as neutral and

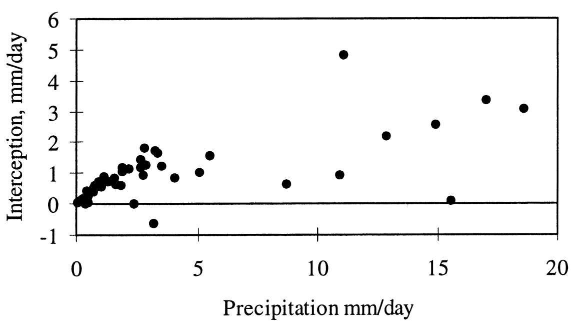

Fig. 1. Daily totals of rainfall interception I versus precipitation P.

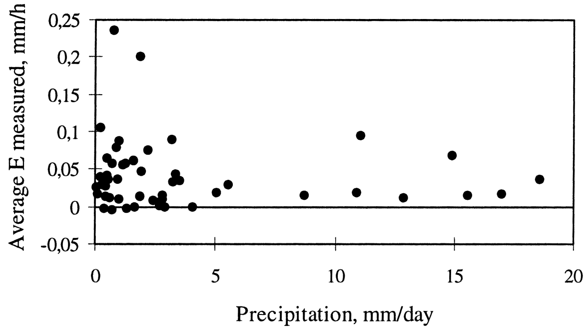

Fig. 2. Average evaporation rate E_m during the rainfall shower versus the amount of rainfall P. E_m over all hours was 0.04 mm h^{-1}.

with $\zeta > 0.03$ as stable (Kruijt, 1994). Based on the average values during rainfall, 5 rainfall events happened during unstable conditions, 3 during neutral and 42 during stable conditions.

During rainfall, evaporation was limited by low energy and high humidity. Furthermore, the sensible heat flux showed a downward direction (Fig. 6). The negative heat flux implies that energy for evaporation is taken from the air above the canopy, but the evaporation rate is still very low. Without this supply, evaporation would be even lower.

The free throughfall coefficient, derived by linear regression from the small storms ($P < 1.5$ mm, $n = 23$), was 0.4. In Fig. 7, the three methods of deriving the storage capacity are shown. The 'Leyton analysis' or minimum method, based on linear regression through 3 selected points in the P versus I graph, resulted in a S_{min} of 1.69 mm. The points with lowest interception were selected. However, the selection of points is critical. When other points with low inter-

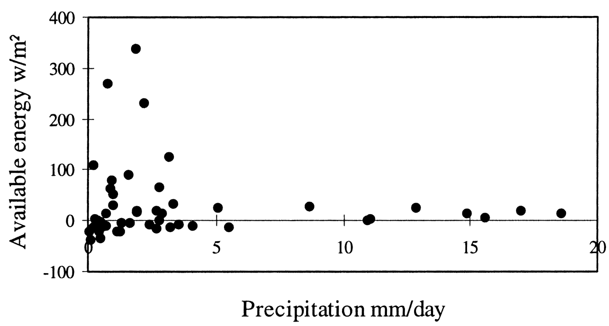

Fig. 3. Average available energy during the showers versus the amount of rainfall.

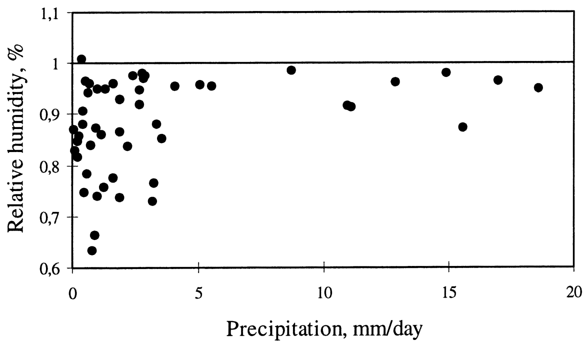

Fig. 4. Average relative humidity versus the amount of rainfall.

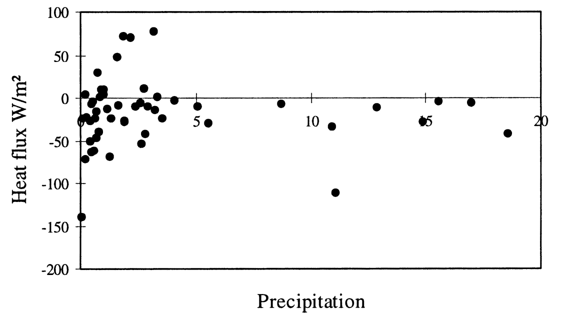

Fig. 6. Average measured sensible heat flux during rainfall hours versus the amount of rainfall.

ception were selected, the analysis would result in a negative, and unknown S. The 3 selected points are shown as '*' in Fig. 7. The '▲' points in the figure are measurements where an error due to areal variability in throughfall was assumed, and usually neglected in the analysis of S_{min}. However, this means that the same variability can occur in the other points, and shows the sensitivity of the minimum method to this areal variability in the data. In the determination of $S_{max,}$ those points were taken into account.

The mean method, by linear regression of P versus I on storms larger than 1.5 mm, given by the sloping broken line, resulted in a S_{mean} of 0.70 ($\pm$0.58) mm, which is much lower. The value of 1.5 mm may in fact be too low, as it is the point at which canopy drip starts, but not the point at which the canopy is saturated. The calculated amount of rainfall required to saturate the canopy (P'_g) is usually higher. The last method, fitting the exponential function on all data, as proposed by Klaassen et al. (1996a, b), resulted in a S_{max} of 2.39 ($\pm$0.75) mm (Fig. 7).

3.2. Reverse modelling

Reverse modelling by application of the Gash model Eq. (5) resulted in an average value for S of 1.77 mm, where the values ranged from 0.5 up to 4.1 mm ($n = 11$). S_c for the sparse canopy model is then equal to 2.77 mm. The reverse exponential model Eq. (6), resulted in an average S_{max} of 2.48 mm, with a range of 0.6 up to 4.1 mm ($n = 12$). The values found for canopy storage were compared with average windspeed and friction velocity during rainfall, but did not show any relationship. However, the number of observations was too small for any conclusions to be drawn.

3.3. Model application

Application of the measured E_m at 70 m, combined with the found S of 1.77, 2.77 and 2.48 mm for the original Gash, Gash95 and exponential models respectively, resulted in overestimation of interception by the models. Fig. 8 shows the results for Gash95 and the

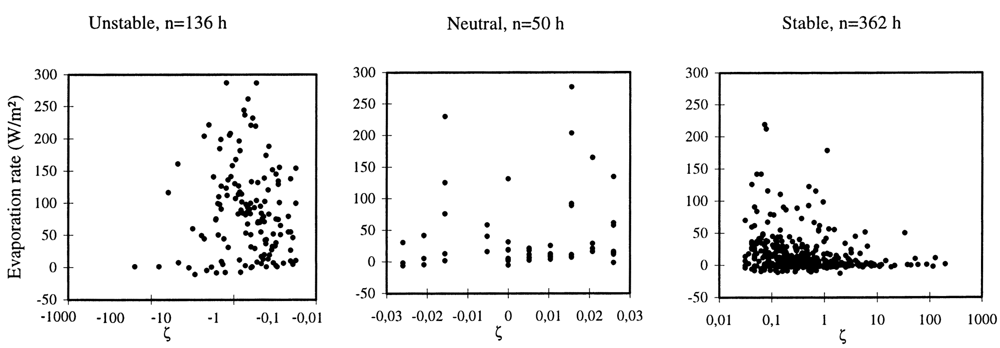

Fig. 5. Average stability factor during rainfall hours versus the evaporation rate. Note the different scales of the x-axis.

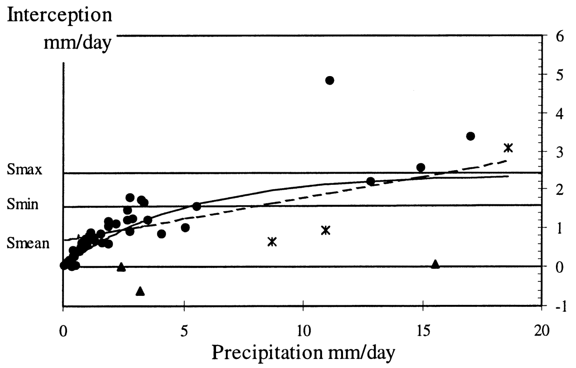

Fig. 7. Derivation of the storage capacity from interception and rainfall data by minimum, mean and fitting method.

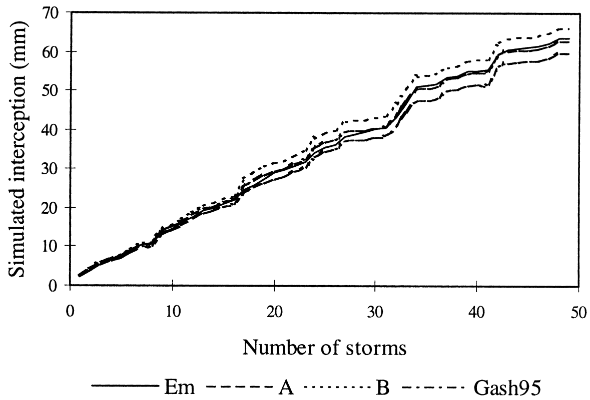

Fig. 9. Comparison of simulated interception by the exponential model using simulated E with different methods for calculating r_a.

exponential model. The original Gash model resulted in a total interception of 57.1 mm, an overestimate of measured interception by 23.6%. The adapted Gash95 model resulted in 55.6 mm, a surplus of 20.3%. The models show good agreement for the very small storms, but strongly overestimate interception when P is close to the calculated saturation point (where $P \approx P'_g$) of the canopy. The exponential model shows an overestimate of 37.4% with an total interception of 63.5 mm. For the last model, the error is more evenly spread over the whole range of rainfall amounts.

The measured and simulated evaporation rates can only be compared directly for storms large enough to saturate the canopy. Conditions during such storms, with low available energy, low humidity deficit and cooling of the canopy, make the application of the Penman equation sensitive to errors in the measurement of net radiation and derivation of available energy. On the other hand, during short storms, when the abovementioned driving forces for the evaporation are available, the Penman equation can be applied more easily. However, evaporation measured in the tower is then a mixture of water fluxes from wet leaves and transpiration, and includes about 15% forest floor evaporation (Grelle et al., 1997). Validation of simulated versus measured evaporation under those conditions requires additional values for water storage, storage capacity and leaf wetness, what makes comparison difficult. Therefore, it was chosen to compare the interception simulation results by the exponential model, applying different estimations of E_P by using the three methods for calculation of r_a (Fig. 9). The Gash95 methods for calculating E_P resulted in an underestimate compared to the use of measured E_m, while the methods A (Eq. (7)) resulted in an over-

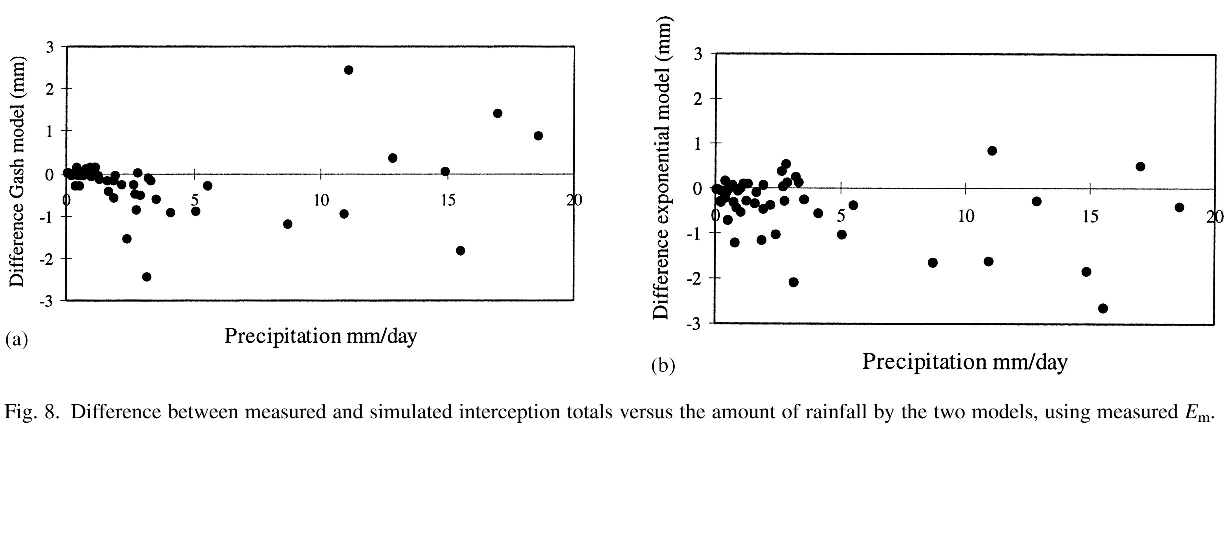

Fig. 8. Difference between measured and simulated interception totals versus the amount of rainfall by the two models, using measured E_m.

estimate. Method B (Eq. (9)) gave good simulation results compared to those using measured E.

4. Discussion

4.1. Throughfall and precipitation data

Lundberg et al. (1996) studied different methods of rainfall interception measurement, and concluded that none of the easily applicable methods gives a good estimate of throughfall. Derivation of an areal average value of throughfall from the applied measurement method showed an error of 20%, which is acceptable, considering the difficulty of measuring throughfall. An error with the same order of magnitude might be possible for the rainfall measurements, which as in many other studies, are measured at a single point, assuming equal distribution of rainfall. The effect of rainfall distribution on interception has, however, rarely been studied until now (Klaassen et al., 1996a).

4.2. The storage capacity and free throughfall coefficient

Values of S_{min} and S_{max} found by reverse modelling and by the minimum and fitting methods, respectively, are almost equal, also in the range of values. The value for S_{max} was higher.

The large overestimate of simulated interception by the models, using measured E_m, may indicate that storage capacity was overestimated. However, measured E_m from the canopy was overestimated by about 15%, because forest floor evaporation was included in the measurement (Grelle et al., 1997). On the other hand, the overestimate and the range found by inverse modelling indicate that a constant value for S used in both models is questionable, and the average S may be higher than that usually given by the minimum method. The S_{max} found by fitting the exponential function gives a lower value than that found by Grelle et al. (1997). This may be due to the use of daily interception data instead of half-hourly data. Using a high time resolution, the point with maximum storage can be found directly (Grelle et al., 1997). The value found by fitting is an average value; the real physical value may be closer to 4.1 mm. Storage capacity is assumed to be constant during a single storm, but is probably variable between the storms. The concept of a variable storage capacity was also suggested by Calder et al., (1996), Calder (1986, 1996) described a stochastic model for rainfall interception. They based their description on an exponential function for canopy saturation, and showed that actual storage is not constant with rainfall depth, but depends on drop-size and intensity of the rain. Storage capacity tends to increase with smaller drops and lower rainfall rate. A variable value for S is further suggested by Klaassen et al. (1996a).

Determination of the storage capacity from daily rainfall and throughfall is questionable. Alltough the fitting procedure gives acceptable results compared to the minimum method, the method is still strongly dependent on the limited number of saturating storms. The process of wetting and reaching a given storage can be considered as an non-linear process, depending on several environmental and canopy-specific factors, which cannot be derived from daily totals of throughfall and precipitation.

Estimation of p from small storms is acceptable, as long as the number of small storms is large enough and it can be assumed that canopy drip is negligible. The Rutter-type model assumes that canopy drip starts when the canopy is saturated, although canopy drip starts before real saturation. This will lead to underestimation of S due to inclusion of storms which do not saturate the canopy.

4.3. The evaporation rate

The absence of driving forces, such as high net radiation and low air humidity, together with stable and neutral conditions during rainfall, makes a clear analysis of correct evaporation simulation difficult. The prevailing stable and neutral conditions during rainfall result in suppressed fluxes. M. Mölder (1997, pers. comm.) concluded from flux-profile measurements that roughness lengths for heat and momentum do not differ for unstable conditions above two times the canopy height. However, the stability correction for heat and momentum does differ just above the forest, being equal at higher levels, and at 70 m the difference is no longer important. Equal roughness lengths can be assumed to be valid for stable as well as for neutral conditions. Although Method B gave the best results, the overestimate of the calculated evaporation rate E_P is not explained by applying a lower roughness length for heat ($z_{0,H}$).

It may be expected that inside the canopy the vapour pressure deficit during rain is lower than measured outside. This may explain overestimation of actual evaporation.

Another explanation for the low measured evaporation rate might be a high internal canopy resistance, or decoupling and poor mixing of the canopy with the atmosphere during rainfall. A 'decoupled' canopy is suggested by Grelle et al. (1999) (this issue) to explain the delay in evapotranspiration found at the same location, during dry hours in the morning. This effect was found not only from measurements at 70 m, but also at 35 m (inside the boundary layer). This suggests that the concept of a high internal canopy resistance, as described by Shuttleworth and Wallage (1985), needs further analysis.

Both models overestimate simulated interception, when E_m and derived S values were used. The overestimates of the interception of storms around the saturation point (when P is close to P'_g) by the Gash model can be explained by the use of the water box concept. When the shower is too small to saturate the canopy ($P < P'_g$), estimated I is independent of E and linear with rainfall, and canopy drip is neglected. However, canopy drip appears before saturation of the canopy, and therefore I is not linear with P.

As stated above, the use of the Penman equation is difficult, since during rainfall only small driving forces are present. In this context, the Gash model simulates the interception of very small storms better than the exponential model, for the simple reason that the evaporation rate is not used in estimation and as long as the canopy drip is small. However, further analysis of a variable storage capacity is needed. It might be assumed that the actual, physical, maximum storage capacity is never reached, because of evaporation during the storm (Klaassen, 1996, pers. comm.). This suggests that derivation of the actual maximum storage capacity from daily rainfall-throughfall data is not possible.

5. Conclusions

The evaporation rate during storms is very low. The low level of available energy and vapour pressure deficit results in limited driving forces for evaporation during rainfall, especially during long showers. The small driving forces for evaporation, and the derivation of energy from cooling of the canopy make the results sensitive to errors when the Penman equation is used. Errors in measuring available energy during such conditions may lead to large errors in the simulation; the reliability of radiation sensors during rainfall needs to be evaluated. An additional resistance in the canopy, and the existence of an internal canopy layer, should be tested to explain the low E. Application of the Penman equation to simulate the evaporation rate requires good description of this possibly high internal layer resistance of the canopy. In addition, the stability correction for aerodynamic resistance above forests cannot be neglected, as is usually assumed.

From this study, it could not be confirmed whether the concepts fractional cover (Gash et al., 1995) or the difference in roughness length for momentum and heat (Lankreijer et al., 1993) do explain the very low measured E.

Determination of S from daily total values of interception and rainfall is uncertain and may be regarded as impossible from daily values, since the number of actually saturating storms is too small and real saturation is probably never reached. The use of the exponential fit results in a more realistic and higher estimate of storage capacity. An advantage of the method is that it is based on more measurements. Reverse modelling showed that the storage capacity was higher than has been applied in other studies, and that it is also a variable value rather than a constant.

Use of measured evaporation rate and estimated S and p resulted in an overestimation by the Gash model. This can partly be explained by neglect of canopy drip during small storms.

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