

Monitoring and modelling canopy water storage amounts in support of atmospheric deposition studies

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Abstract

Canopy water storage amounts were measured with a newly developed measuring system based on the attenuation of a 10.26 GHz microwave signal. Every 5 min, vertical scans were made, over a period of 9 months. A physically based multi-layer interception model with empirical parameters was calibrated using a non-linear optimization technique. The calibrated model appeared to be capable of explaining up to 92% of the measured variance of water storage amounts for an independent validation period when using on-site measurements of meteorological variables. The performance decreased only slightly to 89% when other input sets were used for this period. These were necessary to extrapolate the results to longer time series required for evaluating canopy resistances in the study of deposition of airborne pollutants (Vermetten et al., *Proc. 5th IPSASEP Conf., Vol. 3, 1992*). The resemblance between measured throughfall amounts and simulated results and the plausibility of the model parameters, although they were optimized without setting any limits, enhances confidence in the model results.

1. Introduction

The presence of free water within the canopy has become accepted as an important ecological factor that influences chemical, physical and biological processes taking place on leaf surfaces. Van Breemen et al. (1982) measured throughfall amounts of $(\text{NH}_4)_2\text{SO}_4$ which were three times as high as with deposition by rainfall. The strong correlation between NH_4^+ and SO_4^{2-} concentrations in individual samples and the

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ratio of 2:1 on a molar basis suggest some mechanism of co-deposition. NH_3 is assumed to increase the pH of water layers which are present in the canopy layer, thus stimulating the dissolution of SO_4^{2-} . The effect of co-deposition in water layers was demonstrated in wind-tunnel experiments by Heeres and Adema (1989). In forest canopies, this mechanism makes water act as a sink for NH_3 and SO_2 . To study the mechanisms of deposition of airborne pollutants onto partially wet canopies, estimates of the temporal and vertical dynamics of canopy water storage amounts are first needed. This study of forest canopy wetness has been carried out in support of an interdisciplinary research project on Douglas fir vitality in relation to environmental factors and field investigations into acidifying atmospheric deposition in particular (Evers et al., 1987).

During the past few decades, rainfall interception studies in forests were carried out mainly to assess the amount of water that is available for plant transpiration. Most experiments were based on the difference between gross precipitation, usually measured in nearby clearings, and the net precipitation, which is sampled on the forest floor. The limited costs required to make the measurements have resulted in impressive data sets on the reduction of water inputs as a result of the evaporation of intercepted water (Calder and Newson, 1979). Models were developed for predicting the evaporative losses to the atmosphere and throughfall to the soil. Dynamic simulation models, developed in that context, can be used to model the canopy water storage (Rutter et al., 1971; Calder, 1977; Sellers and Lockwood, 1981; Massman, 1983). These models calculate the canopy water balance on the basis of precipitation, drainage, and evaporation rates, the last two being dependent upon the actual canopy water storage. These models, however, were validated primarily with total throughfall amounts measured at long time intervals, and scarce evaporation measurements. The existing parametrizations, therefore, are not well validated for the purpose of predicting canopy water storage dynamics, thus creating the need for measurements.

None of the existing measuring techniques, such as grid sensors (Barthakur, 1985), measurement of the deflection of water-laden branches (Hancock and Crowther, 1979), and gamma-ray attenuation measurements (Calder and Wright, 1986), could meet the requirements for a quantitative, unattended monitoring system with high vertical and temporal resolution. Therefore, a new system based on the measurement of microwave attenuation was developed (Bouten et al., 1991b) and was used for a 9 month period.

A model simulating canopy water storage dynamics was needed to extrapolate the measurements to periods for which no storage measurements were available. Many numerical interception models have been presented before, either single-layer models (Rutter et al., 1971; Halldin et al., 1979; Massman, 1983) or multi-layer models (Calder, 1977; Sellers and Lockwood, 1981). This paper focuses on the parametrization of an interception model that can be used for reliable extrapolation of a measured time series of canopy water amounts. A multi-layer model was used, as it could not be assumed in advance that the vertical distribution of the canopy water storage is irrelevant to the deposition of airborne pollutants. A physically based model with as few calibration parameters as possible was assumed to give the best results. After calibration and validation the model was used to extrapolate the measured time series

over a period of 2 years. If the reliability of the predicted water storage amounts is found to be satisfactory, the extrapolated simulation time series can be used as input data in the study of deposition rates (Vermetten et al., 1992).

2. Site description

The study was carried out in a 2.5 ha Douglas fir plantation near Garderen, The Netherlands. The firs were 27 years old and had an average height of about 18 m. Their mean stem diameter at breast height was 21 cm. The stand itself was rather homogeneous, with a density of 785 trees ha⁻¹. The canopy was well closed; most living biomass was located between a height of 11 and 14 m. The leaf area index varied from about 8 m² m⁻² in spring to about 11 m² m⁻² in early summer. The aerodynamic roughness length appeared to be dependent on wind direction, ranging from 1.5 m in a SSE direction to 3.2 in a WNW direction (Bosveld, 1991). The stand was surrounded by stands of Scots pine, oak, beech, larch and Douglas fir, and a small clearing at the north. The mean annual precipitation amounts to 800 mm. In the period of study, hardly any snow was present and only very few nights with frost occurred.

3. Methods

3.1. Microwave transmission

A measuring system for monitoring canopy water storage amounts was developed, based on the attenuation of a 10.26 GHz microwave signal by water. A microwave transmitter and receiver were each mounted in a hoist, attached to separate towers standing 15 m apart. Every 5 min a complete vertical scan was carried out during which 20 measurements per second were performed. For every vertical metre of displacement, the mean attenuation, based on more than 100 measurements, and its standard deviation, were calculated on-line and stored on floppy disk. At some height above the tree tops the hoists were stopped for 10 s to perform a non-attenuated reference measurement. From April to December, the system was operational for about 88% of the total time. A complete description of the design has been given by Bouten et al. (1991b).

A calibration was obtained for the conversion of the measured attenuation values to canopy water storage amounts. For this purpose, canopy water balances were calculated using measured precipitation and throughfall rates on nights with low wind speeds (less than 2 m s⁻¹) and low evaporation rates (less than 0.06 mm h⁻¹). The vertically integrated attenuation increment compared with dry conditions was found to be highly correlated ($r^2 = 0.986$) with these calculated water storage amounts. The tangent of this regression line is used to convert attenuation measurements to canopy water storage (Bouten and Bosveld, 1991).

To evaluate water storage amounts, the reproducibility of measurements must be

known. It is not possible to estimate their reproducibility under wet conditions, as water storage amounts change very rapidly within the time needed to perform single scans. Therefore, the reproducibilities of the non-attenuated reference measurements and dry scans were evaluated. Four canopy layers were distinguished: Layer 1, 14–16 m with sunlit tenuous tree tops; Layer 2, 11–14 m, an intermediate level; Layer 3, 8–11 m with shaded branches in the closed part of the canopy; Layer 4, 0–8 m with dead branches.

3.2. The model

A numerical multi-layer interception model with the simplicity of the Rutter model (Rutter et al., 1971) and with four model parameters per layer, was used. For each layer i , the water balance is calculated according to (Fig. 1):

$$\frac{\Delta S_i}{\Delta t} = I_i - D_i - E_i \quad (1)$$

where S (mm) is water storage in the layer, t (day) is time, D (mm day⁻¹) is drainage rate and E (mm day⁻¹) is evaporation rate. The water interception rate, I (mm day⁻¹), is calculated with

$$I_i = a_i(P_{i-1} + D_{i-1}) \quad (2)$$

where P_i (mm day⁻¹) is rainfall which bypasses the i th layer, P_0 is gross rainfall, and $D_0 = 0$. The interception efficiency parameter, a_i , could be interpreted as the layer cover fraction, although its value may depend on branch geometry, needle surface wetting properties, and the kinetic energy of the raindrops intercepted by the layer. The drainage rate is calculated as

$$D_i = b_i(S_i - c_i) \text{ for } S_i \geq c_i \quad (3)$$

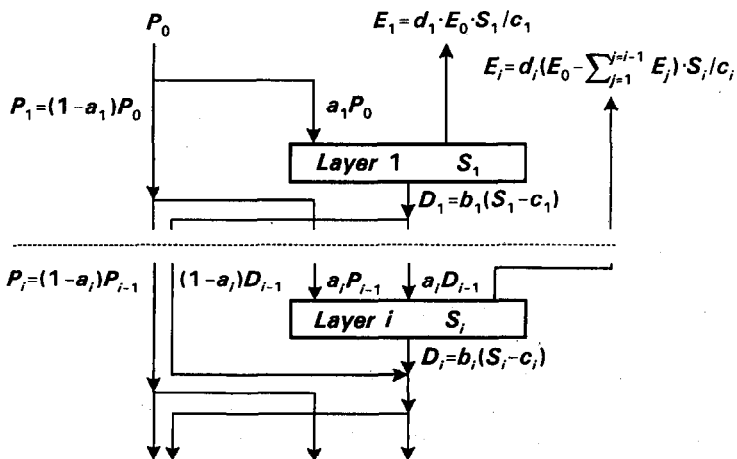


Fig. 1. Outline of the multi-layer interception model for the top layer and one other layer.

and

$$D_i = 0 \text{ for } S_i < c_i \quad (4)$$

where c_i (mm) is the layer storage capacity, and b_i (day^{-1}) is an empirical drainage parameter. Although several models use an exponential function for the drainage rate, a linear threshold model as used by Calder (1977) was chosen for simplicity.

Finally, the evaporation rate from a layer is calculated as

$$E_i = d_i \left(E_o - \sum_{j=1}^{i-1} E_j \right) S_i / c_i \quad (5)$$

where d_i is the empirical evaporation efficiency, and the total potential evaporation, E_o , is determined by (Monteith, 1965)

$$E_o = \frac{\Delta R + \rho c_p \delta e / (r_a + r_b)}{\lambda(\Delta + \gamma)} 86400 \quad (6)$$

where λ (J kg^{-1}) is the latent heat of vaporization, Δ (Pa K^{-1}) is the rate of change of the saturated vapour pressure with respect to air temperature, R (W m^{-2}) is the net radiation, ρ (kg m^{-3}) is the air density, c_p ($\text{J kg}^{-1} \text{K}^{-1}$) is the specific heat of air, δe (Pa) is the vapour pressure deficit, γ (Pa K^{-1}) is the so-called psychrometric constant, r_a (s m^{-1}) is the aerodynamic resistance, r_b (s m^{-1}) is the excess resistance and 86,400 stands for the conversion from seconds to days.

The model parameters a_i , b_i , c_i and d_i were optimized on the basis of least sums of squares of residuals between the simulated canopy water storage amounts and the measured amounts. For this, the simulation model was linked to an optimization program based on the Simplex non-linear optimization algorithm (Nelder and Mead, 1965). Simplex optimization is rather slow. Sometimes more than 100 iterations were needed to find the optimal parameter set. However, the advantage of the method is that it is not sensitive to local minima and that it does not require the derivatives of a function; even non-continuous functions can be handled. As such, it is a very suitable technique for optimizing parameters in dynamic simulation models.

3.3. Meteorological measurements

Rainfall was measured every 3 min in a clearing at a distance of about 0.8 km, using a 400 cm^2 funnel with a resolution of 0.05 mm of rainfall. Additionally, two 480 cm^2 funnels were attached to the top of one of the towers at the research site at a height of 6 m above the tree tops from August to December. The funnels were mounted on high-resolution capacitive water-level recorders with a resolution of 0.02 mm of rainfall. Measurements were carried out every 2.5 min, being synchronized with the microwave attenuation measurements. A comparison of rainfall results at the clearing and the forest stand showed no systematic deviations, although some events were only recorded at one of the sites. For some days when rainfall recording did not function properly, data were available from another research location at a distance of 15 km.

To calculate the potential evaporation (E_o), three different data sets were available:

Data Set 1 (Bosveld, 1991) was used to calibrate and validate the interception model. It was measured in a 36 m tower at the research site and was available for almost the entire period of the canopy water storage measurements. The measurements included profiles of temperature, vapour pressure, and wind speed, as well as net radiation and sensible and latent heat flux densities at 30 m. The aerodynamic resistance (r_a) was calculated as the ratio between the wind speed and the squared friction velocity. The friction velocity was directly deduced from eddy correlation measurements. From a comparison of wind speed and temperature profiles, F.C. Bosveld (personal communication, 1992) found that the excess resistance r_b tended to be negligible compared with the aerodynamic resistance (median value 15.5 s m^{-1}).

Data Set 2 (Vermetten et al., 1990) was used to extrapolate the measured time series of canopy water storage data to cover the entire research period of 2 years. It was also measured at the research location in a 30 m tower and was available for the full period of 1988–1989, except for some gaps owing to instrument problems. The measurements included net radiation, and profiles of temperature, relative humidity, and wind speed. The aerodynamic resistance was calculated from the wind speed at 30 m and the roughness length as a function of wind direction. Corrections were made for temperature stability. A comparison of results of Data Sets 1 and 2 showed that the best agreement was obtained if the excess resistance was taken to be ten times smaller than the values calculated using the formula of Hicks et al. (1985):

$$r_b = \frac{2}{kU_*} \left(\frac{\text{Sc}}{\text{Pr}} \right)^{2/3} \quad (7)$$

where k is the von Kármán constant, U_* is the friction velocity, and Sc and Pr are the Schmidt and Prandtl numbers, respectively.

Data Set 3 was used to fill the gaps in the time series of Data Set 2. It consists of hourly values from a standard meteorological station in Deelen, 25 km east of the research site. The measurements in Deelen were carried out above grassland. For overlapping periods of Data Sets 2 and 3 linear regression functions were calculated for wind speed, air temperature, relative humidity and the relation between net and global radiation. Almost all variables showed high correlations (r^2 above 0.92) with very small deviations from the 1:1 line. Only wind speed showed relatively poor correlation ($r^2 = 0.71$). However, very few gaps occurred in the time series for wind speed.

3.4. Model calibration and validation

To calibrate the model, several rainfall events were selected throughout the year and were put into an artificial sequence of 12 days in total. The events were selected for relatively extreme rainfall intensities and amounts, for low and high evaporative demands both at night and during the day, and for low and high wind velocities. In parameter optimization, mutual interference between parameters is to be prevented as much as possible. As there is only one-way (top-down) interference between parameters, the optimization process was simplified by optimizing the parameters one

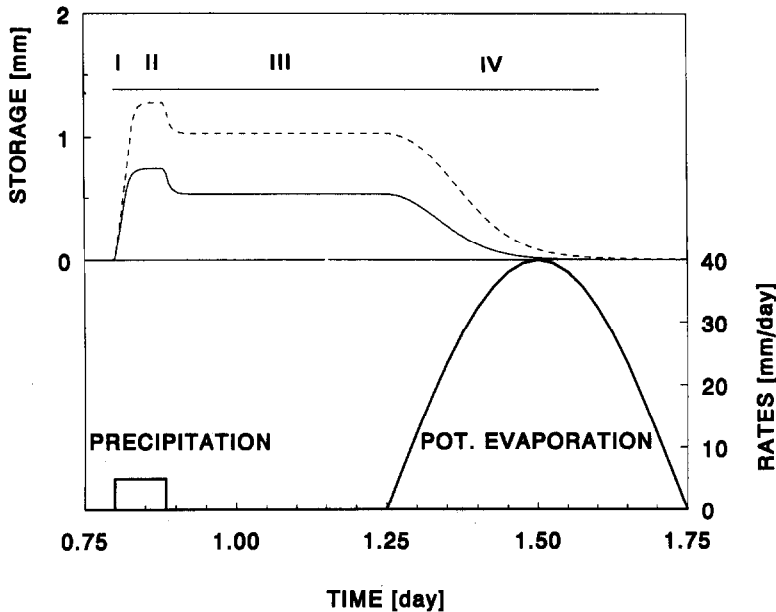


Fig. 2. Simulated canopy water storage dynamics of Layer 2 (continuous line) and Layer 3 (dashed line) for artificial boundary conditions (I, wetting stage; II, drainage stage; III, steady stage; IV, evaporation stage).

layer at a time, starting with the top layer. Moreover, the parameters of one layer are almost independent of one another. They are sensitive to different stages of the wetting and drying cycles (see Fig. 2). The interception efficiency, a_i , determines the rate of storage increase of a layer in the wetting stage (Stage I). The drainage parameter, b_i , is only relevant at high storage (Stage II), whereas intercepted water drains to a steady value, c_i , during nights with no rainfall and negligible evaporation (Stage III). Finally, the evaporation efficiency, d_i , determines the slope of the drying curve (Stage IV).

To test whether one characteristic parameter set can be used throughout the year, the total 12 day calibration period was again split up into the five original individual periods. For each period, each parameter was again optimized one at a time. If trends could be established for parameters, their use would probably improve the performance of the model.

To test the model performance in predicting measured water storage amounts, once again different rainy days were selected and were put into an artificial sequence of 13 days. For this period, the model was run using the calibrated parameter set.

4. Results and discussion

4.1. Reproducibility

The 10 s mean gain of the reference measurements above the forest canopy appeared to be very stable over the year. The standard deviation of the gain equals

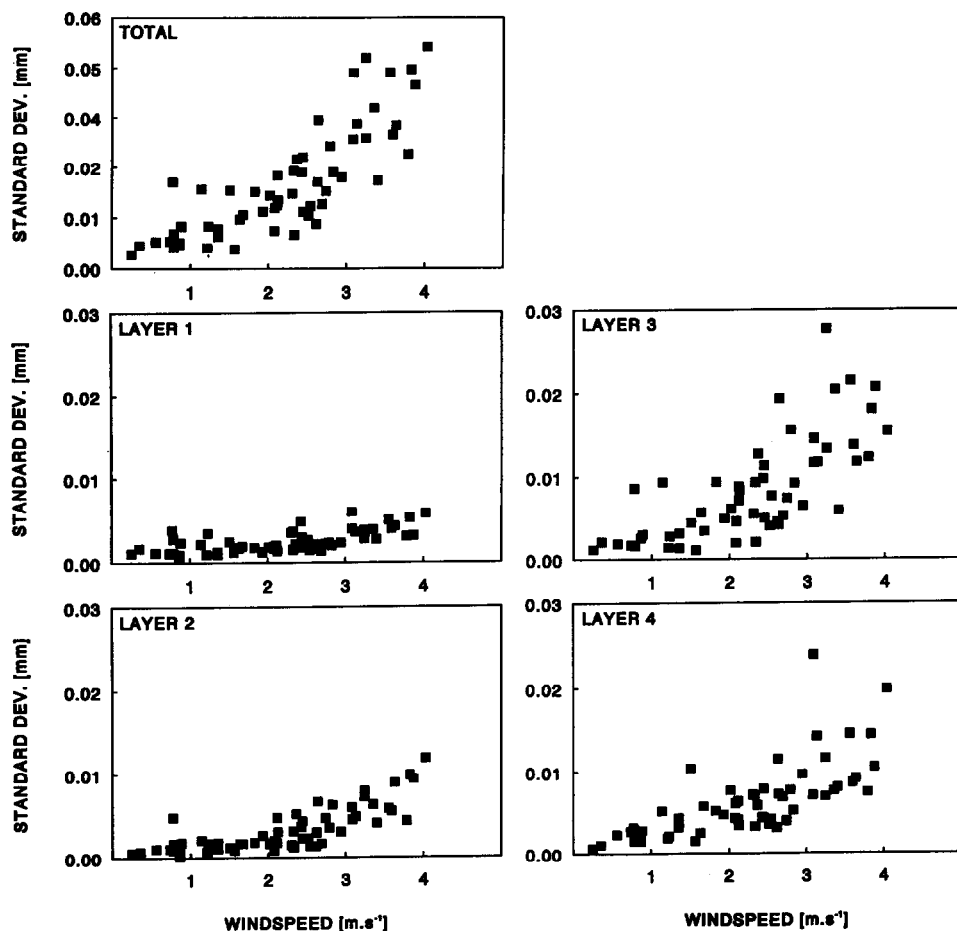


Fig. 3. Standard deviation (mm water storage) of 60 microwave attenuation scans as a function of wind speed at 22 m, for the entire canopy and individual layers (Layer 1 is the top layer).

0.0595 dB, which corresponds to about 0.03 mm water storage for the entire canopy. Trends were found for shorter time intervals, possibly owing to antennae becoming wet during rain or condensation of water vapour. After filtering out those trends, typical standard deviations appeared to be as low as 0.016 dB, which corresponds to about 0.007 mm.

Dry attenuation profiles vary at three different time scales. First, a yearly trend is caused by biomass dynamics with increasing attenuation during the growing season and a decrease from August to May owing to litter fall (Tiktak et al., 1991). Second, sometimes a diurnal trend is found, probably caused by water buffering mechanisms inside the tree (Bouten et al., 1991a) or possibly owing to small amounts of dew. Third, the waving of branches and tree tops in the wind causes variations in attenuation within seconds. An exclusively dry period of 6 days with wind speeds varying

from 0 m s^{-1} to 5 m s^{-1} was evaluated to trace the effects of wind speed on the reproducibility of the attenuation measurements. First, daily trends were filtered out. Then, standard deviations of attenuation over time intervals of 0.1 days were calculated for the four levels mentioned above. Fig. 3 shows these standard deviations, converted to water storage amounts, as a function of mean wind speed over the same time interval. The standard deviation increases with wind speed, varying from 0.005 mm for the top layer to 0.03 mm for the third layer at wind speeds of 4 m s^{-1} .

4.2. Calibration

Table 1(a) shows the optimized parameter set for the case of parameters which are constant (c_{const}) throughout the year. Table 2 shows that the variance of measured storage is largely explained by the model, with the worst values for the top layer and rather high values of more than 90% for the lowest layer.

When optimizing the five original individual periods apart, the overall performance did indeed increase slightly, with the largest improvement being shown by the storage capacity parameter for the top layers (Table 2, c_{opt}). The trends of the optimized storage capacity parameters showed a close resemblance to tree growth dynamics as observed with microwave transmission measurements under dry conditions (Tiktak et al., 1991). It is not surprising that an increase in needle biomass also leads to an increase in the water retaining capacity of the canopy, whereas needle fall causes a decrease. The measured biomass dynamics, therefore, were used to set the storage capacity over the year (Fig. 4). The other parameters (4×3) were then recalibrated (Table 1(b), c_{var}), finally leading to slightly improved explained variances (Table 2, c_{var}). For the canopy as a whole (Table 1, total canopy), parameters a_{tc} and c_{tc} were

Table 1(a)
Calibration set with constant parameters throughout the year

Layer	a_i	b_i (day^{-1})	d_i	c_{const} (mm)
1	0.180	1200	0.090	0.098
2	0.612	317	0.431	0.445
3	0.217	95	0.324	0.888
4	0.289	475	0.398	0.698
Total canopy	0.823	135	0.789	2.129

(b) Calibration set with variable storage capacity (c_i) throughout the year

Layer	a_i	b_i (day^{-1})	d_i	c_{var} (mm)
1	0.186	1170	0.121	0.047–0.119
2	0.246	141	0.305	0.135–0.539
3	0.408	195	0.453	0.857–1.143
4	0.348	830	0.398	0.796–0.796
Total canopy	0.830	153	0.799	2.074–2.584

Table 2

Percentages of variance of the measured storage amounts explained by the model: calibration period (the wind-induced variance is also given as a percentage of the variance of storage amounts)

Input data	Explained variance (%)				
	Layer 1	Layer 2	Layer 3	Layer 4	Total canopy
cal. c_{const}	51	63	84	91	89
cal. c_{opt}	59	78	94	94	92
cal. c_{var}	65	85	90	93	93
Wind effects	0.3	0.13	0.05	0.06	0.06

calculated directly from the values of the individual layers. Parameters b_{ic} and d_{ic} were obtained by fitting the simulation results with Eq. 3 (D against $(S - c)$) and Eq. 5 (E against $E_o S/c$), respectively.

As the wind-induced noise in the measurements is not modelled, the variance caused by this noise is also expressed as a percentage of the total variance of the storage amounts (Table 2). It is clear that the wind-induced variance is almost negligible.

Although the simulated and measured canopy water storage amounts match very well (Fig. 5), a closer inspection shows a few striking deviations. At extremely high rainfall intensities, such as around noon on Day 211, simulated water amounts are much higher than the measured amounts. This is a result of deliberate simplification in the model concept with a constant interception fraction (Eq. (2)) and a linear

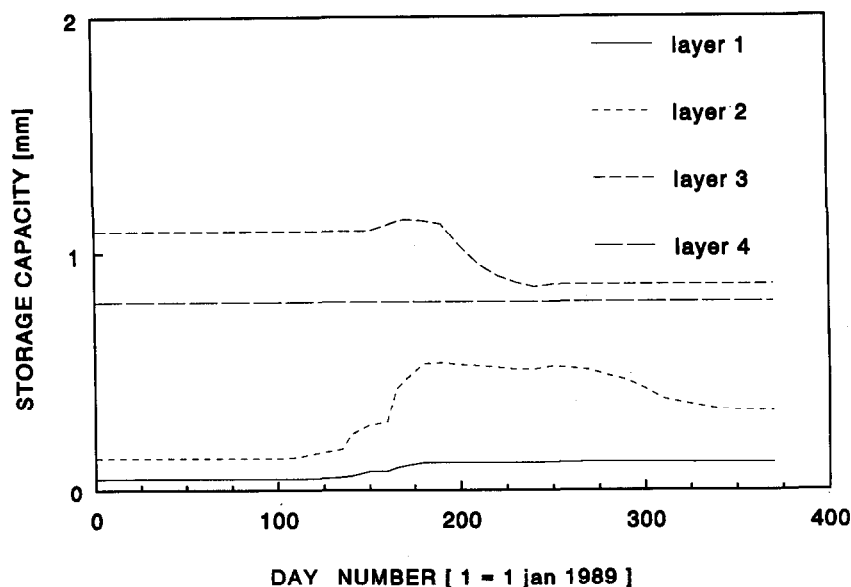


Fig. 4. Storage capacity over the year as deduced from dry canopy attenuation measurements.

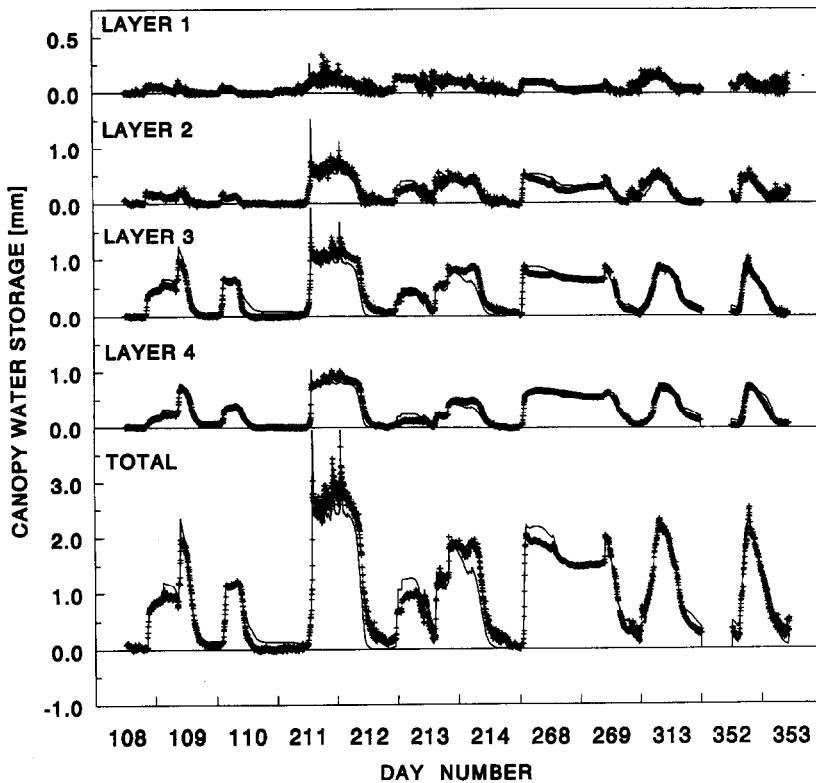


Fig. 5. Measured (+) and simulated (continuous line) canopy water storage dynamics of the entire canopy as well as the individual layers: calibration period.

drainage function (Eq. (3)). Theoretically, one could argue that the interception fraction is dependent on the kinetic energy of raindrops and thus on rainfall intensity (Calder, 1990) or that the drainage function is dependent on wind speed. However, the present data do not justify the introduction of more calibration parameters. A second main deviation occurs during the night of Days 213–214. As a result of a rather high potential evaporation level, the simulated storage amount decreases from 1.9 mm to 1.3 mm, whereas the measured values remain at almost the same level.

4.3. Validation

Fig. 6 shows the measured and simulated water amounts of the independent validation period of 13 days. The fit is almost as good for this independent period as for the calibration period when the same meteorological input data set is used (Table 3, Meteorological Set 1). The model was also run with both other meteorological data sets to check whether the performance becomes worse. The results appear to be almost as good (Table 3, Meteorological Sets 2 and 3). As Data Set 3 does not originate from a forested area, advection effects would have caused higher

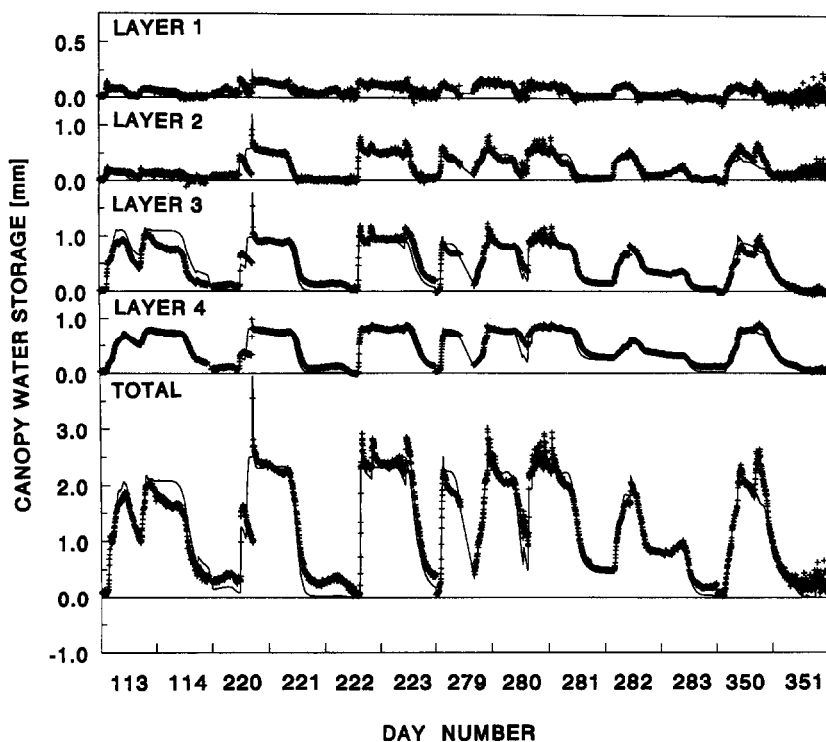


Fig. 6. Measured (+) and simulated (continuous line) canopy water storage dynamics of the entire canopy as well as the individual layers: validation period.

evaporation rates if the regression functions had not been applied for the translation of data values from one site to the other. Apparently, these functions are satisfactory.

Several causes for differences between simulation results and measurements can be identified. The measured storage dynamics can be regarded as being very reliable from the viewpoint of reproducibility. On the other hand, they are deduced from attenuation dynamics under wet conditions as compared with the 'dry' reference situation. For some periods, however, the canopy does not dry completely for several days or even weeks. In these cases, it is not possible to assess the dry reference

Table 3

Percentages of the variance of the measured storage amounts that are explained by the model: validation period

Input data	Explained variance (%)				
	Layer 1	Layer 2	Layer 3	Layer 4	Total canopy
Meteorological Set 1	64	82	85	93	92
Meteorological Set 2	60	79	83	89	89
Meteorological Set 3	62	80	83	88	89

Table 4
Percentage of total time that given threshold values are exceeded

	Threshold value (mm)				
	0.3	0.6	1.0	1.5	2.0
Measurements	38	29	22	15	9
Simulation	35	28	22	13	8
1988	42	34	27	18	10
1989	42	32	23	15	8

situation with high accuracy, thus causing a small offset in the measurements. Differences between simulated and measured storage amounts also occur as a result of incomplete time series of input data. A lack of rainfall data on the research site or missing meteorological measurements cause differences. Finally, measurements sometimes show increasing storage amounts in early morning. As this increase was deduced from microwave attenuation measurements, water buffering mechanisms inside the tree may be the cause (Bouten et al., 1991a). On the other hand, dew formation cannot be excluded. This process is not incorporated in the model and thus causes small differences.

Besides short time series of measured storage amounts, another criterion that can be used for validation is the percentage of the total time that the measured total canopy water storage amount exceeds a certain threshold value (Table 4). The simulation produces almost the same percentages as the actual measured amounts, when the total measuring period is considered. For complete years, the percentages turn out

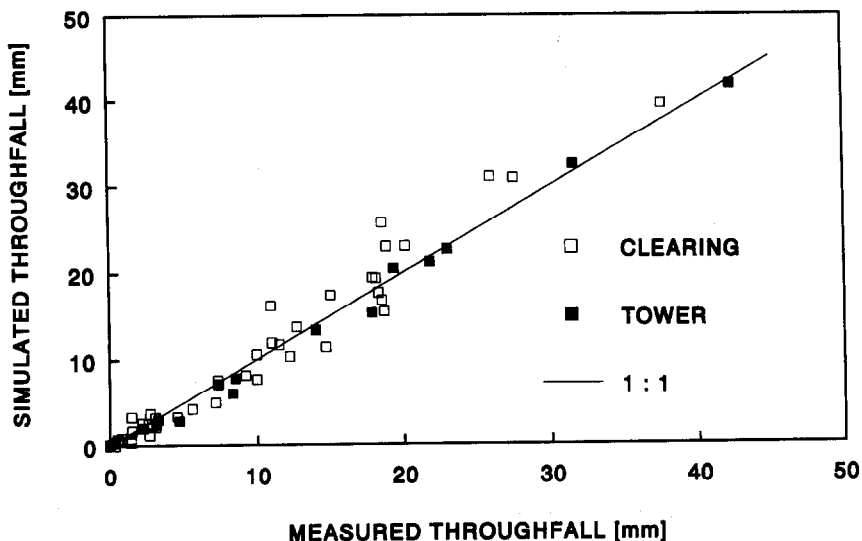


Fig. 7. Simulated throughfall amounts as a function of measured amounts. Rainfall measurements in the clearing (□) or at the tower top (■) served as input to the model.

Table 5

Resemblance of simulated throughfall to measured weekly throughfall amounts

	Clearing	Tower	All
Number of periods	52	18	70
\sum precipitation (mm)	750.6	379.1	1129.7
\sum throughfall (mm)	426.0	217.3	643.3
r^2	0.956	0.993	0.964
Constant (SE)	-0.38 (2.06)	-0.92 (1.03)	-0.38 (1.99)
Tangent (SE)	1.102 (0.034)	1.019 (0.021)	1.059 (0.025)
% Explained variance	0.934	0.992	0.954

to be slightly higher than for the measuring period, owing to the lower evaporation rates in winter.

This simulation study was not aimed at predicting net precipitation amounts reaching the forest floor. However, throughfall amounts may be of interest in deposition studies when wet deposition and wash-off of dry-deposited chemical constituents are incorporated. Moreover, throughfall dynamics serve as one of the boundary conditions in soil water studies (Bouten et al., 1992). Weekly totals of simulated throughfall were therefore compared with the mean amounts measured with 36 funnels with a 480 cm² orifice (Fig. 7). The periods during which the precipitation was measured in the clearing and at the research site at the top of the tower, respectively, are distinguished in Fig. 7. Especially in the second case, the amounts were predicted very well (Table 5). Although throughfall amounts were not used in the calibration procedure, the simulated amounts match the measured amounts; the regression does not deviate from the 1:1 line.

The model parameters, which were all optimized without setting limits to their values, can also be evaluated with respect to their physical plausibility. The interception efficiency, a_i , corresponds to (1-gap fraction) in other models (e.g. Rutter et al., 1971). The interception efficiency of the total canopy, a_{tc} , can be calculated from the values of the individual layers. Its value of 0.830 (gap fraction 0.170) is very plausible and does not deviate from an independent estimate from digitized canopy photographs or the range of earlier reported values of similar forests.

From the optimized canopy storage capacities of the individual layers, the water storage capacity of the total canopy (c_{tc}) was calculated to vary from 2.07 to 2.58 mm, which again is very plausible. Using bark and needle area measurements (Jans et al., 1991), the mean water film thickness at full saturation can be calculated to be 40 μm , 45 μm , 120 μm and 300 μm for Layers 1–4, respectively. However, it is very likely that these are not true thicknesses, as hanging water droplets were often observed under saturated conditions.

The drainage parameter, b_{tc} , obtained by plotting the simulated total drainage rate as a function of canopy water storage amounts, amounts to 153 day⁻¹, which is much higher than the values of 3.74–7.06 day⁻¹ found for spruce (Calder, 1977), and almost twice as high as the values of 76.8 day⁻¹ and 81.6 day⁻¹ found for Sitka spruce (Calder and Wright, 1986). When interpreting these values from the literature, one

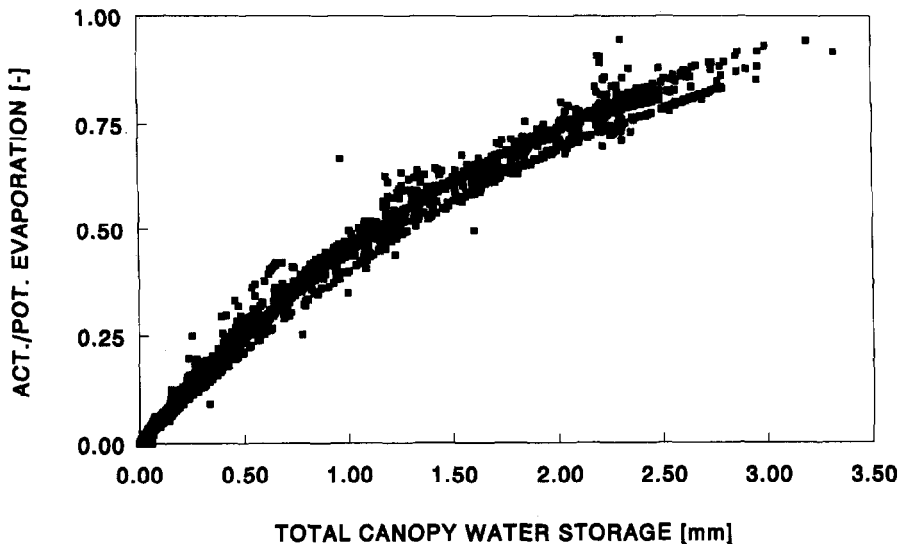


Fig. 8. Simulated ratio actual/potential evaporation as a function of total canopy water storage.

has to bear in mind that the parameters of Calder (1977) were obtained by parameter optimization on the basis of comparison of simulated and measured throughfall dynamics, whereas the values of Calder and Wright (1986) are based on direct measurements. Too few detailed measurements are available in the literature to be able to set the true ranges for the drainage parameters.

The evaporation efficiency parameter as calculated for the entire canopy shows that the actual evaporation equals 80% of the potential evaporation when the water storage equals the storage capacity of all layers. Fig. 8 shows that the actual evaporation does not exceed the potential evaporation at the maximum measured water storage amounts (3.5 mm). Moreover, the ratio d_i/c_i (Table 1(b)) tends to increase with height in the upper canopy layers. Tentatively, this could be attributed to the higher irradiation and lower resistances at the top of the canopy. However, a detailed micro-meteorological study is first needed for a comprehensive interpretation of this trend in physical terms.

5. Conclusions

Measurements of microwave transmission have been shown to be very suitable for monitoring temporal and vertical distributions of canopy water storage amounts. A rather simple multi-layer simulation model appears to be appropriate for predicting canopy water storage dynamics from known time series of rainfall and meteorological parameters. Model parameter values, obtained by parameter optimization using 12 selected days of canopy water storage measurements from 1 year, appeared also to be valid for other periods not included in the calibration. Although constant parameter

values can be used throughout the year, a variable storage capacity, related to the growth dynamics, improves the performance of the model, especially with respect to the upper layers.

After calibration, the model was able to explain more than 90% of the variance of the measured water storage dynamics and up to 99% of the dynamics of weekly throughfall amounts. Although the model parameters are optimized without setting any limits, the values obtained appear to be very plausible.

Measurements and model results have uncertainties. Measurements can deviate from true values over a range of 0.0–0.3 mm owing to poorly defined dry reference values and the temporal dynamics of internal water contents. Simulation results can deviate during periods of dew formation and as a result of differences in rainfall between the research site and the rainfall station.

By combining measurements of canopy water storage amounts with results of a calibrated and validated simulation model, a continuous time series of the vertical distribution of canopy wetness was established in support of the study of surface resistance of a Douglas fir stand to sulphur dioxide. To extrapolate these results to other forests or vegetations, more measurements of canopy water storage dynamics need to be taken first.

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