Nordic Hydrology, 27 (3), 1996, 143-160
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Comparative Model Estimates of Interception Loss in a Coniferous Forest Stand

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Measurements of throughfall in a coniferous forest stand were analyzed and compared with model estimates of interception loss using three different types of models: the Nordic HBV model, the AMOR model and a simplified Rutter model. Two years of seasonal data were available. The 90% confidence interval on estimated average throughfall over the area decreased with storm size and approached a constant value of 15% for events larger than 10 mm of rainfall. Average interception loss was 27% during both the 1993 and 1994 seasons. The Rutter model performed slightly better than the other two; however, all models failed to reproduce the very high interception losses following some of the largest storms. The AMOR model, which is a modified version of the British MORECS model, also underestimated the loss for small and medium-sized storms, and it is necessary to include a linked storage in the model. The Nordic HBV model proved satisfactory as compared to the other two more data demanding models; it does, however, require calibration. The Rutter model has the largest potential to account for the special meteorological conditions prevailing during periods of high losses.

Introduction

Interception losses have long been recognized as an important part of the water balance. It determines net precipitation and the seasonal cumulative loss is commonly 20 to 40% of the precipitation in temperate coniferous stands, *e.g.*, Bringfelt and Hårsmar (1974), Gash *et al.* (1980), Rutter *et al.* (1971), Teklehaimanot *et al.* (1991) and Viville *et al.* (1993). Forest canopies generally experience higher interception losses than low vegetation due to higher interception capacity as well as larger aerodynamic roughness enhancing evaporation of intercepted water. The different rates of evaporation of intercepted and transpired water in forests make it essential that these processes are modelled separately (Stewart 1977).

The amount lost through interception depends on the frequency, intensity and duration of storms, evaporative demand and structure of the plant canopy. Interception loss will naturally exhibit a high local and regional variation, and predictive models of interception loss should be valid in different regions and for different land use. The choice of model complexity depends on the purpose of the study. For water balance design purposes a fairly simple model might prove satisfactory, whereas a more sophisticated model is required if extreme conditions are to be modelled or if the model is to be used outside the design area.

This paper presents the results from an interception study in a coniferous forest stand. Throughfall values were analyzed both to characterize the variability of throughfall over the area, and to compare with model estimates of interception loss. In this study three different modelling approaches are compared against observed losses, and model performance is discussed in view of areas of application.

Models

The Nordic HBV Model

The Nordic HBV model is a conceptual rainfall-runoff model which is a combination of features from several Nordic versions of the HBV model (Sælthun *et al.* 1994). The original HBV model was designed for flow forecasting and has been widely used for hydrological simulations in Norway and Sweden. A general presentation of the HBV model was given in Bergström (1992). The Nordic HBV model introduces a separate interception storage, whereas the traditional HBV model only accounts for interception loss indirectly through a daily evaporation loss. Lindström *et al.* (1994) concluded that the new interception routine generally gave poorer model efficiency, R^2, than the original model, but stressed that the introduction of more realism does not necessarily improve simulation results as old errors might have compensated each other.

The maximum interception storage is given in mm. Water is lost at a potential rate as long as there is water left in the storage. The potential evaporation, *PE*, is calculated for each time step by a simple temperature index method

$$\begin{aligned} PE &= CE\,T \quad \text{for} \quad T > 0 \\ PE &= 0 \quad \text{for} \quad T \leq 0 \end{aligned} \tag{1}$$

where *CE* is a model parameter (mm/°C). Based on comparison with annual estimates of evaporation losses using the Penman-Monteith equation, *CE* was given an annual mean value of 0.16. A seasonal profile is added by applying monthly correction factors to *CE*. Standard monthly correction factors were used (Tallaksen *et al.* 1992), resulting in a range in *CE* from 0.11 in winter to a maximum of 0.26 in June. Calculation is done on a daily basis, and model input, that is daily temperature and precipitation, were calculated on the basis of hourly observed values. The day was chosen to last from 12 a.m. one day to 12 a.m. the following day in order to compare with observed values.

The AMOR Model

In this study a Norwegian version of the MORECS model, AMOR, was used (Tallaksen 1991). The MORECS (Meteorological Office (Great Britain) Rainfall and Evaporation Calculation System) model is described in detail by Thompson *et al.* (1981). It was designed to provide estimates of weekly and monthly evaporation and soil moisture deficits using synoptic weather data, and has proved to give satisfactory estimates of soil moisture deficits (Gardner and Field 1983; Lockwood *et al.* 1989). Evaporation in MORECS is calculated following the Penman-Monteith equation (Monteith 1965), which provides a physically based calculation of evaporation loss from any surface. The main difference between the two model versions is related to the data input system, and the structure of the interception routine does not differ between the models. Direct measurements of net radiation are in general not available, and R_{NE} is net radiation adjusted for differences between surface and screen temperatures using empirical formulae. These modifications led to the following equation, which is the combination equation used in MORECS and AMOR (Thompson *et al.* 1981)

$$\lambda E = \frac{\Delta(R_{NE}-G) + \rho c_p (e_s - e)\,\dfrac{(1+br_a/\rho c_p)}{r_a}}{\Delta + \gamma(1+r_s/r_a)(1+br_a/\rho c_p)} \qquad (2)$$

where E is the rate of water loss, λ latent heat of vaporization, R_{NE} net radiation, G soil heat flux, ρ air density, c_p specific heat of air, e_s saturation vapour pressure at screen temperature, e screen vapour pressure, r_a aerodynamic resistance, r_s surface resistance, Δ rate of change of saturation vapour pressure with temperature, γ psychrometer constant and b given by

$$b = 4\varepsilon\sigma(273.1+T_s)^3 \qquad (3)$$

where ε is the emissivity of the surface, σ Stefan-Boltzmann constant and T_S screen temperature. R_{NE} is the net short- and longwave radiation at the surface obtained from global radiation. MORECS calculates global radiation in terms of relative sunshine duration, whereas AMOR calculates it as a function of cloudiness if observations are not available. Cloudiness is also required in AMOR for the transformation of net clear to actual longwave radiation, whereas MORECS applies sunshine hours for this purpose.

Interception loss depends upon the amount of intercepted water and the evaporative demand. Evaporation from a wet canopy is calculated following Eq. (2) with surface resistance, r_s, equal to zero. In the latter case Eq. (2) resembles the original Penman open water equation (Penman 1948), although he used an aerodynamic function rather than an aerodynamic resistance. Calculations are in AMOR done separately for day and nighttime periods using average hourly values of temperature, wind speed, relative humidity and cloudiness and accumulated hourly values of precipitation and global radiation. The amount of intercepted water, I, is for each period determined from the relation

$$I = Rp_1 \leq I_{\max} \tag{4}$$

where R is rainfall and p_1 the proportion of the rainfall that is intercepted

$$p_1 = 1-(0.5)^L \tag{5}$$

where L is the leaf area index. I is constrained to be less than $I_{\max}$

$$I_{\max} \equiv g\,L \tag{6}$$

where g is the storage capacity per unit leaf area, assumed to be 0.2 mm. Water is lost at the potential rate as long as there is water left in the storage. To account for more than one rainfall event each day or some evaporation of intercepted water while rain is still falling, the amount of rainfall intercepted is enhanced using monthly multiplication factors. In summer it is assumed that the maximum loss will be typically twice the value calculated from Eq. (6). Factors used to multiply $I_{\max}$ varies between one in winter and two in summer. When the evaporative demand is insufficient to evaporate all the intercepted water, the amount that remains at the end of a period is assumed to fall to the ground and not to be carried over to the next period. Day and nighttime values are summarized to give daily values. When compared with observed losses, the interception loss of the first and last day in a period is given as half the day and nighttime values of those days.

The Rutter Model

Rutter *et al.* (1971) formulated the Rutter model for describing the rate and magnitude of inputs, stores, interchanges and losses from a forest canopy during and after a rainstorm. The model has shown that for temperate regions the structure of the forest plays only a minor role in determining interception loss compared with the frequency and duration of storms (Rutter and Morton 1977). For modelling purposes this means that it is possible to operate with a simple interception model. It is, however, necessary to obtain physically based estimates for its parameters.

The Rutter model calculates the running water balance of the canopy and trunks on an hourly basis. The input to the canopy, R', is given by

$$R' = (1-p_2)R \tag{7}$$

where p_2 is the is proportion of rain that falls through the canopy without striking a surface (1-p_2 equals p_1 in the AMOR model). p_2 is often referred to as the free throughfall coefficient. In the original Rutter model the evaporation rate of intercepted water is reduced linearly with storage content, and allowances are made for dripping while the canopy is wet. In this study a simplified version of the Rutter model was adopted and water, as in the other two models, is lost at the potential rate as long as water remains on the canopy. The wet evaporation rate was calculated as in the AMOR model. Daily values were obtained as a sum of the hourly losses, from 12 a.m. one day to 12 a.m. the following day. However, a manual check was performed to ensure that the interception storage was emptied after the rainfall event or was at a minimum before the onset of the next event.

Aerodynamic Resistance

The Penman-Monteith equation requires an estimate of aerodynamic resistance, r_a. It is calculated from the wind speed and surface roughness, using the following relationship (Thom and Oliver 1977)

$$r_a = \frac{1}{k^2 u} \frac{\ln(z-d)}{z_0} \frac{\ln(z-d)}{z_{T,q}} \tag{8}$$

where k is von Kármán's constant, u wind speed, z height above ground, d zero plane displacement, z_0 aerodynamic roughness of the vegetation and $z_{T,q}$ roughness length for heat and water vapour. The wind profile above the forest is usually not known and the aerodynamic parametres of the stand, d, z_0 and $z_{T,q}$, are estimated from the mean vegetation height. The Penman-Monteith equation requires that temperature, humidity and wind speed are measured at the same reference level above the canopy, commonly chosen at 2 metres (Rutter *et al.* 1971; Thom and Oliver 1977).

The MORECS and AMOR models assume zero plane displacement, d, and roughness length for wind, z_0, to be 0.6 and 0.1 of the stand height, respectively, whereas, $z_{T,q}$ is given as 0.2 z_0 (Thom and Oliver 1977). For tall, very tough crop covers like conifers, it is assumed that the upper reference level is 10+d metres above the ground surface and that screen data at 1.2 metres (MORECS) or 2.0 metres (AMOR) apply at this height over a forested area. Wind speed at 10+d metres above the forests is calculated following Oliver (1974) and assuming equal wind speeds at 1,000 metres above ground.

Experimental Site

The study site is located within the Sæternbekken experimental catchment (Myrabø 1994), Fig. 1. The area is forested, mainly by conifers (*Picea Abies*), but also including deciduous forest. Tree density and age vary significantly over the area, ranging from dense forest with hardly any understorey, to a patchy landscape of forest and minor open areas. The site selected for interception measurements is approximately 10 × 30 m, and is considered representative of the heterogeneity found in the area.

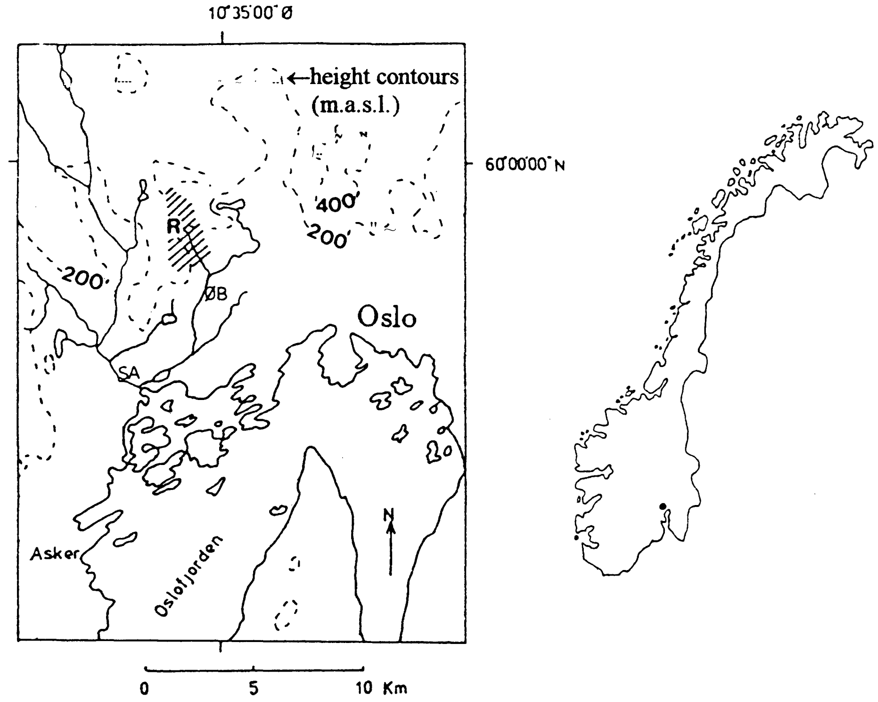

Fig. 1. Sæternbekken research, catchment (cross hatched) and location of study area (R), (Myrabø 1994).

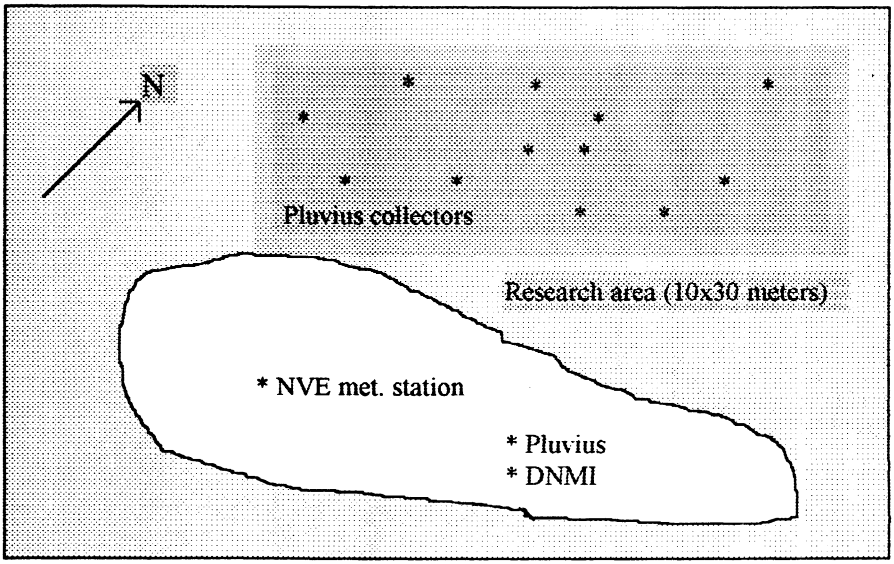

Fig. 2. Measurement site with location of Pluvius collectors (*) in the forest, and meteorological station and rainfall collectors in the clearing.

Instrumental Design

An automatic meteorological station provided hourly recordings of air temperature, wind speed, relative humidity and global radiation. It is located in a small clearing adjacent to the site, Fig. 2. Precipitation was measured using a Geonor vibrating-wire strain gauge (Bakkehøi *et al.* 1985), which records precipitation hourly with a resolution of 0.1 mm. The meteorological station was installed during 1993 and only temperature and precipitation were available on an hourly basis at the site. In 1993 humidity, wind speed and cloudiness were instead taken from Dønski meteorological station, located 5.5 km to the southwest. Observations here were taken three times a day and interpolated hourly values were applied in the modelling (Tallaksen 1991). Wind speed at Dønski was measured at 10 m in an open area, and the calculation procedure for r_a suggested in AMOR was adopted.

Wind speed in 1994 was measured adjacent to the study site, at heights of 2 and 6 m. Assuming a logarithmic wind profile a median of 0.67 m was found for the roughness length, z_0. $z_{T,q}$ and d were defined following the AMOR model. The upper reference level was chosen to be 2 m above the canopy and average wind speed at this height was calculated from the observed wind speed at 6 m in the clearing using the method of Oliver (1974). Correction was made for identical wind speeds at a height of 100 m above zero-plane displacement. The observed humidity and temperature at 6 m were assumed to also apply at a height of 2 m above the canopy. In each year the same input data and calculation procedure for r_a were applied in the AMOR and Rutter models.

Interception losses were estimated from the water balance equation of precipitation less throughfall. Stemflow is generally found to be very low in coniferous forests (Viville *et al.* 1993; Bringfelt and Hårsmar 1974), and was neglected in this study. Throughfall was measured using two types of precipitation collectors, the DNMI (169 mm diameter) and the Pluvius (181 mm diameter) collector, Fig. 3.

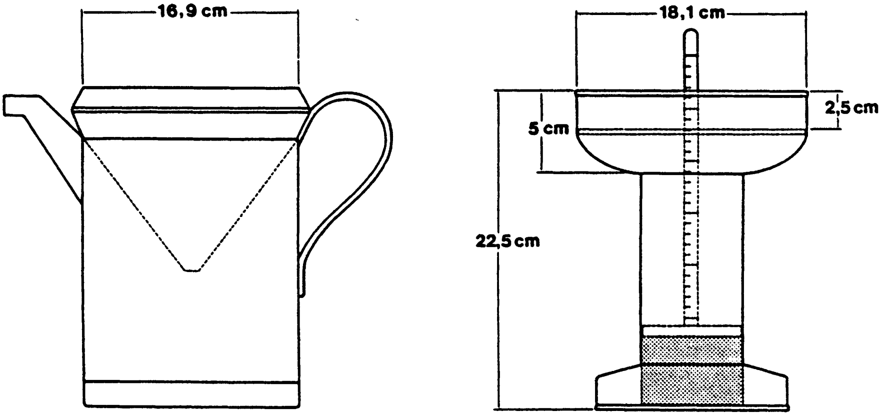

Fig. 3. DNMI (left) and Pluvius (right) precipitation collectors.

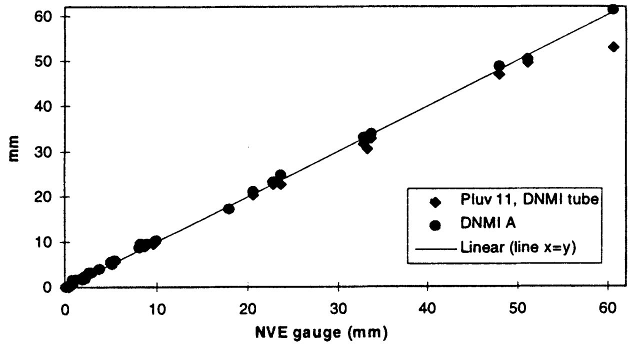

Fig. 4. Comparative precipitation measurements.

Storms larger than 40 mm are liable to underestimation by the Pluvius collectors as water exceeds the inner collector and may be lost due to evaporation and splashing of water. At 60 mm, the water level is approximately 1 cm below the edge. 12 Pluvius and 6 DNMI collectors were placed within the 10 × 30 m plot. The DNMI collectors were randomly moved between each event. In the first year of measurements only 6 Pluvius collectors were available. Analysis of throughfall variability and determination of forest structure parameters were therefore based on data from 1994.

Measurements of throughfall were made as soon as the canopy had dried up after a rainfall event. The Geonor precipitation gauge (labelled NVE in Fig. 2) located in the clearing was used to determine precipitation above the canopy. A Pluvius and a DNMI collector were also placed in the clearing as a check on the performance of these gauges, Fig. 4. Apart from values above 40 mm the observations did not reveal any systematic difference between the collectors, and they showed good agreement with the NVE gauge. Data from the three storms larger than 40 mm were used to compare the Pluvius and the NVE gauge to estimate the measurement error of the Pluvius. The data showed an approximately linear increase in the error (R^2=0.95), and this relationship was used to correct Pluvius data within the range of measurements (46.8-52.9 mm).

Results

Forest Structure Parameters

The density of the canopy cover varies significantly over the area, and although some minor open areas exist on the ground, the canopy above cannot be considered as open. The free throughfall coefficient, p_2, is 0.016 following Eqs. (5) and (7), and this value was used in the model calculations. p_2 can also be estimated from the gradient of a regression of throughfall against precipitation for storms insufficient to saturate the canopy (Rutter *et al.* 1971). Considering 8 storms less than 2.2 mm a gradient of 0.04 was found (standard error 0.11), which is not significantly different from zero. Tree height was measured using an angle meter, and a dominating height

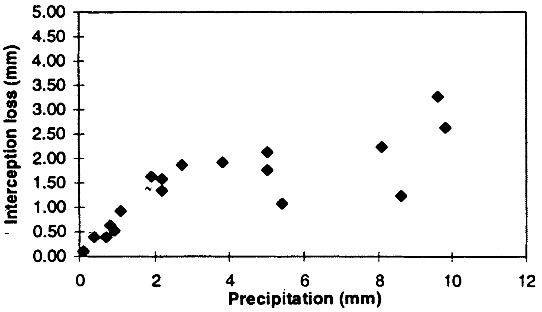

Fig. 5. Interception loss against precipitation for events less than 10 mm.

of about 15 m was found. This value was used in the calculation of aerodynamic roughness.

The canopy capacity, *S*, is commonly estimated from the method of Leyton *et al.* (1967) from a plot of throughfall against precipitation for storms large enough to saturate the canopy (Rutter *et al.* 1971). The upper envelope of these points is thought to represent events when evaporation is minimal, and would ideally be expected to be a line of unit slope which crosses the throughfall axis at -*S*. Drawing of the upper envelope involves a subjective best eye fit which can be difficult if there is a large scatter and few observations. In this study it was decided to determine *S* by fitting a linear regression line to the points. Only storms that consisted of single rainfall events (not including any dry hours) and events that had at least eight dry hours before the onset of the rain were included. The resultant 14 rainfall events gave a storage capacity, *S*, of 2.2 mm and a gradient of 1.05, which is close to the unit value expected. This value is similar to those reported by other workers; *e.g.* Bringfelt and Hårsmar (1974) found a value of 2.0 mm for coniferous forest, and Hutchings *et al.* (1988) reported 2.1 and 2.8 mm for a Sitka Spruce canopy under windy and calm conditions, respectively. A value of approximately 2 mm also seems reasonable from the plot of interception loss against precipitation for small and medium-sized events (all events included), Fig. 5. Interception loss approaches a constant value of 2 mm as precipitation increases to 4 mm, whereas much larger variations are found for higher rainfall events. This can probably be ascribed to differences in rainfall distribution and evaporation rate as well as to dripping during the events.

Throughfall Measurements

Precipitation and throughfall were measured from June to September 1993 and 1994. A total of 15 and 26 rainfall events were recorded, respectively. Detailed presentations of the 1993 and 1994 data were given by van Veen (1993) and Schunselaar (1995), and a preliminary discussion of the 1993 results was presented in Tallaksen and van Veen (1994). Daily precipitation for the two years is shown in Fig. 6. 1993 was characterized by continuous wet weather, which did not include very large storms. A very different picture was presented in 1994 which experienced long dry periods interrupted by some very large storms. Table 1 gives a summary of the meas-

Table 1 – Measured and modelled interception loss (all values are in mm)

			INTERCEPTION LOSS 1993			
Period	**Date**	**prec NVE**	**Field**	**Nor. HBV**	**AMOR**	**Rutter**
1	08.07-09.07	8.8	2	1.1	1.4	2.1
2	09.07-15.07	37.8	13.6	12.3	11.2	15.5
3	15.07-23.07	26.6	6.2	7.6	5.9	4.5
4	23.07-02.08	37.2	8.9	11.5	5.2	8.7
5	02.08-04.08	27	7.7	1.4	1.7	2.3
6	04.08-05.08	0.4	0.4	1.5	0.2	0.4
7	05.08-11.08	22.7	5	6.9	5.6	5.2
8	11.08-13.08	8.3	2.3	5.5	2.5	2.7
9	13.08-18.08	33.2	6.3	4.4	5.6	3.7
10	18.08-26.08	5.1	3	5.1	3.8	4.9
11	26.08-30.08	9	1.5	3.9	1.1	2.2
12	30.08-02.09	2.9	-0.1	1.1	0.7	1.2
13	02.09-03.09	1.8	0.9	2.9	0.7	2.4
14	03.09-22.09	17.9	5.2	4.3	0.8	3.6
15	22.09-28.09	9.9	3.2	3.5	1.2	2.6
Sum		248.6	66.1	72.7	47.6	62.0

			INTERCEPTION LOSS 1994				
Period	**Date**	**prec NVE**	**Field**	**S.E. in I**	**Nor. HBV**	**AMOR**	**Rutter**
1	16.05-29.05	1.9	1.6	0.3	1.9	1.9	1.9
2	29.05-06.06	0.1	0.1	0.0	0.1	0.1	0.1
3	06.06-08.06	0.7	0.4	0.1	0.7	0.7	0.7
4	08.06-11.06	1.1	0.9	0.1	1.1	1.1	1.1
5	11.06-17.06	0.4	0.4	0.0	0.4	0.4	0.4
6	17.06-20.06	20.5	3.0	2.1	3.5	2.6	2.9
7	20.06-22.06	8.6	1.2	1.0	2.5	2.0	3.0
8	22.06-27.06	5.4	1.1	0.7	2.3	3.6	2.5
9	27.06-30.06	33.6	1.0	3.2	2.2	2.6	2.5
10	30.06-08.07	2.2	1.6	0.2	2.2	0.5	2.2
11	08.07-19.07	0.4	0.4	0.0	0.4	0.4	0.4
12	19.07-29.07	9.8	2.6	0.8	2.2	0.3	2.4
13	29.07-03.08	2.2	1.3	0.2	2.2	1.1	2.2
14	03.08-06.08	9.6	3.3	0.9	2.2	2.1	2.7
15	06.08-15.08	60.6	17.8	4.2	2.4	8.4	4.4
16	15.08-18.08	3.8	1.9	0.4	2.2	2.6	2.5
17	18.08-22.08	51.1	12.7	4.4	4.4	3.1	4.4
18	22.08-25.08	5.0	2.1	0.6	2.4	0.5	1.6
19	25.08-27.08	32.8	7.4	2.6	4.4	3.2	3.8
20	27.08-28.08	8.1	2.2	0.7	2.0	1.6	1.6
21	28.08-30.08	0.9	0.5	0.1	1.0	0.4	1.6
22	30.08-04.09	2.7	1.9	0.4	2.2	2.2	2.7
23	04.09-07.09	5.0	1.8	0.6	2.3	1.9	1.5
24	07.09-12.09	47.9	13.3	3.5	7.5	8.8	8.8
25	12.09-14.09	0.8	0.6	0.1	0.8	1.0	1.6
26	14.09-18.09	23.6	9.2	1.8	3.1	6.6	7.2
Sum		338.8	90.4		58.4	59.7	66.7

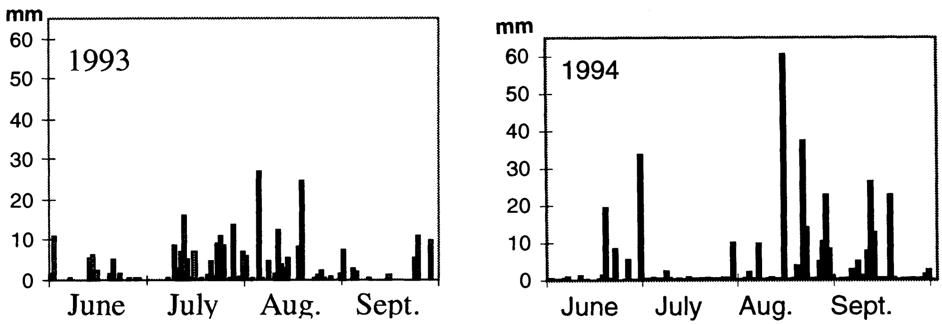

Fig. 6. Daily precipitation during 1993 and 1994.

ured and modelled estimates of interception. Average interception loss was 27% during both the 1993 and 1994 seasons.

The spatial variability of throughfall was found to be higher for small storms. This is reflected in the coefficient of variation, *CV*, Fig. 7, and in the 90% confidence interval, *CI*, on the throughfall estimate (t-distribution), Fig. 8. The analyses were based on data from 18 collectors (1994). Fig. 7 shows how the *CV* approached a lower limit as the storm size increased. Only storms where none of the collectors recorded zero throughfall were included. For storms larger than 10 mm an average *CV* of 0.34 was found. This value is significant higher than reported by Viville *et al.*

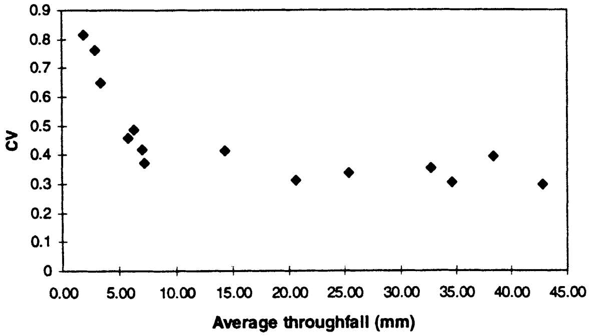

Fig. 7. Coefficient of variation for storms large enough to saturate the canopy.

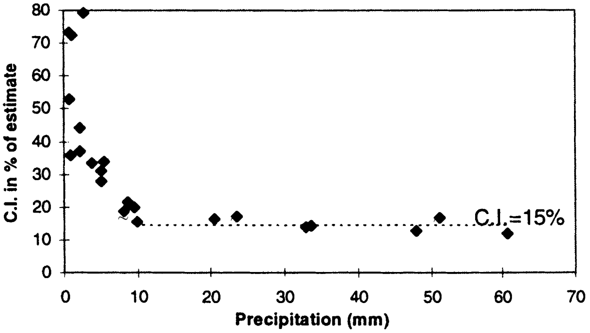

Fig. 8. 90% confidence interval of the throughfall estimate (precipitation > 0.5 mm).

(1993) for a 25 m high stand of *Picea abies* and by Loustau *et al.* (1992) for a Pine stand of 12.6 m. The *CV* was in these studies found to be below 0.20 for larger storms. In Fig. 8 storms less than 0.5 mm were excluded since small storms can give very high *CI* in percentage of the estimate. The same pattern as shown for the *CV* is revealed; for storms larger than 10 mm the *CI* approaches a constant value of 15% of the throughfall estimate.

The standard error, *SE*, is given by the equation

$$SE = \frac{CV}{\sqrt{N}} 100\% \tag{9}$$

where N is the number of collectors. Increasing the number of collectors by a factor 2, from 18 to 36 collectors, will only reduce the standard error with a factor of $\sqrt{2}=1.4$. For large N an approximate 95.4% error bound is $\pm 2(SE)$ and assuming a *CV* of 0.34, the corresponding reduction in error bound would be from 16 to 11%.

A regression analysis was performed to see if some of the collectors explained a large percentage of the variation in the mean value. The mean value was given as the dependent variable, and a linear, stepwise regression was performed with all 18 collectors as independent variables. Pluvius 5 was found to explain 99.25% of the variation, and shown to be preferable to the mean of the 12 original collectors (Schunselaar 1995). It was therefore decided to use Pluvius 5 as an estimate of the mean value for 1993 and for the first eight periods in 1994, when only 12 collectors were available.

Model Comparison

The Nordic HBV, AMOR and the Rutter models were run on the two data sets from 1993 and 1994. The results are shown in Fig. 9, where cumulative values of interception loss for observed and modelled events are plotted, and in Table 1 which gives the interception loss for each event.

The two years showed quite divergent results, which can probably be ascribed to the difference in precipitation pattern during the two seasons. Model predictions agreed well with the observed interception loss in 1993, apart from the AMOR model which underestimated the loss by 18.5 mm (28.0%). This model has a non-linked storage routine, and water is lost to the ground after each day and nighttime period. Experiencing frequent rainfall showers, water that otherwise would have evaporated is often lost, adding up to give a significant underestimation of the loss. The Nordic model overestimated the interception loss by 6.6 mm (10.0%), whereas the Rutter model predicted 4.1 mm (6.2%) less than observed.

In 1994 some very large storms occurred, and the observed interception loss was high. None of the models were able to estimate such high losses, the Rutter model giving slightly better estimates than the other two. The Rutter model underestimated the interception loss by 23.7 mm (26.2%), whereas the Nordic model predicted 32.0 mm (35.4%) less. Calder (1977) applied a Rutter type of interception model on data

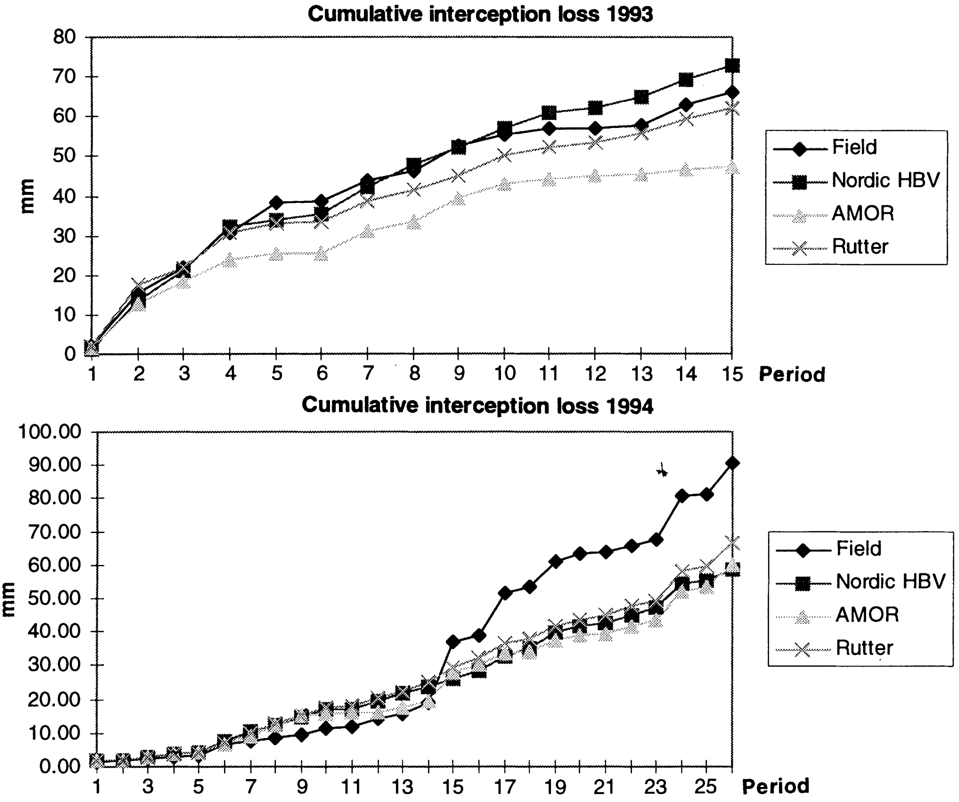

Fig. 9. Cumulative interception loss for observed and modelled interception loss 1993-94.

from a spruce forest in Wales and also found divergent results between years. The hot and dry summer of 1975 showing a general overestimation of the interception loss, whereas the opposite trend was found for the fairly typical year of 1974. A systematic divergence between observed and modelled interception loss (Rutter model) was also reported by Gash *et al.* (1980) for three coniferous forests in Great Britain. The estimated loss was within 20% of the observed loss, showing both higher and lower accumulated losses.

The results from 1994 are in Fig. 10 separated into small (<2 mm), medium (2-10 mm) and large (>20 mm) storms. There were no events observed in the interval 10 to 20 mm. As can be seen from the figure there was a general overestimation of the loss for small-sized storms. This means that not all intercepted water evaporates, and that a minor amount might reach the ground due to dripping. For medium-sized storms, both the Nordic and the Rutter models overestimated the loss slightly, the Nordic model giving very stable values of around 2 mm for all events. This is due to the combined effect of a storage capacity of 2.2 mm and a daily time step. For larger events the loss is roughly given as the number of days with precipitation times 2.2

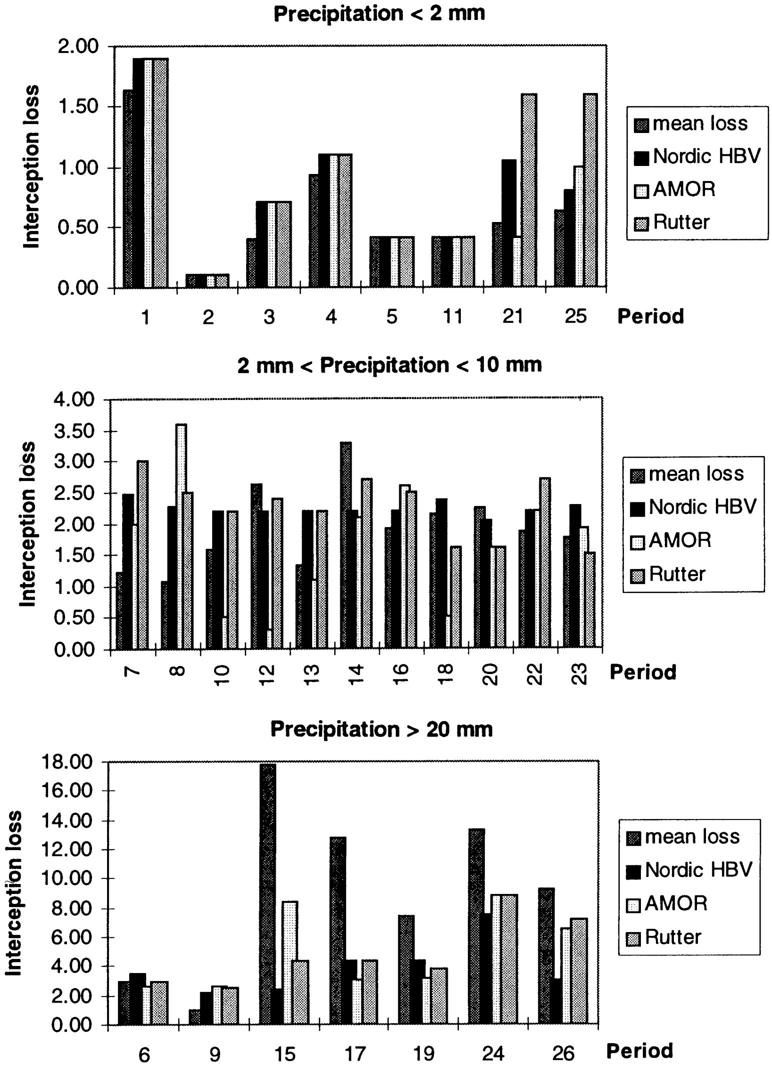

Fig. 10. Interception loss for small, medium and large sized storms.

mm. As a result the model was not able to predict the high losses of large storms that have a composition of wet and dry hours. The AMOR model both highly over and underestimated the loss of medium-sized storms due to the random nature of its storage function. For large storms the observed loss is in general much higher than the estimated loss for all models, the Nordic model giving the lowest estimates.

The events of periods 9 and 19 in 1994 had similar precipitation amounts (33.6; 32.8 mm), the observed interception loss, however, ranged from 1.0 mm (*SE*=3.2) to 7.4 mm (*SE*=2.6). The rainfall of period 9 was concentrated over 7 hours and the resultant loss was low. During period 19 rainfall occurred as a sequence of wet and dry hours, allowing a higher total loss. Stewart (1977) analyzed the energy budget of a pine forest, and showed that when the forest canopy was wet, additional energy was provided by advection of unsaturated air over the forest. On average the evaporation of intercepted water used 127% of the available energy (which was a very close approximation to net radiation). This might partly explain the underestimation in modelled interception loss, which will be larger if the rainfall event occurs as a sequence of wet and dry hours.

This effect does not, however, explain the large loss of periods 15 and 17 in 1994. Rainfall occurred in both periods as one distinct event with no dry hours in between. The rainfall lasted for 23 and 32 hours respectively. Evaporation during rainfall, dry periods lasting less than an hour and stemflow might account for some of the deviation with modelled losses, but one cannot disregard the larger uncertainties in the measurements of throughfall due to the low capacity of the Pluvius collectors. The large rainfall of period 24, however, was partitioned into minor events, and to some extent the models were able to account for this.

Model and Measurement Error

Errors in the measurement of precipitation also contribute to the error in measured interception loss. The standard error in the estimated interception loss is, σ_I

$$\sigma_I^2 \equiv \sigma_{P\,\mathrm{meas}}^2 + \sigma_{T\,\mathrm{mean}}^2 \tag{10}$$

where P_{meas} denotes the standard error in the precipitation measurements, and T_{mean} the standard error in the estimate of the mean throughfall. The latter is attributed to throughfall variability and measurement errors related to the throughfall collectors. Their respective contribution to the total error is not known, although the collectors showed good agreement with the NVE recording gauge except at high values. Assuming a 5% standard error in the precipitation measurement, the standard error on interception loss in 1994 was calculated, Table 1. The 95.4% *CI* on the estimate of interception, equals two times the standard error for large *N*. For the three events with highest losses, the model estimates were outside the 95.4% error bound in period 15, and outside the 68.3% error bound for the events of periods 17 and 24. If instead a 2% error in the precipitation measurements was assumed, only period 24 was within the 95.4% error bound. It can therefore be concluded with high reliability, that there was a significant underestimation of interception loss by all three models in periods when the loss was above 10 mm.

A quantification of the uncertainties related to the estimation of the aerodynamic resistance requires that the sensitivity of the interception estimate is examined. The total interception loss during 1994 for the Rutter model was 66.7 mm. A 20% increase and decrease in the wet evaporation rate were considered and the resultant losses were 72.2 and 63.5 mm. A value of 72.2 mm is still considerably lower than the 90.4 mm observed (Table 1).

Concluding Remarks

Average interception loss was 27% during both the 1993 and 1994 seasons. Considering the 1994 data, including 18 collectors, the 90% confidence interval on estimated throughfall was found to decrease with storm size and approached a constant value of 15% of the throughfall estimate for rainfall events larger than 10 mm. Based on an analysis of selected storms a storage capacity of 2.2 mm was found, and the free throughfall coefficient was not found to be significantly different from zero.

Comparison of model estimates of interception loss showed that neither of the models were able to simulate periods of very high interception losses. The AMOR model also showed considerable underestimation for the 1993 events due to the non-linked storage function, and it can be concluded that this ought to be improved in the model. Until then it is not comparable to the other two models. There was a tendency to overestimate the loss for the small and medium-sized storms in all models, which suggested that the inclusion of a reduction in potential evaporation with storage content and dripping should be considered, like in the original Rutter model.

The more physically based and data demanding Rutter model gave slightly better model estimates, but did not prove to be superior to the other two models. The model, however, has the potential to adapt to new knowledge on the interception process. It can also be a valuable tool when investigating which meteorological conditions favour high losses. This requires an hourly recording of throughfall and preferably also a wetness indicator, since interception loss is governed by the number of wetting and drying cycles of the vegetation. The disadvantage of the Rutter model is that it requires hourly input data that are not available at all sites.

The Nordic HBV model proved to be an equally good choice when limited data were available, with the reservation of model limitation in periods of heavy rainfall. One should remember, however, that in reality the amount lost by interception is determined as an interaction between climate and vegetation, and that the simple Nordic model should be used with care at new sites. Particularly large errors might result if frequent rainfall showers are combined with large storage capacities. The model also needs calibration to estimate the parameter *CE*, which in turn determines potential evaporation. The advantage of the Rutter model is its ability to adjust to other vegetation types without any calibration, and its potential for use in climate and land use impact studies.

The task remains to improve modelling in periods of high losses, which in turn will have the largest effect on the water balance. In order to solve this problem it is necessary to improve our physical understanding of the interception process, that is the interaction between vegetation type and structure on one hand and precipitation and evaporation rates on the other. This requires further field investigations, where it is important to have a high accuracy on both throughfall measurements and climate data in order to identify the kind of meteorological conditions that favour high losses.

Acknowledgments

Thanks are due to the Norwegian Water Resources and Energy Administration (NVE) and the Norwegian Meteorological Institute (DNMI) for providing meteorological data and measurement equipment.

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First received: 24 February, 1995
Final version received: 8 August, 1995
Accepted: 16 August, 1995

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