Simple water balance modelling with few data - calibration and evaluation: investigations from a Danish Sitka spruce stand with a high interception loss

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Abstract Simple evapotranspiration models with few data requirements and Penman reference evapotranspiration for grass (E_{ref}) limiting the actual evapotranspiration are often used to estimate chemical fluxes in ecosystems. The aim of this paper is to show how much the interception loss might exceed E_{ref} in a wind-exposed Danish Sitka spruce stand and to demonstrate the importance of the evaluation of model performance, here represented by throughfall measurements and chemical fluxes. Precipitation, throughfall, soil moisture and soil water chemistry were measured monthly for 1.5 years. Model input was daily precipitation, E_{ref}, leaf area index, root distribution and plant available water. The model interception loss was calculated using an empirical relationship between precipitation and interception loss that was calibrated against the measured interception loss. Interception loss was found to be unusually high, on average 58% of precipitation, which was supported by measurements from two other years with interception losses from 62–68% of precipitation. Transpiration and evaporation from soil were constrained by E_{ref}. The modelled percolation was compared to percolation calculated by a chloride mass balance based on measured values. The percolation was only about 20% of precipitation due to the exceptionally high interception loss, which exceeded E_{ref} by almost 50%. Therefore, in wind-exposed forest stands the interception loss should be modelled separately, as done here, and be calibrated on measured values.

Keywords Chloride; interception; Sitka spruce; throughfall; water balance

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Introduction

Water balances are usually set up to quantify chemical fluxes through ecosystems. Chemical fluxes can be used to determine leaching/depletion of nutrients and critical loads. Mostly, the focus in such studies is on chemistry and not hydrology. Therefore, to estimate fluxes only simple soil water balance models are used, e.g. Nielsen *et al.* (1999) and Giesler *et al.* (2000). Minimum requirements of such models are daily measurements of precipitation, monthly measurements of throughfall and perhaps also measurements of soil water content. Interception loss, evaporation from soil and transpiration are estimated empirically and often limited to reference evapotranspiration (E_{ref}) representing values for a well-watered short grass surface (Kristensen and Jensen 1975; Jensen 1979, 1981; Olesen and Heidmann 1990; Thomsen and Bille-Hansen 1998). The uncertainty of estimating actual evapotranspiration by using E_{ref} instead of more detailed resistance methods or using crop factors in combination with E_{ref} is often regarded as small, but an underestimation of about 10–20% for tall crops has been reported (Aslyng and Hansen 1985). Therefore, for forests a crop factor of 1.1 is reported for Danish conditions (Henriksen 2002), but a distinction between wet and dry evaporation is usually not made. However, the low aerodynamic resistance in forest stands compared to that of crops can lead to a relatively high interception loss, which cannot be taken into account using E_{ref} multiplied by a crop factor. The interception loss in conifers exceeds by far the reference evapotranspiration for grass in wet conditions

(Calder 1982). Therefore, unusually high interception losses might easily be overlooked if the throughfall is not sampled quantitatively.

Chloride fluxes are considered conservative in ecosystems. Therefore, a chloride mass balance using knowledge of the input chloride flux and chloride concentrations at different soil levels allows an estimation of the percolation between the investigated levels. The chloride mass balance can as such be used as a tool to evaluate modelled percolation. On several occasions discrepancies have been found between percolation estimated by the chloride mass balance method and the percolation estimated using a hydrological model (e.g. Beier 1998; Nielsen *et al.* 1999). Difficulties in obtaining representative throughfall amounts and representative chemistry in soil water samples, temporal delays in input/output amounts, as well as uncertainties in model estimations, are often thought to be the reasons for the discrepancies.

In our study, the percolation estimated by the chloride mass balance method was used to evaluate the percolation obtained from a simple water balance model, a modified version of the ET model (Thomsen and Bille-Hansen 1998). Evapotranspiration in the model was initially constrained by E_{ref}. However, throughfall data showed that interception losses by far exceeded E_{ref}. Therefore, the model was modified by incorporating an interception estimation method suggested by Calder (1990), where interception loss is related to precipitation amounts only. Transpiration and evaporation from soil was constrained by E_{ref} multiplied by a crop factor. Since both the chloride mass balance method and the water balance model use the measured throughfall amounts either directly or indirectly, the two methods support each other in evaluating the transpiration/ soil evaporation and percolation of the water balance model.

The aim was to show how a simple hydrological model calibrated on monthly TDR measurements and throughfall measurements can be used in the estimation of chemical fluxes. The results of using different input of net precipitation to the model were tested and the influence on simulated NO_3 fluxes in the soil was demonstrated. The net precipitation was obtained either by (1) a model set-up where E_{ref} limits evapotranspiration or (2) by a model set-up where the model is calibrated on measured throughfall, and transpiration is limited to E_{ref} in combination with a crop-factor. NO_3 was measured in the Sitka spruce stand and was chosen as an example because NO_3 is often applied in environmental science as an indicator for environmental health.

Materials and methods

Description of the field site

In 1933, 10 hectares of Sitka spruce (*Picea sitchensis*) were planted on former heathland at Hjelm Hede, Denmark. The plantation is close to the North Sea (Figure 1) and there is an open plain in the direction of the dominating westerly wind. The area is situated on a late Weichselian outwash plain, at least 20 m above the groundwater table. The soil classifies as Typic Haplorthod with less than 2% clay and about 90% sand (Madsen and Nørnberg 1995). Below 1 m some levels contain large amounts of gravel. The trees are about 25 m high with 850 trees per ha and leaf area is about 6 m^2/m^2. The roots extend to 75–100 cm but intermittent coarse layers of gravel may cause smaller root depths at some places. Mean annual precipitation from 1961–1990 was 875 mm (The Danish Meteorological Institute) and mean monthly temperature ranges from −0.2°C in January to 15.4°C in July. The year 1998 was extremely wet with a precipitation of 1122 mm, while especially high values were found in autumn and winter.

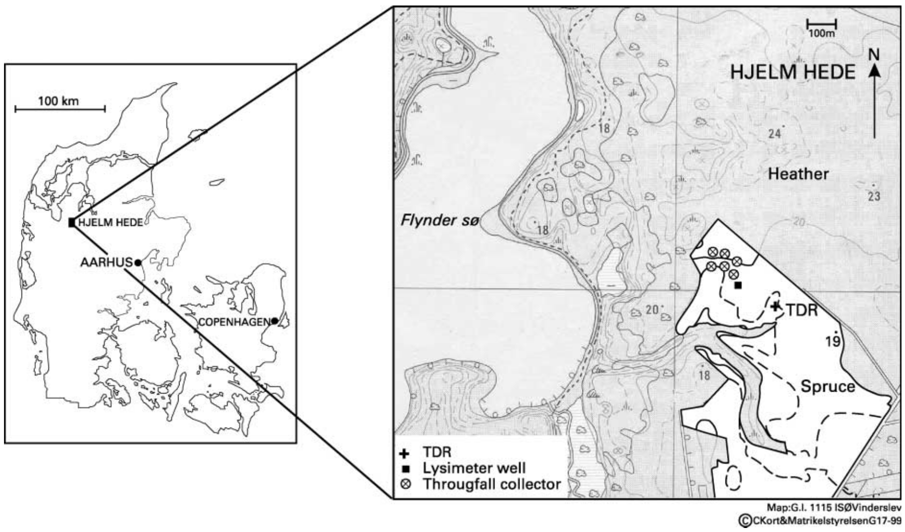

Figure 1 The study area, Hjelm Hede

Instrumentation

The Danish Meteorological Institute registers daily precipitation 2 km south of Hjelm Hede outside the heath area. The precipitation data were corrected with the percentages suggested for moderately sheltered stations by Allerup and Madsen (1979). The Danish Institute of Agricultural Sciences, Foulum, calculated daily reference potential evapotranspiration (E_{ref}) for a 40×40 km area by a modified Penman equation (Mikkelsen and Olesen 1991), where net radiation and soil heat flux are correlated to global radiation.

Six plastic throughfall samplers with openings of 208 cm^2 (Nielsen *et al.* 1999) were placed within the stand 40 m from the western edge (Figure 1). Throughfall was collected monthly from January 1998 to May 1999 on days with air temperatures above zero. All samples were weighed and then analysed chemically for all base cations, Al, Fe, Si, NH_4, H, HCO_3, Cl, SO_4 and NO_3.

Soil moisture was measured manually by Time Domain Reflectometry (TDR) on the same days as throughfall was collected (Figure 1). A total of 15 TDR probes, 20, 50, and 100 cm long, were installed vertically from the soil surface at various distances from one stem 300 m from the western edge (Andersen 1999). The TDR measurements were weighted according to radial distance to stem as in Beier (1998). The measurement area was divided into concentric rings around the stem and the measurements were weighted according to the area represented by the ring in which the probe was placed.

The TDR probes consisted of two 6 mm thick stainless steel rods 5 cm apart. The TDR measurements were calibrated on gravimetric-determined soil water content. The soil samples for gravimetric determination were taken by first removing the TDR probe and then pushing a cylinder of a diameter of 4.8 cm and of the length of the TDR probes into the soil at the same spot. The 20 cm probes were calibrated on 33 soil samples and the 50 cm probes were calibrated on 9 samples.

A comparison of the gravimetric water content to water content derived by the method of TDR showed that the Topp calibration equation (Topp *et al.* 1980) underestimated the low water contents for probes of 20 cm. A second-degree polynomial regression provided a better fit to these data (Figure 2). In order to yield realistic results in the dry end of the regression, the polynomial was forced to approach a water content of zero close to a dielectric constant of 3. For longer probes, the Topp equation gave a fairly good estimate of the water content.

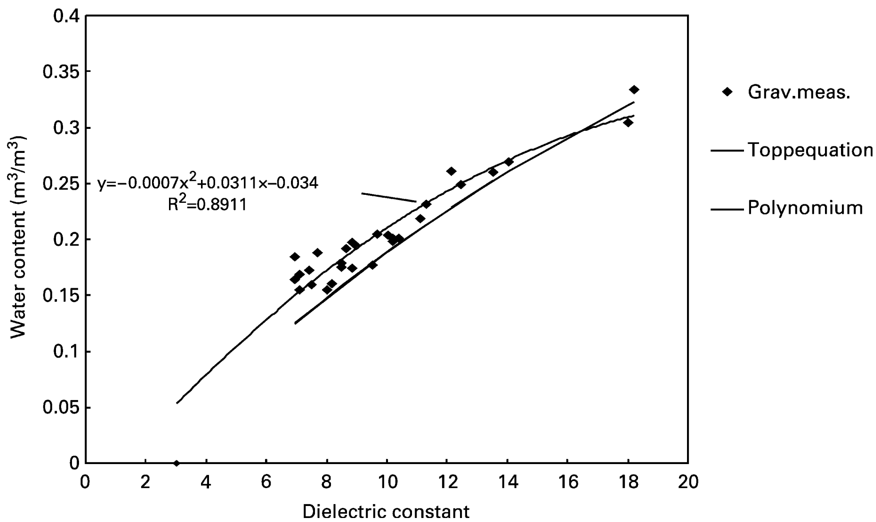

Figure 2 Calibration of the 20 cm long TDR probes.

The top 10 cm of the forest soil of partly decomposed needles is important in the calibration of the 20 cm probes. For longer probes, a substantial part of the measurement volume consists of sand in which the Topp equation is usually found to provide good results. Therefore, the polynomial regression equation was used for the 20 cm probes (Figure 2), whereas the Topp equation was applied for the 50 and 100 cm probes.

A 4 m deep soil core was taken in May 1999. Soil water was extracted from 0.25 m samples by a high-speed centrifuge (1600 rpm in 20 min) and stored at 4°C for chemical analysis of Cl, NO_3, SO_4, HCO_3, Na, K, NH_4, Mg, Ca, Al and Fe.

The leaf area index (LAI) was measured with a Plant Canopy Analyzer LAI-2000 (LI-COR, Lincoln, Nebraska, USA) subsequently adjusted to leaf area for Sitka spruce by a multiplication factor of 1.6, as suggested by Gower and Norman (1991).

Stemflow was considered negligible in accordance with studies in a similar 40-year-old stand in the western part of Denmark (Beier *et al.* 1993) and in a 50-year-old German spruce forest (Flügel 1988). In young stands, stemflow is of relevance and should be measured and included in models (Ford and Deans 1978).

Description of the water balance model and ET model

Soil moisture measurements were used to calibrate a simple water balance model developed at the Danish Institute of Agricultural Sciences, Foulum (Thomsen and Bille-Hansen 1998). The model has previously been used on similar soils in both oak forest (Ladekarl 1998) and heathland (Ladekarl *et al.* 2001). The model consists of three soil reservoirs: an evapotranspiration reservoir found exclusively in the uppermost 20 cm and two transpiration reservoirs extending from ground level to 50 and 100 cm, respectively, corresponding to the length of the TDR probes. Daily values of precipitation and reference evapotranspiration (E_{ref}) are inputs to the model. Essential parameters are wilting point, field capacity, maximum root depth, root distribution and leaf area index. Outputs from the model are daily values of soil water content and percolation from selected soil levels, actual evapotranspiration, evaporation from soil, interception loss and transpiration.

The model is a conceptual model where incoming precipitation on the canopy is adjusted for the estimated interception loss. Interception capacity and E_{ref} limit interception loss. Further evapotranspiration is divided between evaporation from the top 20 cm of soil, and transpiration. Transpiration takes place from the entire root zone, depending both on water content above the wilting point as outlined in Kristensen and Jensen (1975) and on root mass distribution. Water immediately percolates out of the root zone at 100 cm depth if the soil water reservoir is above field capacity. In the model actual evapotranspiration (interception loss + evaporation from soil + transpiration) is not allowed to exceed E_{ref}. This is a typical limiting parameter in soil water balance models for temperate, but not extremely wet, climates. This limitation has shown to be useful in other Danish deciduous forest ecosystems where the model has been used successfully (e.g. Ladekarl 1998; Beier *et al.* 2001; Thomsen and Bille-Hansen 1998).

In order to model the interception loss separately without limiting it to E_{ref} an empirical relationship between interception loss and precipitation found in Calder (1990) replaced the original interception estimation in the model. The interception loss (I, mm/d) was calculated as

$$I = a(1 - \exp(-bP)) \quad (1)$$

where a defines the maximum interception loss and b governs the rate at which interception loss increases with increasing precipitation, P, which is daily precipitation (mm). The parameter a varies for different vegetation types, whereas b is 0.099 for the tree species investigated in Calder (1990). Transpiration and evaporation from soil was constrained by $0.9E_{ref}$, where 0.9 was a crop factor related to coniferous trees (Calder 1990). Thus, the crop factor is only used for evaporation from soil and transpiration. On wet days E_{ref} is reduced with the amount of the interception loss. In case the interception loss exceeded E_{ref} no further transpiration or evaporation from soil is allowed that day.

Chloride balances

Chloride fluxes, Cl, are considered conservative in ecosystems: $Cl_{in} = Cl_{out}$. Usually Cl_{in} is calculated from chloride concentrations in precipitation but, due to a high deposition of chloride in tall crops, input fluxes in the Sitka stand are calculated from measured concentrations in throughfall. The input chloride flux, Cl_{in}, is calculated by accumulating monthly calculated fluxes as follows:

$$Cl_{in} = \sum(\bar{c}_{thr,measured} \cdot \bar{q}_{thr,measured}) \quad (2)$$

where Cl_{in} is the chloride flux (mg/m^2) in the throughfall, $\bar{c}_{thr,measured}$ is the measured monthly average chloride concentration (mg/L) in six throughfall collectors and $\bar{q}_{thr,measured}$ is the measured monthly average throughfall (mm) in six throughfall collectors.

Cl_{out} is defined by

$$Cl_{out} = \sum(\bar{c}_{measured} \cdot \bar{q}_{measured}) \quad (3)$$

where c and q are the average chloride concentrations (mg/L) and percolations (mm), respectively, from any level below the surface.

In the following, measured chloride concentrations from the 4 m deep boring are used to calculate percolation using Eqs (2) and (3). Assuming vertical water flow below the root zone, the calculated percolation can be compared to the modelled percolation from 100 cm.

Results and discussion

Throughfall

Measured throughfall was between 25–54% of the precipitation with no differences between summer and winter periods in 1998 and 1999 (Figure 3). Flügel (1988), in Germany, and

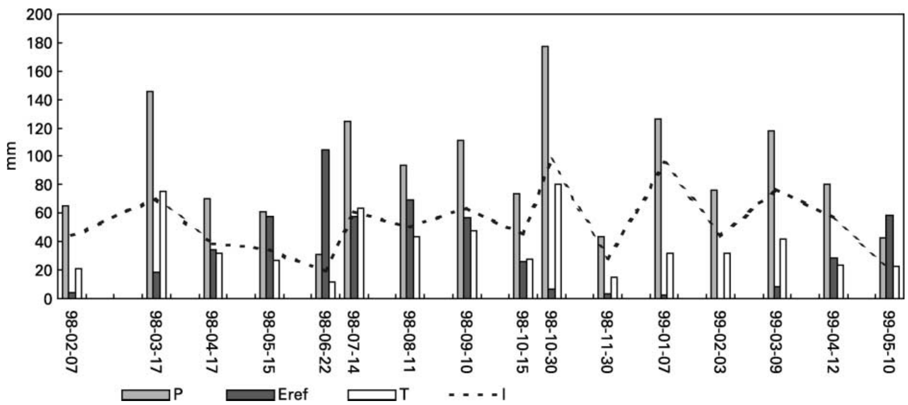

Figure 3 Precipitation (P), throughfall (T), reference evapotranspiration (E_{ref}) and interception loss (I) for 1998–1999. The dates are sampling dates. The collected water is accumulated from the previous sampling data. Samples collected on 7 February represents water back from 7 January. Notice the interval between sampling dates on the x axis as well as the high interception loss

Cape *et al.* (1991), in northern Britain, also reported little or no seasonal variation in throughfall below spruce as expressed as a percentage of rainfall. However, the amount of throughfall recorded is unusually small for Danish forests. In a nearby Danish spruce stand, throughfall was found to be approximately 75% (Schelde 1995; Beier 1998), a result also reported for Swedish, German and British sites (Alavi and Jansson 1995; Benecke 1976; Cape *et al.* 1991). The proximity to the western edge of the stand (40 m) could affect the throughfall amounts although Beier and Gundersen (1989) found that the edge effect on volume and chemistry in a spruce stand was negligible 20 m from the edge.

It can be argued that six throughfall samples were too few to collect representative amounts, since Helvey and Patric (1965) suggest 20 throughfall samples to obtain an acceptable estimate (95%) of throughfall amounts. However, the coefficient of variation between the six samplers varied between 10–30% in 16 sampling periods where throughfall was collected with a mean coefficient of variation of 17%. The variation in measured throughfall amounts compared to modelled throughfall amounts for all sampling periods are presented in Figure 4. The estimate of the mean value of monthly collected throughfall amounts were used to calculate the percolation in both the soil water balance model and by

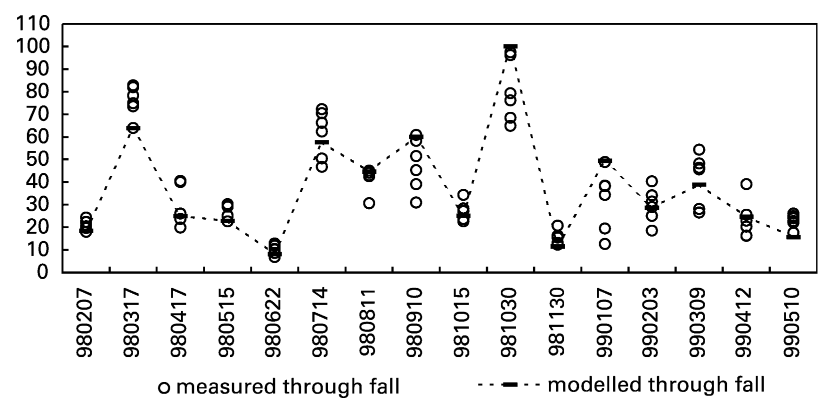

Figure 4 All measured throughfall quantities (mm) and the throughfall calculated by the empirical relationship between precipitation and interception loss (Calder 1990)

the chloride mass balance. The chloride concentration in the throughfall was measured at each sampling period as well and the coefficient of variation varied between 11–51% and the mean value was 26%. More collectors would improve the reliability of the estimate of the mean value of monthly collected throughfall amounts and chloride concentrations. Also, more samplers would give a better description of the variability in the incoming throughfall and therefore more samplers are necessary in more detailed studies.

Monthly interception loss I was calculated by subtracting measured throughfall T from precipitation P. Figure 3 shows monthly reference evapotranspiration for grass (E_{ref}) and interception loss for 1998–1999. The measured throughfall indicates that an unusually large interception loss occurred in our case (58% on average during 1998). The interception loss often exceeded E_{ref}, which is not uncommon in coniferous forest stands (e.g. Leyton *et al.* 1965; Calder 1982; Morton 1984). This is due to a low aerodynamic resistance, a high aerodynamic mixing above forest canopies and a wettable surface in conifers that can sustain a complete surface film of water. Also during winter months it has been shown that interception loss may exceed E_{ref} (Morton 1984), probably due to available advective energy. The measured high interception loss during 1998 and 1999 is compared to precipitation and throughfall measurements from 1992 resembling an average year ($\bar{P} = 875$ mm) and 1996 resembling a dry year in Table 1. From these data it is suggested that the Sitka spruce stand experiences a very high interception loss compared to what is found elsewhere in Denmark. The high interception loss is comparable to what has been reported from highly wind-exposed Sitka stands in Wales (Calder and Newson 1979) where the evapotranspiration was about 864 mm annually, of which interception losses constituted 529 mm and transpiration 335 mm. Annual precipitation was about 2200 mm in the region.

The interception loss in the model was forced to match measured interception loss by tuning a in Eq. (1), since b was found to be constant (0.099) for different vegetation types, including Sitka spruce, in Calder (1990). In Calder (1990) a ranged from 6.6–7.6 mm for different coniferous plantations. In the present Sitka spruce plantation a had to be raised to 9.4 in order to match the measured throughfall. The exceptionally high value of a is believed to be due to the extreme wind exposure of the stand and thus a high aerodynamic mixing above and within the canopy. A comparison of measured and modelled throughfall amount is shown in Figure 4.

Soil water

During the summer of 1998, all soil horizons reached a common water content of 12–13 vol%. During the heavy rainfall in October, all soil layers were rewetted. The water content during winter was more or less stable, ranging from 28 vol% in the top horizon to 22 vol% in the deepest horizon. The coefficient of variation between probes of the same length (Figure 5) showed relatively high variation down to 50 cm during drying and wetting as compared to measurements covering 0–100 cm. The relatively small number of replicates in the present study may indicate high uncertainty, but the variation is comparable to another

Table 1 Measured precipitation (P) and throughfall (T) for the study year 1998, 1992 (an average year) and 1996 (a dry year). The results from 1992 and 1996 are unpublished results from the site lent by K. E. Nielsen, The National Environmental Research Institute, Silkeborg, Denmark

Year	P (mm)	$T_{(measured)}$ (mm)	I (mm)	I (%)
1992	911	292	619	68
1996	588	226	362	62
1998	1122	477	645	58

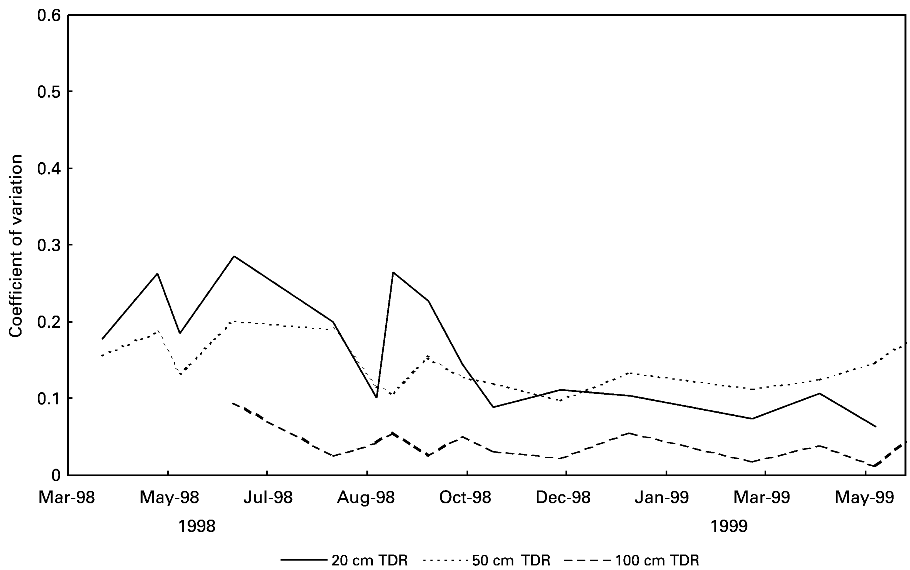

Figure 5 The coefficient of variation of the water content (100 cm probes: $n = 4$; 50 cm probes: $n = 4$; 20 cm probes: $n = 5$)

study in a broadleaved forest (Ladekarl 1998) where, for example, the variation in the top 20 cm reached 35% during summer. During the winter months, the variation was small in all layers. The peaks in September and October 1998 indicated that some kind of heterogeneous wetting took place in the top layers. The water seemed to be redistributed in deeper layers since the variation between the 100 cm probes was very small throughout the year.

Chloride content in the deep 4 m soil core

The chloride concentration in soil water from the 4 m deep soil core approached a constant value of 150 ppm at 3–4 m. Therefore, 150 ppm chloride was used in the chloride mass balance since any seasonal variation in chloride content must diminish with depth. Under the heath area 500 m to the north of the plantation, the chloride content reached a constant concentration 1.5 m below the surface (Hansen *et al.* 1999; Ladekarl *et al.* 2001). The constant concentration level was expected to be deeper under spruce compared to heather due to a more differentiated chloride input in throughfall caused by the taller vegetation and larger leaf area.

The soil water balance model

Transpiration and evaporation from soil were determined by the leaf area index, available soil water content and E_{ref}. The calibrated field capacity in the model was about 26 vol% and lowest water content, also called the wilting point, was between 4.5–12 vol%, depending on soil horizons (Table 2). The wilting point is relatively high in the 0–100 cm layer because roots probably only penetrate to 75 cm and the deepest 25 cm hold a water capacity at about field capacity at all times. The calibrated soil water content was in reasonable agreement with measured values, except for the measurements in late September 1998, late November 1998 (0–50 and 0–100 cm) and the last measurements in May 1999 (Figure 6). In particular the wetting is difficult to model when the throughfall input is heterogeneously distributed. Also, in sandy soils fingering is a common phenomenon, and the measurements in September in particular may indicate heterogeneous wetting since Figure 5 also shows a relatively high coefficient of variation at this period.

Table 2 Parameters used in the model

Parameter	Status/units
a	9.4 mm
b	0.099 mm^{-1}
Leaf area index	6 m^2/m^2
Wilting point, 0–20 cm	9 mm (4.5%)
Wilting point, 0–50 cm	40 mm (8%)
Wilting point, 0–100 cm	120 mm (12%)
Field capacity, 0–20 cm	53 mm (26.5%)
Field capacity, 0–50 cm	130 mm (26%)
Field capacity, 0–100 cm	250 mm (25%)

The percolation from 4 m was calculated from measured chloride concentrations in the boring (Eqs (2) and (3)). This percolation of 187 mm for 1998 is comparable to the modelled percolation from 1 m (242 mm) because percolation is assumed to be constant between 1–4 m below the surface, since no root water uptake is expected below 1 m and lateral flow is assumed negligible in the sandy soil (Table 3). However, the calculation of percolation by the chloride mass balance strongly depends on measurements of throughfall amounts and chloride concentrations in the throughfall collectors since the input to the chloride mass balance is a multiple of the measured chloride concentrations and measured throughfall amounts. Therefore, an increased number of samplers might improve the estimate of percolation. The percolation estimated by the model is dependent on throughfall amounts as well since Eq. (1), which is used to estimate daily throughfall, is dependent on measured throughfall. Due to the dependence on the same input the two methods are not independent and a validation is not possible.

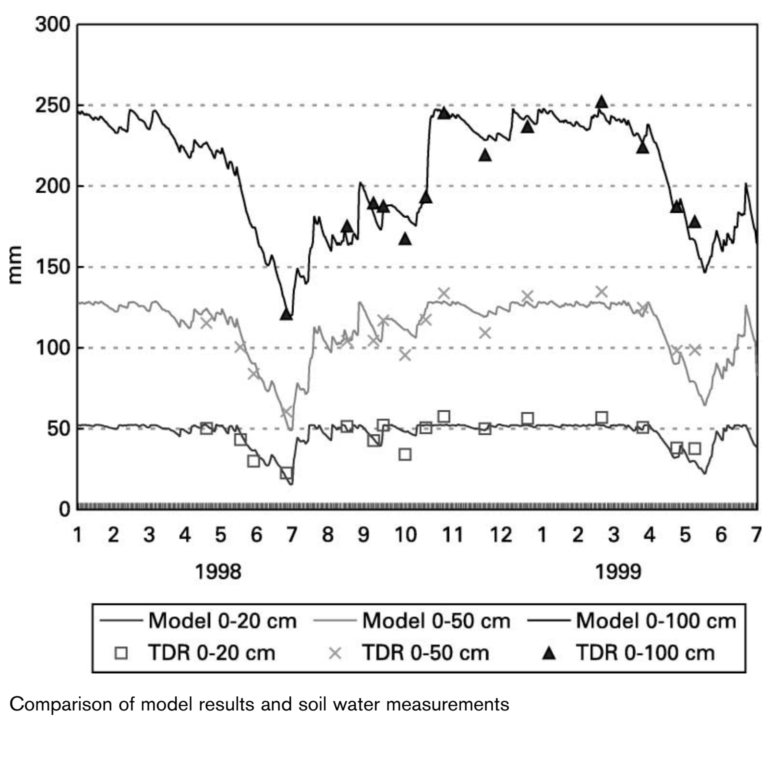

Figure 6 Comparison of model results and soil water measurements

Table 3 Measured water balance variables, results from the ET model and the chloride mass balance method. *P* is the precipitation, *I* is the interception loss, E_{ref} is the reference evapotranspiration for grass, *EA* is the actual evapotranspiration, *T* is throughfall and q_{root} is the percolation from the root zone. In 1998 E_{ref} was 443 mm at the site. All values are for 1998 (7 January 1998 to 7 January 1999)

	Measured (mm)	Soil water model (mm)	Chloride mass balance (mm)
P	1122	–	–
I	645	635	–
EA	–	883	–
T	477	487	–
q_{root}	–	242	187

The percolation estimated by the soil water balance model was only 22% of precipitation and the percolation estimated by the chloride mass balance was 17% of precipitation. The discrepancy between the two methods is rather small. It has earlier been mentioned that discrepancies usually exist between the chloride mass balance method and water balance estimations of percolation. The delay in input compared to output may often be the main reason. At the heath site outside the Sitka spruce stand it was found that, for the second year of two relatively dry years, the chloride balance method and the water balance model agreed better than for the first year, which followed a wet year (Ladekarl *et al.* 2001). The results from the heath site show that, when the chloride concentrations of the net precipitation are alike in two subsequent years, the delays in input and output are of less importance. Also, when measurements of chloride concentrations in the unsaturated zone are from a great depth the within-year variation is probably diminished and a common mean is measured. Additionally, averaging over several years might often diminish discrepancies between delays in input and output. In tall crops input chloride concentrations in throughfall vary inter-annually due to differences in dry deposition dependent on, for example, wind direction and length of dry periods. This variation in input chloride concentrations when throughfall concentrations are used in the chloride mass balance will diminish by averaging the chloride input over a long time span (years).

The low percolation in the Sitka stand is mainly caused by the high interception loss of about 640 mm. The actual evapotranspiration exceeds E_{ref} by up to 100% (Table 3). However, the results are equal to findings in Germany with a similar rainfall, where groundwater recharge was found to be 15% of precipitation and mean annual evapotranspiration to be 79% of precipitation (Flügel 1988).

The estimated transpiration and soil evaporation of about 250 mm in 1998 is relatively low compared to a Swedish study by Alavi and Jansson (1995) and a Danish study in the vicinity of Hjelm Hede by Beier (1998). Alavi and Jansson (1995) found that transpiration and soil evaporation ranged from 276–387 mm/yr in a Norway spruce stand over five years. Beier (1998) found a transpiration of approximately 320 mm/yr during six years in a Norway spruce stand, ranging from about 290–380 mm. However, in another study at the same site Schelde (1995) found that transpiration and soil evaporation ranged from 232–237 mm/yr during the three years following the study by Beier (1998). Thus the estimated result using the soil water balance model calibrated on measured throughfall seems reasonable.

The actual evapotranspiration of about 850 mm during 1998 (Table 3) compared well to the interception loss of 500–600 mm and the actual evapotranspiration of about 850 mm from Wales (Calder and Newson 1979). Benecke and van der Ploeg (1978) found a slightly lower evapotranspiration in Germany, 58% of precipitation, with about half of it lost as interception.

The influence from net precipitation estimation on flux estimations - case example

In order to stress the importance of calibration and evaluation of the soil water balance model using different types of data, a case example using NO_3 is presented in the following. In the Sitka spruce plantation at Hjelm Hede NO_3 was measured monthly in the soil water from different levels in a lysimeter well. The NO_3 output at 60 cm is 73 kg/ha/yr using the model estimate of percolation at 60 cm and the measured monthly concentrations of NO_3 in soil water from that level.

If a calibrated model is not available a water balance might be calculated on E_{ref} and monthly measurements of precipitation. The root water uptake would be restricted to the plant available water content measured by TDR to about 200 mm. The percolation from the root zone (q_{root}) is calculated as

$$q_{root} = P - E_{ref} \quad (E_{ref} < P) \tag{4}$$

For periods with $E_{ref} > P$, the available water content in the root zone restricts evapotranspiration. Using this method the NO_3 output would be 253 kg/ha/yr. Even using a crop factor of 1.1 as reported for Danish conditions (Henriksen 2002), and thus increasing evapotranspiration by 10%, would not be sufficient to decrease the flux to about 73 kgN/ha as estimated from the results from our calibrated and evaluated model. Therefore, it is crucial to studies in forests to focus on the interception loss and to make a separate estimate of the interception loss instead of letting E_{ref} be a limiting parameter.

Conclusion

In this wind-exposed Sitka spruce stand in Denmark the interception loss exceeds by far the reference evapotranspiration and represents more than 50% of the precipitation. The percolation calculated from a soil water balance model was compared to percolation estimated from a chloride mass balance and a good agreement was found.

The following information about the ecosystem was obtained: The measured amounts of throughfall were extremely low (42% of precipitation). The low throughfall input gave very low percolation output volumes as well. The modelled percolation was only 22% of precipitation and the percolation estimate by the chloride mass balance was only 17% of the precipitation. The estimated transpiration was comparable to other sites.

The very high interception loss shows that it is important to distinguish between wet and dry evaporation in forest. It was found that the exponential relation between interception loss and precipitation amounts described the measured interception loss quite well. Therefore, this method is a strong alternative to more input-demanding interception models.

The importance of evaluating water balance models by chemical analysis and calibrating on quantitative measurements of throughfall was clearly demonstrated, especially for cases in which the hydrological measurements are relatively infrequent, only a few samplers are used and the forest is wind-exposed.

The influence of net precipitation estimation on fluxes is demonstrated by a case example using NO_3 flux where a 3-fold difference in flux was found, depending on the water balance method used. Therefore when the focus is on chemistry, and simple hydrologic models are chosen, extra care should be taken to measure throughfall amounts or evaluate the model by, for example, chloride concentrations.

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Abbreviations

E_{ref}	Penman reference evapotranspiration for grass
EA	Actual evapotranspiration
TDR	Time Domain Reflectometry
rpm	rotations per minute
I	interception loss
a	the maximum interception loss
b	the rate at which interception loss increases with increasing precipitation
P	daily precipitation
Cl_{in}	the chloride flux (mg/m^2) in the throughfall
$\bar{c}_{thr,measured}$	measured monthly average chloride concentration (mg/L) in the throughfall
$\bar{q}_{thr,measured}$	measured monthly average throughfall (mm) in the throughfall
Cl_{out}	the chloride flux in any soil/unsaturated zone level
$\bar{c}_{measured}$	measured monthly average chloride concentration (mg/L) in any soil/unsaturated zone level
$\bar{q}_{measured}$	measured monthly average throughfall (mm) in any soil/unsaturated zone level
$\bar{P}$	average precipitation
q_{root}	the percolation from the root zone

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