New Approach to the Measurement of Interception Evaporation

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ABSTRACT

Evaporation of water intercepted by vegetation represents an important (sometimes major) part of evapotranspiration in temperate regions. Interception evaporation is an important process where insufficient measurement techniques hamper progress in knowledge and modeling. An ideal technique to study the interception evaporation process should monitor intercepted mass (and its vertical distribution) and interception loss with high accuracy (0.1 mm) and time resolution (1 min), and give correct area estimates. The method should be inexpensive, require minor supervision during extended periods, and work in dense forests. Net precipitation techniques, in which interception evaporation is determined from the difference between gross precipitation (measured with funnels) and throughfall (measured with funnels, troughs, or plastic sheet net-rainfall gauges) fulfill many of the requirements but usually have a too-low accuracy and time resolution for process studies. Precipitation measurements are normally affected by distortion of the wind field around gauges as well as by adhesive and evaporative losses. Throughfall measurements with precipitation funnels, troughs, or plastic sheet net-rainfall gauges, manually emptied or combined with tipping buckets, usually have too-low accuracy and time resolution for process studies and are impaired by adhesive losses. A new loadcell-based system to determine interception evaporation from gross and net precipitation is presented. A weighing gauge with minimal wind loss is used for precipitation, and weighing troughs are used for throughfall measurements. The weighing troughs minimize adhesive-loss errors and react instantaneously. Preliminary results with the method confirm that it can be used for process studies with a high accuracy (0.1 mm) and a high time resolution (1 min).

1. Introduction

In temperate regions, evaporation of water intercepted by the vegetation represents an important part of the evapotranspiration, and sometimes the major part (Calder 1977, 1990; Viville et al. 1993). There is considerable interest in defining how forest management can be tailored to enhance water yield (Vertessy et al. 1993). Water on the canopy is an important ecological factor that influences chemical, physical, and biological processes taking place on leaf surfaces (Bouten 1992). At regional and global scales, reduction of forests reduces evapotranspiration and affects regional precipitation patterns and global climate (Hutjes et al. 1990). In spite of the large amount of investigations with wet-canopy evaporation, there is no consensus about the sources of energy driving this evaporation process (e.g., Calder 1990; Bouten et al. 1991; Lundberg and Halldin 1994). Physically based interception evaporation models developed by, for example, Rutter et al. (1971), Calder (1977), Sellers and Lockwood (1981), and Massman (1983) have been tested only on net-rainfall and evaporation data. Calder and Wright (1986) used a γ-ray attenuation method and Bouten et al. (1995) and Klaassen et al. (1996) applied a microwave technique to include data on canopy water storage. Development of interception models is held back by lack of techniques to measure state and rate variables (Bouten et al. 1991). Results about evaporation during rain storms are ambiguous. Kelliher et al. (1992) and Yoshida and Hashino (1994) report high evaporation rates during intense rain, while Klaassen et al. (1996) claim that established methods to calculate interception evaporation overestimate the evaporation during rain and underestimate the canopy water storage.

Many attempts have been made in the last 10 years to derive regional fluxes of interception evaporation from small-scale data (de Bruin and Jacobs 1989; Dolman and Gregory 1992; Moore et al. 1993). The objective of the NOPEX (Northern Hemisphere Climate Processes Land-Surface Experiment) project, of which this study is a part, is to study land surface processes at a regional scale for a mixed land cover dominated

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by boreal forest. NOPEX (Halldin et al. 1995) is specifically investigating the transfer of energy, momentum, water, CO_2, and the associated dynamics on a local to regional scale. A substantial part of the NOPEX study is concentrated on the continuous climate monitoring (CCM; Lundin and Halldin 1995) program, and evapotranspiration is a key process in this context. CCM requires measurement of evapotranspiration and interception performed with minor supervision. The characteristics of the newly developed techniques in the CCM program are put in perspective through a review of methods for measuring interception evaporation as the difference between gross and net precipitation. The new improved precipitation and throughfall measurement method, based on loadcells, allows continuous evaluation of interception evaporation. This study is restricted to rain interception. Difficulties associated with snow interception measurements are treated by Lundberg (1993).

2. Methods to measure rain interception evaporation parameters

a. *Miscellaneous methods*

There is a wide variety of techniques used to measure rain interception (water stored in the canopy), canopy-interception-storage capacity, time of leaf wetness, throughfall, canopy evapotranspiration, and interception evaporation (often, but less appropriately, called interception loss). Reviews of interception measurement and leaf wetness methods are given by, for example, Bouten et al. (1991) and Lundberg (1993), whereas canopy-storage-capacity measurements are summarized by Klaassen et al. (1996). Micrometeorological evaporation methods are described by, for example, Garratt (1984) and Sharma (1985). The current study is focused on net precipitation methods.

b. *Net precipitation techniques*

Interception evaporation has traditionally been determined indirectly as the difference between gross precipitation and the sum of throughfall and stemflow (e.g., Horton 1919; Bringfelt and Hårsmar 1974; Calder and Rosier 1976; Gash and Stewart 1977; Rowe 1983; Kelliher et al. 1992). A discussion of methodological problems with such techniques is given by Crockford and Richardson (1990). Throughfall is used here to designate the sum of precipitation falling through the canopy and drip from the canopy. Techniques and accuracies associated with precipitation measurements are discussed by, for example, Sevruk (1986) and with throughfall measurement methods by Crockford and Richardson (1990) and Durocher (1990).

Errors in measurement of rainfall are of crucial importance in interception studies (Calder 1990). Gross precipitation is measured either above the canopy or in an adjacent opening. One of the major problems is related to the undercatch because of the distortion of the wind field around the precipitation gauge. Sevruk (1986) estimates this systematic error to be 2%–10%, while Crockford and Richardson (1990) report events with 20% errors for wind-exposed gauges. A second-order problem is caused by wetting losses from internal walls of the collector and container when emptied. Sevruk (1986) estimated this error to between 2% and 10%, and Günther and Richter (1986) found wetting losses around 0.1 mm per event for a Hellman gauge. Losses of the same order of magnitude were found by Seibert and Morén (1995). In areas where occult precipitation (fog, hoar frost, mist, etc.) cannot be neglected, its measurement is a problem, and Neal et al. (1993) state that it provides the weakest link in estimating interception losses in such situations.

Throughfall has been measured with stationary precipitation funnels (e.g., Horton 1919; Crockford and Richardson 1990; Veneklaas and van Ek 1990), with roving precipitation funnels (e.g., Lloyd and Marques 1988; Hutjes et al. 1990), with troughs (e.g., Reigner 1964; Rowe 1983; Kelliher et al. 1992), and with plastic sheet gauges (e.g., Calder and Rosier 1976; Rao 1987; Tsukamoto et al. 1987; Teklehaimanot et al. 1991; Neal et al. 1993).

Collars around stems are used to collect stemflow, which is then routed to collector bins. Stems are either randomly chosen or selected to represent the girth distribution within a stand. Stemflow is negligible for most coniferous species (values in the range 0.5%–3% are reported by Anderson and Pyatt (1986), Johnson (1990), Viville et al. (1993), and Delfs (1967), with the exception for stands of young Sitka spruce, where stemflow rates may reach 14%–27% (Anderson and Pyatt 1986; Ford and Deans 1978).

3. Requirements for techniques used for interception evaporation process studies

To evaluate the net precipitation techniques, it is necessary to establish criteria that should be fulfilled by an ideal method. The following criteria are related to the goal of studying the process of interception evaporation.

1) The method should work over aerodynamically rough and heterogeneous surfaces such as those of forest stands.
2) Evaporation from a tree in a dense forest differs from that of an isolated tree. An ideal method should be applicable in both dense and sparse forests.
3) The method should work during the quickly changing conditions during and just after a rain.
4) Since the vertical distribution of intercepted water influences the process, the method should provide information on the vertical distribution of intercepted water.
5) Measurements are required with the same time res-

TABLE 1. Net precipitation measurement methods suitable for interception process studies.

Measurement method	Time resolution	Suitable for automated monitoring	Problem with adhesive losses	Problem with wind losses
Gross precipitation measurements				
Funnel, manually emptied	Day	No	x	x
Funnel with tipping bucket	Minute	Yes	x	x
Weighing (vibrating-wire/loadcell) gauge	Minute	Yes	—	x
Throughfall measurements				
Stationary funnels, manually emptied	Day	No	x	—
Stationary funnels with tipping bucket	Minute	Yes	x	—
Roving funnels, manually emptied	Day	No	x	—
Troughs with manually emptied container	Day	No	x	—
Troughs with tipping bucket	Minute	Yes	x	—
Plastic sheet with tipping bucket	Minute	Yes	x	—

olution as the process itself (i.e., 5 min or better) and with an accuracy of approximately 0.1 mm.

6) Installation and maintenance costs should be acceptably low.
7) The technique should be suitable for automated monitoring.
8) The method should be capable of separating interception evaporation during and after rain.
9) The method should give areally correct estimates of interception evaporation.

4. Evaluation of net precipitation techniques used for interception process studies

The three first requirements are met since the net precipitation methods work with rough surfaces in dense forests during the quickly changing conditions after rain. The techniques give only indirect measures of the intercepted mass. Time resolution of the gross and net precipitation measurement depends on the type of data collection (Table 1). Time resolution is usually once per day or per storm if gauges are manually emptied. Time resolution is higher when tipping-bucket gauges are used. Tipping buckets are known to undercatch at high rates because of splash during movement of the buckets, and the calibration factor may alter with time (Marsalek 1981; Adami and Da Deppo 1986). Tipping buckets are consequently less well suited for long-term measurements. Time resolution is not a problem with weighing devices, but the technique is still not widely tested. Vibrating-string gauges are reported to occasionally give irregular error signals (indicating precipitation of 0.2 to 0.4 mm) according to T. Fergus and J. R. Sulebak (personal communication, 1995). Installation and maintenance costs for a net precipitation study can generally be regarded as small compared to the costs associated with most micrometeorological and interception storage measurements methods. The suitability of the net precipitation technique for automated monitoring mainly depends on the type of data collection (Table 1). The technique is not capable of separating interception evaporation during and after rain. The net precipitation method fulfills most of the requirements provided that problems with gauge losses and area representativity can be solved.

The greatest difficulties with precipitation measurement are the losses because of wind and adhesion (Table 1). Weighing gauges do not suffer from adhesive losses. Wind loss problems are larger if a gauge is located above the canopy than in a clearing because of the higher wind speeds, but the rain in a clearing might not be representative if the clearing is too distant.

A great problem with throughfall measurements is that of achieving representative area averages. Kimmins (1973), who worked with funnels in four different stands in a 120-yr-old forest, gives examples where estimates on a 95% confidence level based on a few gauges are associated with errors of 20%, whereas several hundred gauges are required to achieve a 5% error in the estimated mean throughfall (Fig. 1, curves 1–4).

A trough, because of its length, covers much of the throughfall variability and less troughs than funnels are needed to achieve a given accuracy. The quotient between the number of troughs and funnels required to reach a given accuracy is highly dependent on the spatial correlation of the throughfall. Crockford and Richardsson (1990) compared troughs (5 m $\times$ 0.22 m) with plastic funnels (5 cm $\times$ 5 cm) and showed that the number of gauges needed can be reduced to approximately one-fifth by using troughs instead of funnels. An error encountered with troughs is water splashing out from them if the troughs are angled at less than 23° to the horizontal (Reigner 1964; cited by Crockford and Richardson 1990). Another disadvantage with troughs compared to funnels is that they suffer from larger adhesive losses because of their larger receiving surface.

The plastic sheet method yields areally correct averages, but some authors report adhesive losses and risk of blockage of gutter in large storms (Teklehaimanot et al. 1991). There is a risk of holes developing in the sheets after long usage and from branch fall. Irrigation below the sheet may be required when used for prolonged periods to avoid water stress of the stand. The

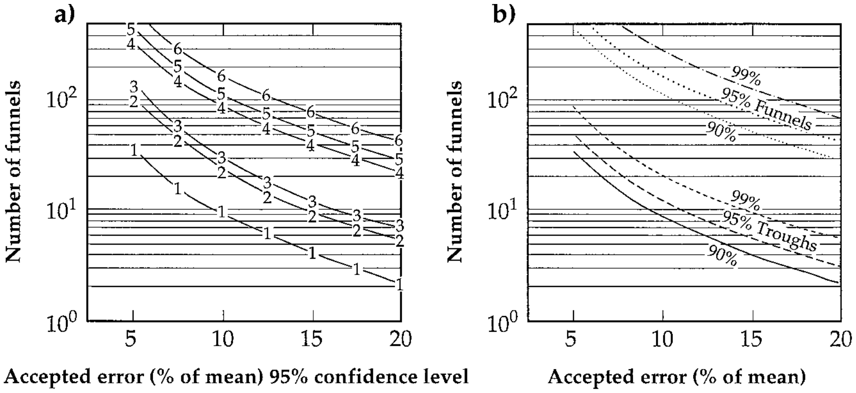

FIG. 1. (a) Number of funnels needed to sample throughfall in different forest stands as a function of the accepted maximum error at the 95% confidence level. Curves 1–4 represent different stands in a 120-yr-old forest (redrawn from Kimmins 1973). Curves 5 and 6 represent calculated values based on published throughfall fields from Ford and Deans (1978; curve 5), and from Bouten et al. (1993; curve 6). (b) The number of funnels and troughs needed to sample throughfall with different maximal errors at given confidence levels, calculated from the data of Bouten et al. (1993).

difficulties with constructing and maintaining plastic sheet gauges makes Teklehaimanot et al. (1991) conclude that funnel gauges are probably more suitable for long-term measurements.

One way to overcome the need for a large number of funnels is to relocate the funnels either at fixed time intervals or after each precipitation event, as recommended by, for example, Lloyd and Marques (1988). The roving method taxes manpower resources and is, therefore, less well suited for continuous monitoring. The method gives areally correct long-time estimates of interception evaporation but results for single events are less meaningful.

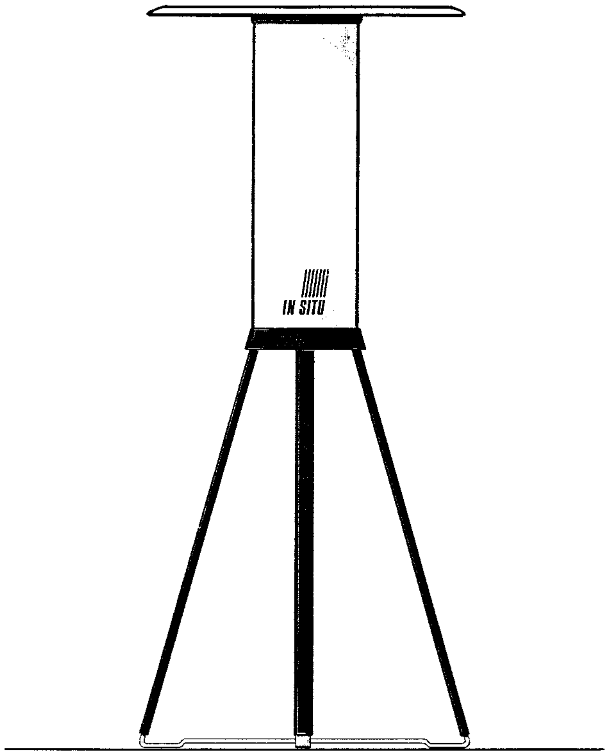

FIG. 2. The weighing precipitation gauge.

5. Loadcell-based weighing system for interception measurements

An improved net precipitation measurement system based on loadcells was designed by In Situ Instruments for use in the NOPEX CCM program. The system comprises a weighing precipitation gauge with a new type of wind shield for measurements of gross precipitation and weighing troughs for throughfall measurements.

a. Precipitation gauge

The precipitation gauge (IS200W, In Situ Instruments) is designed to minimize evaporation and adhesion losses and has a new type of wind shield to minimize wind losses. The shield consists of a flange with its upper surface mounted level with the rim of a cylindrical collector (Fig. 2). The diameter of the flange is about three times the diameter of the collector. The outer edge of the flange has a small angle to minimize the disturbance of the wind field. The upper surface of the flange consists of a special cloth to prevent raindrops from splashing.

The accumulated weight is measured with a loadcell (Tedea Huntleigh, type 104 H, of accuracy 0.015 mm according to the manufacturer) connected to a data logger. A prototype of the precipitation gauge was tested by Lindroth (1991) in a wind tunnel and in the field. This limited field test showed the catch to be 98% of that of a reference pit gauge compared to 95.4% for a shielded Swedish standard gauge (SMHI gauge). Seibert and Morén (1995) performed an extended test where

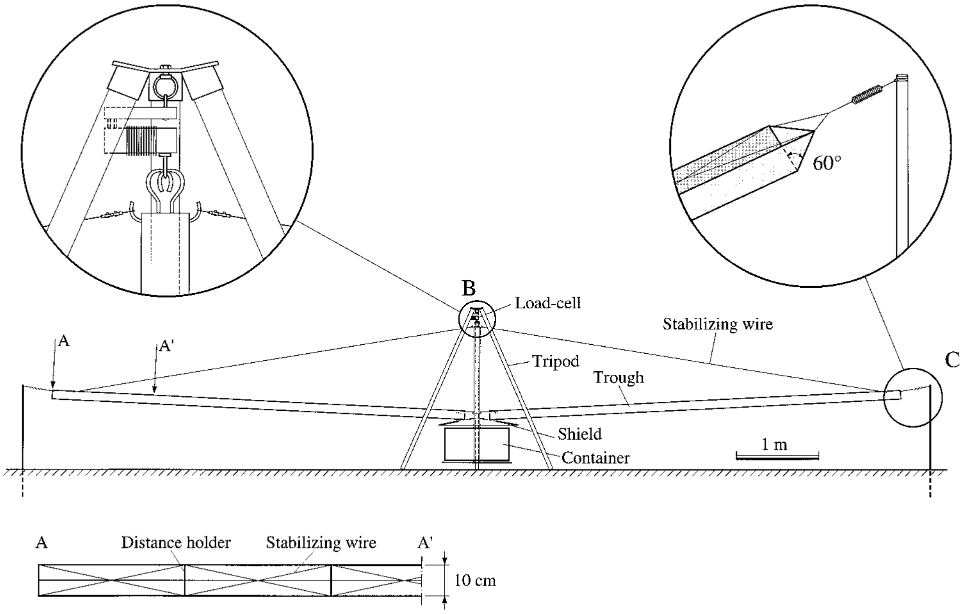

FIG. 3. The weighing throughfall gauge: (a) troughs, (b) loadcell, (c) stabilization arrangement.

FIG. 4. The weighing throughfall gauge.

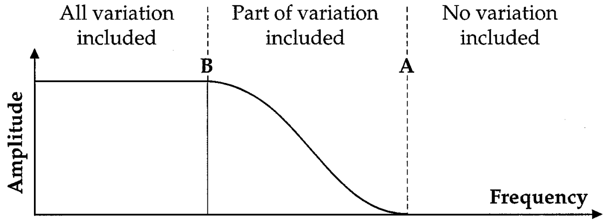

FIG. 5. Low-pass filter with breakpoints *A* and *B*.

the In Situ gauge was evaluated against three different types of gauges (Hellman, SMHI, and tipping-bucket gauges). Also this test confirmed that both wetting and wind losses were reduced with the In Situ gauge. Seibert and Morén (1995) found that the In Situ gauge required a correction to compensate for a temperature dependence of the loadcells.

b. Throughfall gauge

The throughfall gauge consists of two 5-m-long and 0.1-m-wide V-shaped aluminium troughs resting on a stainless steel container attached to a tripod (Figs. 3 and 4). The troughs are equipped with distance sleeves and wires to keep the collection area constant (Fig. 3a) and are angled at 60° to the horizontal (Fig. 3c) to avoid splash problems. The troughs are inclined at 5°–10° toward the container where the water is collected. Each pair of troughs and their container are weighed as one unit to avoid problems with adhesive losses. Weighing is done with the same type of loadcell as is used in the precipitation gauges. The loadcell links a tripod with a pole holding the container and the troughs (Fig. 3b). Heavy plates are attached to the bottom of the container, and the outer ends of the troughs are attached through springs to solidly mounted poles to minimize wind-driven oscillations of the weighed unit (Fig. 3c). A shield is attached to the tripod to avoid throughfall entering directly into the container. The total weight is kept below the maximum limit by manually emptying with a siphon when the container becomes nearly full. The emptying interval depends on the rainfall regime and throughfall characteristics for a given stand, but the container volume should be sufficient in most climates to avoid emptying more frequently than once a month. The loadcell (Tedea Huntleigh, type 355) is hermetically sealed in stainless steel and has a total error (according to the manufacturer) of less than 0.03% of the rated load within the compensated temperature range $-10°C$ to $+40°C$. The loadcells were calibrated by placing a known weight in the container and reading the weight increase from the logger (CR10, Campbell Ltd). The scanning frequency was high (six records per minute) to allow filtration of weight data. The measured weights were continuously subject to a white noise because of small movements of the troughs and container. Occasional high wind speed gusts lifted the troughs and caused a systematic net reduction of the weight.

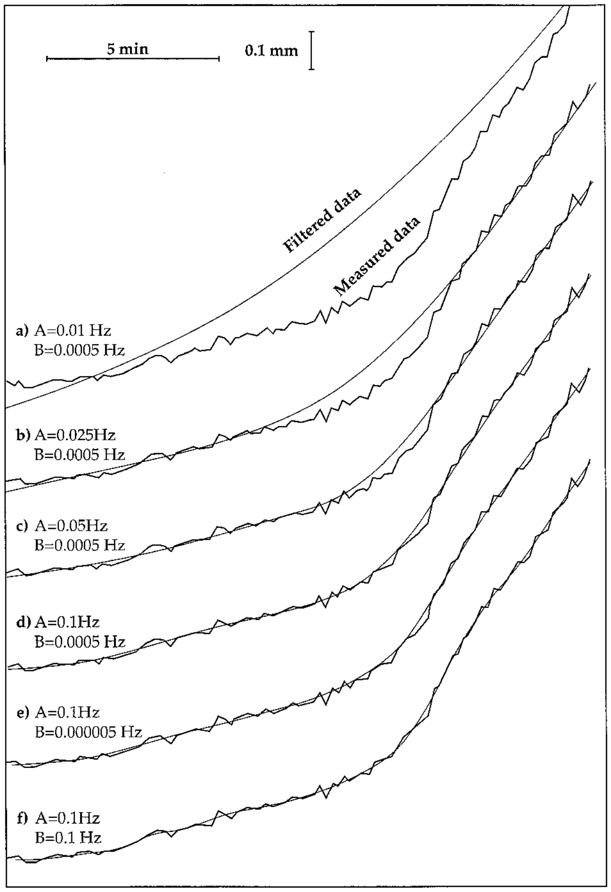

FIG. 6. An event with a steep weight increase. Measured throughfall and filtered throughfall with different breakpoint values *A* and *B*.

The weight signal was filtered to get correct time averages. Three different filters were tested. The first was a two-parameter low-pass filter (Fig. 5). The filter was written in Matlab (1992) (the Matlab Signal Processing Toolbox can also be used if available). The second was a rectangular (one parameter) filter, whereas the third filter was a simple 1-min average. Two time series with different characteristics were used to evaluate the filters. The first series showed a sharp increase in throughfall weight (Fig. 6), whereas the second time series was characterized by the effects of wind gusts and no precipitation (Fig. 7). The two-parameter low-pass filter excluded all frequencies above a breakpoint A. Contributions from frequencies between breakpoints A and B were weighed with a cosine function (Fig. 5). The value of the breakpoints was determined subjectively by visual comparison of the filtered and original time series. The one-parameter low-pass filter was given as the special case of the two-parameter filter for which $A = B$.

Evaporation from the container could be fairly large during hot summer periods (Fig. 8). This evaporation could be reduced by using aerohydraulic oil on the water surface (Bakkehøi et al. 1985) and/or a shield of the

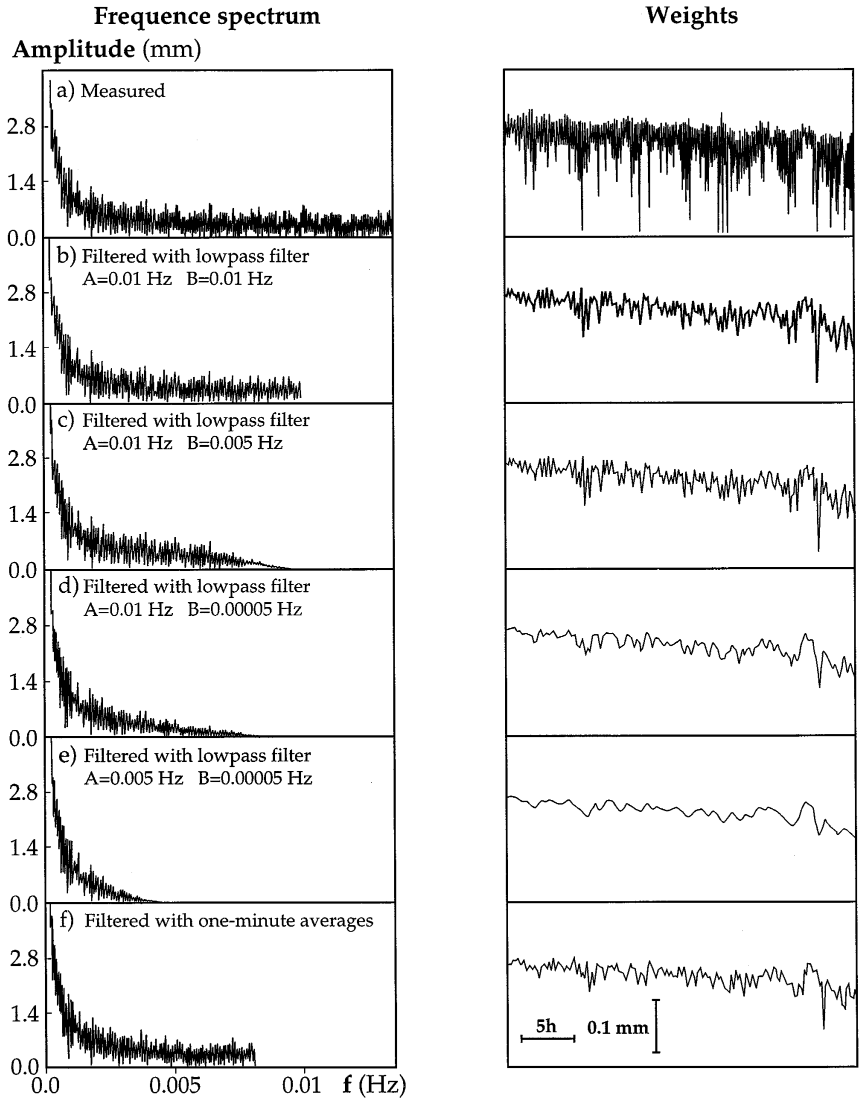

FIG. 7. Frequency spectrum and weight time series during one windy event (a) measured, (b)–(f) filtered.

type used for evaporation reduction in precipitation funnels. A correction for the container evaporation was made afterward since the size of the error was not realized in time. Two week-long periods with no precipitation and hot weather (Figs. 8a,c) were used to determine individual corrections for the different throughfall gauges. Container evaporation E_C was approximated with a Dalton-type formula $E_C = (k_1 + k_2 w)(e_a^* - e_a)$, where k_1 and k_2 are empirical constants, w is wind speed (measured at 28 m), e_a^* is the saturation vapor pressure of air, and e_a is the actual vapor pressure of the air (at 28 m). The values of the constants were subjectively determined for each gauge. The loadcells were subjected to a small temperature dependence at high air temperatures. Measured weights W_M (kg) were corrected to W_C (kg) for air temperatures (at 28 m height) exceeding 20°C through $W_C = W_M - (T_{-3\text{h}} - 20)/150$, where $T_{-3\text{h}}$ is the air temperature (°C) with a 3-h lag.

The number of gauges n needed to get an estimate of a normally distributed variable with a specified accuracy a (maximal error divided by average m) at a confidence level L can be calculated from the standard deviation σ (Benjamin and Cornell 1970, 386–96):

$$n \geq \left(\frac{\sigma t_L}{am}\right)^2, \tag{1}$$

where t_L takes values of 1.64, 1.96, and 2.58 for L equal to 90%, 95%, and 99%, respectively. Ten new throughfall gauges were placed in the mixed pine–spruce forest at the Norunda Common, 30 km north of Uppsala, Sweden, the location of the NOPEX Central Tower Site

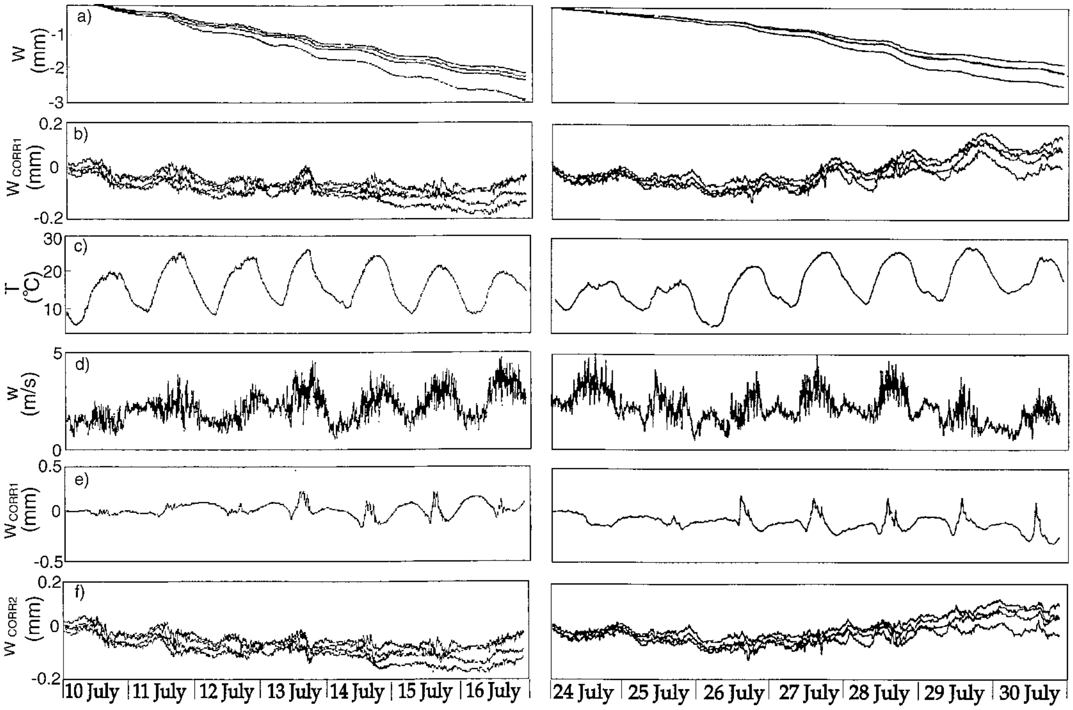

FIG. 8. Throughfall gauge signals and weather during two hot periods with no precipitation and with considerable evaporation from the gauge containers in the 50-yr-old stand. The left row is for 10–16 July 1995. The right row is for 24–30 July 1995. (a) Registered weight W of gauges 1, 2, 4, and 5; (b) weights corrected for evaporation W_{CORR1} of gauges 1, 2, 4, and 5; (c) air temperature at 28 m; (d) wind speed at 28 m; (e) throughfall weight, corrected for evaporation, W_{CORR1} of gauge 3; (f) throughfall weight corrected for evaporation and temperature dependency of loadcells W_{CORR2} of gauges 1, 2, 4, and 5.

(Lundin and Halldin 1995). To get an estimate of the standard deviation σ of throughfall in this forest, published data were used on throughfall variability from two other coniferous forests. The high-density throughfall values (represented as maps) from a 35-yr-old Douglas fir stand with 885 stems ha^{-1} and mean height of 20 m, published by Bouten et al. (1993), were assumed to be most representative for the Norunda site. Throughfall data from a study by Ford and Deans (1978) in a 14-yr-old Sitka spruce stand with 3600 stems ha^{-1} and a mean height of 6.5 m were used as a complement. The standard deviation of a throughfall estimate for a set of measuring devices in a specific configuration was determined with a GIS technique. The throughfall values were digitized (grid 0.17 m) and a normal-distributed random noise of 4% was added to the published data to compensate for the smoothing when the original maps were created [Bouten et al. (1993) using a Kriging technique, whereas Ford and Deans (1978) used SYMAP software]. Imaginary funnels (area = 0.02 m^2) were randomly placed in the throughfall fields, and the standard deviation for the funnels σ_F was determined with GIS software (Surfer for Windows 1994). The same operation was performed with troughs (area = 0.1 m × 10.0 m). Values for throughfall averages m and standard deviations σ were calculated. The number of devices n needed to get a given accuracy at a specified confidence level were calculated assuming the throughfall to be normally distributed. The quotient between the number of funnels n_F and troughs n_T needed to get the same accuracy at a given confidence level was finally calculated by rearranging Eq. (1):

$$\frac{n_F}{n_T} = \left(\frac{\sigma_F}{\sigma_T}\right)^2. \tag{2}$$

6. Results

The best filter for the throughfall time series was selected as a compromise between requirements to filter out white noise during intensive throughfall events and systematic uplifts caused by wind gusts (Figs. 6 and 7). Low values for breakpoint A in the two-parameter filter smoothed out the curve too much (Figs. 6a–d). Wind gusts of approximate 8 m s^{-1} at 28 m (approximately 5 m above the canopy) caused considerable wind lift of the troughs (Fig. 7a right), seen as a high-frequency noise (Fig. 6a left). All filters gave much smoother curves than the measured ones (Figs. 7b–f, right). The two-parameter filter with $A = 0.005$ Hz and $B = 5 \times 10^{-5}$ Hz gave the subjectively best result to suppress wind-lift effects. The optimal two-parameter filter for both tested time series was given by $A = 0.01$ Hz. A

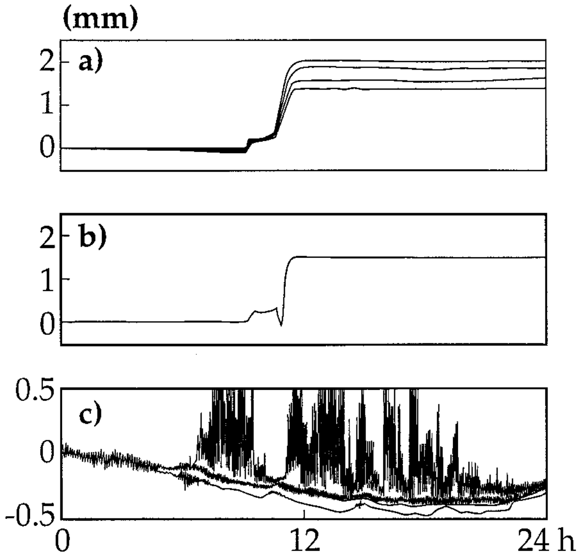

Fig. 9. Accumulated throughfall in the 50-yr-old stand. Registered weights on 17–23 October 1994 given as (a) normal signals from gauges 1, 2, 4, and 5; (b) an occasionally erratic signal from gauge 3; and (c) example of "electronic noice" from one of the five gauges on a day in July 1995.

range of values for breakpoint B gave similar effects on the filter characteristics (Figs. 6d–f and Figs. 7b–d) and the one-parameter filter ($A = B$) was only slightly less efficient than the best two-parameter filter (Fig. 7b). The simple 1-min average filter gave a somewhat smoother curve than the one-parameter filter (Figs. 7b and 7f).

The correction for container evaporation was successful (Fig. 8b). The correction for the loadcell temperature dependence (Fig. 8f) gave a small improvement. There was a tendency for a remaining but very small (less than 0.1 mm per 24 h) daily variation. The largest remaining variation was approximately 0.06 mm per 6 h (0.01 mm^{-1} h). One of the loadcells gave erroneous result during the hottest periods (Fig. 8e) for yet unknown reasons. A few times it was obvious that the measured weight from one of the loadcells was false (Figs. 9a,b). Two of the loadcells were sometimes subjected to an "electronic noise" (Fig. 9c). Based on the throughfall field from Bouten et al. (1993), the probability of a given throughfall, average from the GIS-based analysis was approximately normally distributed both for troughs and funnels (Fig. 10a). Standard deviations were about 50% of the funnel average and 20% of the trough average (Table 2). Around 40 funnels were needed to achieve an accuracy better than 20% of the average at a 95% confidence level (curve 6, Fig. 1a). An unrealistically large number ($>$600) of funnels would have been required to achieve an accuracy of 5% at the same confidence level. Five troughs resulted in accuracies of 14.5%, 16.5%, and 20% at confidence levels of 90%, 95%, and 99% (Fig. 1b). The results were not sensitive to the exact size of the random correction to the published throughfall field.

The behavior of the loadcell-based interception measurement system is demonstrated with data from one precipitation gauge and throughfall gauges during the autumn 1995. The measurements were part of the NOPEX CCM program (Lundin and Halldin 1995). At the central tower site, a 100-m-high tower is located in the center of an extensive and relatively homogeneous forest (Fig. 11). The forest consists of several mature pine–spruce stands. Five gauges were located in a 50-yr-old stand (L-stand) and five other in a 100-yr stand (C-stand). The L-stand had a closed canopy with occasional openings and was dominated by Norway spruce (*Picea abies*, 70%) and Scotch pine (*Pinus silvestris*, 30%). The average height was around 20 m and the average diameter at breast height (dbh) was about 24 cm. The C-stand had a more open canopy and was dominated by pine (60%) and spruce (40%). The average height was around 24 m and the mean diameter at breast height was about 26 cm. The August–September climate for the area is characterized by temperatures around 10°C and a monthly precipitation of 70 mm (Alexandersson et al. 1991). The accumulated interception evaporation measured between 15 August and 1 October 1995, with precipitation during 20 out of 61 days, was 23% of precipitation (84 mm) in the C-stand and 32% in the L-stand.

Four sequential days with several showers and a total gross precipitation P_G of 10.0 mm (Fig. 12b) was recorded in September 1995. The average (for each five gauges) accumulated throughfall P_N was 7.7 mm in the C-stand and 6.9 mm in the L-stand (Fig. 12b). Accu-

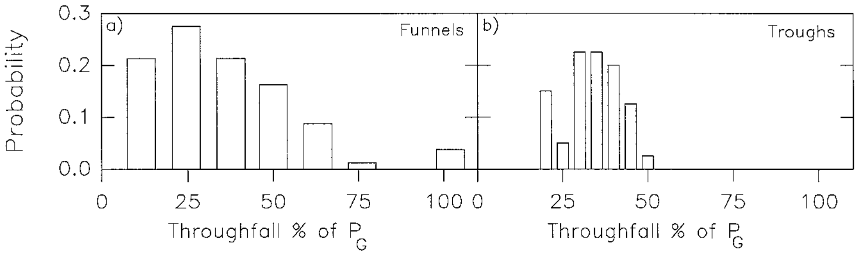

Fig. 10. Throughfall distribution (expressed as fraction of gross rainfall P_G as measured with hypothetical (a) troughs (n = 40) and (b) funnels (n = 80). Calculations were carried out with a GIS technique on the basis of a throughfall field in Bouten et al. (1993).

TABLE 2. Simulated averages m and standard deviations for throughfall measured with funnels σ_F (σ_F = 200 cm^2) and troughs σ_T (L = 10 m, W = 0.1 m) and quotient between number of funnels n_F and troughs n_T needed to get the same standard error. Simulations were performed with a GIS technique from literature data.

Source	Precipitation	m (mm)	σ_F (mm)	σ_T (mm)	n_F/n
Bouten et al. (1993)*	One 6-mm event	2.06	1.35	0.37	13
Ford and Deans (1978)**	26.4 mm in a week	8.80	4.75	1.79	7

* Throughfall measured with TDR technique (48 sensors over 50 m) interpolated with Kriging technique.

** Throughfall measured with 104 funnels (d = 152 mm) covering 15% of the ground area, interpolated with SYMAP software.

mulated throughfall in the C-stand varied among the gauges from 7.4 mm to 8.3 mm (Fig. 12c). The average interception evaporation during this period was 2.3 mm for the C-stand and 3.0 mm for the L-stand. Around 0.3 mm was intercepted on the canopies (average of both stands) during the smallest showers, whereas somewhat less than 1 mm was intercepted per event for showers larger than 2 mm (Fig. 12e).

7. Discussion and conclusions

The ideal measurement technique for interception process studies should continuously monitor intercepted water and its vertical distribution and interception evaporation with high accuracy (0.1 mm), high time resolution (1 min), and give correct area estimates. The method should be inexpensive, require minor supervision, and be operable in dense forests.

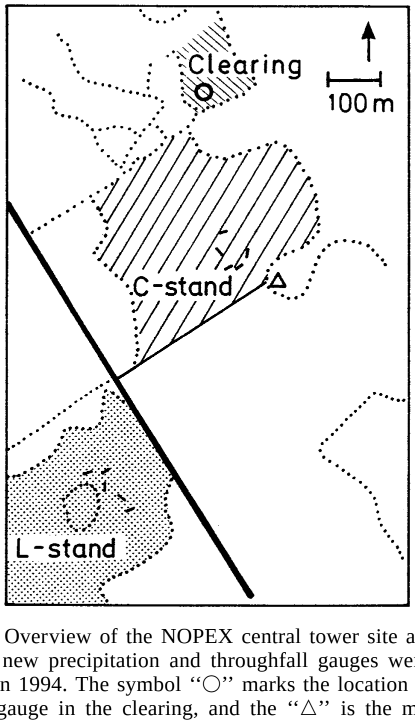

FIG. 11. Overview of the NOPEX central tower site at Norunda, where the new precipitation and throughfall gauges were put into operation in 1994. The symbol "○" marks the location of the precipitation gauge in the clearing, and the "△" is the mast with a precipitation gauge in the top for wind, temperature, and humidity measurements. Throughfall gauges are marked with small lines. The dotted lines show borders between stands whose ages are given in years.

The traditional method in which interception evaporation is determined from the difference between gross precipitation (measured with funnels) and throughfall (measured with funnels, troughs, or plastic sheet net-rainfall gauges) fulfills many of the requirements but has a too-low accuracy and time resolution for process studies. Precipitation measurements are normally affected by distortion of the wind field around gauges and adhesive and evaporative losses. Throughfall measurements with precipitation funnels, troughs, or plastic sheet net-rainfall gauges, manually emptied or combined with tipping buckets, are impaired by adhesive losses.

The loadcell-based net precipitation system, designed to overcome the weaknesses of traditional systems, required careful processing of the weight signal before the throughfall could be determined. The noise produced by wind gusts could be filtered out successfully with a two-parameter low-pass filter. For wind speeds below 6 m s^{-1} (5 m above the canopy), which was the normal case, a simple 1-min-average filter was acceptable. Only small effects of wind can be expected on the troughs for wind speeds between 6 m s^{-1} and 10 m s^{-1}. Wind speeds above 10 m s^{-1} could cause the troughs to be dislodged and come into direct physical contact with the legs of the tripods. Errors because of mechanical movements (primarily caused by wind) were normally less or much less than 0.1 mm after filtering of the signal. The high signal-sampling rate produced a large amount of data for storage. This problem could be resolved by inclusion of the filter already in the logger. For less sophisticated loggers an alternative could be to store the 1-min-average values and sort out time periods with a wind speed exceeding the 6 m s^{-1} threshold in retrospect.

Evaporation from the containers could be reduced by a layer of aerohydraulic oil, but a separate correction was shown to be sufficiently good. It was difficult to separate the evaporation correction from a possible temperature dependence of the loadcells in the field. Our result indicated that the loadcells had a notable temperature dependence at high temperatures. This indication is also confirmed by the findings of a temperature dependence in loadcells of the same type used in the In Situ precipitation gauges (Seibert and Morén 1995). The loadcell in the precipitation gauge is probably more exposed to large temperature variations since it is con-

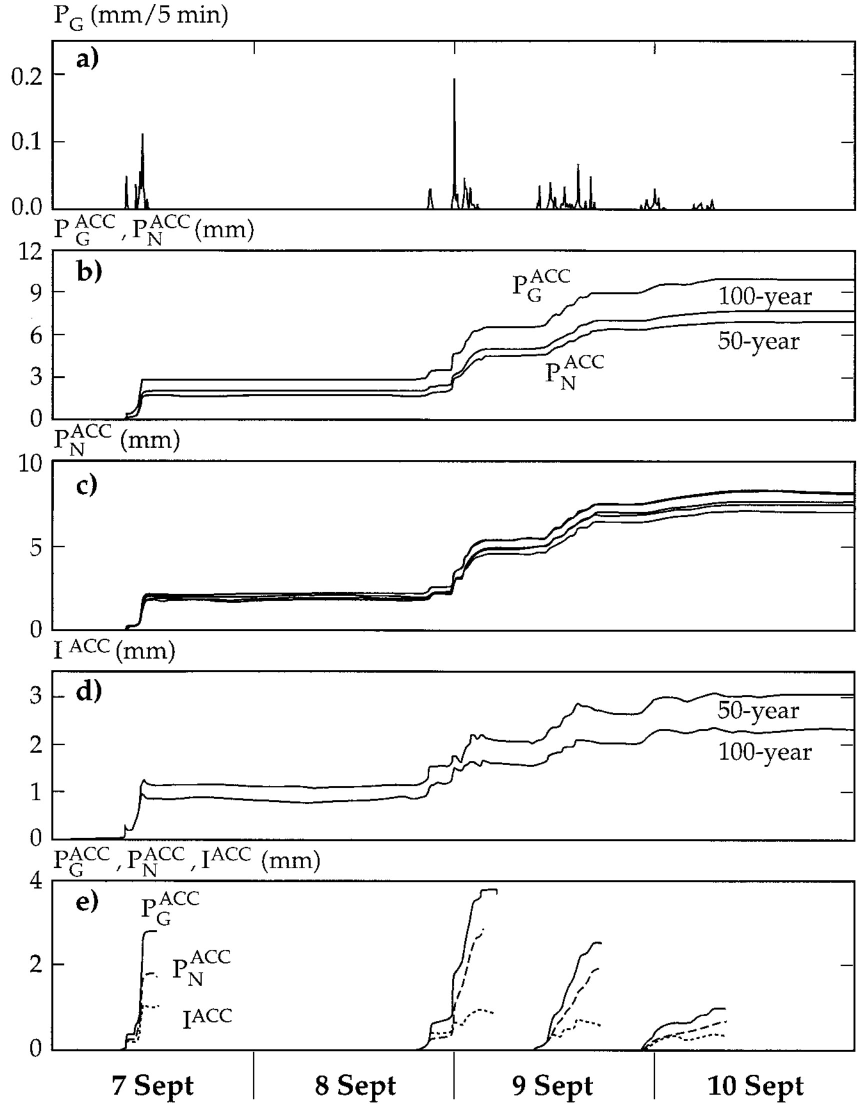

Fig. 12. Precipitation P_G, throughfall P_N, and interception evaporation I at the 50- and 100-yr-old stands on 7–10 September 1995. Superscript ACC denotes the measured, accumulated weights. (a) Measured precipitation; (b) average throughfall in the two stands together with the corresponding precipitation; (c) throughfall as measured by each gauge in the 100-yr-old stand; (d) Cumulative interception evaporation I^{ACC}; and (e) precipitation, throughfall, and interception evaporation accumulated for individual events (average for both stands).

tained in a nonventilated box, while the loadcells of the throughfall gauges are freely exposed to the surrounding air. A sun shield would probably be useful to protect the loadcell from excessive temperatures. The remaining error after correction for evaporation from the container and temperature dependence of the loadcell was always less than 0.01 mm h^{-1}. Since the temperature during the calibration period was extremely high, it is probable that the errors are normally much less than this.

An expected advantage with weighing the troughs was that adhesive losses were directly accounted for. An unresolved issue with the weighing technique is the separation of drip from the canopy and evaporation from the trough directly after a rain shower. A practical problem was associated with litter from the trees, which gradually assembled in the troughs and which was manually removed approximately once a month. The dry weight of this detritus was negligible but it absorbed water during rainfall thereby prolonging evaporation from the trough. To separate drip from evaporation of adhesive water in the troughs, one could weigh only the container and not the troughs or have the container separately weighed. Such a solution would also minimize the problems of wind lifting the troughs.

It was not always possible to explain the causes of clearly erratic signals (e.g., Fig. 9b) that some of the loadcells occasionally presented. One likely explanation is that the suspended trough-container unit came in direct contact with the supporting tripod. The throughfall gauges were randomly placed in the terrain, and this procedure created practical problems with maintaining a safe distance between troughs and legs of the tripods. The sometimes small margins might have been exceeded because of wind-induced oscillations or tripod movements because of soil settling. Since erratic signals were often related to high wind speeds, the first explanation is the most likely one. It may be wise to restrain requirements of randomness when physically locating the throughfall gauges in return for securing mechanically good arrangements. An inspection should take place, especially after major storms, to guarantee that the gauges have not been dislodged.

Around 10 times as many funnels as troughs are needed to achieve a given accuracy for a measured throughfall average in the throughfall fields published by Bouten et al. (1993) and Ford and Deans (1978) (Table 2). This confirms the findings of Crockford and Richardson (1990) that the number of gauges can be reduced by approximately one order of magnitude if troughs are used instead of funnels. The use of a 0.17-m grid size in the GIS analysis means that round funnels ($d = 0.17$ m) were approximated by square funnels and that troughs were not 0.1 m but 0.17 m wide. This approximation did not essentially influence the results. Assuming that the spatial pattern of throughfall at the Norunda site was in accordance with the pattern presented by Bouten et al. (1993), the relative error of the measured averages from the five gauges in each stand was estimated to have a maximum error of 20% at a confidence level of 99% (Fig. 1b). The spatial correlation at the Norunda site may be different from the one given by Bouten et al. (1993), and it may vary with precipitation intensity. The estimated accuracy can still be considered as a probable upper limit. The throughfall variability used was higher than those reported by Kimmins (1973) and Ford and Deans (1978). The close agreement between measured throughfall from different troughs also supports this contention (Fig. 12c). A definite statement about the accuracy of the measurements in Norunda would require resource-intensive experiments to map the throughfall field in detail. Areally representative data on interception with a high time resolution is a prerequisite for the parameterization of the rain interception process in hydrological and meteorological models. Interception data of this kind should, furthermore, be available for a broad range of rainfall events and conditions. Such data can be guaranteed only from multiannual, continuous time series because of the highly stochastic nature of precipitation. The loadcell-based system presented in this paper makes such measurements possible on a fairly low budget. The system is limited to direct monitoring of throughfall and can give only indirect information on the intercepted water. Optimal use for process studies would be achieved by combining this system with direct methods to measure the intercepted mass (e.g., the microwave or displacement-transducer methods) and the evaporation (e.g., the eddy correlation method). For studies of chemical, physical, and biological processes taking place on wet leaf surfaces, it would be preferable to concentrate on systems designed for direct measurement of the surface wetness.

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