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The Use of Lysimeters in the Study of Soil Surface Processes: Modelling and Measurement Applications

J. Ahonen[1], *S. Tattari*[2], *K. Granlund*[2] *and J. Soveri*[2]

[1] 6409 65th Avenue NE, #225, Seattle WA 98115, USA
[2] Finnish Environment Agency, P.O. Box 140, FIN-00251 Helsinki, Finland

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Abstract

Four lysimeters situated in central and southern Finland were used to study percolation processes. Model simulations were done with two different physically sound soil water models and with a transfer function model.

The objective was first to replace any percolation values that were missing and second, to simulate the soil water storage variation. The sensitivity of the model to the parameters used in calculating the hydraulic conductivity was determined.

The physical soil water models failed to predict, and thus failed to replace, missing daily percolation values. A transfer function model was satisfactory in predicting missing values for a short period of time. The simulation of soil moisture storage variation by the two physically based models was good. However, distribution of soil water content within the profile proved to be difficult to achieve. The coarseness of texture and the disturbed stratification hampered modelling.

Key words: hydrology, percolation, soil moisture variation, lysimeters

1. Introduction

The groundwater monitoring network of the National Board of Waters and the Environment in Finland comprises 54 stations representing the country's different geological and climatological conditions (*Soveri*, 1985). Each station has equipment for measuring the groundwater level and soil moisture content, and 47 of the 54 stations have a lysimeter enabling percolation to be measured (Fig. 1). The main objective of this study was to gain insight into water flow in the unsaturated zone and to clarify the factors having the greatest influence on the amount of percolation water. The properties of different lysimeters were therefore compared in order to determine the differences and similarities in their behavior. For the comparisons, water balances, daily variation in percolation, and soil moisture were studied to find out whether the lysimeters could be grouped according to their properties. The geographical location, precipitation-percolation relation and other local factors were also taken into account. Second, the dependence of monthly percolation on climatic factors was examined by means of statistical analysis.

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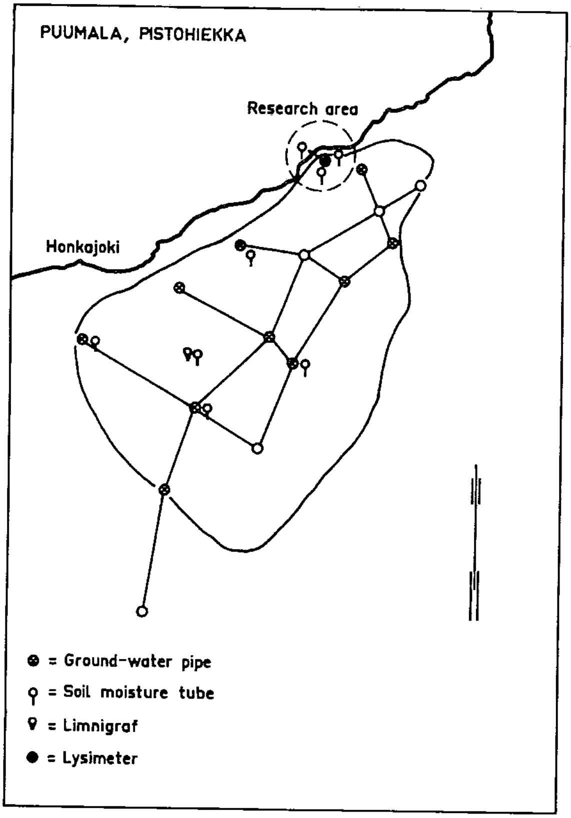

Fig. 1. Example of a groundwater station and the location of its equipment.

The percolation water time series are not always complete; lacking data complicates the calculation of monthly or semi-annual water balances. Model applications were carried out in order to examine the possibility of using modelled values to replace the missing daily values. The sensitivity of percolation and soil water storage with regard to some model parameters was also studied.

Four lysimeters representing typical groundwater recharge areas were selected for studying water flow processes. The research period was limited roughly to the summer of two years, the actual observation period ranging from June 1 through September 30 in 1983 and 1984. The time series for these two years were most complete at all four stations. Two one-dimensional soil water models were used to simulate water flow processes, emphasis was placed on the amount of lysimeter percolation water. The results obtained with the models were compared with the actual measurement results, and the goodness of the fit was estimated.

2. *Materials and methods*

2.1 *Site description of the stations*

The four lysimeters selected for the study were those situated at Oripää (60°55'N, 22°41'E), Pistohiekka (61°34'N, 28°01'E), Kangaslahti (63°25'N, 28°05'E), and Pesiöjärvi (Mäntyniemi) (64°57'N, 28°33'E) (Fig. 2). All the stations are located in natural forest areas.

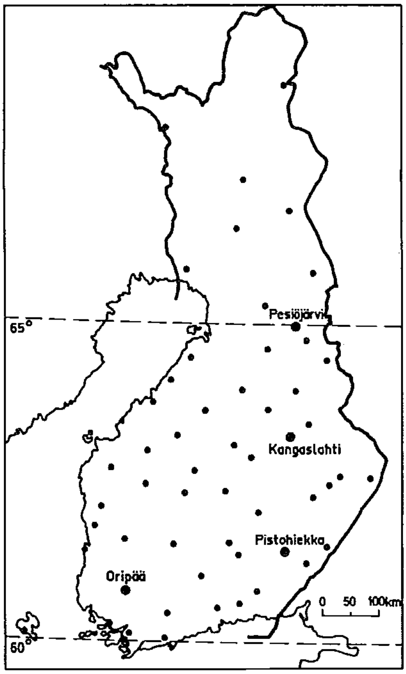

Fig. 2. The network of the groundwater observation stations in Finland, including the stations selected for this study.

Oripää is situated in the southwestern Finland. The size of the catchment area is about 7 km^2, and it is located on a piny esker of sand and gravel. The station's two lysimeters were installed in 1972 and 1974, respectively. Two precipitation gauges are located near the lysimeters, and soil moisture is measured at five points. The groundwater level lies approximately 5 meters below the soil surface. Climatological data used in the study was collected at the Jokioinen observation station, 40 kilometers from Oripää.

Pistohiekka is situated on an esker in southeastern Finland. The catchment area is considerably smaller, 0.9 km^2. The soil is coarser than in Oripää but, the texture in the lysimeter itself is finer (Fig. 3). The lysimeter was installed in 1975. Near the lysimeter, the groundwater table lies at a depth of 8 meters. The climatological data for the study was gathered at an observation station 3 kilometers from Pistohiekka.

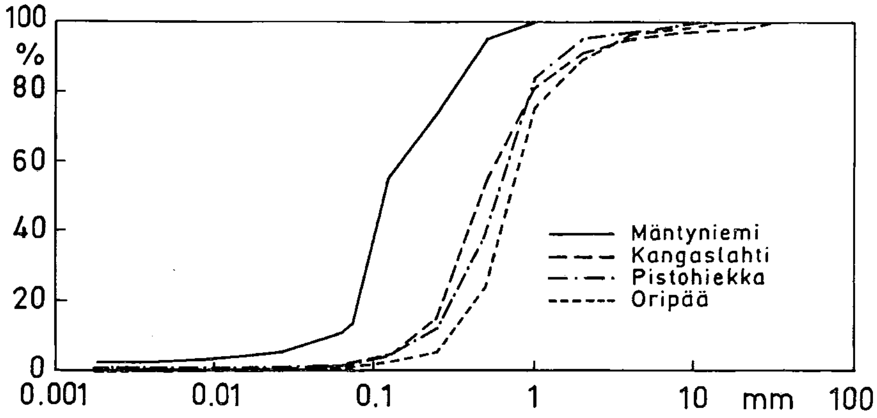

Fig. 3. Average grain size curves of the four lysimeters.

The third lysimeter, Kangaslahti, is situated in central Finland and was built in 1976. The catchment area is 0.8 km^2. Pine forest and coarse sandy soil also dominate in this area. The soil texture of the lysimeter is very similar to that of Pistohiekka. The climatological data was measured about 29 kilometers from Kangaslahti.

The hydrological observation area of Pesiöjärvi is large, 102.5 km^2. It is also situated in central Finland, although further north than the others. There are four groundwater stations in the area. The Mäntyniemi lysimeter, built in 1981, was chosen for the study. It is situated in sandy soil which is clearly finer than that of the others. The groundwater level is about 5 meters below the soil surface. The climatological data was obtained from the observation station in Suomussalmi village, about 20 kilometres from Mäntyniemi.

2.2 *Construction and management of lysimeters*

A lysimeter is an underground soil container. The lysimeters used in the study are non-monolithic draining lysimeters, which means that the soil stratification is disturbed during installation. The depth of the lysimeter is 1.7 meters (except at Pistohiekka, where it is 2 meters) and the bottom layer consists of a 0.15 meter gravel layer. At the bottom of the round metallic soil container there is a pipe, 20 mm in diameter, that leads the percolation water out to the container (Fig. 4). Changes in the water level in the container are registered by a recorder so that percolation can be read at desired time intervals. The recorder paper is changed every second week and the container emptied when necessary. The quantity of water in the container is measured and then compared with the amount measured by the recorder. The less the percolation, the greater is the error in the recorded value as compared to the observed value. In optimal conditions the measuring accuracy is ± 0.1 mm/d; otherwise the accuracy is ± 0.2-0.5 mm/d (*Vesterinen et al.*, 1991).

Percolation water is normally observed during the frost-free season, usually between May and October. Winter percolation is measured only in Oripää. Elsewhere, even though the lysimeters are installed in permeable soils where little frost forms, the frost causes problems with the instruments. Winter percolation is, however, negligible in all but exceptionally mild winters.

One soil moisture tube is placed inside the lysimeter vessel, and two outside of it (Fig. 4). This makes it possible to compare the changes in soil water content inside the vessel and in naturally draining soil. The neutron scattering method is used to observe the variation in soil water content once a month.

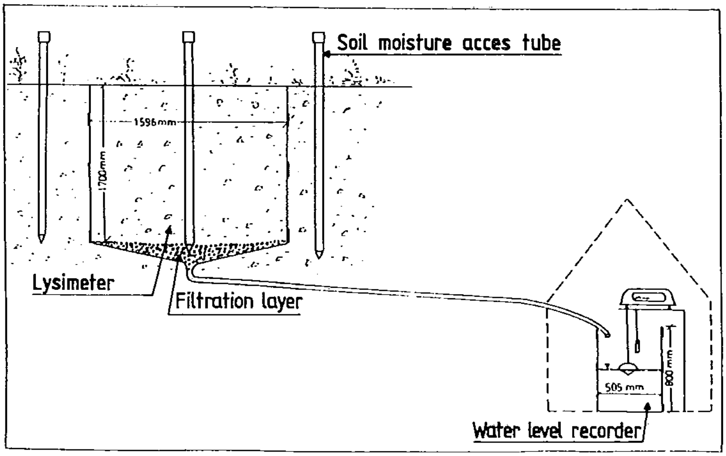

Fig. 4. Scheme of the lysimeter and the location of soil moisture tubes.

2.3 Uncertainties in the Study

2.3.1 Disfunctions

In a one-year period, the disfunctioning time of the lysimeters accounts for from 5 % to 25 % of their operating time. One of the most difficult problems is to detect whether the lysimeter is partly clogged or leaking, thereby resulting in abnormally low percolation values. Furthermore, the study of observations requires caution, as not all the anomalies are errors. Other explanations for such discrepancies are possible, including for example, high evaporation rates. Also, because the observation visits to the sites are rare, the water container may overflow, thus preventing further registration by the recorder. The recorder timer is another potential source of inaccuracy. In a two-week period, the recorded time can exceed the time observed by 4 to 5 hours.

2.3.2 Precipitation and soil water content

Not all the lysimeters have a rain gauge in the vicinity. In Finland rains are often very local during summer. The water balance calculations may involve some uncertainty if the climatological station is located far away from the lysimeter. The precipitation values must also be corrected, using a coefficient that includes the effects of wind, evaporation and wetting (*Kuusisto*, 1986).

Soil water content is measured with a neutron probe. Its repetition, when properly calibrated, is about 0.7 % of volume (*Tattari* and *Granlund*, 1989); on the lysimeter scale, this means an error of about 10 millimeters. Inside the lysimeter, the moisture content is typically lower at the uppermost 30-40 cm than that measured outside, and by contrast, it is typically higher in the bottom layers (Fig. 5). Moisture profiles inside and outside the lysimeter can also differ significantly. This discrepancy may stem from disturbance of the soil stratification in the lysimeter during installation. Also, the outlet pipe may be clogged by fine soil particles, or its insufficient leading capacity may cause the moisture to collect at the bottom, resulting in water flow processes inside the lysimeter differing from those outside of it. Furthermore, soil water models are not specifically intended for lysimeter simulations; thus uncertainties in the modelling results can be expected.

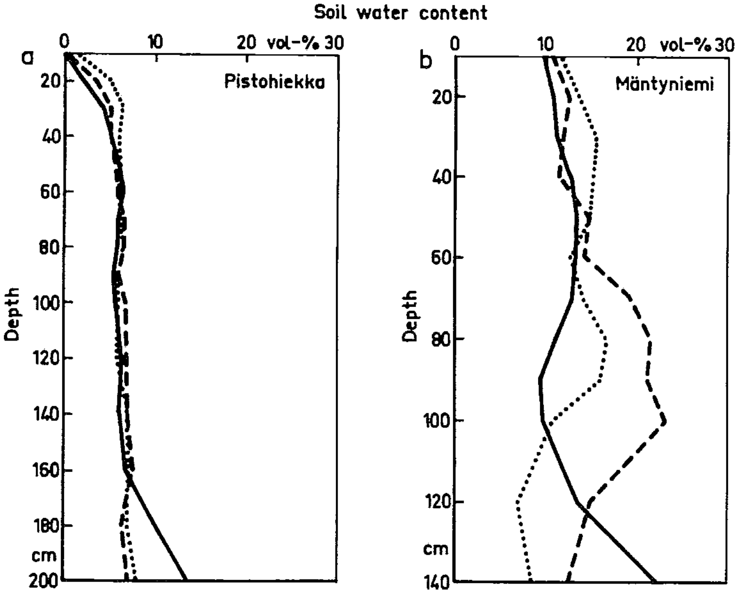

Fig. 5. Moisture profiles inside (solid line) and outside (dashed lines) the lysimeters in Pistohiekka (a) and Mäntyniemi (b).

2.4 *Water balance*

The water balance method and the Penman-Monteith equation (*Monteith*, 1965) were used to calculate the evapotranspiration between June and September. The water balance was calculated with the equation:

$$E_{\mathrm{act}} = P_{\mathrm{corr}} - Q_{\mathrm{l}} - \Delta S \tag{1}$$

where:

E_{act} = Actual evapotranspiration, mm
P_{corr} = Corrected precipitation, mm
Q_{l} = Lysimeter percolation, mm
ΔS = Change in soil water storage, mm.

The observed changes in water storage, precipitation and percolation were used in the calculations.

2.5 *Model descriptions and derivation of parameters*

Two soil water models were used to simulate percolation through the lysimeter. Both originating in Sweden, the PROBE model was developed by *Svensson* (1985) and the other, the SOIL model, by Jansson and Halldin in 1979 (*Jansson*, 1991). The principal difference between the models is that calculation of soil water flow is based on the moisture diffusion in PROBE and on the continuity equation in SOIL. There are also some differences in the parameters used for solving the unsaturated hydraulic conductivity (K). In PROBE, the K-value and the matric potential are solved by using the relations of *Clapp* and *Hornberger* (1983):

$$K = K_s\,(\Theta/\Theta_s)^{2b+3} \tag{2}$$

$$\Psi = \Psi_s\,(\Theta/\Theta_s)^{-b} \tag{3}$$

where

K = hydraulic conductivity
Θ = soil moisture
b = empirical coefficient
Ψ = matric potential
Index s = saturation.

In the SOIL model, the K-value is solved by using the empirical equations of Brooks and Corey (ref. *Camillo et al.*, 1983) and the analytical solution of Mualem (ref. *Camillo et al.*, 1983):

$$K = K_s\,(\Psi_a/\Psi)^{2+(2+n)l} \tag{4}$$

where Ψ_a = air entry tension
n = tortuosity factor
l = pore size distribution.

In PROBE simulations, daily values of precipitation and potential evapotranspiration were used. The initial values of soil moisture and saturated hydraulic conductivity were given. The b value was taken from the literature (*Clapp* and *Hornberger*, 1978). The model was calibrated by setting the missing parameters (saturated moisture content, saturated matric potential and porosity) to the values that gave the most accurate result of the percolation through the lysimeter during the summer of 1983. The second year was simulated with the same parameter values. First, a constant value of evapotranspiration, 2 mm/day, was used. Then, daily potential evaporation was calculated with the Penman equation and multiplied by a factor depending on the soil moisture status to get the actual evapotranspiration rates. The simulations were repeated to determine whether these values improved the results. At the lower boundary, a vertical water flow was assumed to take place, assuming that the unsaturated bottom had the same hydraulic conductivity as calculated for the bottommost layer of the lysimeter.

In the SOIL model, the meteorological data used were the daily values of precipitation, air temperature, cloudiness, wind speed and relative air humidity. The pore size distribution index and the tortuosity factor were taken from the literature (*Karvonen*, 1988). The actual transpiration was calculated with the Penman-Monteith equation, while the soil evaporation was based on the surface energy balance approach. Water flux through the lower boundary was assumed to occur only by gravitation.

Previous studies on the sensitivity of the SOIL model (*Jansson*, 1986) showed that the water tension was influenced most by unsaturated hydraulic conductivity. In this study, the sensitivity analysis was done for the parameters needed in calculating unsaturated hydraulic conductivity, and their resulting influence on the amount of percolation water and soil water storage was studied. In the analysis, one parameter at a time was altered by 5% of its nominal value. The analysis was done for the Mäntyniemi lysimeter, which has a layered soil profile and where the saturated hydraulic conductivity increases downwards as the soil coarseness increases. The fine sediment proportion decreases sharply at depths of 60-70 cm (Fig. 6).

A transfer function model was also used to predict the lysimeter percolation. Using a *SAS* (1990) program, a transfer function that explained percolation by precipitation only was identified for the lysimeter of Kangaslahti. The form of the function used was (*Ahonen*, 1992):

$$Y_t = \left(\frac{b_0 + b_1 B + b_2 B^2}{1 + f_1 B} \right) * \left(1 + b_3 B^{10} \right) * u_{b-2} + \varepsilon_t \qquad (5)$$

where y_t = output variable at moment t
u_t = input variable at moment t
b and f = lag parameters
ε_t = noise term
B = backshift operator.

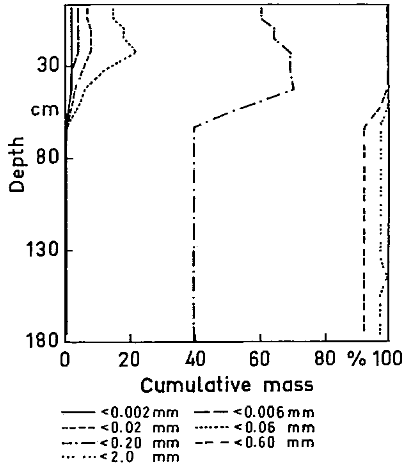

Fig. 6. Textural composition of the lysimeter in Mäntyniemi.

Daily values of percolation were first predicted for the whole summer based on the measurements made on the previous day. Then a prediction for 15 days was made, using the measured percolation only as the initial value.

3. *Results*

3.1 *Texture and climatic conditions*

There were considerable differences in the amount of percolation between the lysimeters (Table 1). The proportion of precipitation that flowed through the lysimeters at the four stations also varied substantially (Table 2). In Pistohiekka less than 20 % of summer precipitation percolated, while in Mäntyniemi the value was greater than 50 %, even though the soil of Mäntyniemi is finer grained. In Oripää, the corresponding figure ranged from 35 % (1983) to 51 % (1984). The discrepancy is explained by the greater precipitation which occurred in 1984. The figures were opposite in Kangaslahti; 70 % (1983) and 44 % (1984). Correspondingly, in this case the higher precipitation occurred in 1983.

Table 1. The water balance components (June 1- September 30) of the four lysimeters in 1983 and 1984.

Station	Year	P_{corr} mm	Q_l mm	ΔS mm	ΔW cm	E_{act} mm
Kangaslahti	1983	320	220	-8	-14	108
	1984	253	107	-29	-35	175
Mäntyniemi	1983	273	149	-11	-81	135
	1984	307	174	+20	-22	113
Oripää	1983	291	105	+13	-19	173
	1984	416	230	+7	-7	179
Pistohiekka	1983	289	36	+26	-36	227
	1984	395	66	+67	-27	262
ΔW= change in groundwater level						

Table 2. The relative proportion of percolation of the monthly precipitation (%) at the four stations during 1983 and 1984.

Month	Kangaslahti		Mäntyniemi		Oripää		Pistohiekka	
	1983	1984	1983	1984	1983	1984	1983	1984
June	76	29	79	17	38	36	17	12
July	85	46	41	48	42	70	26	23
August	62	58	90	76	22	54	12	35
September	59	43	25	87	37	43	6	5
Mean	70	44	59	57	35	51	15	19

In Oripää and Pistohiekka, the soil moisture content normally retained less than 25 % by volume. There are low permeable layers in the profiles under the topsoil; those layers probably prevented percolation, thus favoring evaporation. In Kangaslahti and Mäntyniemi, moisture values sometimes reached or exceeded 30 % by volume. In Mäntyniemi, the finer soil texture explains the higher moisture content.

In long-term analysis, the precipitation and the percolation correlated. Pistohiekka was an exception; during the years analyzed the percolation was lowest although the precipitation was high. This is partly explained by the deeper soil profile, which is capable of storing greater amounts of water. During shorter time periods, the soil moisture before the rain event and the intensity of the rainfall have a great effect on percolation. Most of the rain falling on the dry soil could be retained, and therefore no increase in percolation was seen. If a single rain event is followed by a warm and dry period, most of the rain water could evaporate. Therefore, no impact on percolation was detected even if wet conditions had prevailed before the rain event.

An example of precipitation-percolation in Oripää during June 24-July 7, 1983 and Sept. 17-30, 1983 is presented (Fig. 7). The simulated soil water storage is the same in the beginning of both periods. The first period was preceded by eight rainless days, when the soil water storage decreased. At the beginning of the second period, several rainy days increased the soil water storage. In the first case, the rain water was retained mostly in soil. In the second case, the rain caused an increase in percolation. It can be assumed that this was because the initial water storage in the soil profile deviated differently. In the first case, the topsoil was probably dry and the water was located in the lower layers. The input water could be retained in upper layers. In the second case, the topsoil was probably wet and the newly input water resulted in saturation and a waterflow downwards, reflected as an increase in percolation.

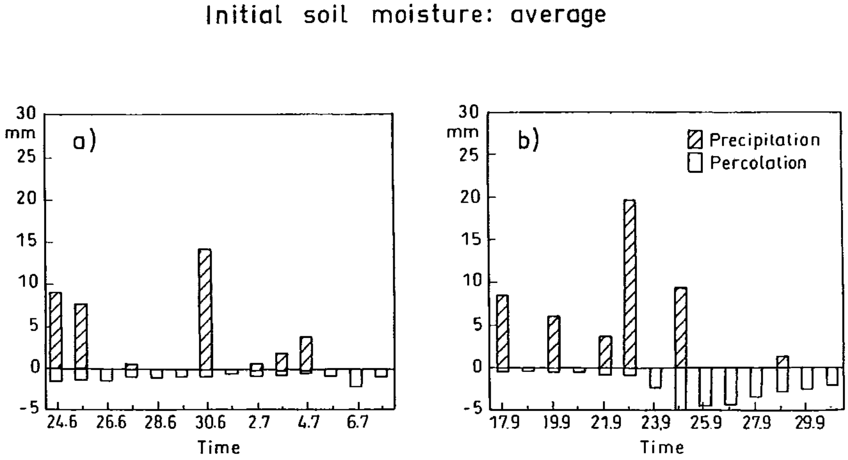

Fig. 7. Daily precipitation and percolation in Oripää between (a) June 24 - July 7, 1983 and (b) Sept. 17 - Sept. 30, 1983.

3.2 Water balance

The Penman-Monteith method gave typically higher evapotranspiration than the water balance method (exception: Pistohiekka) (Fig. 8). The cumulative water balance evapotranspiration was highest for Pistohiekka and second highest for Oripää in both years studied. This was realistic because of their southern location. The Penman-Monteith method gave the highest evapotranspiration in Oripää, but the variation between the stations was small, especially in 1984.

Some similarities were detected in the water balances of the four lysimeters. Soil water storage typically decreased during August and increased during September. August was generally the driest month, when the percolation was lowest in half of the cases. The groundwater level decreased at all the stations during the summer (Table 1). When the consecutive years were compared, lower precipitation was found to yield less percolation and a deeper decrease in the groundwater level. At Oripää and Pistohiekka, the year with the lower precipitation also had a lower evapotranspiration, whereas at Kangaslahti and Mäntyniemi, the year with the lower precipitation had the higher evapotranspiration.

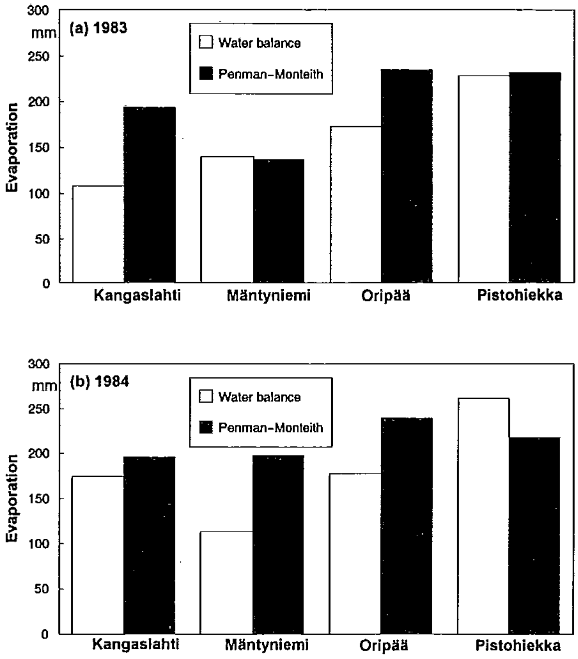

Fig. 8. The evapotranspiration sums (June 1 - Sept 30) calculated (a) by the water balance and (b) by the Penman-Monteith method for the stations in 1983 and 1984.

3.3 Regression analysis

Comparison of the variations in the water storage and percolation revealed similarities between the lysimeters of Kangaslahti and Mäntyniemi and, correspondingly, between Oripää and Pistohiekka. To understand the similarities, an attempt was made to explain the percolation by the precipitation and the cumulative temperature sum in uni-variable regression analysis. At Oripää and Mäntyniemi, the precipitation caused more variation in the percolation (Table 3). At Pistohiekka and in Kangaslahti, the temperature explained most, over 70 % of the variance in percolation. The climatological factors did not explain the percolation of resembling lysimeters in a similar manner. Therefore the similarities must originate more in the local soil properties; macropores, soil stratification, etc.

Table 3. Parameter estimates by the analysis of variance.

Station	Variable	Estimate of standard	Estimate of multiple	R^2
Oripää	Temperature Precipitation	-5.5130 +4.9040	+0.167 +0.493	0.159 0.644
Pistohiekka	Temperature Precipitation	-13.964 +11.022	+0.126 +0.095	0.760 0.051
Kangaslahti	Temperature Precipitation	-12.352 +38.665	+0.197 -0.074	0.707 0.020
Mäntyniemi	Temperature Precipitation	+68.213 +0.8280	-0.050 +0.649	0.044 0.438

3.4 Modelling results

Both soil water models successfully simulated the volume of percolation water during average summer flow, but did not give accurate daily estimations (Figs. 9 and 10). The models failed to simulate situations where the observed percolation varied widely. PROBE tended either to give a smooth fit to the percolation, or to exaggerate the peaks. SOIL gave more daily variations but often inhibited water flow. The differences between

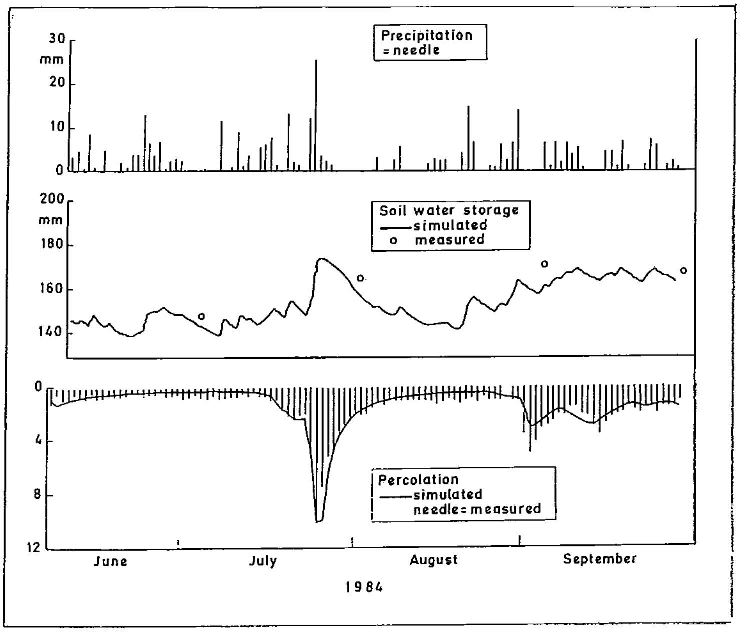

Fig. 9. The measured precipitation, the simulated (SOIL) and measured soil water storages and simulated percolation (SOIL) in Mäntyniemi between June 10 and Oct. 1, 1984.

the observed and the simulated cumulative values in the period of June 1 to September 30 were relatively large in all the cases. While calibrating the PROBE model, the cumulative values differed from 29 % (Oripää) to 57 % (Mäntyniemi). The simulations for the following year differed from 28 % (Kangaslahti) to 79 % (Oripää). In SOIL simulations, the respective differences ranged from 33 % to 107 % and from 12 % to 82 %. For both years, the difference was smallest for Kangaslahti and largest for Pistohiekka.

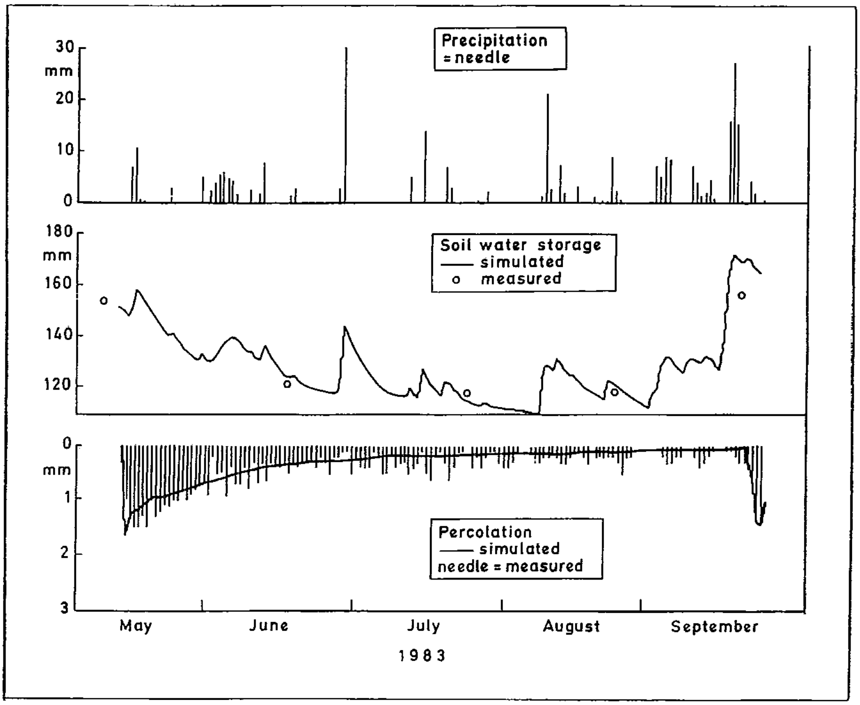

Fig. 10. The measured precipitation, the simulated (PROBE) and measured soil water storages and the simulated percolation (PROBE) in Pistohiekka between May 9 and Sept. 30, 1983.

The models were successful in simulating the soil water storage (Figs. 9 and 10). In some cases the calculated water storage was less than that observed, but the relative changes in the storage between two observation times were simulated successfully. The different method used to calculate evapotranspiration for the PROBE model did not have a major effect on the percolation or soil water storage results.

The sensitivity analysis of the SOIL model showed that percolation water was influenced most by the tortuosity factor. Daily differences between the values calculated with the nominal and the altered parameters (5 % difference) ranged from 0 % to 13 %, i.e. from 0 to 1.2 mm/d. The sensitivity of percolation to the pore size distribution index was greatest in the topsoil, where it caused a deviation of from 0 to 0.2 mm/d. The soil water storage was mostly influenced by the pore size distribution index (Fig. 11). The tortuosity factor also caused variation. The sensitivity to both parameters was strongest in topsoil and also at the depth of 60 cm, perhaps because of a sharp decrease in the fine soil particles of this layer. The soil water storage and the percolation were both insensitive to the saturated hydraulic conductivity.

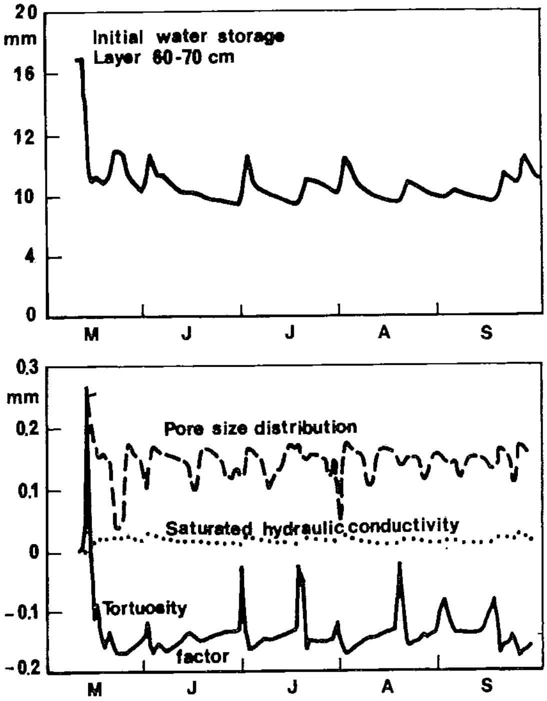

Fig. 11. The sensitivity of the simulated soil water storage variation to the parameters n, l and Ks at a depth of 60-70 cm.

Prediction of the percolation by a transfer function model was successful when the prediction was based on the previous day's measurement according to equation 4. When the prediction was based on the simulated input percolation values, the model succeeded in following the measured percolation values for a period of one week, but thereafter it started to deviate (Fig. 12).

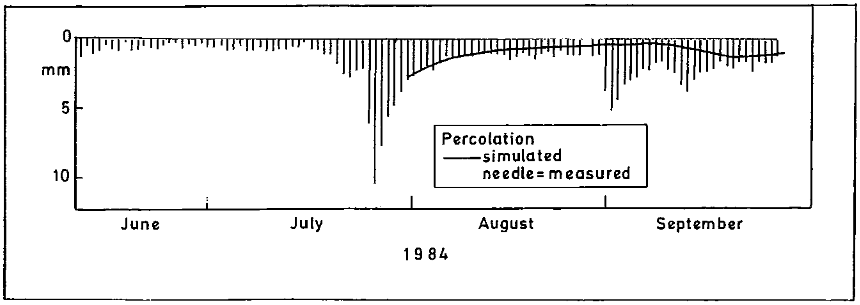

Fig. 12. The percolation predicted by a transfer function model at Kangaslahti.

4. Discussion of modelling

All the soil profiles used in the study were stratified. This stratification may account for the difficulties encountered in PROBE simulations. The model was unable to solve the equations if there were large differences between the soil layers. In addition, the coarseness of soil caused problems, owing to the existence of steep wetting fronts and dry initial conditions (*Hills et al.*, 1989). With both physically sound models, large deviations in daily percolation values were observed and therefore the missing percolation water values could not be replaced by the modelled ones on a daily basis. A transfer function model, instead, could be used for predicting the percolation for a short period, e.g. a couple of days. The availability of the complete long-term time series, needed for identifying the model, limits its applicability. When annual cycles of the percolation values are not available, identification must be done separately for each summer. If the daily values of soil moisture had been available, a better model could have been constructed.

Both soil water models were sensitive to the rain events, which easily caused changes in soil water storage. In half of the cases, the agreement between the simulated total soil moisture storage and the measured one was good. In the other half, soil water storage diminished sharply in the beginning of the simulation period and then remained too low during the whole period, perhaps because of excessive evapotranspiration or an erroneous water retention curve. On the contrary, the simulations of soil moisture content for individual soil layers differed from the measured soil moisture content quite randomly and independently of depth (Fig. 13). Therefore the moisture deviation inside the profile could not explain which of the above factors caused the error in simulation. However, comparison of the evapotranspiration sums calculated with the water-balance method and with the Penman-Monteith method revealed large discrepancies. Precipitation values obtained from the nearest observation station could cause some uncertainties in the water-balance evaporation. The water-balance method, however, must be considered the more reliable method in this study, on the basis of the measured values. The Penman-Monteith equation, which was used in model simulations, was not very reliable, and the errors in soil water storage might be attributed mostly to this poor reliability.

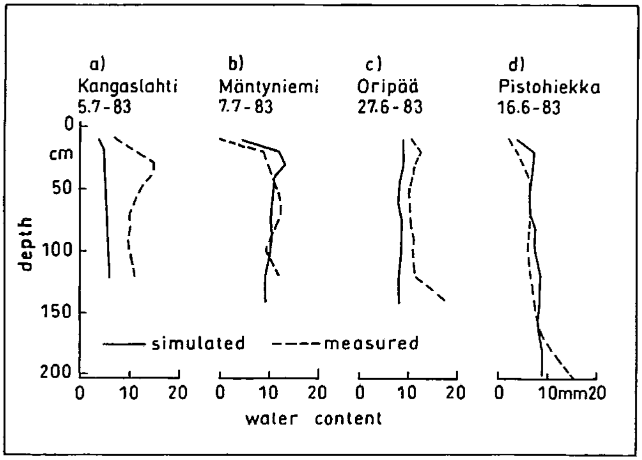

Fig. 13. Measured and simulated soil moisture profiles in the lysimeters.

The sensitivity analysis of the SOIL model showed the importance of the tortuosity factor and the pore size distribution index in calculating water fluxes and soil moisture in layered soil. Both of these factors are nonmeasurable but indicate the local characteristics within the profile. The sensitivity analysis supported the study of the daily percolation data between the stations, indicating that the macropores and other local soil properties must have a dominant influence on percolation. In modelling, estimation of these two parameters should be done very carefully. Measured water retention curves would be very useful, besides of more theoretical methods.

The insensitivity of percolation to the saturated hydraulic conductivity was quite surprising. However, alteration of Ks-value by 5 % may not have been large enough to reveal its real effect. Laboratory measurements of K_S have showed a 60 % variation within even sandy soil samples (sand content 80 %); *Tattari* and *Granlund* (1994). On the other hand, owing to the low soil moisture content in the lysimeters, the insensitivity of percolation to the K_S could have been expected. In dry conditions, the second factor in equation 4 naturally becomes dominating.

5. *Conclusions*

Percolation values predicted by a transfer function model could be used to replace daily percolation values measured through the lysimeter that were lacking for short periods. The values simulated by the physically sound soil water models applied in this study could not be used for that purpose, but these simulated values could be used for predicting the soil moisture storage. Further testing of this conclusion would require daily measurements of soil water content. Even if the relative variation of soil water storage could be simulated, the moisture variation in separate soil layers could not. The inability to simulate moisture variation in the soil layers might be the reason for the relatively low agreement between the observed and the calculated percolation values.

The local soil properties dominate percolation through lysimeters. Monthly evapotranspiration can be calculated by the percolation measurements, soil moisture and precipitation measurements provided that the rain gauge is placed in the neighborhood of the lysimeter. These results are local and are not representative of areal values. When no detailed data on the vegetation and meteorological variables is available, the Penman-Monteith equation is not a reliable method for calculating evapotranspiration from a lysimeter.

For further studies, two or three lysimeters representing different climatological and geological conditions should be chosen. More detailed measurements of soil moisture, vegetation and the soil water retention curve should be carried out at the stations, to improve model applicability.

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