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The Summer Water Balance in a Danish Oak Stand

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The summer water balance in a Danish oak forest was studied during a period of 5 years. Interception reduces rainfall inside the forest by about 15%. Variations of the saturated soil moisture amount to some 10% of the water available to plants. Nevertheless, in most summers low soil moisture only restricts evapotranspiration during July. Insufficient leaf area is a major factor in restricting evapotranspiration: oak leaves develop late, and defoliation by insects also has a noticeable effect. The difference between potential and actual evapotranspiration normally ranges between 50 and 100 mm but reached 150 mm in 1976. Yet even in this dry year the vegetation recovered at once as soon as the water stress had been removed.

Introduction

Recent hydrological investigations in Denmark (Dansk Komite for Hydrologi 1981, Miljøstyrelsen 1983) have mainly concerned agricultural areas. In contrast, only part of the hydrological cycle in forested areas has been thoroughly investigated, e.g. Holst and Kristensen (1981) and Holstener-Jørgensen (1959, 1961). We have carried out an integrated investigation of the hydrological processes in a deciduous subarea within a Danish forest. In this paper we present an analysis of data on precipitation, soil moisture and evapotranspiration, mainly from the growth period, and we discuss some possible interactions and relationships between these parameters.

Garrett (1979), Raupach (1979) and Raupach and Thom (1981) have shown that Monin-Obukhov similarity theory is not valid in the transition layer above a rough canopy. This means that it is not possible to make reliable estimates of evapotranspiration by means of micro-meteorological methods using flux profile relationships. Accordingly, we have tried to measure evapotranspiration in the growth period by using the water balance equation combined with soil moisture measurements. We have also compared the evaporation of intercepted water with the total evapotranspiration from an analysis of rainfall data.

The Field Area

Tinning Skov is situated on a flat morainic plateau in eastern Jutland. It consists of stands of deciduous and coniferous trees covering an area of 480 ha. The present hydrological study is concentrated in a small catchment of about 2.5 ha in an oak stand of 20 ha in the north-western part of the forest (Fig. 1a).

The oak stand is nearly 70 years old and the average height is close to 17 m. The stand density is about 1,000 trees/ha and there is a well-defined canopy layer in the upper 5 m of the stand. In summer a dense undergrowth of fern (*Pteridium aquilinum*) and raspberry (*Rubus idaeus*) develops a secondary canopy with a height of 0.5-2 m.

In five 3-5 m deep auger holes we only found glacial till. However, in nearby water supply wells impermeable tertiary clay deposits are found to underlie the glacial deposits at moderate depths – probably about 10 m below the field area. Although a 1 m sand deposit separated the glacial and tertiary clays in a well 1.5 km SE of the plot, the general impression from the geological data is that percolation through the till is very restricted. As was to be expected, we therefore find a water table close to the surface. In winter it is situated at a depth of 0.3-1 m, whereas during summer it gradually drops to a depth of 2-3 m. In core samples a change from oxidized to reduced compounds is found at a depth of 2.75 to 3.5 m.

Water drains from the area through an artificial network of 0.5-1.5 m deep ditches with a density of about 800 m/ha. We determined the amount and distribution of rainfall inside the forest from weekly readings during selected periods in the years 1973-1981. Up to 1978 we estimated gross precipitation as defined by Zinke (1967), from 2 gauges in clearings 200 and 800 m from the stand, marked M1 and M2 in Fig. 1a, and one gauge outside the forest, M3. Additional information on duration was recorded by an automatic gauge NW of the stand – A1 in Fig. 1a. Despite the short distance between these gauges weekly readings may differ considerably during convective rainfalls. The annual rainfall, however, is within a few percent. Since 1978 only weekly readings from A1 and from an automatic gauge some 10 km NE of the forest are available.

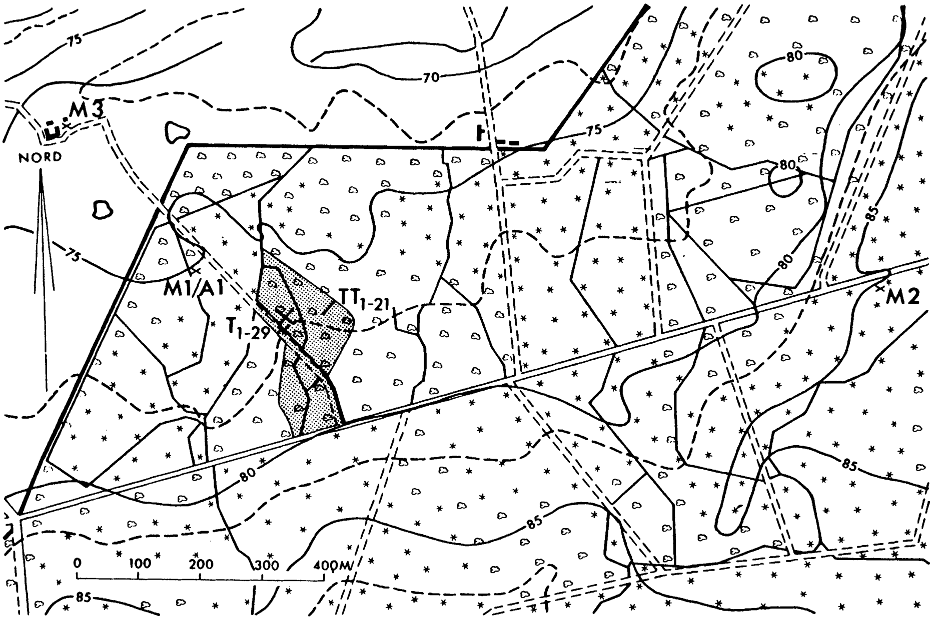

Fig. 1a. The Western part of Tinning Forest with the field area (shaded). The positions of rain gauges are indicated with crosses. Rain gauges T_{1-29} and TT_{1-21} below the canopy are also shown.

Throughfall from the upper canopy was estimated from 29 gauges placed on the forest floor with a spacing of 2.5 m on 2 lines crossing at right angles marked T_{1-29} in Fig. 1a. We cleared the undergrowth to a distance of 1 m from these gauges.

Total throughfall at ground level was measured at 21 gauges (area 121.0 cm^2, protected against evaporation) that we placed carefully in the undergrowth on each side of a narrow deep ditch. These gauges are marked TT_{1-21} in Fig. 1a.

In an oak stand stemflow plays a very small part in the net precipitation during the growth period. Thus Carlisle et al. (1967) give 2.1% on a yearly basis. We measured stemflow on 10 randomly chosen trees, and during 3 summers the average value was less than 2%. We will therefore not discuss stemflow in detail here, but will take up its average value in our later discussion of the water balance.

We measured soil moisture from 1976 by the neutron scatter method in calibrated aluminium access-tubes. These were set in pre-augered holes to avoid compaction (Fig. 1b). Originally we emplaced 4 tubes, two (SM1 and SM2) to a depth of 3.3 m and the other two (SM3, and SM4) only to 1.4 m. In 1979 a soil pit was dug at SM3, this tube was removed, and control of the density and moisture readings was carried out. In general we obtained two to three readings per month. However, there are several gaps in the measurements because of instrumental

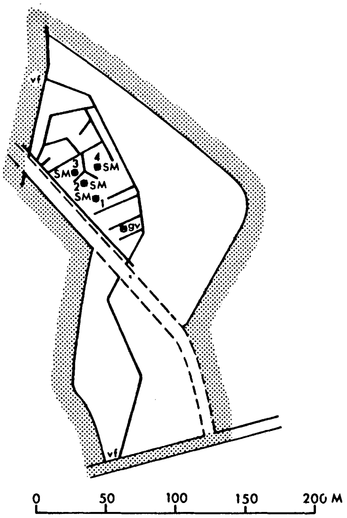

Fig. 1b. The catchment area in the oak stand. Area 2.57 ha. The main drainage ditch runs along the middle. In the field plot itself all the ditches are shown.
SM 1-4: the four soil moisture tubes,
gv: ground-water level recorder,
vf: runoff measuring stations.

failure. A soil-filled container was buried to a depth of 15 cm near each tube. Before each measurement the container was placed over the tube to prevent loss of neutrons to the atmosphere.

In general runoff does not occur during the growth season except during very wet periods. Then it was calculated by means of a rating curve from continuous recordings of the water level in the main ditch that drains the area.

Interception

Gauges in clearings and outside the forest have been corrected for loss due to aerodynamic effects (Rasmussen and Halgreen 1978). In contrast, we have not corrected the gauges in the forest, since wind speeds recorded at 2 m's height during 2 summers were usually less than 1 m/s and never exceeded 2 m/s.

Wetting loss as described by Allerup and Madsen (1979) has not been corrected for in this section but will be dealt with later. Possible systematic patterns in throughfall, as reported by Linskens (1951), were studied by means of an analysis of variance. We have found no systematic effects which could complicate evaluation of the average throughfall. The full analysis will be discussed in a later report.

Conceptual models for the interception process in a forest have been proposed by Rutter et al. (1971) and Jackson (1975). In these models an important parameter is γ – the free throughfall coefficient – which is defined as the relative part of the canopy where raindrops may fall direct to the ground (Rutter et al. 1971). Interception, I, may then be calculated as

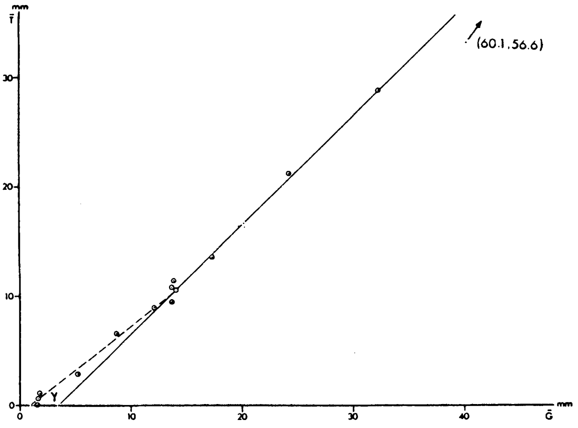

Fig. 2. Throughfall, $\bar{T}$ for single showers as a function of gross precipitation, $\bar{G}$.

$$I = \begin{cases} (1-\gamma)N & , \quad N < I_0 \\ (1-\gamma)I_0 = I_1 & , \quad N \geq I_0 \end{cases}$$

where I_o is the value of rainfall N for which the canopy has been completely wetted (canopy saturation value). I_l is the storage capacity. Using data from the summer periods 1973-75 for gauges $T_{1\text{-}29}$, and following the procedure of Bringfelt and Hårsmar (1974), we have calculated the following estimates for the oak canopy

$$1 - \gamma = 0.28\%, \quad I_1 = 1.6 \text{ mm}, \quad I_0 = 5.8 \text{ mm}$$

However, there is an additional interception loss in the dense undergrowth. When viewed from the ground the entire canopy forms a complete cover and $\gamma = 0$. For rainfalls as small as 1.5 mm throughfall is observed in the gauges $T_{1\text{-}21}$ while for very small rainfalls the canopy catches all the water. Therefore by use of the pluviograph information we first selected weeks with a single continuous rainfall. Preliminary analysis of these weeks shows that I_o = 8-10 mm. In the remaining data we then selected weeks with 2 and 3 continuous rainfalls all of more than 8 mm and separated by a rainless day. Let n be the number of such rainfalls in a week. We can then calculate the average throughfall $\bar{T} = T/n$ and average gross precipitation $\bar{G} = (G\text{-}S)/n$. (T, G and S are respectively the total throughfall, gross precipitation and stemflow in the particular week). For the summers 1980 and 1981 values of $\bar{T}$ versus $\bar{G}$ are shown in Fig. 2. For values of $\bar{G}$ above about 10-12 mm the points lie close to a 45° line. From such values we calculate the interception capacity $I_1 = (\bar{G}\text{-}\bar{T}) = 3.5$ mm with a standard error $s_I = 0.5$ mm. It is

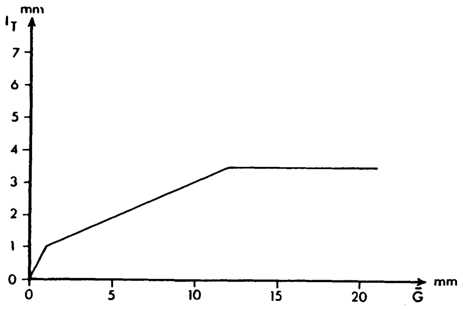

Fig. 3.
Interception loss I_T as a function of gross precipitation $\bar{G}$, for single showers.

important to realize that I_1 includes loss due to evaporation during rainfall. As reported by Gash (1979) such loss may be substantial. The coefficient γ is obtained by regression analysis in weeks with a single rainfall where $G = G \leqslant 10$ mm. This gives $\gamma \cong 0.7$, but there is a considerable scatter in the points. It should also be noted that for $\bar{G} \leqslant 1$ mm all water is retained in the canopy.

Fig. 3 shows interception loss I_T as a function of gross precipitation $\bar{G}$. Using this model and the data from the automatic gauge we calculated an interception loss of 51.0 mm (14.7%) for the period June to September 1981. This can be compared to the measured loss of 56.9 mm (16.4%).

Soil Moisture

During the year water saturation range is between 20-50% in the upper soil horizons and it decreases gradually down to about 2 m depth. Below this the standard error is fairly constant (near 0.7% $\simeq$ sampling error). Fine roots can be seen down to about 1.75 m.

Below 1.5 m the soil contains 28-30% silt and 18-20% clay, so that there is a considerable capillary rise. During dry periods when the water table falls from 2 m to 3 m's depth, no change can be detected in the corresponding soil moisture data, so the associated change in moisture must be less than 1%. Thus even if the decline of ground-water table should be a result of capillary transport towards the root zone, only small amounts of water (<10 mm) can be involved.

Simultaneous readings in the 4 access tubes at the same depth differ somewhat due to local inhomogeneities, but when moisture changes are calculated over the entire sampling interval, they differ less than 5 mm. The soil moisture variation in the root-zone, as presented in Fig. 4a, is therefore calculated from SM1 and only to a depth of 1.95 m. Fig. 4a also shows the potential evapotranspiration (*Ep*) measured at the Ødum State Experimental Station some 10 km away. Fig. 4b shows additional climatic information from Ødum.

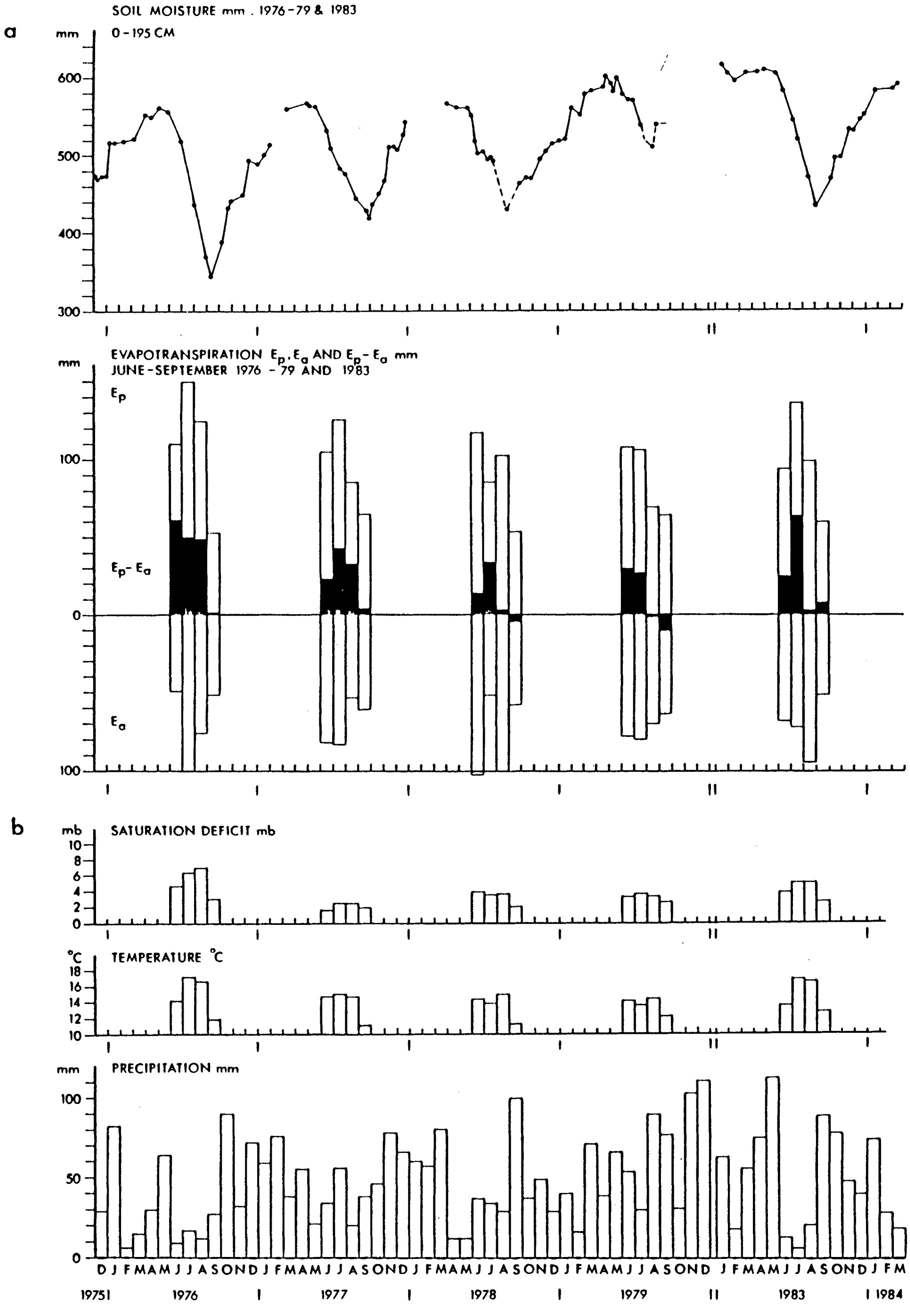

Fig. 4. a) Soil moisture variations and summer water balance in the oak stand, Tinning, 1976-79 and 1983.

b) Meteorological data from Ødum, 1976-79 and 1983.

The annual variation in the root-zone ranges from 100 mm in the relatively wet year 1979 with a low potential evapotranspiration, to nearly 250 mm in the very dry year 1976, when *Ep* was large. A gradual increase – most outstanding in the high winter values – is seen during the period 1976-83. As 1975 and 1976 were dry years soil moisture increased only slowly during the winter 1975/76, reaching a maximum of about 560 mm in May 1976. The winter maximum increases to nearly 580 mm in 1979. In January 1983 values of about 600 mm are reached, and this level continues with little variation until the end of May. Despite this trend, each winter the water table rose to within about 0.5 m below the surface, and surface runoff occurred in the ditches. However, 1980-81 and 1981-82 were wet years, with frequent runoff even in the summer period.

The change in the saturation values from 1976 to 1983 – about 40 mm – must almost certainly be ascribed to hysteresis effects. This is supported by the fact that about 30 mm of the observed difference represents an increase in soil moisture in the zone 0.95-1.95 m's depth. The wilting point is about 1/3 of the field capacity for a soil of this type (Holst and Kristensen 1981). Thus hysteresis affects about 10% of the water available to the vegetation.

Evapotranspiration

Fig. 4a shows that from June to September the average difference between actual evapotranspiration (*Ea*) and *Ep* is just under 100 mm. However, dry years are overrepresented in the data. If we take 1977 and 1978 as more typical of the average conditions then *Ep-Ea* is probably about 50-75 mm. Most of this difference arises during June and July since *Ea* is close to *Ep* during the rest of the growth period. In comparing *Ea* and *Ep* we must point out, however, that the *Ep* estimated from the HL 315 evaporimeter is likely to be too large in dry summers. For evaporimeters on Sjælland (Zealand), Mogensen and Hansen (1979) find an overestimation of nearly 15% for the period April-Oct. 1976, and they ascribe this to an oasis effect. Thus the difference *Ep-Ea* is likely to be smaller in July-August 1976 and July 1983 than actually recorded.

The oak trees develop their leaves during the first part of June when the soil moisture is fairly high. Insufficient leaf density, as expressed in the leaf area index (*LAI*) thus explains the *Ea*/*Ep* ratio of $\simeq$ 3/4.

The sudden pause in the decline of soil moisture that occurs in July 1978 and June/July 1979 is an interesting anomaly. Rainfall was not unusually high, but caterpillars of *Tortrix viridana L.* and *Operophtera brunata L.* had defoliated considerable parts of the canopy.

Part – perhaps most – of the *Ea-Ep* difference in July 1978 and 1979 may thus be a result of this attack.

Discussion

About 200 mm of the precipitation from June to September is used for evapotranspiration. An additional 140 mm is drawn from soil moisture. The evapotranspiration from June to September is thus about 350 mm. The difference between precipitation and run-off in eastern Jutland is about 400-425 mm for the whole year. Compared to this our findings for the four summer months are rather high. A partial explanation may lie in the correction of precipitation for systematic errors. This produces "additional" water which is not available to evaporation for instance by interception. A further factor may be the development of roots down to about 2 m depth. This makes larger amounts of water available to the oak stand than is true for many crops.

In September, when soil moisture usually increases elsewhere, we can observe that it is still decreasing in the deeper zones. In dry years this decline may last until mid-October. At the same time we observe the rapid increase in the Ea/Ep ratio from values about 1/2 to 2/3 in July. Presumably roots from the undergrowth do not penetrate as deeply as the oak roots do. During July, and occasionally in August, the undergrowth may thus be exposed to greater water stress.

In the majority of summers low moisture content does not appear to be the most important cause of reduced evapotranspiration – especially not for the oak trees. This is despite the fact that reductions of saturated soil moisture due to hysteresis occur. Low leaf area is at least as important. In the first place, oak leaves develop very late and leaf area is therefore inadequate in the early summer. Additionally, there are frequent attacks by defoliating insects, and this effect on evapotranspiration can be directly observed.

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