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Estimation of Canopy Reservoir Capacity and Oxygen-18 Fractionation in Throughfall in a Pine Forest

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Amount and oxygen-18 content of rainfall and throughfall have been monitored in a pine forest in Uppsala during summer 1983. It is found that the free throughfall coefficient, C, the canopy reservoir capacity, S, and the critical value of rain, R_0, are ≈ 0.5, 2.1 mm and 4.1 mm respectively. The average value of throughfall is about 60% of rainfall. Generally, the throughfall is enriched in oxygen-18 with respect to rainfall, but in very few cases depletion has been observed. The enrichment or depletion in throughfall have been graphically predicted and agree fairly well with the observations. Oxygen-18 values of throughfall have been simulated by a model describing isotopic fractionation in throughfall. Using estimated relative humidity and temperature during the rainfall, the simulations describe quite closely the observed fractionation. It is felt that more accurate estimates of C, S and fractionation in throughfall can be obtained by monitoring rain and throughfall in small fractions of about 0.2 mm or even less.

Introduction

Before precipitation reaches the soil surface, part of it is intercepted by the tree canopy. The incoming raindrops continue to "fill up" the leaf reservoir, until it is filled to its maximum capacity and then dripping begins. Dripping may even begin much earlier by wind action. That part of rain which goes straight through the open space between leaves plus the dripped water is termed here as throughfall. Conceptually rain and throughfall in one storm event have been described by Rutter *et al.*

(1971) and by Bringfelt and Hårsmar (1974) in the following manner. If rainfall R does not exceed a certain critical amount R_0, then throughfall is a function of R such that

$$T = C R \qquad (1a)$$

$$T = R - S - E \quad \text{when} \quad R \geq R_0 \qquad (1b)$$

$$S = (1-C) R_0 \qquad (1c)$$

where C is the coefficient of free throughfall and S is the amount of water that can be stored by the canopy; which is synonymous with storage capacity of Zinke (1967) and canopy saturation value of Layton *et al.* (1967). In the present study, stemflow is assumed to be negligible. This is assumed to be small for trees with downward sloping branches, since stemflow was found to be 1% of rainfall in Norway spruce, Delfs (1965). The process of evaporation and isotopic exchange with the atmosphere bring about a change in the isotopic composition of intercepted water on the canopy, a portion of which drips down as throughfall and the rest evaporates back to the atmosphere. The enrichment or depletion of intercepted water is dictated by several factors, namely, the relative humidity, the difference between the δ-values of rain and atmospheric vapour and the temperature, which determines the isotopic fractionation coefficient, α. Hence the net amount of rain or throughfall reaching the soil surface will not have the same isotopic composition as that of the original rain. A knowledge of the isotopic composition of throughfall is important for studies concerning the use of isotopic composition of meteoric water as hydrological tracer to investigate the origin of groundwaters. This has also been stressed by Gat and Tzur (1966). In the streamflow separation studies with stable isotopes, estimates of the contributions of surface runoff and groundwater to streamflow are strongly influenced by the rain input and its isotopic composition. In a basin where the areal extent of the tree canopy is significant, an accurate estimation of throughfall and its δ-value is very important. In a pilot study in a pine forest in Uppsala, the 18_O fraction in throughfall, the canopy reservoir capacity and the throughfall coefficient have been estimated.

Experimental Methodology

Field studies were started in summer 1983 in a pine forest in Uppsala. Rain was collected in an open area about 15 m from the edge of the forest, using a tipping bucket type rain gauge. Throughfall was collected in the forest in 4 gutters each 5 m long placed below the tree canopy. The total area of the gutters was $(20 \times 0.1\ m^2)$ i.e. 2 m^2. All the gutters emptied into a 25 l can placed below the ground surface. Rainfall and throughfall were collected between 5 to 15 hours after the rain events.

^{18}O content of atmospheric vapour was monitored about 5 km away from the forest on a daily basis. Detailed method of ^{18}O sampling of atmospheric vapour has been described by Saxena and Eriksson (1984). From the tipping bucket rain gauge, the intensities and durations of rains, and the dry periods between successive rainfalls have also been measured. The ^{18}O contents are expressed as δ ‰ SMOW.

Isotopic Fractionation in Throughfall – Some Theoretical Aspects

In a continuous rain, when the canopy reservoir capacity is exceeded, the throughfall T can be expressed as

$$T = T_C + T_F - E$$

where T_C is the overflow from the canopy, T_F is the amount of free throughfall and E is the evaporation from the canopy. Further

$$T_C = R(1-C) \quad \text{and} \quad T_F = R\,C$$

where C is the free throughfall coefficient and R is total rainfall.

The isotopic content of the throughfall (δ_T) is thus

$$\delta T \equiv \frac{\delta_c T_C + \delta_p T_F}{T} \qquad (2)$$

where δ_c, δ_p are the δ-values of the canopy reservoir and rain respectively.

For the calculation of δ_c, it must be borne in mind that the canopy reservoir is subjected to fractionation as soon as it begins to fill, and after saturation is reached further rain inputs simply overflow. Thus we have a system of open water body with inputs as rain and outputs in the form of evaporation and overflow. For the sake of simplicity, this system is assumed to be isotopically well mixed.

The mass balance of the canopy reservoir with respect to time can be expressed as

$$\frac{ds}{dt} = I - Q - E \qquad (3)$$

where S – amount of water in the canopy reservoir, I – rain on canopy, Q – overflow from the canopy and E – evaporation

Similarly, from the isotopic balance we have

$$\frac{d}{dt}(S\,R_S) = I\,R_I - Q\,R_Q - E\,R_E \qquad (4)$$

R_S, R_I, R_Q and R_E are the isotopic ratios of the reservoir, rain, overflow and evaporation respectively. Integration of Eq. (4) yields

$$S = S_0 - \int_0^t (E+Q-I)\,dt \qquad (5)$$

From Eqs. (3), (4) and (5), we get

$$\frac{dR_S}{dt} \equiv \frac{E(R_S-R_E)-I(R_S-R_I)+Q(R_S-R_Q)}{S_0 - \int_0^t (E+Q-I)\,dt} \qquad (6)$$

In δ-notation Eq. (6) takes the form

$$\frac{d\delta_c}{dt} \equiv \frac{E(\delta_c-\delta_E)-I(\delta_c-\delta_p)+Q(\delta_c-\delta_Q)}{S_0 - \int_0^t (E+Q-I)} \qquad (7)$$

where δ_c, δ_p, δ_E and δ_Q are the δ-values of the canopy reservoir, rain, evaporate and overflow from the canopy, respectively.

For rains exceeding the critical value R_0, the canopy reservoir gets saturated, the incoming rain drips from the leaves and $I - Q - E = 0$. Since the reservoir is assumed to be well mixed, $\delta_c = \delta_Q$ and Eq. (7) is modified. Thus,

$$\frac{d\delta_c}{dt} \equiv \frac{E(\delta_c-\delta_E)-I(\delta_c-\delta_p)}{S_0} \qquad (8)$$

S_0 in the above case is a constant, which is the canopy reservoir capacity. From the above equations, knowing the values δ_p, δ_E, E and I, time rate of changes in δ_c can be calculated.

The δ-value of the evaporate, i.e. δ_E, can be obtained from the expression

$$\delta_E \equiv \frac{1/\alpha(1+\delta_c)-h(1+\delta_a)}{(1-h)\beta} - 1 \qquad (9)$$

δ_a being the δ-value of atmospheric vapour, h the relative humidity, α the fractionation coefficient and ß a constant. Eq. (9) is similar in form to that obtained by Craig and Gordon (1965).

Initially, the δ-value of the canopy will be the same as the δ-value of rain, i.e., $\delta_c = \delta_p$. Due to evaporation and molecular exchange with the atmospheric vapour, the canopy water will tend to achieve an isotopic steady state or equilibrium with the atmosphere. The δ-value of the canopy reservoir at steady state is given by δ_{cs}, such that

$$\delta_{cs}-\delta_a \equiv (1+\delta_a)\,\frac{1/\alpha-h-\beta(1-h)}{\beta(1-h)-(1/\alpha)} \qquad (10)$$

In the present case it is just an approximation of the true δ_{cs}, because neither further mixing of the canopy water with incoming raindrops nor canopy overflow is considered. In Fig. 1,δ_{cs} and δ_p are synonyms.

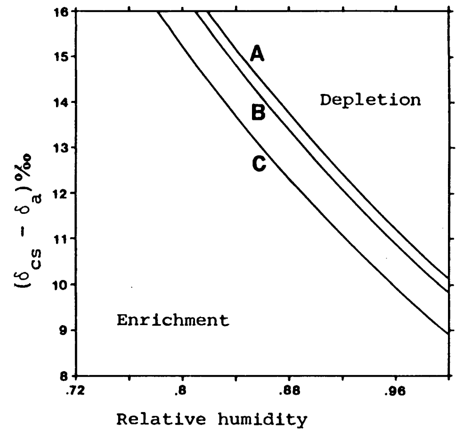

Fig. 1. Isotopic difference between rain and atmospheric vapour vs relative humidity. Region above Curve *A* signifies depletion, and below enrichment. Curves *B* and *C* are valid for higher temperatures, i.e., smaller α's. After A. Rodhe (personal communication).

The variation of $\delta_p - \delta_a$ with respect to humidity is shown in Fig. 1, wherefrom, knowing the prevailing relative humidity during the rainfall, one can qualitatively predict whether the throughfall will be enriched or depleted with respect to a certain rainfall. For example, if temperature during rainfall is 10°C, then $\alpha = 1.0103$ and curve *A* is valid. Assuming that $h = 0.97$, then for $\delta_p - \delta_a \leqslant 10.95‰$ enrichment will take place, while δ_p-$\delta_a \geqslant 10.95‰$ will cause depletion and for $\delta_p - \delta_a = 10.95‰$ equilibrium is attained.

Using Eqs. (2, 8 and 9) a mathematical model has been worked out to simulate δ_T. S_0 is given a start value 0.1 mm and $\delta_c = \delta_p$ for the first step of evaporation. Experimentally observed values of $S = 2$ mm, $R_0 = 4$ mm and $C = 0.5$ were used in the model calculations. Simulations of δ_T were done only for those events for which rainfall exceeded 4 mm. For events ≤4 mm, the canopy reservoir does not saturate, there is no dripping from the canopy and ideally δ_T should be equal to δ_p.

Results and Discussions

Canopy Reservoir Capacity and Rainfall – Throughfall Relationships

Rain and throughfall of 24 storm events observed at Uppsala from June to September 1983, are shown in Fig. 2. For rain amount 3.7 mm, the upper envelope of the observation points steepens and the values of throughfall for a given value of rainfall get rather scattered. The inflexion point of the upper envelope represents the canopy saturation, Rutter *et al.* (1971), which in the present case is 3.7 mm.

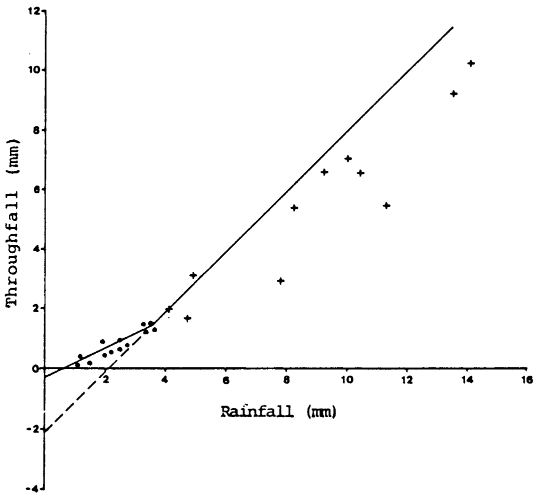

Fig. 2.
Throughfall-rainfall relationship in a pine forest in Uppsala.

Thus, for the critical rain amount (R_0) = 3.7 mm, the canopy reservoir is completely filled and further rain drips from the canopy as overflow, and throughfall $T = R - E$. To the left of the inflexion point, i.e. for rain $\leqslant$ 3.7 mm, throughfall can be expressed as

$$T = C\,R$$

The regression line between throughfall and rain for $R \leqslant 3.7$ mm is

$$T = 0.49R - 0.3 \qquad (r) = 0.92$$

(Ideally there should be no intercept).

Thus the experimental value of C, the free throughfall coefficient for the Uppsala pine forest is about 0.5.

The observed slope of the upper envelope is close to 1, Fig. 2 , which agrees with the ideal slope = 1, since after the canopy saturation, $T = R - E$, E the evaporation being negligibly small during the rainfall. Generally, the value of E during the rain is assumed to be $\approx$ 0.1 mm/hour. It is assumed that the vertical scatter of the points to the right of the inflexion point is mainly due to variation in evaporation from the wet canopy, Leyton *et al.* (1971). The negative intercept of the upper envelope on the throughfall axis is the canopy reservoir capacity and is about 2.1 mm at Uppsala. The critical value of rain, R_0, may now be calculated from Eq. (1c) again, since S and C are already known. From Eq. (1c), $R_0 = 4.1$ mm which agrees fairly well with the graphical estimation of $R_0 = 3.7$ mm obtained earlier. For a coniferous forest in Velen basin, Sweden, Bringfelt and Hårsmar (1974) obtained $S = 2$ mm, $C = 0.5$ and $R_0 = 4$ mm. It is seen that a similar picture emerges for the pine forest in Uppsala also. The interception loss at Uppsala, for $R \geqslant 4$ mm is about 42% of rainfall compared to 20% total loss obtained by Bringfelt and Hårsmar (1974), 20 to 40% for coniferous forests obtained by Zinke (1967) and 36% in old Norway spruce obtained by Delfs (1965). On the other hand, Rutter *et al.* (1971) found S to vary from 1 to 1.3 mm, $C \approx 0.25$ and the interception loss varied from 12 to 42% in individual storms in Corsican pines.

Fractionation in Throughfall

The isotopic differences $(\delta_p - \delta_a)$ between rain and atmospheric vapour for all the rain events have been checked qualitatively using Fig. 1, curve A. It has been found, Table 1, that barring 4 events out of 24, all the events show enrichment or depletion as predicted by the trend curve A. Strictly speaking, fractionation in throughfall should be considered only for those events for which rainfall $\geqslant R_0$ and the canopy contributes to throughfall by dripping.

Therefore, model simulations in Table 1 are only shown for 11 such events. Except the first event, the graphical predictions regarding enrichment/depletion of the throughfall agree fairly well with the model simulations. However, graphical predictions have been done for all the events, as some dripping normally occurs due to wind action even before the canopy reservoir attains saturation. Generally, the deviations from predicted enrichment/depletion vary from 0.2 to 0.3‰. This shows that qualitatively the trend curve A is a good measure of the nature of fractionation occurring in the canopy reservoir. Alternatively, the isotopic difference $(\delta_t - \delta_p)$ between throughfall and rainfall has been plotted against $(\delta_p - \delta_a)$, Fig. 3. Since isotopic equilibrium between canopy water and atmosphere is attained when $(\delta_p - \delta_a) = +10.95$‰, block 1 shows enrichment and block 3 depletion. It is seen graphically that only two events in block 2, having $\delta_p - \delta_a >$ +10.95‰, show enrichment, whereas according to prediction from curve A they should be depleted, and two events show neither enrichment nor depletion. The few disagreements observed depend upon a variety of other processes which can completely change the isotopic picture of the throughfall. Dansgaard (1953) observed that a single rain may or may not be uniform in its ^{18}O content as rain proceeds with respect to time. For example, in showers the ^{18}O of rain decreased somewhat at the end, while in a warm-front, the initial rain had low ^{18}O while the later part was increasingly heavy. Assuming that rain is isotopically lighter at the end, then part of the end potion will be held in the tree canopy and the throughfall will be enriched. On the other hand, if rain is lighter in the beginning, then the throughfall will be depleted. In the light of the above circumstances, we are faced with a complex interplay between fractionation in the canopy and the differential isotopic content of single rain storms. Thus, in the above discussions, we assume that in general, the rainfall is more or less uniform in its ^{18}O content. Simulations have been done to estimate δ_T, i.e., δ-value of throughfall, using Eqs. (2) (8) and (9). The evaporation during the rain has been assumed to be 0.1 mm/hour, relative humidity has been varied from 90 to 96% and the temperature has been kept constant, i.e. 10°C. The isotopic content of atmospheric vapour, δ_E, is equal to the

Table 1 – Amount and $\delta^{18}O$ of rain and throughfall, isotopic difference between rain and atmospheric vapour (δ_p-δ_a), throughfall and rain (δ_t-δ_p), predicted enrichment/depletion from Fig. 1 and simulated δ-value of throughfall (δ_T) from the model.

Date	Rainfall (mm)	$\delta^{18}O$ Rain (‰)	Through-fall (mm)	$\delta^{18}O$ Through-fall (‰)	(δ_p-δ_a) (‰)	(δ_t-δ_p) (‰)	Predicted enrichment (E) /depletion (D)	Simulated δ_T (‰)
83-06-02	10.0	-5.4	7.1	-5.2	11.4	0.3	D	-5.2
83-06-04	1.1	-8.2	0.1	-8.3	11.0	-0.1	D	
83-06-05	14.0	-9.6	10.3	-9.1	9.5	0.5	E	-9.1
83-06-27	2.5	-4.7	0.6	-4.8	13.9	-0.1	D	
83-06-28	3.6	-8.0	1.3	-7.4	10.6	0.6	E	
83-06-29	13.5	-15.6	9.2	-15.3	3.8	0.3	E	-15.4
83-06-30	7.8	-10.0	2.9	-9.7	9.4	0.3	E	-9.5
83-07-01	4.9	-9.1	3.1	-8.9	8.8	0.2	E	-8.7
83-07-02	1.9	-7.6	0.9	-7.1	10.2	0.5	E	
83-07-04	2.0	-6.2	0.4	-6.4	13.9	-0.2	D	
83-07-04	1.5	-10.4	0.2	-10.2	9.7	0.2	E	
83-07-18	1.0	-5.4	0.2	-5.4	14.9	0.0	E	
83-07-28	3.5	-6.5	1.5	-6.4	10.8	0.1	E	
83-07-28	9.2	-8.6	6.6	-8.3	8.7	0.3	E	-8.3
83-07-30	3.3	-8.7	1.5	-8.7	10.6	0.0	E	
83-08-12	10.5	-11.3	6.6	-11.0	9.0	0.3	E	-10.0
83-08-24	2.2	-8.5	0.5	-8.3	11.2	0.2	D	
83-08-27	1.2	-4.8	0.4	-4.8	12.9	0.0	D	
83-09-04	2.5	-6.3	0.9	-6.7	11.1	-0.4	D	
83-09-08	4.7	-16.4	1.7	-15.6	6.4	0.8	E	-14.4
83-09-16	11.3	-8.7	5.4	-8.2	9.6	0.5	E	-8.1
83-09-21	3.3	-9.0	1.2	-9.0	10.5	0.0	E	
83-09-23	8.2	-9.3	5.4	-8.6	10.3	0.7	E	-8.7
83-09-24	17.2	-9.9	10.4	-8.7	10.2	1.2	E	-9.0

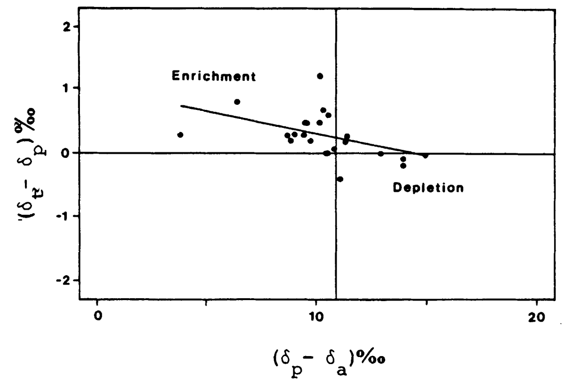

Fig. 3.
Graphical representation of fractionation in throughfall.

values observed on the rainy days. It is found that the observed and simulated δ-values of throughfall in Table 1 agree fairly well. The regression equation between δ_T simulated and δ_T observed is δ_T simulated = 0.93 δ_T observed - 0.418‰ (for 11 events). The coefficient of correlation $r = 0.992$.

δ_E is very sensitive to small variations in h, Eq. (9), and so is δ_C. Thus a small change in h results in a sharp change in δ_T. The simulations therefore have an inherent drawback on account of the uncertainty in the measurement of h. During the experiment, h was not measured in the field, therefore only expected values of h have been used in the simulations.

From the available data it is observed that in general weighted throughfall is enriched with respect to rain by about 0.3‰, the extreme values being as low as 0.1‰ to 1.2‰ at the maximum. Gat and Tzur (1966) applied the Craig-Gordon formula, Craig and Gordon (1965) to estimate the enrichment of the canopy reservoir in semi-arid conditions. They expected an overall enrichment in the throughfall to be about 2‰, assuming that the next rainfall washes off the enriched residue from the canopy cover. In contrast to this, all the rainfalls considered in this study are separated from the previous and the next storm by at least 10 hours. Since the time for the canopy reservoir to dry out is about 5 hours for Swedish conditions, Bringfelt and Hårsmar (1974), the possibility of extra enrichment from the previous rains residue is ruled out in the present study at Uppsala.

Conclusions

This pilot study shows that for rains exceeding the critical value $R_0 = 4$ mm, the throughfall is about 60% of rainfall for a pine forest in Uppsala. Since the throughfall catching gutters were kept inclined for drainage in the collection can, the actual value of throughfall is thus more than 60%. The isotopic enrichment of throughfall varies from 0.1 to 1.2‰, assuming that rains are uniform in their ^{18}O distribution in time. Hence, for studies on the separation of stream runoff using stable isotopes, it is important to modify the rain's isotopic composition in order to achieve higher accuracy. For an accurate prediction of throughfall fractionation, the measurement of relative humidity during and after the rainfall is necessary. For better estimates of the canopy reservoir capacity, the free throughfall coefficient and the critical value of rain, it is essential to monitor rain and throughfall with a resolution of about 0.2 mm or less, rather than treating throughfall on a cumulative basis.

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