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Throughfall, Stemflow and Interception Loss in a Mixed White Oak Forest (*Quercus serrata* Thunb.)

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Throughfall and stemflow measurements in a 60-year-old white oak stand (*Quercus serrata* Thunb.) were carried out during two periods totalling eleven months, from August to November 1993 and from May to November 1994, in order to clarify the rainfall partitioning of this forest. Troughs and spiral-type stemflow gauges connected to tipping bucket-gauges were used for throughfall and stemflow measurements. Seventy-five storms were analyzed individually. Coefficients of variation for throughfall and stemflow ranged between 5-25% and 20-70% respectively. Partitioning of net rainfall in throughfall and stemflow represent 72% and 10% of the gross rainfall respectively. Multiple regression analyses were carried out to determine the stemflow variability. It was determined that maximum rain intensity was highly correlated with stemflow and this variable explained a further 5.5% of the stemflow variation. Estimates of averaged lag time and drainage after rain cease for stemflow were 290 and 164 min, while estimates for throughfall were 60 and 104 min. respectively. The canopy saturation was estimated from continuous storms and showed a value of 0.6 mm. The trunk storage capacity was estimated at a value of 0.2 mm. The interception loss from the forest canopy was estimated in 18%. Interception loss was heighly correlated with rainfall characteristics such as duration and intensity.

Key words: canopy storage, interception loss, rainfall partitioning, stemflow, throughfall

The most important aspect of canopy interception is the proportion of rainfall falling on plant canopy which is collected, stored and subsequently lost by evaporation. In Japan 25 millions hectares are covered by forests, which is approximately 70% of its territory, 30% of these woodlands are classified as protected forests, such as Water Conservation Forests which contain upper streams of rivers and water reservoirs (NLAPO, 1991).

Studies of forest hydrology in temperate regions have shown that interception loss, the evaporation which results from rainfall intercepted by forest canopy and evaporated before reaching the ground, is an important component of the total forest evaporation (Gash and Morton, 1978). However, most of the studies were carried out in coniferous forest stands. Broad-leaved forests occupy about 38% of the forested area in the Chugoku region and therefore it is of interest to investigate the hydrological properties of these forests. Measurement and modelling of interception loss from forest is an essential requirement in the prediction of the effects of forests on the water yield of afforested catchments. The objective of the present work was to study the rainfall partitioning and the interception loss in a representative nature konara stand (*Quercus serrata* Thunb.).

Materials and Methods

1 Study area and stand characteristics

The study area is located in Hiruzen Experimental Forest of Tottori University, Okayama Prefecture, at 80 km Southwestern of Tottori City, Japan, (35°19′N, 133°35′E). A plot (20 × 20 m) with a dominant overstory of konara trees (*Quercus serrata* Thunb.), 60-year-old stand and undergrowth dwarf bamboo (*Sasa paniculata* Makino et Shibata) (Kawahara, 1983) was selected at an elevation of 750 m (Fig.1). The mean annual temperature and precipitation are 11.3 ℃ and 2,140 mm (1,600 mm from April to November), respectively (Tottori Univ., 1991). The climatic diagram of Hiruzen area is represented in Fig. 2.

According to NLAPO (1991), 20,000 years ago the vegetation of this area was a cool temperate, deciduous, broad-leaved forest; now typical vegetation are broad-leaved trees, such as kunugi (*Quercus acutissima* Carruth.) and konara, the latter is distributed everywhere in Japan except in Hokkaido. Stand characteristics as mean tree height and mean tree crown area were assessed in 14.6 m and 21.5 m^2 respectively. Likewise, the averaged annual leaf dry weights were determined from litterfall measurements and using a factor of leaf area per unit of weight (18 m^2 kg^{-1}) the leaf area index of this stand was estimated at a value of 5.2.

Soil types are Ando soils, these are generally called volcanic ash soils, the traditional name, Kurobokudo (black fluffy soils) is widely used also. Kurobokudo have developed from pyroclastic materials or parent materials relatively rich in pyroclastic materials, in the Hiruzen area these were formed by past eruptions of the Daisen volcano. They are characterized by a high organic carbon content (usually exceeding 5%), low bulk density (less than 0.85 g cm^{-3}), high values of exchangeable Al (Otowa, 1986) and soil pH values between 4.5-5.7 (Tottori Univ., 1991).

2 Measurements

The research was based on the analysis of individual storms in August-November 1993 and May-November 1994. During winter, from December to March no attempt was made to carry out measurements due to heavy snowfall. After each rainfall event, precipitation in the open area (gross rainfall), throughfall and stemflow were analyzed. Thus, only storms

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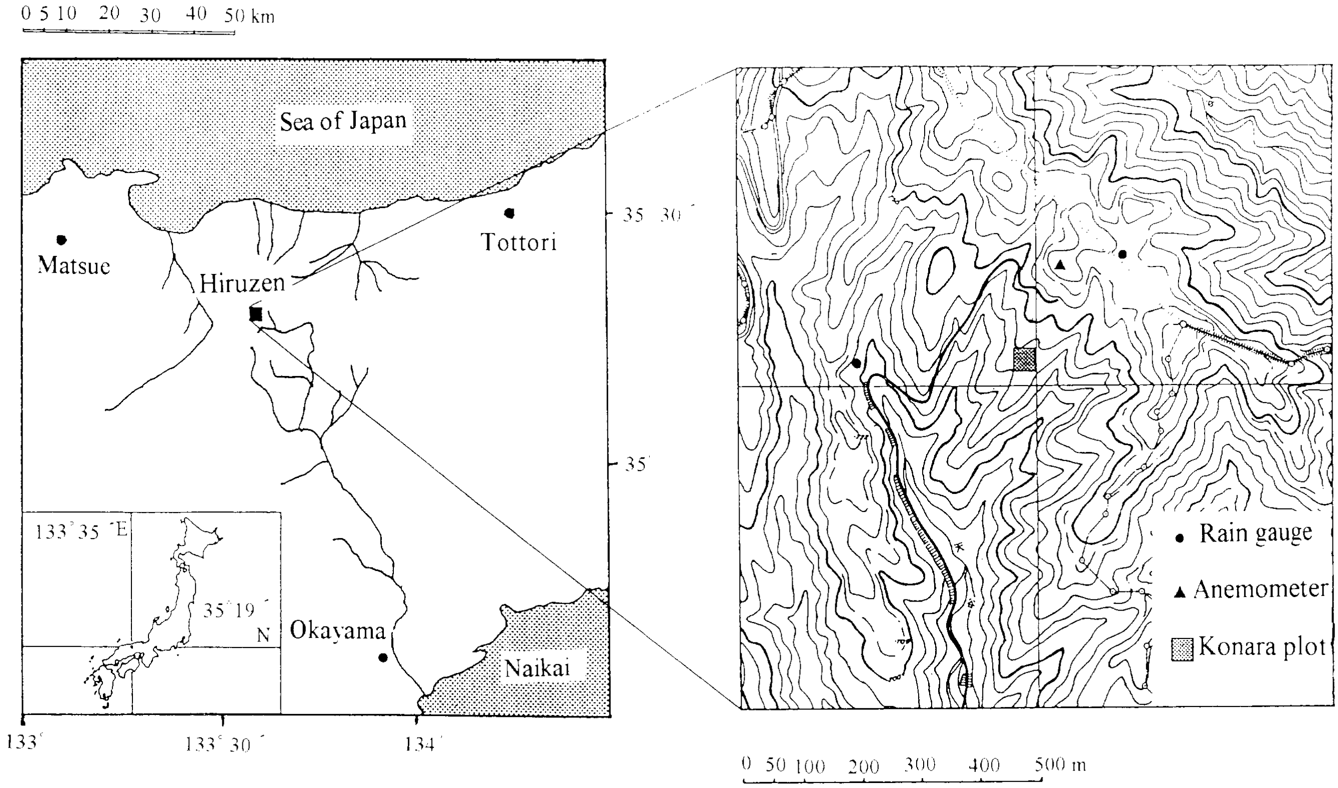

Fig. 1 Location of the study site and positioning of instruments (rain gauges and anemometer) at Hiruzen.

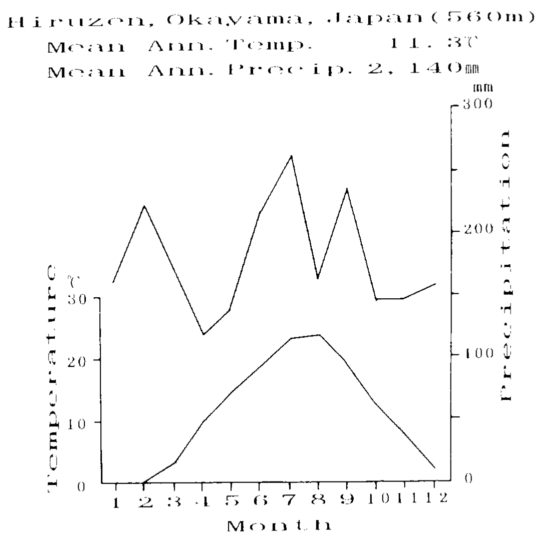

Fig. 2 The climatic diagram of Hiruzen area in Okayama, Japan.

preceded by at least 12-h or 8-h daylight without prior rain were considered, on the assumption that the canopy was dry (Mitscherlich and Moll, 1970; Jackson, 1975; Gash and Morton, 1978; Rowe, 1983). A total of 75 storms was analyzed.

1) Gross rainfall

Three tipping bucket-gauges; one of 0.1 mm and two of 0.5 mm resolutions, were set at 1.5 m above the soil surface in the open area neighboring the experimental plot (Fig.1). Data were stored in KADEC-UP recorders at one and 10-min intervals respectively.

Net rainfall in this study was considered as the quantity of rainfall that reaches the forest floor, the sum of throughfall and stemflow.

2) Canopy throughfall

A plot of 10 × 10 m was selected and troughs were used to collect the throughfall, as troughs form continuous transect, they should be more effective in overcoming throughfall variability. Thus, eight V-shaped plastic troughs of 20.5 cm wide and 2 m length, which have a cross-section similar to the ideal rain-gauge funnel were set at 1.6 m above the soil surface. Troughs were arranged in circle and four of them connected to one 500-cc tipping-bucket gauge by plastic hose of 1.5 cm diameter. This system gave a throughfall resolution of 0.31 mm and data were stored in a Maxell memory card for TEAC DL-101M recorder (eight channels) at 1-min intervals. Another four troughs were connected individually to standard tipping-bucket gauges giving a system of high precision, which was useful in small rain events to assess throughfall resolutions of 0.039 mm; these data were stored in a KADEC-UP recorder at 1-min intervals. Inside troughs a plastic net was used as strainer to retain litter, which was weekly picked up to avoid obstruct water to flow into the gauges.

3) Stemflow

Stemflow water was measured from the flow on the stems in 16 trees. A wired rubber hose 3 cm in diameter with perforations of 1.5 × 2.5 cm at 4 cm intervals was set on the stems at 1–1.5 m height to make spiral-type stemflow gauges. Every stem was prepared (without bark) by setting the hose on a smooth surface. The stemflow gauges were pressed against the stem along the previous cleaned smooth surface and fastened closely to the trunk. The upper and lower parts of the hose were held by wire and sealed with silicon. Each trough formed two and a half loops around a stem at an angle approximately 30° to the horizontal plane. Twelve trees were connected in groups of four stems to 50-cc tipping bucket-gauges and data were stored at 1-min intervals in a TEAC DL-101M recorder. In addition, stemflow from another four trees was

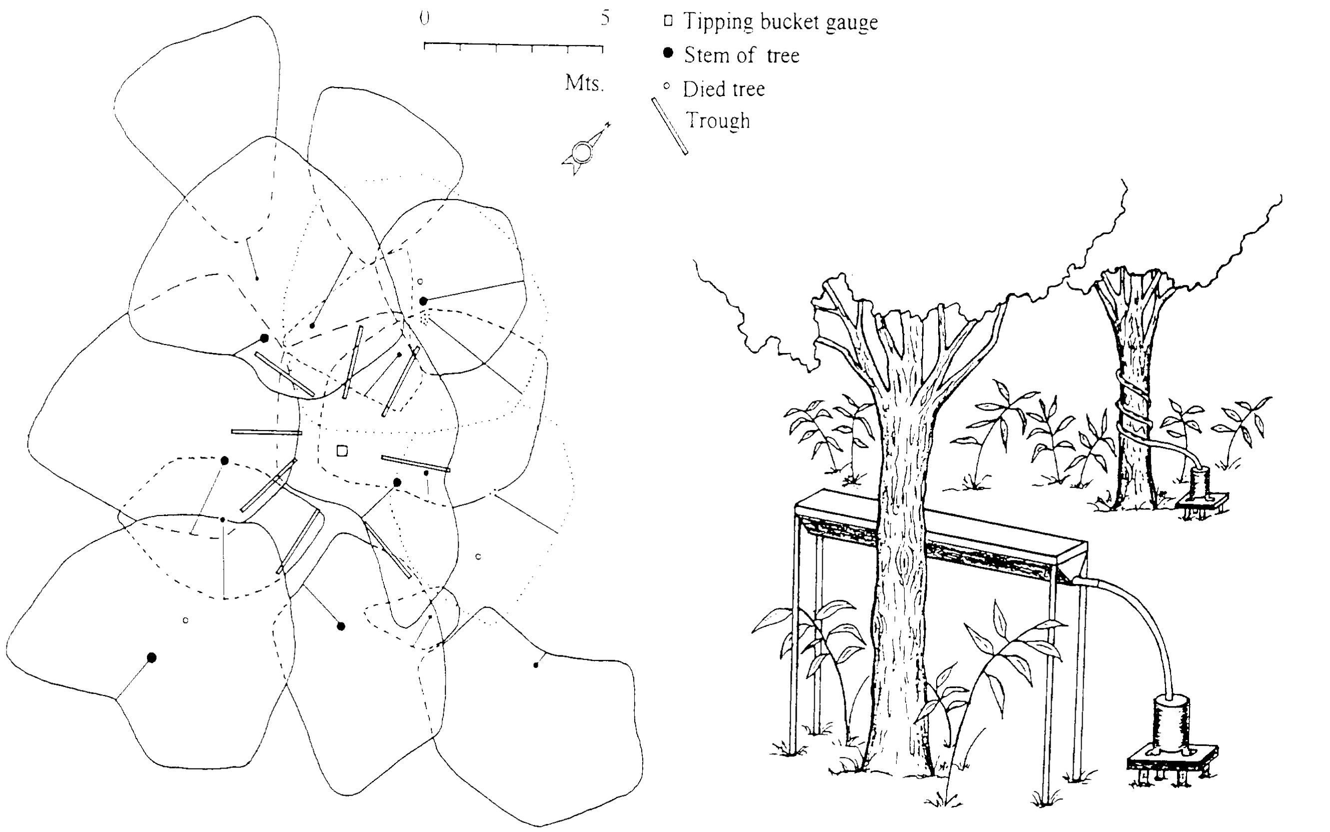

Fig. 3 Vertical crown projection map and layout of instruments in a natural oak forest stand on the Hiruzen Experimental Forest of Tottori University, in Okayama.

collected individually and measured in standard tipping-bucket gauges, data were stored in a KADEC-UP recorder at 1-min intervals. From the crown area a converting factor was obtained for each tree to change volume of water to mm depth.

The layout of the instrumental design and the vertical crown projection of trees are shown in Fig.3.

4) Windspeed

Windspeed was monitored by means of a 3-cups anemometer placed 1 m above the forest canopy near to the plot (Fig.1). Data were stored in a KADEC-UP recorder at 1-min intervals.

3 Estimation of canopy storage capacity

Interception loss is governed by the number of wetting and drying cycles on the vegetation, these in turn, will generally be related to the number and size distribution of the showers. The relevant characteristic of the vegetation is the amount of water stored in the canopy in a single shower sufficient to exceed the capacity of the vegetation to retain water on its surface. This characteristic is known as the interception storage capacity or canopy saturation value. (Leyton *et al.*, 1967). Thus, canopy storage capacity was determined by plotting gross rainfall (R) *versus* net rainfall (Nr) for individual continuous storms up to 2 mm; extrapolating the relationship between Nr and R to find the amount of rain that falls before throughfall begins, *i.e.*, R at $Nr = 0$

Results and Discussion

1 Rainfall characteristics and windspeed

During the studied period in Hiruzen, 36% of the total amount of rain fell in storms of more than 100 mm (representing only 4% of all storms) (Fig. 4a). Mean storm intensities (Fig. 4b) of less or equal to 2 mm h^{-1} occurred in 81% of all storms (5% of the total rain volume), while mean intensities between 2−3 mm h^{-1} happened in 12% of all storms (50% of the total rainfall). Also, 65% of total rain fell in storms of more than 20 h of duration (16% of all storms), while storms of less than or equal to 10 h of duration occurred in 70% of all storms (19% of the total amounts of rain) (Fig. 4c). Furthermore, mean windspeed (Fig. 4d) of less or equal to 3 m sec^{-1} occurred in 64% of all storms (60% of the total rainfall).

2 Rainfall partitioning

Net rainfall (Nr), konara throughfall (Kt) and stemflow (SF) catches are correlated with gross rainfall (R) (Fig. 5). In the net rainfall and throughfall case, the correlation is particularly high (with a correlation coefficient of 0.995), while a lower correlation coefficient (0.90) is observed for stemflow.

On a storm basis throughfall averaged 72.3% with a range of 45.1−87% of the total precipitation and standard deviation of 8.8%. The spatial variability of throughfall of five automatic recording gauges averaged 11.8% and ranged from 5−25% coefficient of variation and the standard deviation showed an approximately linear increase with increasing throughfall (Fig.6). Similar finding for Duijsings *et al.* (1986) were reported in an oak/beech stand (10−30%). Furthermore, coefficient of variation showed a curvilinear increase with decreasing throughfall at values below 10 mm, with throughfalls greater than 10 mm coefficient of variation appeared to be

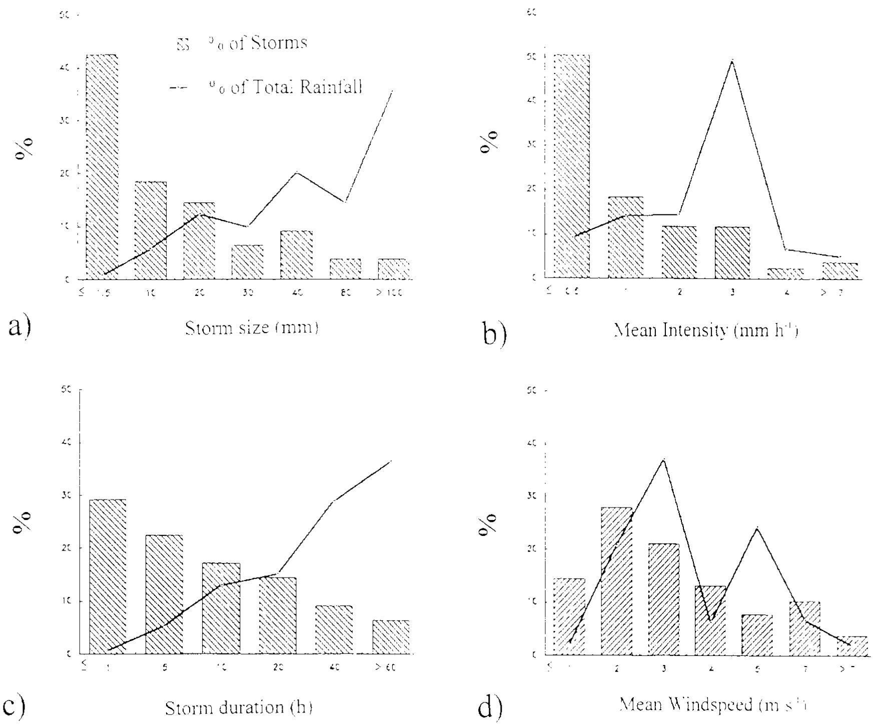

Fig. 4 Frequency distributions (percentage of total number of storms) of storm size (a), mean intensity (b), storm duration (c), and mean wind speed (d). Lines indicate percentage of total rainfall volumes corresponding to the respective categories.

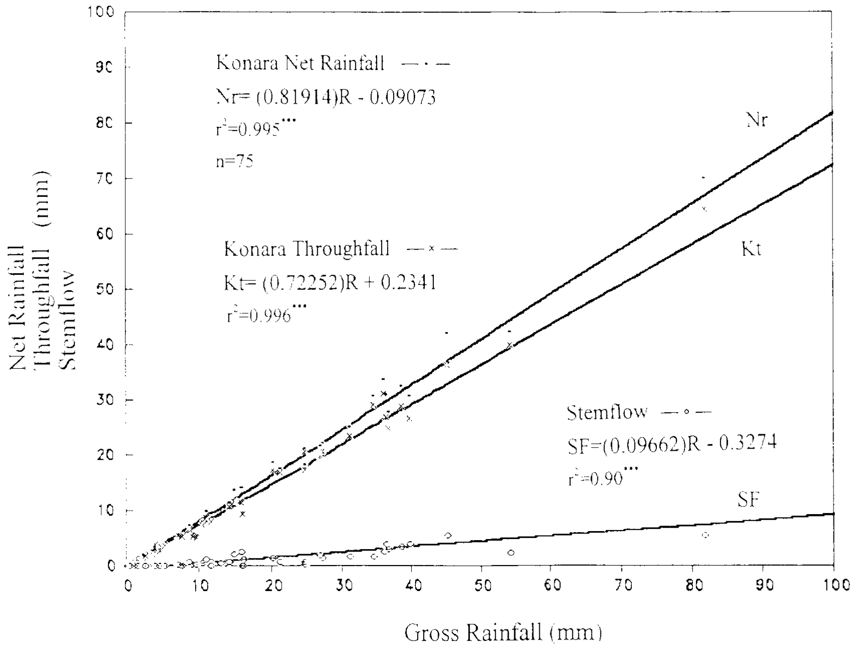

Fig. 5 Relationship between the partitioning of net rainfall and gross rainfall.

fairly constant (Fig.8).

Stemflow averaged 5.23% with a range of 0–17% of the total precipitation and a standard deviation of 4.3% on a per-storm basis. The variability of stemflow of seven automatic recording gauges averaged 42% and ranged from 20–70% coefficient of variation (Fig. 7). Likewise, stemflow coefficient of variation tended to decrease asymptotically with the increase in gross rainfall (Fig.8), as observed in throughfall.

Stemflow is more variable than throughfall, but these errors in the stemflow estimates will have only a small effect on the net rainfall because of the relatively small proportion of precipitation involved, especially in light storms events.

3 Stemflow variation

Several statistical relationships were conducted with the stepwise procedure including variables of storm characteristics (duration and intensity) and windspeed, in order to assess the contribution of such variables to the variation of stemflow. A multiple regression analyses for stemflow (*SF*) including the variables gross rainfall (*R*) and maximum rain intensity (Max. *Ri*) showed highly significant correlation and explained a further 5.5% of the variation of stemflow, the equation is as follow:

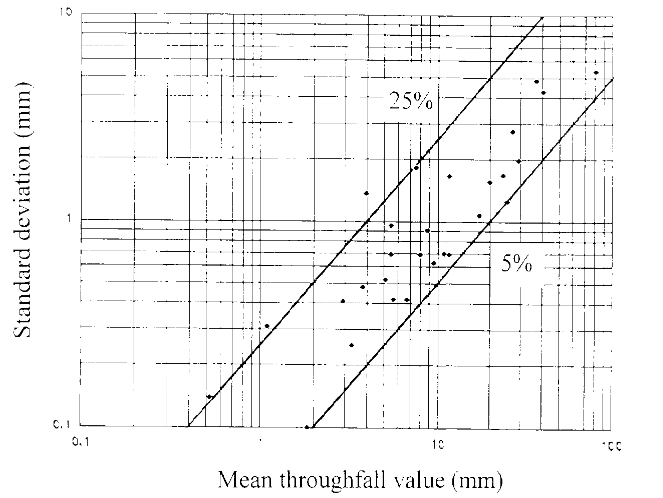

Fig. 6 Spatial variability of throughfall of five gauges (5−25%) and the relationship between the mean and standard deviation of throughfall.

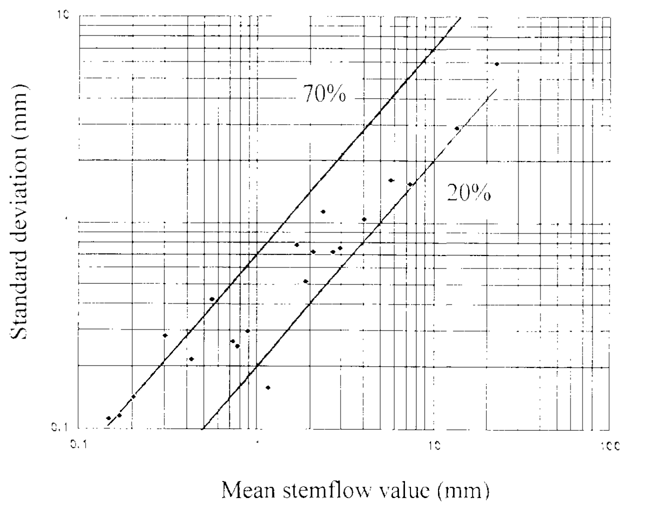

Fig. 7 Variability of Stemflow of seven gauges (20−70%) and the relationship between the mean and standard deviation of stemflow.

$$SF = (0.1154)\,R - (0.397)\ \mathrm{Max.}\ Ri + 0.0307$$
with $r^2 = 0.95^{***}$, $n = 75$.

The results showed that rain intensity affected principally stemflow but not throughfall. High rainfall intensity may produce branch flow that exceeds the capacity of the flow paths (Herwitz, 1987), and drips occur. This causes stemflow yield to be lower than for an event of similar total volume but with lower intensity (Fig.9). Likewise, Weihe (1985) reported that the relation between stemflow and throughfall was influenced by rainfall intensity. On the other hand, although several studies have showed that throughfall increased with wind speed because of drip effect (Mitscherlich, 1971; Heuveldop *et al.*, 1972; Jackson, 1975; Weihe, 1985). However in this study throughfall did not show any relationship with wind speed.

4 Lag time and drainage after rain cease (DARC)

Lag time, the time difference between the start of the rain and the initiation of throughfall or stemflow, and DARC, the time difference between the cease of the rain and the end of throughfall or stemflow, were estimated for every individual storm. All clocks of the recorders (throughfall and stemflow gauges) were synchronized with the gauge of gross rainfall to calculate lag time and DARC.

Throughfall lag time (*TL*) on a storm basis averaged 60 min (*SE* = 11), and throughfall DARC averaged 104 min (*SE* = 11). Storm characteristics as duration (*Sd*) and maximum rain intensity (Max. *Ri*) were highly correlated with *TL*, the equation is as follow:

$$TL = (2.6909)\,Sd - (6.024)\ \mathrm{Max.}\ Ri + 33.199$$
with $r^2 = 0.51^{**}$, $n = 42$.

Gilbert (1953), cited by Helvey and Patric (1965), found in an oak stand that throughfall did not begin during the first 30 min of storms less intense than 2.5 mm h^{-1}, while storms more intense than 11 mm h^{-1}, throughfall started about five minutes after rain began.

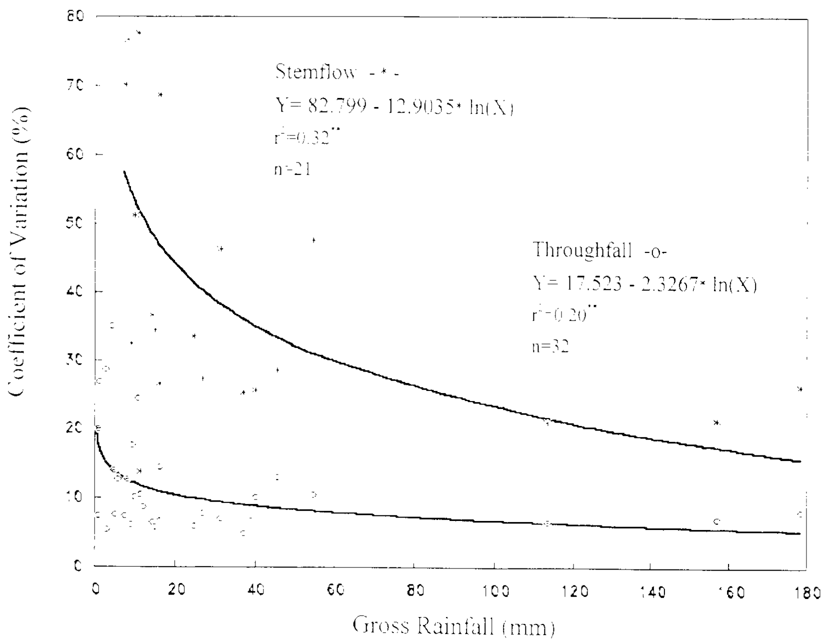

Fig. 8 Relationship between the coefficients of variation and gross rainfall for stemflow and throughfall.

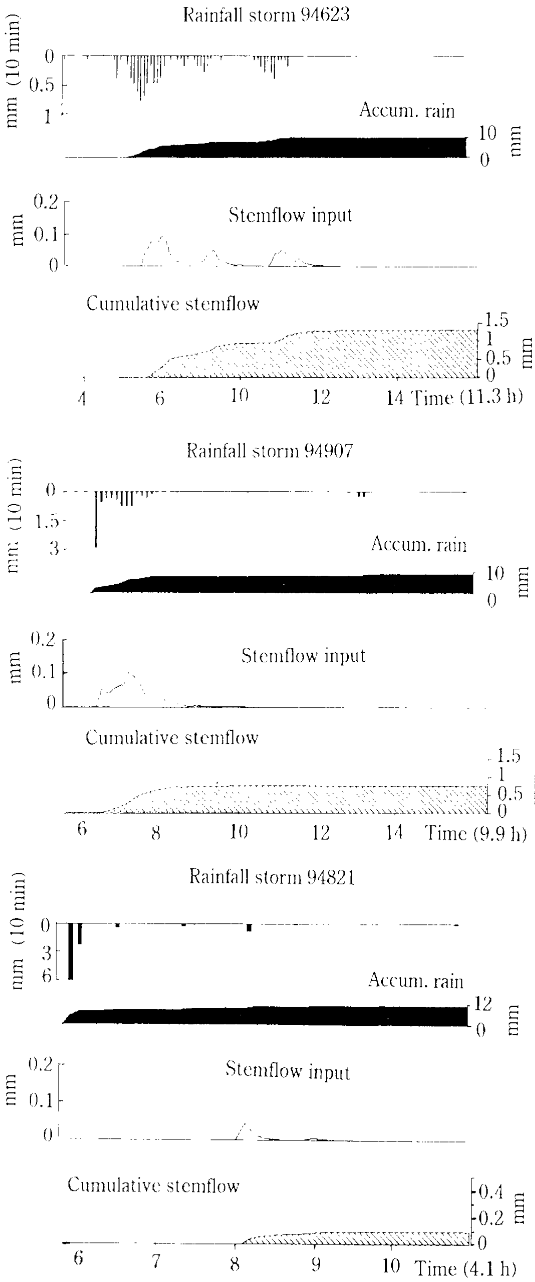

Fig. 9 Stemflow variation with storms of different rainfall intensity, comparison of three storms of similar size and duration, but different rain intensity.

Stemflow lag time (*SL*) on a storm basis averaged 290 min (*SE* = 56), and stemflow DARC averaged 164 min (*SE* = 26). A multiple regression equation was developed for *SL*, including the variables storm duration, gross rainfall, average windspeed (AW_s), maximum windspeed (MW_s) and stemflow:

$$SL = (8.534)\,Sd + (9.266)\,R - (78.39)\,AW_s + (75.814)\,MW_s - (104.6)\,SF - 197.2$$

The correlation was highly significant ($r^2 = 0.78^{**}$, $n = 28$).

In general, depending upon rainfall intensity, stemflow did not occur for rainfall events below about 5 mm. Similar findings were reported by Brown and Barker (1970) in a mixed oak stand and by Crabtree and Trudgill (1985) for a beech stand. Moreover, Neal *et al.* (1991) found that about 8 mm of rainfall was required before stemflow occurs in beeches.

5 Interception loss

Interception storage capacity was determined by the method of Leyton *et al.* (1967), estimations gave a canopy saturation value of 0.6 mm. Likewise, Rutter *et al.* (1975) and Dolman (1987) reported a canopy saturation value of 0.8 mm for oak stands.

Trunk saturation capacity, the depth of water required to saturate the trunk, was estimated to be about 0.2 mm from linear regressions between stemflow and gross rainfall, using the method outlined in Gash and Morton (1978).

The interception loss (*Ic*) for each storm was estimated by the difference between gross rainfall and the sum of throughfall and stemflow. The lineal regression of interception loss on gross rainfall for individual storms is shown in Fig. 10.

The interception loss results of this study agree well with those reported by Dolman (1987) in an oak stand in The Netherlands and show similar trends with Tanaka *et al.* (1984). Interception loss values ranged from 0.08-36.3 mm on a per storm basis or 4.8-100% of gross rainfall. Interception loss was heighly correlated with rainfall characteristics as *Sd*, Max. *Ri.* and average rain intensity (Avg. *Ri*). The contribution of such variables to the variation of interception (about 2%) was assessed in the following multiple regression formula:

$$Ic = -(0.031)\,Sd + (0.1798)\,R + (0.5267)\,\text{Max.}\,Ri - (0.568)\,\text{Avg.}\,Ri + 0.2234$$

with $r^2 = 0.94^{**}$, $n = 71$.

The variable Avg. *Ri* was calculated by dividing the rainfall amount falling during the event by *Sd*. Thus, this variable is related with storm duration and both have a negative sign. Also is necessary to mention that the factor continuity is also involved in this relationship but the observations were not enough to divide the events in continuous and discontinuous to carry out this analysis. Since long period storms present usuàlly more dry gaps (discontinuous event) and the canopy fills and empties as the rain period come and go increasing loses for evaporation.

Total interception loss for the studied period reached 223.7 mm, about 18% of the gross rainfall. It is important to mention that rainfall amount in 1994 (from April to November) was anomalous, without typhoons and accounting only with 55% of the mean normal precipitation for this area.

Conclusion

The percentage of the rainfall partitioning resulting in throughfall and stemflow were 72% and 10% respectively. Estimating values of the canopy storage capacity and the trunk storage capacity were 0.6 and 0.2 mm respectively. The coefficients of variation for throughfall and stemflow in this study were ranged between 5-25% and 20-70% respectively. These ranges are considered acceptable and agree well with those reported for others studies (Helvey and Patric, 1965; Duijsings *et al.*, 1986).

Multiple regression analyses showed that, addition of maximum rainfall intensity to the simple linear equation (*SF ver-*

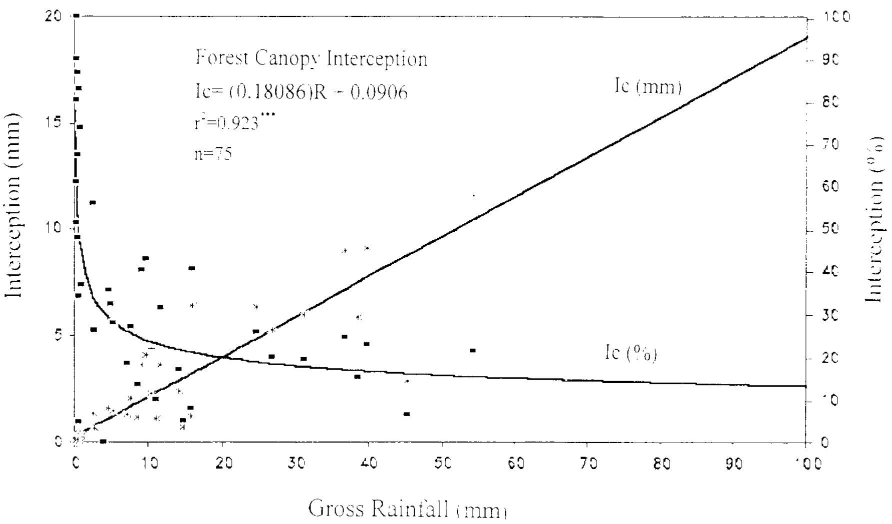

Fig. 10 Relationship of the forest canopy interception loss and the gross rainfall.

sus R) explained a further 5.5% of the variation of stemflow. Rain intensity affected principally stemflow but not throughfall. Stemflow began after 5 mm of rainfall and averaged lag time was about five times more delayed than lag time of throughfall, while averaged DARC did not show significant differences.

Overall, the interception loss by the konara forest canopy for 75 storms was 18% of the gross rainfall measured in an adjacent open area. Interception loss was heighly correlated with rainfall characteristics such as duration and intensity. The contribution of such variables to the variation of interception loss was 2%.

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