RAINFALL PARTITIONING BY AN ARID WOODLAND (*ACACIA ANEURA* F. MUELL.) IN SOUTH-WESTERN QUEENSLAND

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Abstract

In this study of rainfall characteristics, throughfall was highly positively correlated with precipitation. Stemflow and interception were positively correlated with precipitation. Rainfall intensity did not significantly affect the stemflow or interception components, though throughfall was shown to increase with increasing intensity for rainfall events up to 6 mm aggregate. A positive relation was shown between tree size and interception, while negative relationships were found between tree size, and throughfall and stemflow for various classes of precipitation events. Volume of stemflow waters was positively related to tree size. The results are discussed in terms of soil infiltration characteristics, and the woodland community.

I. INTRODUCTION

All vegetation intercepts a certain quantity of incoming precipitation and redistributes the water to the atmosphere by evaporative processes, and to the underlying soil surface. Trees in particular influence soil moisture distribution. Some species possess a canopy structure such that a high proportion of the incoming precipitation is intercepted, the remainder falling directly or indirectly via lower flora canopies to the soil surface as throughfall. While some of the intercepted water is held by the various canopy surfaces such as leaf and bark, the remainder is channelled to the ground by the leaves, branches, and stems (stemflow), to be readily absorbed in close proximity to the tree bole. Mulga (*Acacia aneura* F. Muell.) with its vertically orientated leaves and branches, is particularly well adapted to intercepting a high proportion of rainfall, much of which is channelled to the ground as stemflow (Slatyer 1965).

Losses of intercepted water by evaporation in the humid forested regions can reach 254 mm annually (Helvey and Patric 1965*a*, 1965*b*). Proportionate losses in the semiarid and arid regions would further increase moisture stress in the vegetation of these zones.

Evidence in support of incorporating a tree parameter variable into regressional analysis of throughfall and stemflow with precipitation was shown by Helvey and Patric (1965*a*) and Orr (1972). Orr (1972) suggested that throughfall should be adjusted for percentage canopy density, and stemflow for tree diameter breast height (d.b.h.). He further pointed out that the combination of these two relationships yielded an equation for net rainfall.†

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† Zinke (1967) provides the following definition of net rainfall:

Net rainfall = precipitation − rainfall intercepted and held by the tree.

Stemflow volume has been shown to bear a linear relationship with the square of the d.b.h. in a *Pinus sylvestris* (Scot's pine) stand (Rutter 1963). Such relationships could be expected to occur in other woodlands, as relationships between stem size and wood weight, and stem size and leaf weight have commonly been shown (Whittaker and Woodwell 1968; Burrows and Beale 1970).

This paper presents the results of a rainfall interception study of mulga with particular emphasis on the effects of rainfall characteristics and tree size on the partitioned components.

II. Method

The experimental site was situated on the Experimental Reserve, 5 km south of Charleville. *Acacia aneura* was the dominant tree species, while *Eremophila gilesii* F. Muell. (green turkey bush) formed a sparse shrub layer. Perennial grasses, particularly *Aristida* spp. and *Danthonia* spp., and herbaceous plants such as *Sida* spp. and *Abutilon* spp. comprised the ground flora. *Cheilanthes sieberi* (mulga fern) was very common.

The soil was a sandy-loam, lateritic red earth (Gn 2·11) varying in depth from 1 to 2 m. Nutritionally, the soil was very infertile and highly acidic (pH 4·5).

Twenty-eight trees, comprising all the classes outlined by Burrows and Beale (1969), were selected at random. Each tree was characterized in terms of basal area, height, canopy area, and mean canopy radius. Tree sizes ranged from a basal area of 25·92 cm^2 to 1011·60 cm^2, and heights from 3·8 to 12·71 m.

Rubber rings were fixed to the larger trees with contact cement, and plastic cement was used to stop leaks around the rubber. Polyethylene tubing conducted water from the catchment ring to a suitably sized container.

Stemflow from the smaller trees was collected by affixing a rubber trough in a spiral around the stem. The lower end of the trough was placed over a 12·5 cm diameter plastic funnel which directed stemflow water into a receptacle.

Throughfall was measured by 74 wedge-shaped gauges (catchment area 37 cm^2) placed in fixed positions beneath the tree canopies.

Precipitation was measured by seven wedge-shaped gauges (catchment area 37 cm^2), distributed randomly through the study area. Each gauge was positioned so that a minimum 45° unrestricted view of the sky was afforded in all directions, as recommended by Helvey and Patric (1965*b*). A 20 cm rainfall duration recorder was also positioned within the area. In addition, detailed records of rainfall — both quantity and duration, temperatures, relative humidity, and wind speed were made available from the Commonwealth Bureau of Meteorology Station, situated 2 km from the site.

Precipitation, stemflow, and throughfall were generally measured as soon as possible after each rainfall event. It was therefore possible to isolate the quantities of the partitioned components from individual storms rather than on a daily or weekly pattern as reported elsewhere (Carlisle *et al.* 1965).

The stemflow data were converted from volume to equivalent depth of water by dividing by the horizontal projection area of the individual tree canopies. The tree projection area was calculated by measuring the distance from the tree bole to the canopy periphery at six points on the periphery, and treating each segment so outlined as a sector of a circle. The radian being known, the area of each sector could be calculated, and by addition, the tree projection area found.

All data was analysed by multiple regressional analysis.

The study covered the period December 1970 to March 1972.

III. Results

The precipitation recorded during the experimental period is shown in Table 1.

Table 1

RAINFALL RECORDED DURING EXPERIMENTAL PERIOD, DECEMBER 1970–MARCH 1972

Values are average of seven gauges except where indicated

Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
7.xii.70	1·00	15.vii.71	2·76	7.xi.71	15·50
8.xii.70	2·00	16.vii.71	14·36	25.xi.71	2·80†
20.xii.70	15·80	23.vii.71	14·43	30.xi.71	5·75
22.xii.70	3·75	6.viii.71	1·00	3.xii.71	9·25
16.i.71	4·89	7.viii.71	14·50	20.xii.71	3·25†
18.i.71	2·06	8.viii.71	17·58	22.xii.71	2·00†
24.i.71	1·49	14.viii.71	1·92	26.xii.71	54·00†
30.i.71	36·34	20.viii.71	0·50†	27.xii.71	120·00†
9.ii.71	7·50	4.ix.71	4·00†	4.i.72	4·00
11.ii.71	13·67	13.ix.71	29·86	6.i.72	7·50
19.ii.71	29·33	16.ix.71	18·43	13.i.72	2·50†
5.iii.71	31·00	21.ix.71	0·25†	11.ii.72	22·00
6.iii.71	17·36*	26.ix.71	4·75†	18.ii.72	9·50†
9.iii.71	11·92	16.x.71	12·46	5.iii.72	7·43
16.iv.71	2·54	30.x.71	1·75†		
18.iv.71	6·04	2.xi.71	27·83		

* Consisting of falls during the night of 5/6.iii.71 and morning of 6.iii.71.

† Recorded from pluviometer at site.

Table 2

RELATIONSHIP BETWEEN THROUGHFALL AND PRECIPITATION FOR FOUR PRECIPITATION SIZE CLASSES

t, throughfall (mm); p, precipitation (mm)

Storm class (mm)	Regression	DF	R^2
0–6·25	$t = -0{\cdot}318 + 0{\cdot}726p$	74	0·839
6·25–12·5	$t = 0{\cdot}567 + 0{\cdot}592p$	30	0·619
12·5–25	$t = -1{\cdot}176 + 0{\cdot}737p$	70	0·571
>25	$t = -4{\cdot}970 + 0{\cdot}888p$	19	0·307

Over the experimental period 18% of the gross precipitation was channelled as stemflow.

Regressions differing significantly ($P < 0{\cdot}01$) were obtained when stemflow (s) data from precipitation (p) > 10 mm and < 10 mm were analysed separately (Fig. 1):

$$s\,(p < 10\text{ mm}) = -0{\cdot}330 + 0{\cdot}262p \quad (R^2 = 0{\cdot}827),$$

$$s\,(p > 10\text{ mm}) = 1{\cdot}112 + 0{\cdot}131p \quad (R^2 = 0{\cdot}635).$$

A linear relationship between throughfall and precipitation was shown (Fig. 1). The regression of best fit was:

$$t = -0{\cdot}357 + 0{\cdot}733p \quad (R^2 = 0{\cdot}952),$$

where t is the throughfall (mm) and p the precipitation (mm).

Regressional analyses of the throughfall data from storms classified into four size classes resulted in regressions depicting the throughfall–precipitation relationship for each class (Table 2).

Lower regression correlation coefficients resulted from using this method compared with the whole data method.

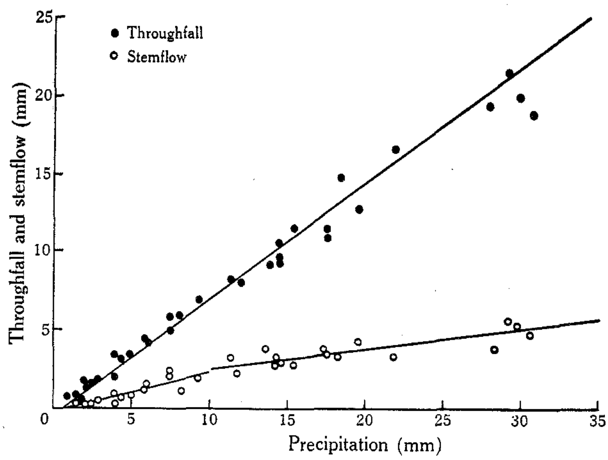

Fig. 1.—Relationships between throughfall and stemflow, and precipitation for all falls recorded during the experimental period.

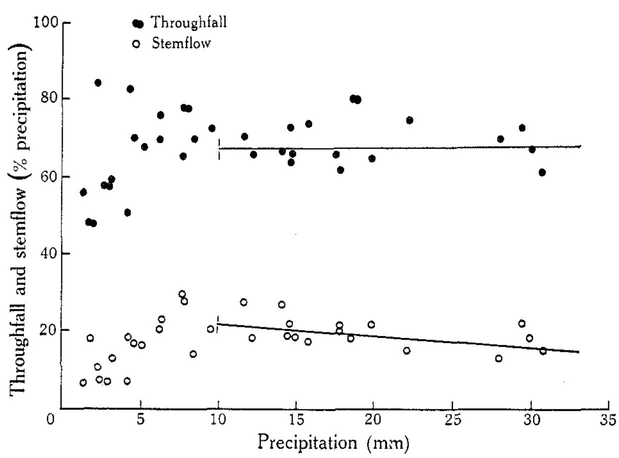

Fig. 2.—Relationships between throughfall and stemflow (expressed as percentage of precipitation), and precipitation for all falls recorded during the experimental period.

In order to show the fairly constant relationship between throughfall and stemflow for precipitation events greater than 10 mm, regressional analysis was carried out on the throughfall and stemflow data expressed as a percentage of precipitation (Fig. 2).

Regressions so obtained were as follows:

$$\% \, t \, (p > 10 \text{ mm}) = 67 \cdot 91 + 0 \cdot 04p \quad (R^2 = 0 \cdot 895),$$

$$\% \, s \, (p > 10 \text{ mm}) = 25 \cdot 39 - 0 \cdot 30p \quad (R^2 = 0 \cdot 808);$$

where $\% \, t$ is percentage throughfall, p precipitation (mm), and $\% \, s$ percentage stemflow.

As interception = gross precipitation − (throughfall + stemflow), the interception values for each storm could be calculated.

Interception was shown to be positively correlated with precipitation, the regression

$$r = 0 \cdot 348 + 0 \cdot 121p \quad (R^2 = 0 \cdot 467),$$

where r is interception (mm) and p precipitation (mm), depicting the relationship (Fig. 3).

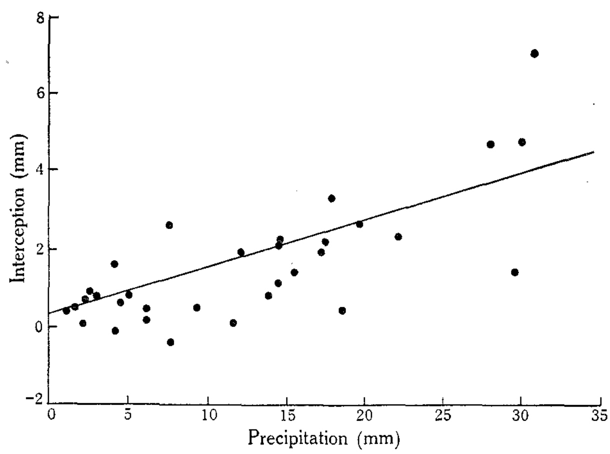

Fig. 3.—Relationship between interception and precipitation for all falls recorded during the experimental period.

On two occasions negative interception was recorded. That is, the sum of throughfall and stemflow exceeded the recorded precipitation. Interception comprised 13% and throughfall 69% of the precipitation over the experimental period.

Rainfall intensity did not have a consistent effect on the proportions of throughfall. Only in the storm class 0–6·25 mm was there a positive correlation between throughfall and intensity. With increasing intensity, throughfall tended to increase for storm sizes 0–6·25 mm and >12·5 mm, but decreased for the 6·25–12·5 mm class.

Stemflow and interception were independent of intensity. Regressional analysis showed the following throughfall–intensity relationships:

$$\text{Storm class } 0\text{–}6 \cdot 25 \text{ mm:} \quad t = 1 \cdot 413 + 0 \cdot 063y \quad (R^2 = 0 \cdot 462),$$

$$\text{Storm class } 6 \cdot 25\text{–}12 \cdot 5 \text{ mm:} \quad t = 7 \cdot 771 - 0 \cdot 413y \quad (R^2 = 0 \cdot 358),$$

$$\text{Storm class } >12 \cdot 5 \text{ mm:} \quad t = 11 \cdot 363 + 0 \cdot 424y \quad (R^2 = 0 \cdot 073),$$

where t is throughfall (mm) and y intensity (mm hr^{-1}).

The coefficient of variation of precipitation was lower than that of throughfall, while that of stemflow was the highest. Regressional analysis was used to construct the curves in Figure 4. The regressions of best fit were:

$$\text{Coefficient of variation of mean precipitation} = 3\cdot836 + (13\cdot983/p) \quad (R^2 = 0\cdot438),$$

$$\text{Coefficient of variation of mean throughfall} = 23\cdot767 + (29\cdot237/p) \quad (R^2 = 0\cdot389),$$

$$\text{Coefficient of variation of mean stemflow} = 37\cdot892 + (113\cdot043/p) \quad (R^2 = 0\cdot588).$$

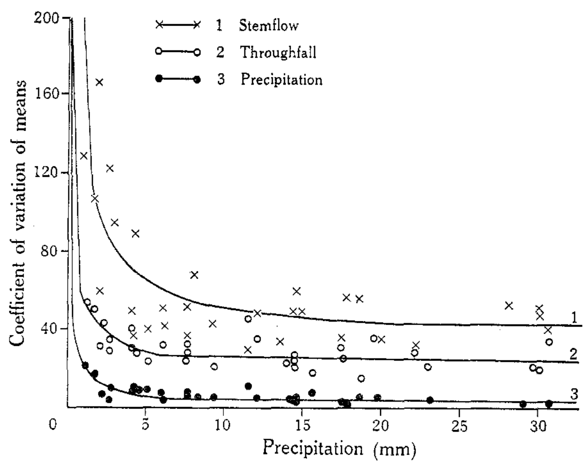

Fig. 4.—Relationship between coefficients of variation of the means of precipitation, throughfall, and stemflow. Points are means of individual storm data.

In an attempt to clarify the effect of tree size on the partitioned components, the data were grouped into various precipitation classes and analysed. Precipitation classes were 0–5, 5–12·5, 12·5-25, and >25 mm. The results of this analysis are shown in Table 3.

Generally, throughfall and stemflow decreased, and interception increased, with increasing basal area.

Tree basal area markedly affected the absolute quantity of water channelled down the stem. Table 4 shows regressions of stemflow and basal area for four size classes of precipitation (0–6·25, 6·25–12·5, 12·5–25, and >25 mm).

Stemflow data (litres) from individual trees for all the storms measured were also analysed. Generally, curvilinear regressions fitted the data from the smaller trees, while linear regressions described the relationships between stemflow (litres) and precipitation for the larger trees.

Trees were further classified according to basal areas, and regressional analysis was again used for the stemflow–precipitation data. The basal area classes were 0–100, 100–300, 300–650, and >650 cm². The results of this analysis are detailed in Table 5. Again, curvilinear regressions show the relationship for smaller trees, while linear regressions fit the data from trees of basal area >100 cm².

In an attempt to improve the relation between easily measurable tree parameters and stemflow volume, the data were analysed so that the horizontal projection of canopy area (HCP) to the ground was included as an independent variable.

TABLE 3

RELATIONSHIPS BETWEEN TREE BASAL AREA AND THE PARTITIONED COMPONENTS OF RAINFALL

b, basal area (cm^2); t, throughfall (mm); s, stemflow (mm); r, interception (mm)

Storm class (mm)	DF	Regression	R^2
0–5	93	$t = 1 \cdot 505 - 0 \cdot 0003b$	0·004
		$s = 0 \cdot 550 - 0 \cdot 0005b$	0·094
		$r = 0 \cdot 348 + 0 \cdot 009b$	0·216
5–12·5	72	$t = 6 \cdot 587 - 0 \cdot 002b$	0·047
		$s = 2 \cdot 104 - 0 \cdot 0009b$	0·063
		$r = -0 \cdot 041 + 0 \cdot 002b$	0·309
12·5–25	92	$t = 11 \cdot 760 - 0 \cdot 002b$	0·053
		$s = 4 \cdot 024 - 0 \cdot 001b$	0·092
		$r = 0 \cdot 295 + 0 \cdot 003b$	0·322

TABLE 4

RELATIONSHIP BETWEEN STEMFLOW AND BASAL AREA FOR FOUR STORM CLASSES

s, stemflow (litres); b, tree basal area (cm^2)

Storm class (mm)	Regression	R^2
0–6·25	$s = 1 \cdot 631 + 0 \cdot 026b$	0·307
6·25–12·5	$s = 7 \cdot 751 + 0 \cdot 076b$	0·545
12·5–25	$s = 0 \cdot 369 + 0 \cdot 162b$	0·812
>25	$s = 13 \cdot 810 + 0 \cdot 280b$	0·788

The introduction of HCP into the regressions did not significantly improve the regression coefficients over those for the simple stemflow–basal area relationship.

TABLE 5

RELATIONSHIP BETWEEN STEMFLOW AND PRECIPITATION FOR FOUR BASAL AREA CLASSES

s, stemflow (litres); p, precipitation (mm)

Basal area	Regression	DF	R^2
0–100	$s = -2 \cdot 235 + 1 \cdot 446p - 0 \cdot 026p^2$	297	0·648
100–300	$s = 0 \cdot 191 + 2 \cdot 198p$	83	0·503
300–650	$s = -6 \cdot 842 + 6 \cdot 047p$	139	0·671
>650	$s = -5 \cdot 128 + 8 \cdot 085p$	78	0·814

IV. DISCUSSION

The relationships developed between throughfall and precipitation and stemflow and precipitation for all rainfall events during the experimental period were not unexpected, and are in agreement with previously published work (Voigt 1960;

Patric 1966; Orr 1972). There is, however, a marked difference between the quantities of stemflow and throughfall presented here and those shown for a mulga scrub in central Australia (Slatyer 1965). Throughfall in the present study is higher and stemflow lower than those reported by Slatyer (1965) from similarly sized rainfall events. Leaf morphology could account for these differences. Mulga phyllodes in central Australia tend to be longer and narrower than those in the Charleville district (Everist 1948), so it is highly probable that more water is intercepted but less held by the phyllodes in central Australia. More of the intercepted water could thus be channelled down the stems of the arid phenotype, which would result in a higher proportion of intercepted rainfall being partitioned as stemflow. This view is supported by the fairly constant quantity of interception reported by Slatyer (1965) compared with the increasing interception reported here.

The slight tendency for percentage stemflow to decrease with precipitation in excess of 10 mm (Fig. 2) can be attributed to stem and leaf drip. Once the foliage and bark is wet, some water droplets fall directly to the ground instead of being channelled to the tree bole by the stems. This also accounts for the two regressions for stemflow: one for precipitation <10 mm and one for precipitation >10 mm. A similar situation was reported by Slatyer (1965) in his stemflow study of mulga. It could be expected that the slight decrease in the stemflow component of the partitioned rainfall would be reflected in a slight increase in the throughfall component. This does not appear to have been the case, as the slope of the regression of percentage throughfall and precipitation is slight (0·04) and throughfall percentages from rainfall events in excess of 10 mm are relatively constant ($68 \cdot 68 \pm 5 \cdot 18$ %). However, as stem drip tends to occur at particular places (e.g. the intersection of two branches) it is reasonable to expect that this phenomenon would not be recorded in the throughfall gauges.

Canopy components have to be wetted before stemflow occurs, though it is not necessary for all surfaces to be saturated. The regression of stemflow on precipitation for precipitation < 10 mm indicates that stemflow begins when 1·5 mm of rain has fallen. This is slightly less than the figure of 2·5 mm reported by Slatyer (1965). Extrapolation of the regression $t = -0 \cdot 357 + 0 \cdot 733p$, where t is throughfall (mm) and p precipitation (mm), indicates that throughfall is first measurable following 0·5 mm of precipitation. This is very close to the precipitation of 0·8 mm reported by Slatyer (1965) to be required before throughfall occurs under mulga in central Australia.

The results presented here indicate that interception increases with precipitation, although interception over the study period was still $1 \cdot 53 \pm 1 \cdot 61$ mm per storm, whereas it was previously reported that interception of precipitation by mulga remained fairly constant at 1·5–2·5 mm (Slatyer 1965). The predominant factors affecting interception are probably the duration of the rainfall event, and the occurrence of short (20 min) rainless periods during an individual event.

Negative interception was recorded twice. Such anomalies were also reported to occur under mulga in central Australia (Slatyer 1965). Slatyer suggested that errors in the throughfall gauge readings, particularly those gauges located in proximity to the canopy periphery, and calculation of the mean throughfall from the replicate gauges could account for these anomalies. In addition to possible errors in the throughfall measurement and analysis, it is also possible that the precipitation over the canopy itself could in fact be higher than that measured in the adjacent clearings owing to increased air turbulence around the tree as suggested by Slatyer (1965). Further, gusty conditions with wind velocities up to 46 $km\,hr^{-1}$ prevailed during one of the storms in which the sum of stemflow and throughfall exceeded gross precipitation. Such conditions could have increased recorded throughfall owing to mechanical shaking of the branches causing stem drip.

Loss of intercepted water by evaporation is high, and most if not all of the 13% of intercepted precipitation is lost to the atmosphere. This represents a significant annual loss of about 64 mm in an area receiving less than 500 mm of rain annually.

Long-term records are probably necessary before significant effects of rainfall intensity on the partitioned components are evolved. Particularly is this so in a semiarid or arid region, as the chances of recording similarly sized rainfall events of varying intensity is low when only a few falls are recorded each year.

Nevertheless, the results show that throughfall from precipitation up to 6·25 mm increases with increasing intensity of rainfall. This compares favourably with the results of Aranda and Coutts (1963). The decrease in throughfall with increasing intensity in the storm class 6·25–12·5 mm cannot be explained, but the low correlation coefficient casts doubts on whether this does in fact occur. The low correlation coefficients for the other regressions of throughfall with rainfall intensity point to the necessity for long-term records of partitioned parameters, although the results indicate that both stemflow and interception are independent of intensity. These results contrast with those reported to occur under mulga in central Australia (Slatyer 1965). However, when the data presented in Table 7 of Slatyer's paper are examined, it is found that the mean percentage throughfall was 55·67 (SD = 1·97) and the mean percentage stemflow was 42·18 (SD = 5·56). The wide scatter of points for percentage stemflow and the small number of such points (11 only) throw doubts on the validity of the conclusion that stemflow decreases and throughfall increases with increasing rainfall intensity. It would, however, appear reasonable to expect that such a situation does in fact occur.

Coefficients of variation for all parameters decrease sharply with increasing gauge catch up to about 5 mm, but stabilize as precipitation further increases (Fig. 4). Precipitation is the least variable, while the stemflow coefficient of variation is the highest. As throughfall and stemflow depend on tree morphology, variation of these parameters would be expected to be higher than that for precipitation. The trends in variation are similar to those reported by Helvey and Patric (1965*b*), although the overall variation in the present study is higher.

The regressions developed depicting the relationships between basal area and the partitioned components throughfall, stemflow, and interception (Table 3) generally show a fair correlation. As could be expected, more variability exists when storms are classed according to rainfall aggregate than when the data from the individual storms are analysed. There was a tendency nevertheless for throughfall and stemflow to decrease and interception to increase with increasing basal area. The decrease in throughfall and stemflow with increasing basal area was fairly constant for all classes. These results are in concurrence with those of Helvey and Patric (1965*a*) and Orr (1972), who showed evidence in support of incorporating a tree parameter variable into regressional analysis of throughfall and stemflow with precipitation.

The increase in interception with basal area (Table 3) is also in agreement with the conclusion of Helvey and Patric (1965*a*), although in their comprehensive review of the subject Helvey and Patric claimed that there was no consistent evidence that interception losses were greatly affected by a variety of canopy densities. The regressions developed for individual storms (not published) do not show a consistent basal area affect on interception. Nevertheless the relationship has been shown on a large number of occasions. This result was unexpected because although the leaf weight of mulga increases with the basal area (Burrows and Beale 1970) the leaf area index tends to decrease (Pressland, unpublished data). Thus the ratio of leaf area to the horizontal projection area of the canopy decreases, even though the total area of leaf available for rainfall interception increases as the basal area increases. A possible explanation is that a higher percentage of rainfall is intercepted by the branches of larger trees than those of smaller trees. This is conceivable, as unpublished data of the author show that the wood weight of mulga increases exponentially with the basal area, as has been reported for other species (Baskerville 1965).

The effect of tree basal area on volume of stemflow is evident in the regressions displayed in Tables 4 and 5. From a given-sized storm, stemflow volume increases with the basal area. Such relationships were demonstrated for Scot's pine by Rutter (1963) but the volumes recorded from mulga are much greater than those from Scot's pine. The high quantity of stemflow water from mulga suggests that stemflow is ecologically important to species growing in the arid regions of the world. This is particularly so as the stemflow waters infiltrate the ground within 45 cm of large tree trunks and within 15 cm of stems of small trees. If the stemflow is calculated on an "area of infiltration" basis, the equivalent of 140 mm of rain can enter the soil of this zone from a rainfall of 25 mm. Thus the effective rainfall is increased up to six times in this area, compared with the inter-canopy area.

Water from even small precipitation events can be utilized more readily by mulga for a longer period than grass and shrub species in the same environment as the available water is stored at a greater depth close to the tree, compared with the inter-canopy area, while still being within the root zone of the tree.

In semiarid or arid regions, deep percolation of stemflow water below the rooting zone of the trees would be a comparatively rare event. More than 75 mm would be required in one rainfall event for significant losses in this manner to occur since the 100–200 cm soil profile will hold 2 mm water per 1 cm soil depth.

The study presented here was a portion of a complete water balance study being undertaken near Charleville under varying densities of mulga. The results are pertinent to the work as they provide the precipitation input data necessary for such a study. A relationship can be developed between net rainfall and precipitation by considering throughfall and stemflow as a single variate.

$$\text{Net rainfall} = -0\cdot687 + 0\cdot995p, \quad (p < 10 \text{ mm})$$

$$\text{Net rainfall} = 0\cdot755 + 0\cdot864p, \quad (p > 10 \text{ mm})$$

where p is precipitation.

The inclusion of a basal area parameter into the net precipitation equation results in a multiple regression for net precipitation:

$$\text{Net precipitation} = 0\cdot048 + 0\cdot885p - 0\cdot0015b,$$

where p is precipitation (mm) and b the mean basal area of all trees in the study area (cm^2).

This regression can be used to determine the net precipitation under thinned stands, important in any water balance study.

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