

# RAINFALL INTERCEPTION AND STEMFLOW IN AN ORANGE PLANTATION

By

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The partition of rainfall was studied for two years in two mature orange orchards in an area with 530 mm mean annual rainfall. Stemflow was estimated to occur only if the daily rainfall exceeded 2.3 mm. Such flow, which was linearly related to the amount of precipitation, totaled 7% during the rainfall season. Throughfall was estimated to occur whenever the daily rainfall exceeded 0.4 mm. The quantity, which was also linearly related to the amount of precipitation, came to about 79–86%. This low value of canopy saturation was confirmed by direct measurement on two detached branches. The amount of interception was estimated at 7–14% of the seasonal rainfall. Long-term records of rainfall at Rehovot were used to estimate average and extreme values of the rainfall components for the main citrus growing area. It was estimated that 22% of the rainfall intercepted by the canopy is effective in reducing transpiration losses and only the remainder, 6–11% of the total precipitation, can be considered as a true water loss to the plant-soil system.

## INTRODUCTION

Irrigated citrus plantations play a very important role in the agricultural hydrology of Israel. The average quantity of water applied to them represents one-third of that used in agriculture and nearly one-fifth of the total national water consumption. Moreover, the crop is concentrated in a relatively narrow strip within the coastal plain, which also contains the main centers of urban and industrial water consumption. The need for a study of the different components of the water balance of these plantations is therefore obvious.

Interception of rainfall by the canopy, with its subsequent evaporation from the wetted leaf surfaces and infiltration through the canopy, are of considerable interest and potential importance and form the subject of the investigation reported in this paper.

When rainfall or over-tree irrigation is intercepted by a crop canopy, evaporation from the wetted surfaces may occur at a rate that is substantially different from that of the same canopy exposed to the same weather but in a dry condition. It has been suggested that this difference in rate of water loss depends on the relative size of the

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aerodynamic and stomatal resistances to the diffusion of water vapor (7, 9). The greater the size of the latter resistance compared with the former, the greater the relative amount of evaporation from intercepted water on the leaf, compared with that from within.

A mature citrus plantation has an aerodynamically very rough surface, implying a low aerodynamic resistance. By contrast, the restriction of stomata to one side of the leaf, and their dimensions (5, 10), strongly suggest that the stomatal resistance will be high. Direct measurements confirm this view (12). In such circumstances it is obviously of interest to determine how much water is intercepted by the plantation and how much is evaporated.

The partitioning of the rainfall, i.e., the pathway of the intercepted water that is *not* evaporated, is also of interest for two reasons. In the case of a mature plantation with complete ground cover, any intercepted water reaching the soil surface will contain an increased concentration of aerosols, such as salt or radioactive nucleids, etc., compared with that found in open area rainfall. Moreover, the rainfall will be distributed less uniformly than that in an open area as it is channeled differentially via the leaves and stems of the canopy. These considerations are even more important in the case of plantations that are irrigated by above-canopy sprinkling.

Although rainfall interception has been described for many different climates and vegetative covers, no reference could be found to fruit plantations. An extensive literature review of quantitative aspects of rainfall interception has been made by Delfs (2), and a more recent review is provided by Helvey and Patric (3); Monteith (7) has recently reviewed a number of investigations into the rate of evaporation from wetted plant canopies.

## SITES AND METHODS

Measurements were made during two rainfall seasons, 1965/66 and 1966/67, at two mature orange plantations in the central coastal belt. During the first season the measurements were made at Nezer Sereni (34°50'E, 31°55'N, 75 m MSL), where the mean annual rainfall is 543 mm. During the second season measurements were made near Rehovot (34°49'E, 31°54'N, 65 m MSL), where the long-term mean annual rainfall is 530 mm. Both plantations were typical commercial orchards of Shamouti oranges giving high yields and receiving the standard recommended irrigation practice. In both cases the observation sites were surrounded by a very large area of similar plantations.

The trees were about 35 years old and approximately 4 m high. The ground cover was complete and at Rehovot the leaf area index was measured and found to be 7, i.e., 7 cm<sup>2</sup> leaf surface per 1 cm<sup>2</sup> soil surface. The trees were planted 4 m × 4 m apart, giving some 60 trees per dunam\*.

\* 1 dunam = 1000 m<sup>2</sup>.

The site at Nezer Sereni (subsequently referred to as site A) was subdivided into four plots, each consisting of trees diagonally adjacent; the four plots formed the corners of a rectangular area, 90 m  $\times$  20 m. The measurements made at Rehovot (subsequently referred to as site B) were more intensive and were confined to a 4 m  $\times$  4 m plot between four trees of similar shape and size.

#### PRECIPITATION ABOVE THE CANOPY

It was considered essential to measure the precipitation actually falling on the canopy at both sites, and for this purpose a number of methods were used (8, 13). Standard 200 cm<sup>2</sup> Hellman-type raingauges were used at 1 m above soil surface, and a modified Victor-type (1) small-orifice (6.65 cm<sup>2</sup>) raingauge was exposed 0.5 and 1.00 m above the canopy.

At site A a standard raingauge 2.5 km NW of the experimental site was read daily, while two small-orifice gauges at 0.5 m above the canopy between the plots were read weekly by an observer standing on top of a ladder.

At site B a standard raingauge and a small-orifice raingauge were placed 1 m above the soil surface at a climatological station 300 m S of the experimental site. Two small-orifice raingauges were mounted 1 m above the mean height of the canopy of the experimental plot, while measurements were made by lowering the mast with raingauge into a tube sunk into the ground to a depth of 3 m. All raingauges at site B were read daily at 8 a.m.

#### STEMFLOW

A gauge was developed which was capable of measuring accurately the intercepted rain flowing down the tree stems. Bicycle tires were split open and nailed into position on the tree trunk. A double component cement provided a waterproof connection between the tree trunk and the stem girdle; tests showed that this system remained leakproof for long periods providing that the detritus in the girdle was removed frequently. A plastic hose led from the girdle to a sunken measuring can.

A full season's measurements of stemflow are not available from site A. At site B, four such stemflow gauges were operated throughout the rainfall season, one on each of the tree trunks within the experimental plot. The stemflow was measured at 8 a.m. on each day that rain was recorded at the open site.

#### THROUGHFALL

At both sites, throughfall — the amount of rain reaching the soil surface via canopy drip — was measured with small-orifice raingauges. These were exposed at 0.3 m above the soil surface, mounted in neutron scattering access tubes. Small-orifice raingauges were chosen so that they would provide the minimum interference with the soil moisture measurements and micrometeorological studies, carried out at the same site.

At site A, 40 raingauges were used, divided into four plots, each of which contained ten raingauges arranged diagonally across three rows of trees. Four of the gauges were 0.5 m from the nearest tree trunk, four at 1 m distance and two at the midpoint between two trunks, about 2 m from them. Data from the throughfall gauges were recorded weekly.

At site B, 38 raingauges were mounted in a regular grid between the four trees of the experimental plot. The gauges were placed in four rows of seven gauges and two rows of five gauges with a distance of 0.8 m between the rows and 0.7 m within the rows. The gauges were measured at 8 a.m. on each day that rain was recorded at the open site.

## RESULTS

### PRECIPITATION

The relationship between the individual values of precipitation falling on the canopy, obtained at both sites with both types of raingauges, is presented in Fig. 1, where the means of the two gauges above the canopy are plotted against the readings made with the standard raingauges. Seasonal totals of the means of the two above-canopy measurements were 101 and 102% of those obtained from the standard raingauges for sites A and B, respectively.

The 1965/66 rainfall season was considerably drier than average, whereas that of 1966/67 was considerably wetter than normal.

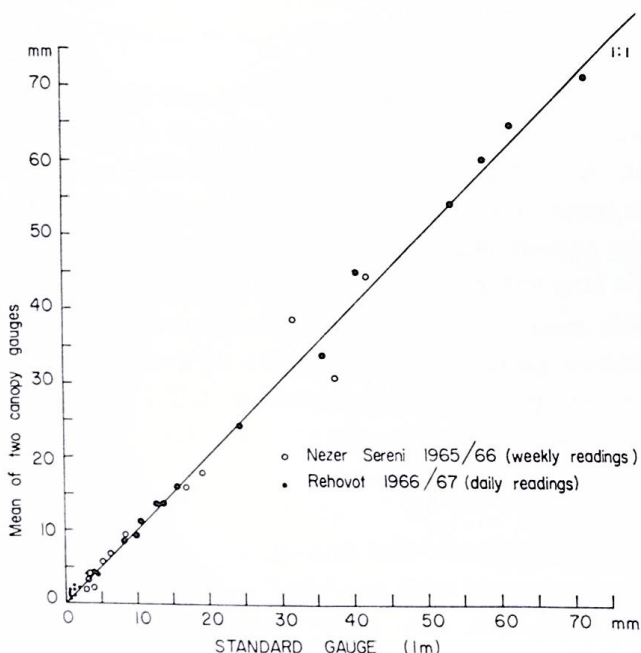


Fig. 1. Relation between precipitation measured with a standard raingauge at 1 m above the soil surface and the mean precipitation as measured with two canopy raingauges (individual days).

## STEMFLOW

A close agreement existed between the individual measurements on the four trunks. When precipitation above the canopy was greater than 40 mm/day, the measuring cans of the stem girdle gauges overflowed and therefore during five days of heavy rainfall the measurements could not be used. A smooth curve was found for site B when the mean stemflow in liters was plotted against the standard raingauge readings in mm (Fig. 2B). This relationship was extrapolated and used to calculate stemflow during the five occasions when measurements were not available. The amount of stemflow was converted to rainfall equivalent on the basis of total ground area; the value of this method of calculation is supported by the fact that the canopy covered the ground area almost completely.

The amount of stemflow at site B during the measurement period was calculated to be equivalent to 47 mm or 7.2% of the precipitation falling on the canopy.

## THROUGHFALL

TABLE 1

MEAN MEASURED SEASONAL TOTAL PRECIPITATION, THROUGHFALL AND DERIVED STEMFLOW PLUS INTERCEPTION AT SITE A, 7.III.65 - 28.III.66

Component	P l o t			
	I	II	III	IV
Precipitation, mm (%)	306 (100)	306 (100)	188 (100)	293 (100)
Throughfall, mm (%)	242 (79.1)	242 (79.1)	156 (83.0)	241 (82.3)
S.E. (mm)	21	20	16	20
C.V. (%)	8	8	10	9
Stemflow + interception, mm (%)	64 (20.9)	64 (20.9)	32 (17.0)	52 (17.7)

The total throughfall at site A is presented in Table 1 as the mean of the ten gauges for each of the four plots together with the coefficients of variation. On several occasions irrigation was applied during the same seven-day period that rain fell and the measurements during such periods have been discarded. For this reason the open area precipitation values given in Table 1 differ from plot to plot. Values of stemflow plus interception were estimated as the difference between throughfall and open area precipitation (Table 2, Fig. 2A).

TABLE 2

MEASURED SEASONAL PRECIPITATION, THROUGHFALL, STEMFLOW AND INTERCEPTION AT SITE B,  
10.XI.66 — 17.V.67

Component	Computation method					
	Mean of 38	Mean of 10 diagonal	Mean of 5 random	Mean of 10 random	Mean of 15 random	Mean of 20 random
Precipitation, mm (%)	649 (100)	649 (100)	649 (100)	649 (100)	649 (100)	649 (100)
Throughfall, mm (%)	550 (84.7)	520 (80.1)	512 (78.9)	535 (82.4)	547 (84.3)	555 (85.5)
S.E. (mm)	19	28				
C.V. (%)	3	6				
Stemflow + interception, mm (%)	99 (15.3)	129 (19.9)	137 (21.1)	114 (17.6)	102 (15.7)	94 (14.5)
Stemflow, mm (%)	47 (7.2)	47 (7.2)	47 (7.2)	47 (7.2)	47 (7.2)	47 (7.2)
Interception, mm (%)	52 (8.0)	82 (12.6)	90 (13.9)	67 (10.3)	55 (8.5)	47 (7.2)

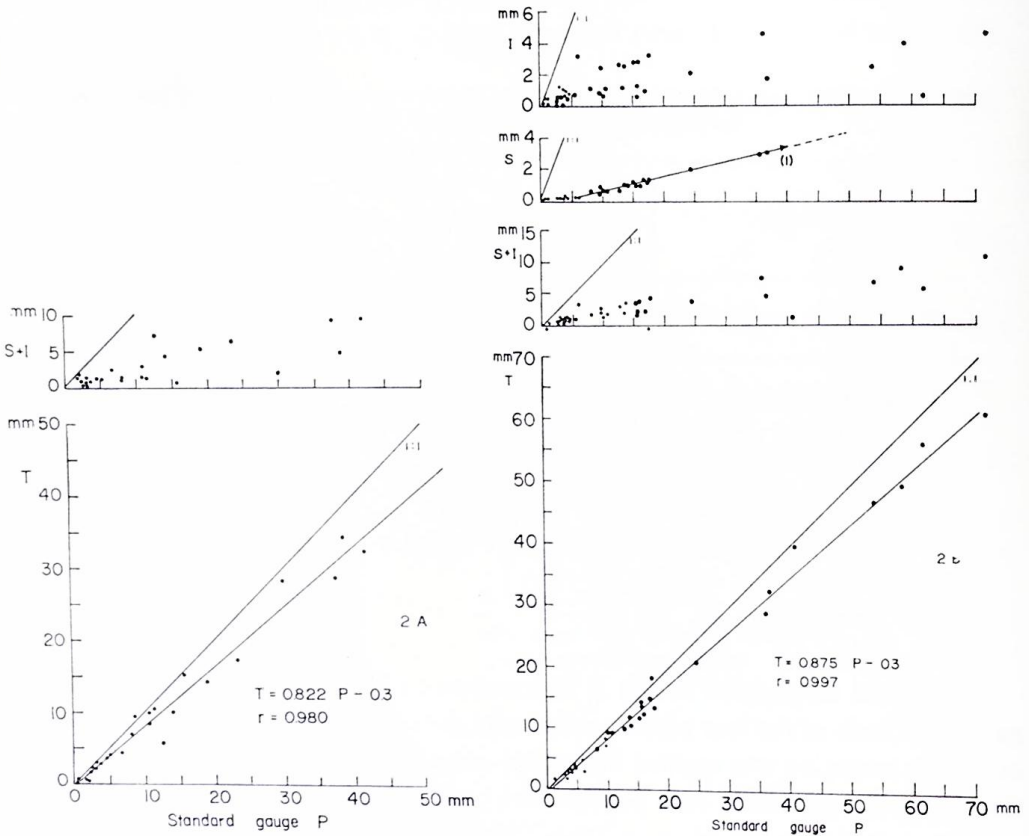


Fig. 2. A: Precipitation (P), throughfall (T) and derived estimates of stemflow plus interception (S + I) at site A.  
B: Precipitation (P), throughfall (T), stemflow (S) and derived estimates of interception (I) at site B.

During the early part of the rainfall season, four of the throughfall gauges at site B gave abnormally high readings, greatly in excess of open area precipitation. When individual daily values of throughfall from these four gauges were plotted against the corresponding values of open air precipitation, the points fell on two distinct lines with the abrupt change in the relationship corresponding to the date of the fruit harvest (Fig. 3). After this date the relationship of the four gauges corresponded to that of the remaining gauges. It therefore seems most likely that the abnormally high readings were caused by rain dripping from oranges immediately above the raingauges. As the diameter of the fruit exceeds that of the raingauge at the start of the rainfall season, and yet is never large enough to provide a complete rain shadow for the raingauge orifice, it is clear that the presence of fruit could explain the obtained skew distribution of rainfall. (A laboratory test with a single small fruit suspended under a rainfall simulator confirmed that the distribution of rain below the fruit was positively skewed.)

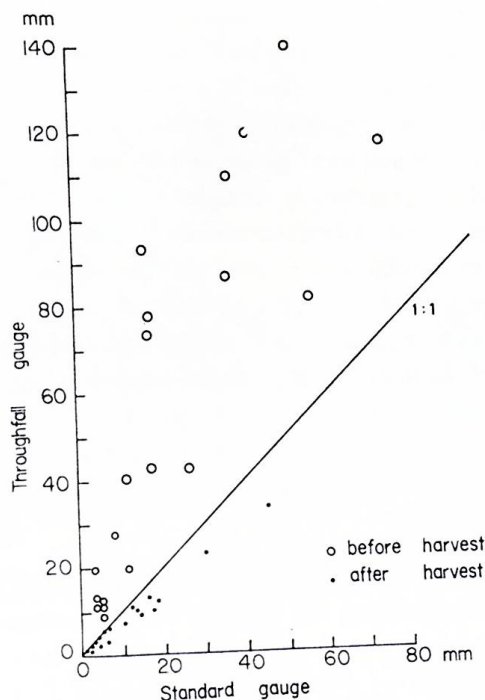


Fig. 3. Relation between precipitation measured with a standard raingauge, and throughfall at gauge No. 3 before and after fruit harvest (site A).

In the results presented the pre-harvest abnormally high readings from the four throughfall gauges were corrected from open area precipitation values using the post-harvest relationship for the same gauges.

In Table 2, throughfall is given both as the corrected mean of the 38 gauges and as the mean of ten gauges on two diagonal lines between the trees, i.e., the same sampling

pattern as used at site A. In addition, mean throughfall was calculated from 5, 10, 15 and 20 randomly chosen gauges from the systematically located network, with the random selection repeated after approximately 25 mm of open air precipitation. As at site A, the variation of throughfall was calculated and also the difference between open air precipitation and throughfall was used to estimate the value of stemflow plus interception (Table 2, Fig. 2B).

## DISCUSSION

### PRECIPITATION ABOVE THE CANOPY

A close agreement is shown in Fig. 1 for both sites between the measurements of rainfall above the canopy with the small-orifice raingauges, and at 1 m above the soil surface with the standard Hellmann raingauges. This agreement is somewhat surprising as two types of errors are known to occur in above-canopy gauges. Water adhering to the side of the collection tube of the small-orifice raingauge after emptying would lead to a cumulative overestimate of rainfall, especially during days of light rainfall when readings of the amount are subject to large observational errors. On the other hand, there is likely to be greater turbulence around the orifice of a raingauge above the canopy than around the orifice of the same raingauge at 1 m above the ground surface, and this would result in a decreased catch.

The performance of the standard gauge at 1 m has been tested by comparison with readings from a pit gauge generally regarded as the most accurate raingauge (8), by comparing four years of rainfall measurements at Gilat (31°19'E; 34° 39'N; 130 m MSL). Seasonal totals of rainfall as measured with the standard gauge were 101, 99, 102 and 98%, respectively, of those measured with the pit gauge.

There was no evidence from either site of any significant difference between the amount of rainfall measured in the replicate above-canopy gauges, or of any consistent difference between that measured above the canopy and at 1 m above the soil surface. For these reasons, the standard raingauge readings at both sites have been taken as giving the most accurate estimate of the amount of precipitation falling on the canopy.

### STEMFLOW

The total stemflow during the 1966/67 rainfall season at site B amounted to 7.2% of the precipitation reaching the canopy. No data were obtained at site A. No comparable measurements were found in the literature for other plantation trees but this small proportion agrees with previously reported findings for forest trees: e.g. Reynolds and Leyton (11) found 5% in a young spruce forest.

The close relationship at site B between precipitation above the canopy (P, mm) and stemflow (S, mm) has already been referred to and illustrated in Fig. 2B. A linear regression equation of S on P has been calculated from the individual data and is given in Eq. 1:

$$S = 0.888 P - 0.2 \text{ mm, } r = + 0.99 \dots\dots\dots [1]$$

The threshold value of precipitation above which stemflow commences is therefore  $P = 0.2/0.888 = 2.3 \text{ mm}$ .

## THROUGHFALL

The total throughfall during the 1965/66 season at site A amounted to 81% of the precipitation reaching the canopy. Table 1 shows good agreement between both the percentage throughfall and the variability of the measurements for the four plots. At site B the coefficient of variation for total throughfall was somewhat less than that at site A when data from ten diagonally spaced gauges were compared (Tables 1 and 2).

In general, in spite of the relatively high values for the coefficients of variation there was no clear throughfall distribution pattern beneath the canopy, the amounts being unrelated to either distance from the nearest stem or the number of obstructions immediately above the throughfall gauges. Such a result is to be expected only with a virtually closed canopy crop. However, the distribution of total throughfall, as presented in Fig. 4, shows a certain pattern, but all attempts to relate this pattern quantitatively to canopy characteristics have failed.

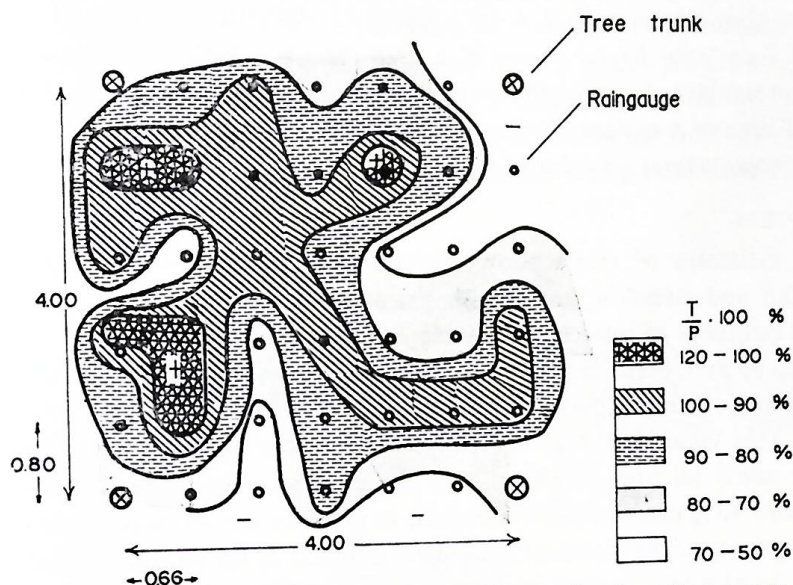


Fig. 4. Pattern of seasonal throughfall (T) at site B given as fraction of open area rainfall P; lines connect points of equal deviation from total seasonal open area rainfall (P) (649 mm). Distances are given in meters.

When throughfall was calculated on the basis of a random and changing position of gauges, the method often recommended to decrease variability (14), the total amount of throughfall increased with increasing number of gauges used (Table 2). This supports the view, given earlier, that when the raingauge orifice area is less than that of the rain-obstructing elements, any increase in gauge number increases the possibility of measurement at high drip points and so gives a positive skew distribution. Even so, when expressed as percentage of open area precipitation, the range in throughfall values obtained with different patterns and numbers of gauges was not very large, varying between 79 and 86%.

The relationship between precipitation above the canopy ( $P$ , mm) and mean throughfall ( $T$ , mm) was linear at both sites (Figs. 2A, B), with a greater scatter at site A. Linear regressions of  $T$  on  $P$  resulted in the following equations:

$$\text{Site A: } T = 0.822P - 0.3, r = 0.980 \dots \dots \dots [2a]$$

$$\text{Site B: } T = 0.875P - 0.3, r = 0.997 \dots \dots \dots [2b]$$

The greater slope at site B may be due to an overestimate in throughfall due to gauge errors caused by the more frequent measurements at this site.

The threshold value of precipitation above which throughfall commences (crop canopy saturation) is  $0.3/0.822$  and  $0.3/0.875$  mm at sites A and B, respectively, averaging 0.4 mm. The fact that it is substantially less than the threshold for stemflow agrees with Reynolds and Leyton's findings in a spruce forest (11).

This crop canopy saturation value was confirmed in a laboratory measurement. Two branches of a mature orange tree at site B, representing young and old foliage, were completely saturated and the amount of water retained, expressed on a leaf area basis, was found to average  $9 \times 10^{-3}$  g/cm<sup>2</sup>. Multiplying this value by the leaf area index of 7 cm<sup>2</sup>/cm<sup>2</sup> found at site B, a crop canopy saturation value of 0.6 mm is found, not significantly different from that calculated from equation 2b. The use of the total leaf area of a mature Shamouti orange tree (98 m<sup>2</sup>) given in ref. (6) results in a crop canopy saturation value of 0.55 mm.

#### INTERCEPTION

The estimates of interception, derived from measurements of precipitation, throughfall and stemflow, include all the errors involved in these measurements. Thus the estimates of interception at site B during the 1966/67 rainfall season range from 47 to 90 mm, depending upon the sampling pattern of throughfall adopted. The corrected mean of all 38 gauges gives a value of 52 mm, or 8% of the incident precipitation. This value is low compared with most tree canopy values reported, but these are nearly all from forests in high rainfall areas. The value is also lower than the figure of 13% calculated for Coweeta, as given in Helvey and Patric's review of results obtained in investigations in hardwood forests of the eastern United States (3). The only local measurements of interception are those of Heth and Karschon (4) for *Eucalyptus* groves, who report values between 14 and 16%. The glaucous nature of the citrus foliage and the smooth wood may well explain the low values found.

The results reported herein were used to calculate the approximate size of the different rainfall components for mature orange orchards in the coastal belt of Israel. Twenty years of I.M.S. rainfall records (1935/36 — 1954/55) from Rehovot were analyzed by classing the rain of individual days into six groups according to its absolute amount. Relationships between  $P$ ,  $T$ ,  $S$  and  $I$  for these six groups of  $P$  were obtained from the data at sites A and B. These relationships were used to calculate interception and stemflow both for the average of 20 years and for the wettest and driest years between 1930 and 1960; the results (Table 3) show close agreement between average, wettest and driest years.

TABLE 3

ESTIMATES OF THE RAINFALL COMPONENTS IN MATURE ORANGE GROVES NEAR REHOVOT  
FOR THE AVERAGE RAINFALL SEASON BETWEEN 1935/36 AND 1954/55, AND FOR THE  
WETTEST AND DRIEST SEASONS BETWEEN 1931 AND 1960

Component	Mean of 1935/36-1954/55	Wettest season, 1951/52	Driest season, 1959/60
Precipitation (%)	100 (530mm)	100 (883mm)	100 (265)
Throughfall (%)	80.1	80.5	79.8
Stemflow (%)	6.7	6.9	6.3
Interception (%)	13.2	12.6	13.9

Finally, Monteith's formula (7) was used to calculate how much of the intercepted water evaporating was effective in replacing transpiration and how much can be considered as a "waste" or "luxury consumption". Local values of air temperature were used, and the mean values of aerodynamic and stomatal resistance of a mature orange orchard presented by Van Bavel *et al.* (12). The estimated ratio of evaporation from a wetted canopy to transpiration from a dry one was 4.6 : 1, indicating that 22% of the interception loss (7.2 — 13.9%) was effective in reducing transpiration. The remaining 5.6 — 10.8% of the total precipitation can be considered as a true water loss to the plant and soil system.

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