Predictive Models for Estimating Net Rainfall and Interception Losses in Savanna Vegetation

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Abstract

Although interception experimental plot results vary, research has indicated that similarities do exist. Independent plot results could therefore be grouped together for application on a regional basis. In this study it is shown that the results from five independently designed and analysed experimental plots vary over a surprisingly narrow range. Collective regression models are formulated for stemflow, interception losses and net rainfall. For net rainfall the variation between the five plots is only 2 mm with a gross rainfall of 25 mm, and less than 1 mm with a gross rainfall of 15 mm. The Gash interception loss model is also tested with satisfactory agreement between observation and estimation. The model overestimated interception losses from a group of storms by 7,8% on average and underestimated interception losses from another group by 4,5%.

Introduction

Water availability is believed to be the major determinant of the structure and efficiency of semi-arid savanna ecosystems (Huntley and Morris, 1978). Detailed information on the water relationships, and thus the interception process, of savanna vegetation is therefore essential for proper management policies. When subjected to stress through overgrazing, abnormal fire regimes or radical changes in the animal component, these systems are easily and rapidly degraded and take a much longer time to recover than do higher rainfall ecosystems (Huntley and Morris, 1978). If confined to a specific plot, rainfall interception data have limited value. However previous studies (Pienaar, 1961; Helvey and Patric, 1965) have indicated that results from experimental plots in the same vegetation type do not differ significantly. The purpose of this study is, therefore, to formulate predictive models from existing savanna interception data. For this purpose the data of five interception experimental plots were used (De Villiers, 1976a; 1976b; 1977; De Villiers and De Jager, 1981). These models should simplify and improve plant water relations analyses and thus contribute to better understanding and management. It should also find practical application in rainfall-runoff modelling and ground-water balance studies.

The Experimental Sites

Three of the rainfall interception plots were situated in a stand of mixed acacia bushveld 30 km north of Pretoria at the Roodeplaat Dam (25° 27′ S; 28° 22′ E). It is a summer rainfall region with the mean annual rainfall of 650 mm falling mainly in the form of thunderstorms. The mean annual temperature of this region is 18,0°C, whilst the mean monthly temperature varies between a maximum of 33,8°C in January and a minimum of − 1,5°C in June. Extreme daily temperature values exceed 38,0°C. Conditions for evaporation are therefore favourable, and the mean annual A pan values exceed 2 000 mm. The vegetation of the area is a relatively open savanna with *Acacia caffra* the dominant tree and *A. karroo*, *A. robusta* and *Dombeya rotundifolia* well scattered. The shrubs are dominated by *Grewia flavescens* and *Ehretia rigida* (De Villiers, 1975).

The other two experimental plots were set up in a *Burkea africana – Ochna pulchra* tree savanna approximately 100 km north of the three acacia plots, near Nylstroom (24° 42′ S: 28° 25′ E). According to the South African Weather Bureau (1974) the two sites have similar climates. The experimental technique comprised two methods. Firstly, the surfacing of three canopy projections on the ground with impervious floors creating macro-rain gauges giving net rainfall readings, and secondly, the placing of ordinary rain gauges below the canopy, and comparing these catches with gauge catches outside the canopy. This technique was followed on two plots. The analytical technique was mainly regression analyses.

Stemflow

After the interception process a part of the rainfall flows down the stems as stemflow. Stemflow volume is largely determined by the form of the canopy, and to a lesser extent, by bark texture. Previous studies (Leonard, 1961; Rutter, 1963) have indicated that differences in stemflow volume between stems of different bark textures varies little. The mechanism of the process varies with type of bark. Stemflow is a flow process with smooth bark species and a drip process with rough bark species. Wicht (1941) and Jackson (1971) established an empirical relationship between stemflow and stem diameter which could facilitate the calculation of stemflow.

Three savanna stemflow data sets were used in the composition of a collective stemflow regression model (De Villiers, 1976b; 1977; De Villiers and De Jager, 1981). The regression equations of two of these data sets are shown in Table 1. Stemflow was sampled from 14 stems in the first study and 15 in the second. Tree and shrub stems were divided into 20 mm diameter classes on the two experimental plots. Sample stems were then selected in all classes for stemflow measurements. The diameter classes varied between a class of 20 mm and less and a class of 260 mm to 280 mm.

An analysis of variance was computed on the data sets and it

TABLE 1
GROSS RAINFALL (Pd) AND STEMFLOW (St): REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS (DE VILLIERS 1976b; 1977).

Dominant tree	Equation	Correlation coefficient	Showers
Acacia caffra	$St = 0{,}07\ Pd - 0{,}10$	0,90	34
Acacia caffra	$St = 0{,}05\ Pd - 0{,}09$	0,87	27

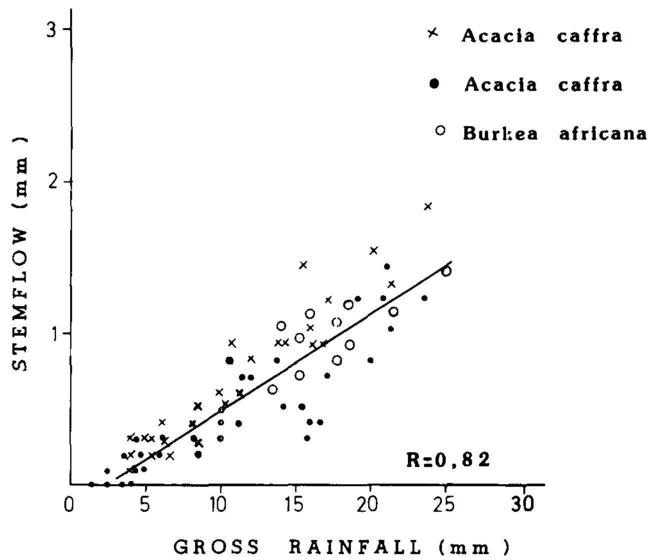

Figure 1
Gross rainfall and stemflow in mm per storm

indicated that the differences between the two sets were insignificant. From Table 1 it follows that the variation in the estimation of stemflow between the two regression equations is only 0,5 mm when the gross rainfall is 25 mm. With a gross rainfall of 15 mm the same variation is only 0,3 mm. In the context of the whole process these values are small.

Stemflow from a third study in a *Burkea africana* stand (De Villiers and De Jager, 1981) was then compared to the abovementioned data sets. Only one diameter class was sampled in the *Burkea africana* study. An analysis of variance showed that the differences between the *Burkea africana* stemflow and the stemflow of the two other data sets were insignificant for comparable diameter classes. A collective regression equation was therefore computed from all the savanna data and defined as St = 0,05 Pd – 0,44 (Figure 1) with a correlation coefficient of 0,82.

Net rainfall

Net rainfall is the total of throughfall, drip and stemflow and forms the component of the gross rainfall that reaches the soil surface. Five data sets were used in an effort to compute a collective net rainfall regression model for savanna vegetation. Regression equations for these data are shown in Table 2. An analysis of covariance was computed on the data sets and it indicated that significant differences exist between the data sets.

TABLE 2
NET RAINFALL (Nr): REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR FIVE PLOTS (DE VILLIERS 1976a; 1976b; 1977; DE VILLIERS AND DE JAGER, 1981).

Dominant tree/shrub	Equation	Correlation coefficient	Showers
Acacia caffra	Nr = 0,87 Pd – 1,51	0,99	58
Acacia caffra	Nr = 0,87 Pd – 1,70	0,99	58
Acacia caffra	Nr = 0,87 Pd – 1,23	0,99	58
Burkea africana	Nr = 0,92 Pd – 1,16	0,99	34
Ochna pulchra	Nr = 0,92 Pd – 1,06	0,99	34

These differences are however small, as becomes evident when the regression models in Table 2 are compared. Variation in the estimation of net rainfall between the 5 models is only 2 mm with a gross rainfall of 25 mm and less than 1 mm with a gross rainfall of 15 mm.

A collective regression model was therefore calculated and a linear model

Nr = 0,89 Pd – 1,06 (Figure 2)

with a correlation coefficient of 0,90 resulted.

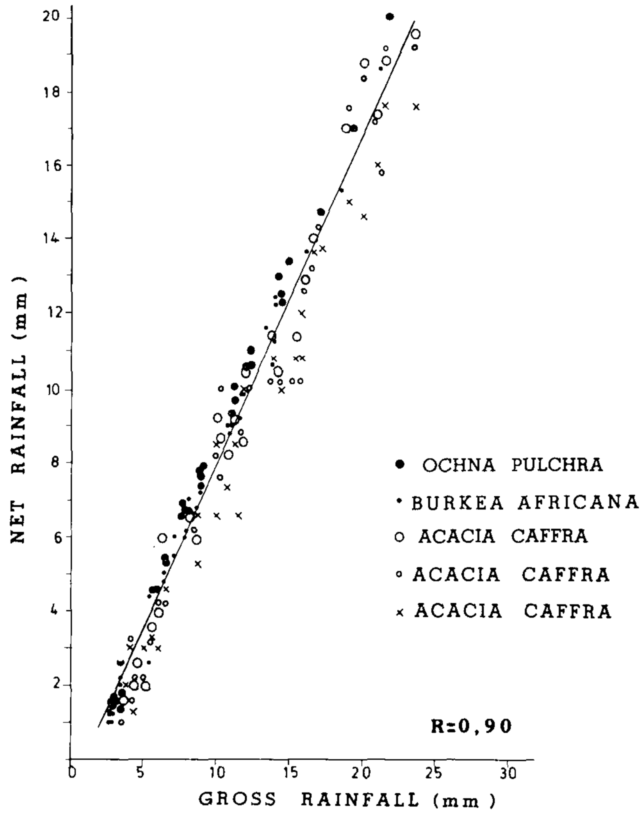

Figure 2
Gross rainfall and net rainfall in mm per storm for five studies

Interception Loss

Interception loss is the portion of the rainfall that is retained by the aerial portion of the vegetation and is either absorbed by it or is returned to the atmosphere by evaporation. It is calculated by subtracting net rainfall from gross rainfall or by adding evaporation losses to the storage capacity of the vegetation cover (De Villiers, 1975).

TABLE 3 RELATIONSHIPS BETWEEN INTERCEPTION LOSSES (I) AND GROSS RAINFALL (Pd) FOR FIVE PLOTS (DE VILLIERS 1976a; 1976b; 1977; DE VILLIERS AND DE JAGER, 1981)			
Dominant tree/shrub	**Equation**	**Correlation coefficient**	**Showers**
Acacia caffra	I = 0,05 Pd + 1,60	0,79	58
Acacia caffra	I = 0,07 Pd + 1,70	0,78	58
Acacia caffra	I = 0,13 Pd + 1,17	0,73	58
Burkea africana	I = 0,07 Pd + 1,17	0,61	34
Ochna pulchra	I = 0,05 Pd + 1,07	0,63	34

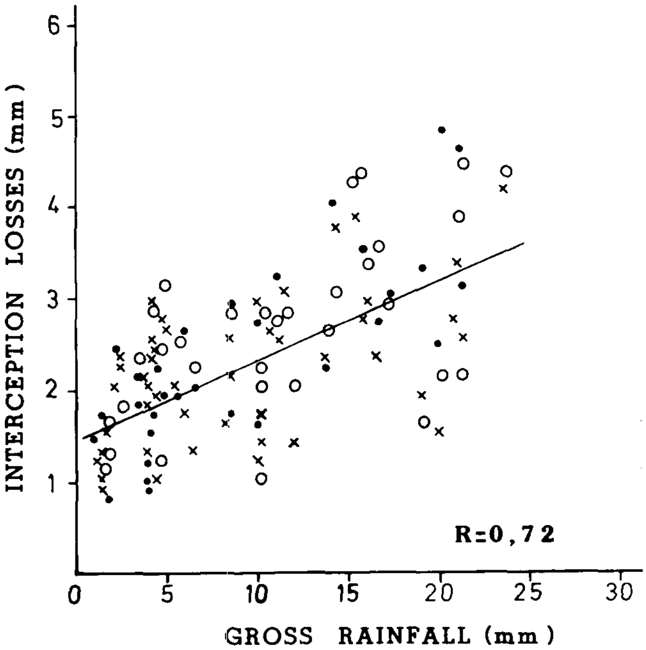

Figure 3
Gross rainfall and interception losses in mm per storm for three plots in Acacia caffra

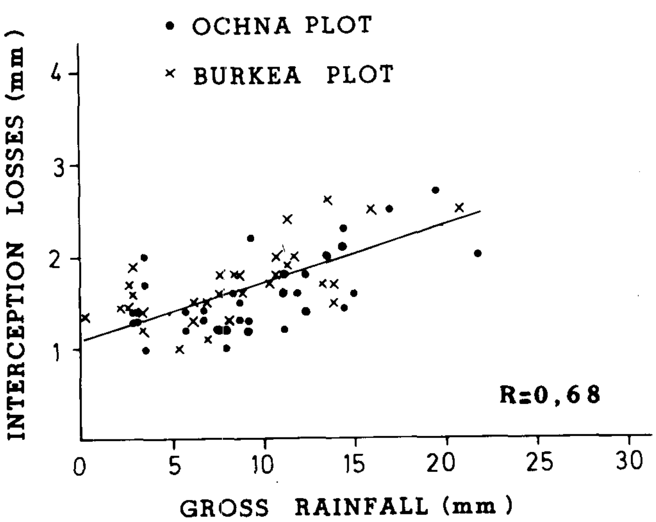

Figure 4
Gross rainfall and interception losses in mm per storm for two plots

The development of a linear model depicting the relationship between gross rainfall and net rainfall opened the possibility of expressing interception loss in a similar collective regression model. The regression equations used in this computation are shown in Table 3. An analysis of covariance was computed and it indicated that significant differences exist between the data sets. These differences are such that the compilation of a collective regression model is not meaningful.

A further covariance analysis was subsequently computed on the data of the first three equations, and although the result improved, the differences were still significant. The re-calculation was repeated on the data of the last two equations in Table 3 with the same result. The data was subsequently filtered retaining only showers with intensities between 2 mm and 12 mm per hour. Showers in this category are typical of savanna vegetation regions. Two linear regression models were calculated with the filtered data (Table 4, Figures 3 and 4).

TABLE 4 INTERCEPTION LOSS: COLLECTIVE REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR *ACACIA CAFFRA* AND *BURKEA AFRICANA*			
Dominant tree	Equation	Correlation coefficient	Showers
Acacia caffra	I = 0,09 Pd + 1,49	0,72	116
Burkea africana	I = 0,06 Pd + 1,14	0,68	68

TABLE 5
INTERCEPTION LOSSES (I) AND DURATION (T) IN CERTAIN RAINFALL INTENSITY CATEGORIES

Intensity: 2,0 – 4,4 mm/h			Intensity 4,5 – 6,9 mm/h			Intensity: 7,0 – 12,0 mm/h		
No.	I mm	T min	No.	I mm	T min	No.	I mm	T min
1	1,5	65	1	2,3	100	1	4,0	155
2	1,6	120	2	3,2	140	2	4,0	170
3	1,5	115	3	2,8	136	3	4,7	240
4	1,5	100	4	2,7	130	4	4,1	160
5	1,4	90	5	1,6	85	5	2,9	120
6	1,4	90	6	2,2	105	6	3,9	165
7	1,6	100	7	2,4	115	7	4,6	230
8	0,9	80	8	2,6	120	8	4,1	155
9	1,7	120	9	1,7	90	9	2,8	110
10	1,8	125	10	1,8	90	10	3,6	135
11	1,7	120	11	2,8	145	11	2,8	105
12	1,5	100	12	2,9	150	12	2,6	100
13	1,4	95	13	1,8	95	13	2,8	115
14	1,3	70	14	2,5	120	14	4,2	185
15	1,6	110	15	2,5	110	15	2,9	120
16	1,7	115	16	1,7	90	16	2,5	140
17	1,7	125	17	2,0	100	17	3,0	130
18	1,8	120	18	1,6	90	18	2,6	100
19	1,4	90	19	2,0	100	19	3,2	140
20	1,6	115	20	2,1	100	20	3,4	145
21	1,6	110	21	2,7	110	21	3,9	155
22	1,4	90	22	2,2	100	22	3,0	130
23	1,2	80	23	2,5	120	23	2,7	110
24	1,3	95	24	2,0	100	24	3,2	140
T	**36,1**	**2440**	25	2,7	120	T	**82,1**	**3455**
A	**1,5**	**101,6**	T	**57,3**	**2761**	A	**3,4**	**143,9**
			A	**2,3**	**110,4**			

T = total
A = average

TABLE 6
INTERCEPTION LOSSES, RAINFALL INTENSITY (In) AND RAINFALL DURATION (T) RELATIONSHIPS

Intensity category mm/h	Observations	Equation	Correlation coefficient
2,0 – 4,4	24	I = –0,44 + 0,31 In + 0,01 T	0,92
4,5 – 6,9	25	I = –1,38 + 0,42 In + 0,01 T	0,96
7,0 – 12,0	24	I = –1,89 + 0,26 In + 0,02 T	0,97

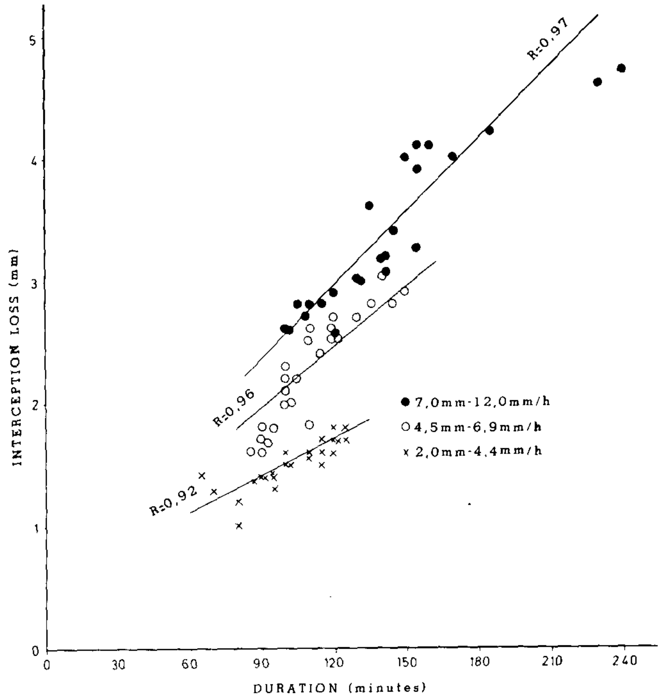

Figure 5
Interception losses, rainfall intensity and rainfall duration relationships

The data were further analysed in an effort to trace the reason for the discrepancy in interception losses between the two studies. It became evident that the gross rainfall parameters, duration and intensity, differed significantly. In the Acacia study the average storm duration and intensity was higher than in the Burkea study. This was probably due to differences in rainfall totals and nature of rainfall. The Acacia study was done under above normal seasonal rainfall conditions, characterised by storms of relatively long duration and intensity. In the Burkea study, on the other hand, the seasonal rainfall was normal. Some storms in the Burkea study were furthermore divided into two or more smaller storms, if interruptions of more than 10 min occurred. This obviously affected the results.

As variations in storm durations and intensities are directly linked to variations in interception losses, it was considered necessary to establish a relationship between these variables. Data from the two studies were therefore divided into three rainfall intensity categories in such a way that some relationship existed between the three variables (Table 5). Multiple linear regression analyses were subsequently computed on the data of Table 5 and the results of these analyses are shown in Table 6. From this table and Figure 5 it is evident that the consideration of rainfall duration and intensity resulted in satisfactory models. Jackson's (1975) explanation that a higher rainfall intensity results in higher rainfall storage in canopy, and thus an increased evaporation rate, apparently also applied to storms in this study.

The Gash Interception Loss Model

Gash (1979) formulated an interception loss model that is simpler and easier to apply than the Rutter model (Rutter *et al.*, 1971) without losing any of it's objectivity and physical reasoning. The model's primary assumption is that it is possible to represent the real rainfall pattern by a series of discrete storms, separated by sufficiently long intervals for the canopy and trunks to dry. Within this simplifying assumption the procedure then adopted, is to perform an analytical integration of the total evaporation loss of intercepted rainfall, by replacing the actual rate of rainfall and evaporation applicable to each storm by the average rates deduced for all storms. In order to carry out this analytical integration procedure it is necessary to introduce the following simplifying assumptions:

- The meteorological conditions prevailing during any wetting-up of the canopy are sufficiently similar to those prevailing for the rest of the storms. The mean conditions of rainfall and evaporation, over all storms in the period, therefore can be considered to apply in these transient situations.
- The logarithmic dependence of the 'drip-rate' on the degree of canopy saturation, observed by Rutter *et al.* (1971), is sufficiently sensitive so that there is in effect virtually no drip from the canopy during wetting-up; and the amount of water on the canopy at the end of a storm is quickly reduced (within 20 to 30 min) to S, the minimum value necessary for saturation, independent of the initial value when rain ceased (Gash, 1979).

The Gash (1979) interception loss model was subsequently tested against the savanna data, with satisfactory agreement between observation and estimation. The model is defined as:

$$\sum_{j=1}^{n+m} I_j = n(1-p-p_t)P'_G + (\bar{E}/\bar{R})\sum_{j=1}^{n}(P_{Gj}-P'_G) + (1-p-p_t)\sum_{j=1}^{m} P_{Gj} + qS_t + p_t \sum_{j=1}^{m+n-q} P_{Gj}$$

Where I = the depth of water intercepted and lost by evaporation, i.e. the interception loss;
n = storms that saturate the canopy separated by a sufficient period for the canopy to dry;
p = the free throughfall coefficient i.e. the proportion of rain which falls through the canopy without striking a surface;
p_t = the proportion of rain which is diverted to the trunks as stemflow;
P'_G = the amount of rain necessary to saturate the canopy;
$\bar{E}$ = the mean evaporation rate during rainfall;
$\bar{R}$ = the mean rainfall rate;
P_G = the gross rainfall;
S_t = the trunk water store;
m = the number of storms insufficient to saturate the canopy; and
q = the storms above critical rainfall S_t/p_t necessary to fill the trunk store.

Twenty n measured storms and 10 m measured storms were selected randomly and tested with the Gash model. These results are given in Table 7.

TABLE 7
MEASURED AND ESTIMATED INTERCEPTION LOSS VALUES

Twenty n storms				Ten m storms			
No.	Gross rainfall (mm)	Measured intercep-tion loss (mm)	Estimated intercep-tion loss (mm)	No.	Gross rainfall (mm)	Measured intercep-tion loss (mm)	Estimated intercep-tion loss (mm)
1	8,5	2,1	2,1	1	1,7	0,8	1,3
2	8,2	1,6	2,1	2	1,5	1,0	1,1
3	10,5	2,8	2,5	3	1,2	1,2	0,9
4	10,2	2,2	2,4	4	1,7	1,3	1,3
5	10,2	1,7	2,4	5	1,7	1,5	1,3
6	11,5	3,1	2,7	6	2,5	1,8	1,9
7	10,7	2,6	2,5	7	2,0	2,0	1,5
8	14,5	3,0	3,2	8	1,2	1,3	0.9
9	13,7	2,3	3,0	9	1,5	0,9	1,1
10	15,2	3,9	3,3	10	2,5	2,0	1,9
11	15,7	3,5	3,4				
12	16,0	2,9	3,4	T	17,5	13,8	13,2
13	15,7	2,7	3,4				
14	16,5	2,3	3,5	A	1,7	1,4	1,3
15	17,2	2,9	3,6				
16	11,2	2,5	2,6				
17	16,7	3,5	3,6				
18	21,0	4,6	4,3				
19	21,5	4,4	4,4				
20	19,0	3,3	4,0				
T	283,7	57,9	62,4				
A	14,2	2,9	3,1				

T = total
A = average

The maximum difference between observed and estimated loss for a single storm is 1,2 mm. The difference between observed and estimated total losses are 4,5 mm for n storms and 0,6 mm for m storms. The model therefore overestimated n storms on average by 7,8% and it underestimated m storms by 4,5% on average.

The inputs into the model for individual storms and for storm totals were the following:

1. $\bar{R} = 5,7$ mm/h representing the mean rainfall rate calculated from the gross rainfall data of five savanna interception plots (De Villiers, 1976a; 1976b; 1977; De Villiers and De Jager, 1981).
2. $\bar{E} = 0,7$ mm/h is an empirical value based on the same interception plot data.
3. $p = 0,26$ mm was obtained from Gash (1979).
4. $p_t = 0,05$ and $S_t = 0,44$ were obtained from the stemflow equation formulated in this paper.
5. These values were then used to calculate $P'_G = 1,1$ mm with the method suggested by Gash (1979).
6. The values for the storms n, m and q were 20, 10 and 20 respectively.

Discussion and Conclusion

Students of interception are often confused by the variation in results on the subject. However, reviews of regional research (Pienaar, 1961; Helvey and Patric, 1965) may reveal unifying patterns similar to those established in this savanna study. Throughfall measurements, for example, are surprisingly similar over a range of canopy conditions. Stemflow, highly variable in savanna vegetation covers, is nevertheless predictable from gross rainfall records and although the average stemflow per storm is often less than 5% of the gross rainfall, it represents a concentrated application of water to soil at a point where conditions are ideal for entry. Sufficient water is added to the soil to cause wetting to considerable depth. For the storms that have been investigated, interception losses for savanna vegetation vary in most cases between 15% and 20% of the gross rainfall, which is far from an insignificant quantity of water. The evaporation rate and the rainfall rate are primary variables influencing this loss. Interception losses in savanna vegetation are not greatly affected by a variety of canopy conditions.

The formulation and discussion of the models in this paper suggests that further conventional interception plot experiments in savanna vegetation in Southern Africa are not necessary. However, data concerning the rainfall characteristics and the evaporation rate are essential for an accurate estimation of interception losses.

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