EVALUATION OF RAINFALL INTERCEPTION MODELS IN A MAIZE FIELD

BY

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ABSTRACT

Rainfall interception is a component of effective rainfall and is an important component in agriculture because of the latter's use in irrigation and drainage projects. A rainfall interception study was carried out at Kabanana farm plot no. 2952 M, a peri urban area in Lusaka, Zambia. The objectives of the study were (a) to measure rainfall interception by maize crop growing in a freely drained soil and (b) to evaluate and validate the models developed to represent rainfall interception loss.

Standard raingauges placed adjacent to the study area and beneath the canopy of the maize plant were used to measure rainfall amounts. Funnel like collars were used to measure stemflow. A planimeter was used to measure leaf area required for the calculation of leaf area index and the data from the nearby University of Zambia meteorological station was used to estimate crop evapotranspiration.

The results of the study showed that the interception process by a maize plant brought about an interception loss of 10%. Interception loss without stemflow was 27.4% implying that 17.4% of the incident rainfall reached the ground by flowing down the stalk of the maize plant as stemflow.

Of the four models tested the models developed by Merriam (1960), Leonard (1965) and De Jong and Cameron (1979) did not represent the process of interception by a maize plant. The linear regression model adopted by Gash (1979) which is insensitive to canopy structure was 93% significant for a two sided t-test at 95% confidence interval.

It is highly recommended that the models should be calibrated before being adopted and a model should be developed that includes among the usual measurable parameters, leaf area configuration and branching patterns.

DECLARATION

I **HOPESON ISAAC SIMWANZA**, do here by declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work, and has not been submitted for a degree in any other university.

Date 11th OCTOBER 1996 Signature

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LIST OF ABBREVIATIONS AND SYMBOLS

LAI	Leaf area index
INTCEP	Total interception
P	Total rainfall/Gross precipitation
T	Throughfall
S	Stemflow
C	Canopy storage capacity
Ea	Rate of evaporation from vegetation surface
Sc	Ground cover fraction
C_t	Depth of water on the canopy at time t
q	Fraction of rainfall passing the canopy without being intercepted
r	Rainfall intensity
Dr	Drainage rate
DAYS	Days from planting
ETo	Reference crop evapotranspiration
W	Temperature-related weighting factor
Rn	Net radiation
f(U)	Wind related function
(ea-ed)	Difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air
c	Adjustment factor to compensate for the

effect of day and night weather conditions

1. INTRODUCTION

Rainfall is a very important source of water for crop production. It provides fully or partially the water needed for crop growth. In rainfed agriculture, rainfall provides all water needed by the crops during the growing season, whereas, in irrigated agriculture, irrigation supplements the amount of water supplied by rainfall. Rainfall also generally decreases the daily evapotranspiration (ET) by decreasing solar radiation (cloud cover effect), increasing air humidity and reducing the transfer of sensible heat from adjacent non-irrigated areas to well-irrigated crop areas (Thadei, 1992). However, not all rain falling on the earth's surface is useful to the crop grown.

The portion of rainfall useful for plant growth is often referred to as effective rainfall. Effective rainfall is that portion of rainfall that contributes to meeting the ET (evapotranspiration) of a crop (Hershfield, 1964). From an agricultural point of view, this effective rainfall is defined as that portion of rainfall that is useful directly or indirectly to the crop production at the site where it falls and without pumping (Dastane, 1978). Thus effective rainfall can be presented as:

$$ER = IT + EV + TR + MS \qquad (1)$$

Where:

ER = Effective rainfall

IT = Rainfall interception

EV = evaporation from the soil surface

TR = Transpiration during growth

MS = Microstorage

This implies that effective rainfall is the portion of total rainfall that remains after the portions which are not useful have been subtracted, i.e:

$$ER = RF - DP - RO \qquad (2)$$

Where:

ER = Effective rainfall

RF = Total rainfall

DP = Deep percolation

RO = Runoff

Effective rainfall as a component of rainfall is an important concept in agriculture because it is often used in planning, design and operation of irrigation and drainage projects and the selection of crops and seasons in which crops can be productively grown. Thus effective rainfall includes (a) that intercepted by the plant canopy, (b) that lost by evaporation from the soil surface, (c) that lost by evapotranspiration during crop growth, (d) the fraction of rainfall that contributes to the necessary leaching of salts, and the fraction that promotes cultural operations either before or after sowing without any harm to the yield and quality of the principal crops, and (e) microstorage. Fig.1.1 is a schematic representation of the components of rainfall.

Effective rainfall will affect the daily operation of irrigation projects. Timing and the amount of water applied to the field should take into account the effective rainfall received to avoid excess of water (over-irrigation) hence accurate knowledge of effective rainfall received within 24-48 hours is required for planning the next irrigation (Dastane, 1974).

Interception is the portion of rainfall which wets and adheres to vegetation surfaces until it evaporates into the atmosphere (Merriam ,1960; Zinke, 1965; Fleming,1975; Aston,1979).The level of evapotranspiration is controlled mainly by three factors, namely: plant characteristics that include the extent of ground cover and stage of growth, water availability in the soil and evaporative demand (Dastane, 1974). According to Horton (1919), total interception equals leaf storage capacity plus evaporation loss during the storm. Hamilton and Rowe (1949) have considered interception to be the process in which rainfall is caught by the vegetation canopy and redistributed as throughfall, stemflow, absorption and evaporation from the vegetation. In most of the traditional rainfall interception studies interception loss has meant the difference between gross precipitation and net precipitation (throughfall plus stemflow) (Hewlett, 1967). Therefore the rainfall striking vegetation may be retained on the leaves or blades of grass, flow down the stems of plants and become stemflow, or drip from leaves and stems of the plant to become part of throughfall. The other component of throughfall is that portion of rainfall which passes through the canopy without being intercepted at all.

The fate of water intercepted by tree cover has long been the subject of debate (Stanhill, 1970). Water lost in transit between the lower atmosphere above the vegetative canopy has been under investigation for a considerably long time.

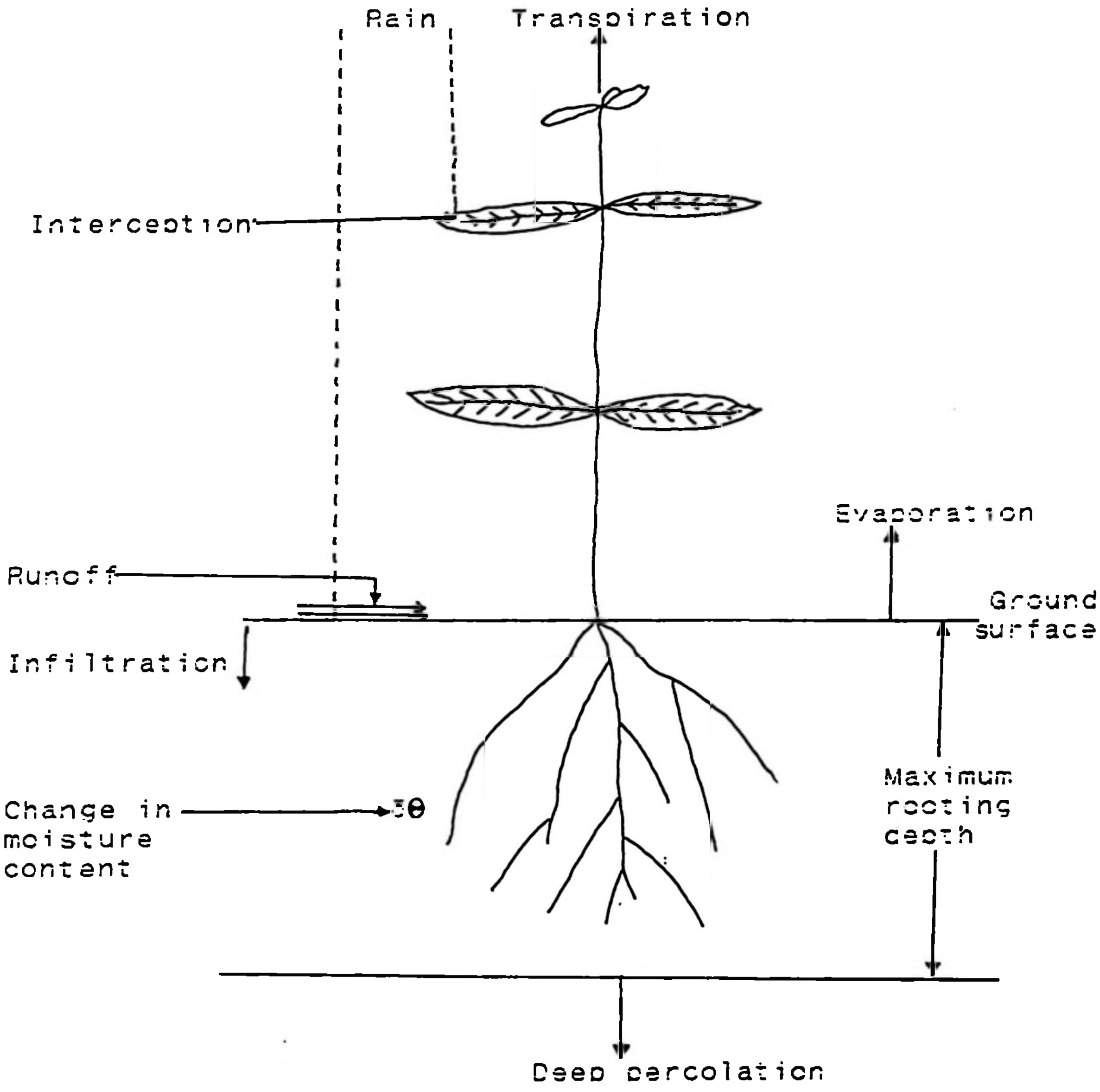


Figure 1.1 Schematic representation of components of rainfall. (after Thadei, 1992).

Interception is important as it reduces the impact and amount of rainfall at the ground surface, thus increasing infiltration and decreasing runoff. According to Buttler and Huband (1985) rainfall interception by vegetation is an important hydrologic process. In a protective sense interception may reduce the impact and amount of rainfall at the ground surface. In a wasteful sense it reduces the amount of rain available for water yield from cropped areas. Therefore there is every reason to be interested in this all-important problem of water policy and to take into account the role of vegetation cover in all its divergent manifestations (Schalck, 1967). Interception is also of significance in element cycling, since the evaporation of intercepted rain can lead to considerable concentration of 'rain out' elements including radionuclides (Stanhill, 1970). These elements together with leached leaf constituents and leaf deposits from dry 'fallout', will subsquently be washed from the plant canopy by later rains.

The infiltration of rainfall through the plant canopy via stemflow, throughfall and canopy drip can also increase heterogenity in the distribution of soil water, associated soil nutrients and, consequently, plant growth.

Interception of rain in plant canopies plays a significant role in the water balance since under the same environmental conditions evaporation from the rough vegetational cover is much more rapid than transpiration (Eriksson and Grip, 1970).

Hydrologists are often required to estimate evaporation losses from crops both in studies of irrigation schemes and for predicting the effect of a landuse change as part of a water resource study (Calder, 1977).

There is a general concensus today that interception evaporation must be treated as a separate part of plant evaporation and this makes interception studies important (Halldin, 1988).

Although in some cases the effect of interception may be quite small, no model structure will be complete without the process (Goodell, 1963). Physically based models are those which use general laws of physics of the real system or theoretical principles (Woolhiser and Brakensick, 1982). The parameters of these models have a physical significance to the system being modelled. This investigation therefore is an attempt to evaluate and test the validity of the selected models that have been developed to quantify rainfall interception.

Predictive models which are empirical in nature are essentially required to provide solutions to field problems facing irrigation engineers. The models are useful for future planning. Validated models can then be used in other places and yield good results provided the conditions do not differ very much from those under which the models were developed. But most of the available empirical models which estimate interception cannot be transfered to other regions or areas of development since their parameters have no physical significance to the systems they simulate.

Some studies that have been carried out on rainfall interception by crops and grass have used artificial rainfall. Results from simulated conditions cannot be said to be very valid when it comes to natural conditions. Experiments on natural conditions are required so that the results obtained can be of greater use to planners.

The evaluation of rainfall interception and validating the available models will be a valuable tool in potential applications in estimating rainfall interception as an input to effective rainfall estimation for operating irrigation systems and evaluating models currently used for estimating rainfall interception.

In rainfall interception studies the method used must account satisfactorily for nearly all the components of rainfall interception. The functions used to represent interception contain two parameters that give the process a physical basis. These are canopy density and the maximum interception storage capacity.

Because measurements of the relevant physical factors are relatively easier in woodlands than in other types of vegetation , much of the experimental data on interception concern forested areas. Several researchers have reviewed the available methods for measuring rainfall interception (Zinke,1967; Merriam, 1961; Brandt, 1986 and Bras,1990).

Due to the fact that very few investigations have been done to evaluate the extent of rainfall interception in cropped areas there is need to evaluate and validate models most of which are otherwise developed for forested areas.

The main objective of the study is to evaluate existing models for defining rainfall interception in cropped areas.

The specific objectives are:

(a) To measure rainfall interception by maize crop grown in a freely drained soil at Kabanana farm, Zambia.

(b) To evaluate and validate the available rainfall interception models applicable to the semi-arid tropical conditions of Zambia.

2. LITERATURE REVIEW

2.1 Introduction

Much of the experimental data on interception concern forested areas and much of the existing literature concern the same. The existing models were developed for forested areas and therefore this chapter is an attempt to review the literature concerning interception in both forested areas and cropped areas. The models to be evaluated and validated in this investigation on rainfall interception in a cropped area emanate from studies conducted on forested areas. Experimental data on rainfall interception in agricultural crops particularly cereals is scarce.

2.2 Factors influencing rainfall interception

The amount of rainfall reaching the ground surface is largely dependent upon the nature and the density of the vegetation cover. This cover intercepts part of the falling rainfall and temporarily stores it on its surfaces from where the water is either evaporated back into the atmosphere or falls to the ground. Rainfall interception is dependent upon a number of factors. The factors affecting interception include (a) canopy storage capacity, (b) meteorological factors, (c) duration of rainfall (d) rainfall frequency and (e) leaf area index.

2.2.1 Canopy storage capacity

The canopy storage capacity represents the ability of the vegetation to collect and retain falling rain. The storage capacity of a leaf may then be considerd to be the amount of water a leaf is able to retain on its surface. The amount of water retained by the leaf or its storage will be dependent on leaf area index, storm intensity, surface tension forces resulting from leaf surface configuration, liquid viscosity and mechanical activity (Leonard,1965). Therefore at the begining when all leaves and twigs are dry, canopy storage capacity is high and a high percent of rainfall does not reach the ground. Leaf surface configuration will vary with type and condition of the leaves in a canopy. This may change with season of the year, insect activity and growth factors. As the leaves wet during a rain storm the weight of the water on them at least overcomes the surface tension by which it is held and after that further additions from rainfall are nearly completely offset by the water droplets falling from the lower edges of the leaves. Thus it is important to note that after the storage has reached its capacity, storm size becomes unimportant in storage consideration. The application of canopy saturation values (or maximum storage capacity) to a local rainfall climate requires an analysis of shower size, number and frequency in time. According to Hamilton and Rowe (1949), interception storage amounts should range between 0.25 mm and 9.14 mm. These figures were obtained by regressing interception loss on rainfall and the resulting intercept is the canopy saturation value, (Fig.2.1). According to Stanhill (1970) the storage capacity of the canopy can be obtained from the slope and intercept of a linear regression of throughfall on above-canopy rainfall (gross rainfall) using data of individual storms or, more usually, individual days of rainfall. Hamilton and Rowe (1949) suggest that one would not greatly be in error to estimate about 1.3 mm storage capacities for rain for most grasses, shrubs and trees.

2.2.2 Meteorological factors

During long continuous rains the interception may be closely related to the rate of evaporation so that the meteorological factors affecting the latter are also relevant to this discussion. Evaporation probably represents a major component of interception. The high diffussion rate will transport the first portion of the storm precipitation out of the canopy. As the storm continues, temperature conditions in the canopy approach adiabatic; the saturated atmosphere decreases penetration of solar energy through the canopy, net radiation diminishes to a low level and energy for the removal of moisture becomes a limiting factor in the interception process. At maximum storage the amount of subsequent interception is a function of evaporation alone. However, while rainfall is falling, conditions are rarely likely to produce high rates of evaporation and in this case windspeed tends to dominate. Other conditions remaining constant, evaporation tends to increase with increasing wind speed so that during extended periods the interception is greater in windy than in calm conditions. However, this observation may not be applicable to rain of short duration during which the effects of high wind speed on canopy storage capacity, by prematurely dislodging water collected on vegetation surfaces, outweighs the greater evaporative losses (Viessman et al.,1977). On theoretical grounds based on consideration of the heat balance, it might be argued that the evaporation of water from wet foliage should be largely compensated by a reduction in transpiration. In their experiments on grasses Burgy and Pomeroy (1958) concluded that evaporation is

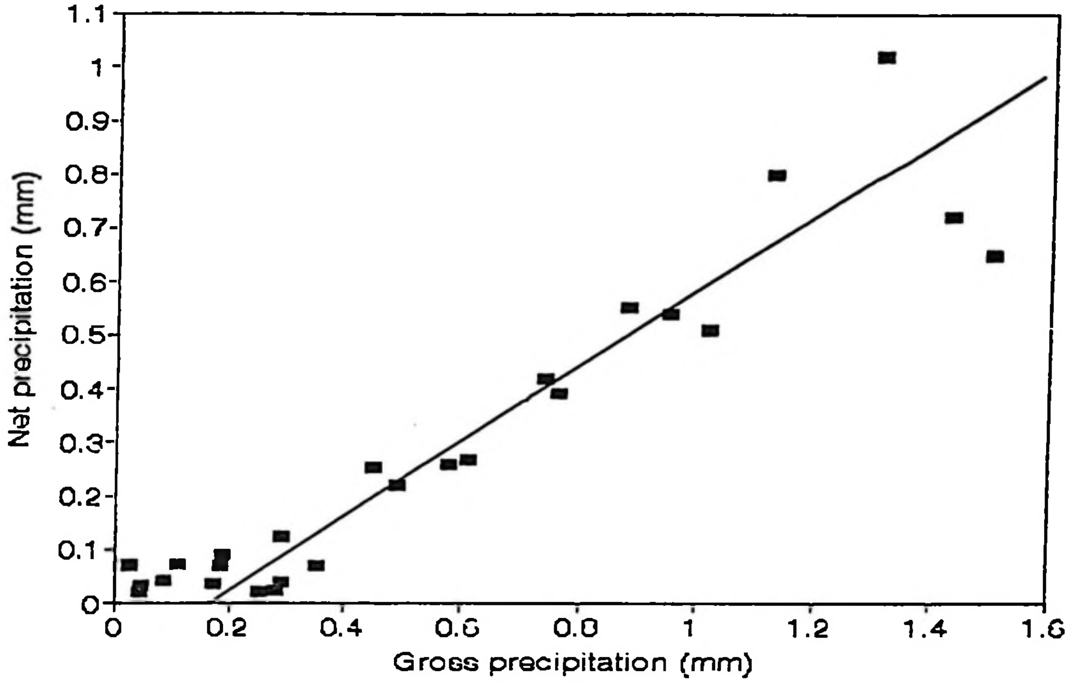


Figure 2.1 Net and gross precipitation for 23-year Norway spruce plantation 7.62 m^2 basal area. (Bagley wood, 1965)

NOTE: The intercept on the x-axis is the canopy saturation value which is 0.1524 mm.

indeed equally balanced by a reduction in transpiration so that with this type of vegetation the net loss of water due to interception is zero. Other experiments have suggested that this is not the case with trees and shrubs. Sykes (1960) and Wells (1963) quoted by Leyton et al. (1967), working with potted tree seedlings or detached shoots and leaves have shown that the rate of evaporation of intercepted water can be in the order 5 to 10 times that of transpiration with unrestricted water supply and under the same environmental conditions.

Evidence is accumulating mostly from forested areas to support the conclusion that intercepted water evaporates much faster than transpired water and therefore much of the interception loss represents an additional loss in the water balance. More realistically field experiments by Rutter (1963,1967), Patric (1966), Helvey (1967) and Leyton et al. (1967) indicated that during the winter period the loss of intercepted water considerably exceeded the transpiration rate in the same environmental conditions. The principal causal mechanism for the reduced water yield from upland forests, relative to hill pasture, is the greatly increased evaporation rates from wetted forest canopies during and following rainfall (Rutter,1963; Rutter et al., 1971;

Calder,1977,1979; Gash and Morton,1978; Calder and Newson, 1979). At some point in time after rainfall ceases, all of the intercepted water will be evaporated.

2.2.3 Duration of rainfall

The duration of rainfall is a secondary factor in that it influences interception by determining the balance between the reduced storage of water on vegetation surface on one hand and the increased evaporative losses on the other. Data collected by Horton (1919) and in a number of later investigations showed that interception increases with the duration of rainfall but only gradually so that the relative importance of interception decreases with time. Delfs (1965) presented results of the measurement of interception in the Harz and in the Sauerland areas of Germany. Results showed that small amounts of 2 to 5 mm of rain are almost completely intercepted by the crowns of Norway spruce. But for rainfalls of more than 25 mm 81 percent reached the ground. The amount and length of rainfall therefore affect the amount of interception considerably.

2.2.4 Rainfall frequency

Since most of the interception occurs at the start of the storm when the vegetation surfaces are dry and the canopy storage capacity is large, it will be apparent that rainfall frequency is of considerable significancy than either duration or amount of rainfall. The influence of rainfall intensity on interception has been very noticeable in some cases. Eschner (1965) presents us with a report concerning intensity. During his observation of a heavy thunderstorm in which 74.6 mm of rain fell within three and half hours, only 2 percent was intercepted and the interception was 25 percent from a continuous rain with 70.5 mm of rain over fifty hours. Plants subjected to low rainfall intensities require much larger times to reach canopy saturation which along with unsaturated ambient conditions provide opportunity for loss by evaporation and possible uptake of water by plants (Aston,1965).

2.2.5 Leaf area index (LAI)

As earlier mentioned leaf area index has a direct bearing on canopy saturation value (canopy storage capacity). By definition leaf area index (LAI) is the ratio of the leaf area to its projected area on the ground. Measurements of leaf area are normally done by the use of a planimeter. only one side of the leaf has its area measured. The total area for all the leaves including that of the stem is then divided by the ground projected area to get LAI. Leaf area index increases and reaches a maximum at the period of maximum vegetative development. At this stage the plant intercepts more rainfall. After the plant has matured the leaves break towards the end of the season thereby reducing foliage cover. Consequently, the leaf area index reduces.

2.3 Earlier studies on rainfall interception

2.3.1 Interception by forests

Investigations in the interrelations between forests and elements of the climate began about 132 years ago. In 1862 Krutzsch started measurements of rainfall under a pine stand. He found as a first result that the interception became greater with increasing rainfall (Friedrich,1965). Linsley et al. (1949) suggest that interception of rainfall may be assumed to take the form of an exponential curve as the amount of rainfall is increased from zero to some high value (for a specified duration). Seppanen (1964) noted that interception in Scotch pine increased exponentially with an increase in rainfall. Merriam (1960) discussed interception in terms of its two components, storage and evaporation. He concluded that only the storage term would follow the exponential term.

Bringfelt and Harsmar (1974) working on data from the summer and autumn of 1973 on rainfall interception in a forest of the Velen hydrological representative basin used the difference between the amount of water collected from troughs installed in clearings and the amount of water collected in troughs installed under the canopy in order to determine the amount of water intercepted by the canopy. In this way, errors due to differences between types of gauges are thought to have been eliminated. They found the amount of intercepted water to be 74 mm compared to a total fainfall of 288 mm. This means that 26% of the total rainfall was intercepted.

Roberts et al. (1982) working on stands of Scots pine and corsican pine in the Thetford Chase East Anglia compared interception by the canopies of the two species by measuring throughfall in both stands. Twenty-four raingauges (127 mm diameter) were located randomly within a grid of 30 m * 15 m in each stand. These were emptied and reallocated randomly every two weeks for 21 months. Gross rainfall was measured above corsican pine stand. In the presentation of their results, rainfall interception by each stand was calculated as the difference between gross rainfall and throughfall. Differences over the whole experimental period and for each 2-week sample were tested for significance. Interception by Scots and Corsican pine for the whole period was not significantly different. Significant differences did exist on nine out of the forty-one sample occasions, but these were small and no clear systematic relationship emerged between species. However, stemflow was not measured in their experiment because they point out, by quoting Gash and Stewart (1977) and Rutter et al. (1971), that stemflow has been shown to be negligibly small in Scots and Corsican pine. The interception values reported were 32 percent of rainfall and are the same as those reported by Gash and Stewart (1977) for Scots pine. Miller et al. (1976) found interception of between 30 and 34 percent in a 38-year old Corsican pine stand in North-east Scotland. According to Rutter and Morton (1977) and Gash and Morton (1978) the similarity of these results is expected since interception by forest canopies has been shown to be much more dependent on rainfall amounts and duration than on differences in canopy structure.

Willis et al. (1975) measured throughfall and stemflow in a Northern hardwood forest west of the village of Alberta. Throughfall was measured under the canopy using universal raingauges. Measurements of stemflow were obtained by means of a spiral gutter placed near the base of the study tree. Measurements were taken during the summer months only of 1957 to 1961 and 1963. Their results show that low intensity storms produce less throughfall than that for storms of greater intensity. Storm duration was also found to have a pronounced effect on throughfall; storms of high intensity but with short to moderate duration resulted in the greatest throughfall. Their results on stemflow indicate that there was little stemflow during storms of 0.76 mm and less for all study trees. They explain that this lack of stemflow could be due to absorption of the water by the bark. However stemflow increased geometrically during rainfall of 0.76 mm and greater, the smallest tree demonstrating the most rapid increase. They attribute this to the relatively smooth bark and ascending branches of small trees as opposed to the scaly bark and wide spreading branches of large trees.

Calder and Newson (1979) plotted interception losses expressed as fraction of the annual rainfall, from British forests against annual rainfall using results obtained from the experiments of Law (1956), Rutter (1963), Leyton et al.(1967), Gash and Stewart (1977) and Courtney (1978). A consistent trend is demonstrated on the graph (Fig.2.2): the interception fraction decreases with increasing rainfall.

Reviewing a broad range of Russian, European and American data, Rakhmanov (1962) suggested that coniferous forests together with sparse woods and inhibited stands on peat bogs and other marshy terrain, intercept an average of 25-35 percent of the annual rainfall compared with 15-25 percent by broad leaved forests. Fig.2.3 shows data from Eidmann and Hoppe, quoted by Penman(1963) and Geiger (1957) respectively, on which this contrast is clearly illustrated.

Stemflow is usually measured volumetrically and the amounts are subsequently converted to millimetres of water by dividing them by projected crown area (Bruijnzeel, 1990). Several investigators reported stemflow from large diameter trees to be less than for smaller stemmed trees (Bruijnzeel, 1990). This may be ascribed to differences in branching patterns. The amount of stemflow in forested areas depends largely upon the roughness of the bark (Lull,1964). Rowe (1941) found that in the case of some smooth barked trees, like beech, this could amount to 15 percent of the rainfall, while Kittredge (1948) found much lower values of 2 percent to 3 percent for rough barked pines.

Other experiments have gone further into the analysis of the hydrological response of different parts of a given tree. Hutchinson and Roberts (1981) examined one response variable stemflow, in a partitioned tree canopy and related stemflow production to canopy storage capacity and canopy morphology. Their results indicate that the horizontal projection ('interception area') of each branch increases exponentially with increasing branch length. The sum of the branch interception areas yielded a total interception for the tree of 37.4 m^2 whereas a simple projection of the canopy onto a horizontal plane produced an area of 16.2 m^2. They also established that the water storage capacity of each branch was a linear function of the branch interception area. The vertical distribution of storage capacity relative to the positions of the stem flow collars is shown on Fig.2.4.

2.3.2 Interception by crops and grasses

Interception losses from total leaf area of a continous cover of mature grass or shrub are similar in magnitude to those from trees during the season of maximum development. Since their season is short, however, total annual interception loss from grasses is considerably less than from, say, deciduous woodland.

Some information is available on the interception loss from agricultural crops, and from cereals in particular, although the data are scarce in relation to those from forested areas. Fig.2.5 is based upon early data of Wollny reported by Baver (1956) and shows interception by corn, soybeans and oats. Interception increases initially with increasing crop density. After a certain covarage has been attained however, the subsequent increase of interception is slight, as shown by the latter portions of the curves, and in general it can be said that average interception by fully developed oats, soybeans and corn is 23, 35 and 40 to 50 percent of total rainfall respectively. Measurements of stemflow were not made and the figures would therefore have to be reduced by an appropriate amount to be representative of the real interception loss. Lull (1964) reported observations by Haynes for the same three crops during the growing season, which showed that interception losses from oats, soybeans and corn respectively were about 7, 15 and 16 percent of the total rainfall.

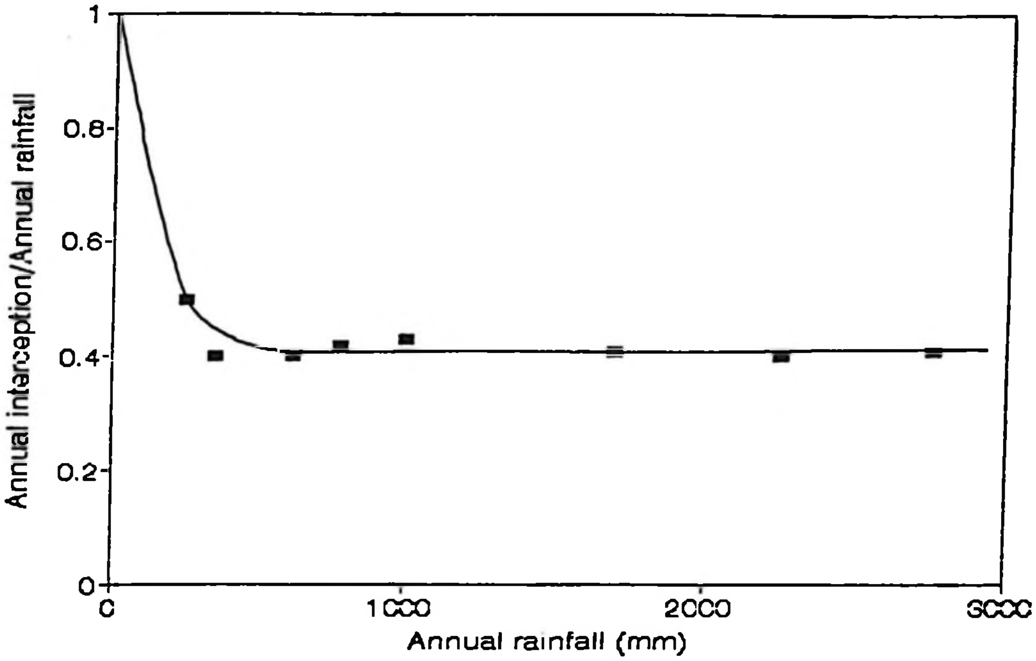


Figure 2.2 Measurements of annual interception loss, expressed as a fraction of the annual rainfall plotted against annual rainfall (after Calder and Newson, 1979)

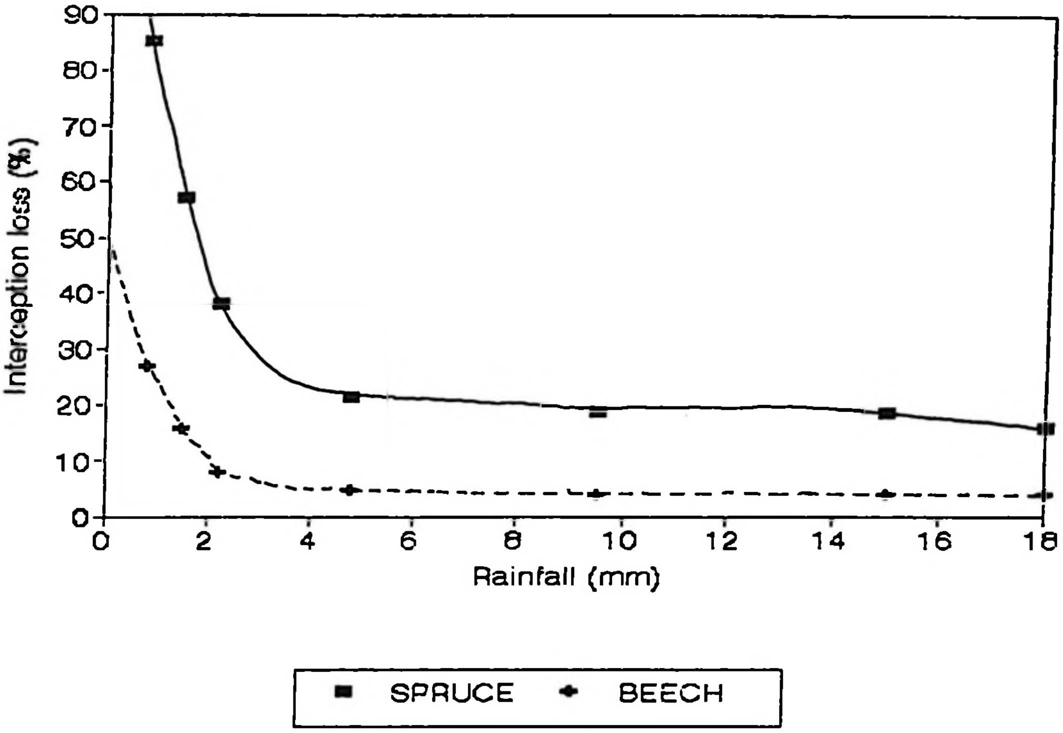


Figure 2.3 Summer interception losses from spruce and beech forests Based on data from F.E. Eidmann quoted by Penman (1963) and from E. Hoppe quoted by Geiger.(1957).

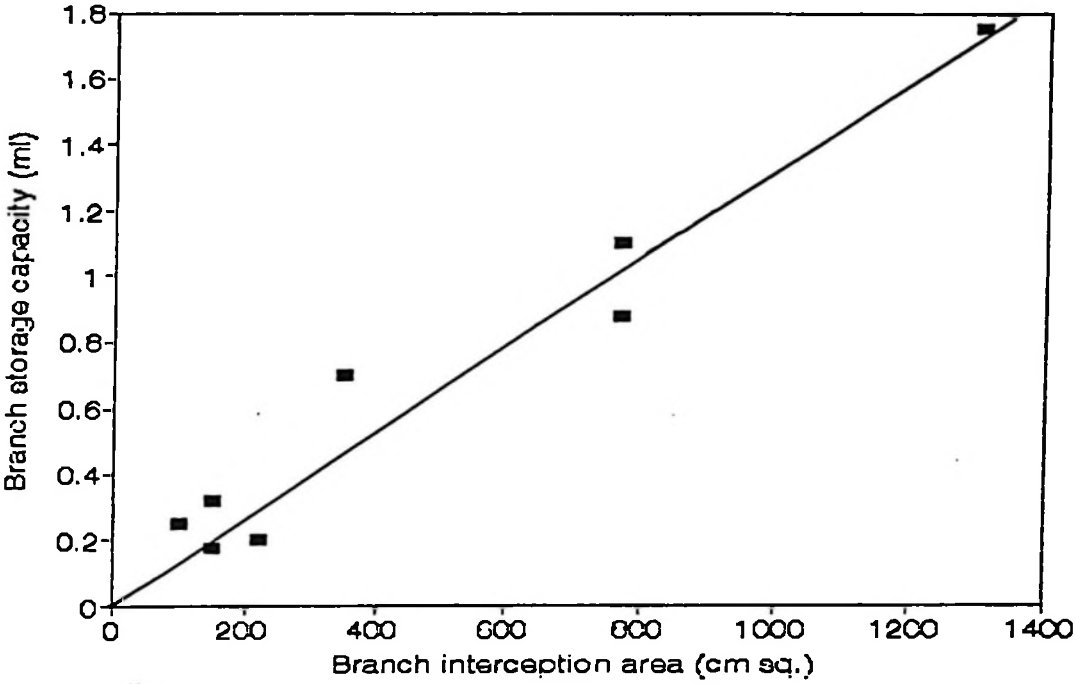


Figure 2.4 The relationship between water storage capacity of branches and branch interception area. (After Hutchinson and Roberts, 1981).

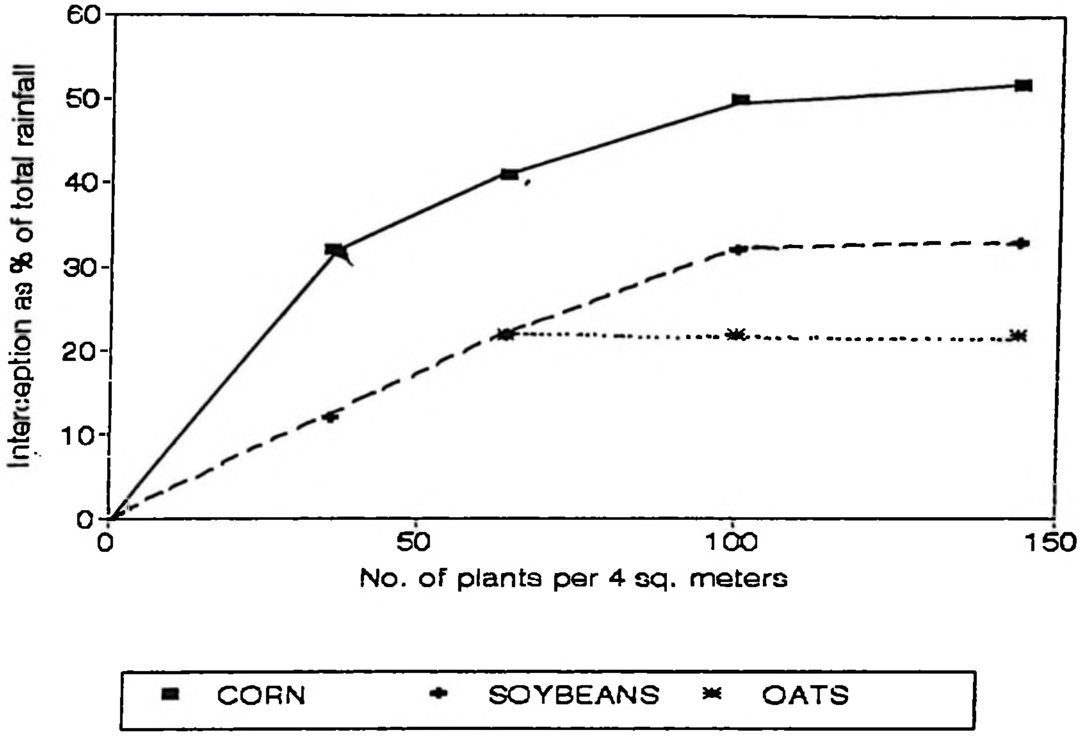


Figure 2.5 Interception by three agricultural crops

(Based on data from Wollny quoted by Baver, 1956)

Hayness (1940) measured canopy penetration under corn by means of galvanized metal pans 10.16 cm deep and 106.68 cm x 106.68 cm wide which he placed between the drill rows. Water running down the plant stalks was diverted into catchment basins by means of a funnel like collar sealed to the stem by wax. Corn under which ground rainfall measurements were made was in 106.68 cm spacing between rows, with average 35.56 cm hill spacing for the 1937 records and 22.86 cm spacing for the 1938-39 records. Corn reached a height of 91.44 cm before rainfall in measurable quanttities was intercepted by the crop canopy. At the period of maximum vegetative development corn had 55-65% foliage cover, LAI of 2.4 and a height of 2.44 m. As leaves matured and broke away toward the end of the season, foliage cover was reduced. Hayness observed that the amount of water reaching the ground by following the corn stalk is relatively large. The data on Table 2.1 represent full growing season for corn.

Clark (1940) estimated the importance of stemflow in wheat using long, narrow troughs placed on the ground across the rows. Throughfall was collected with the stems of cut plants inside and outside the troughs and no consistent differences were found between the two arrangements. He concluded that the amount of water running down the stems is not large. Throughfall with and without stemflow in tall veld grass in South Africa was measured by Beard (1962) using similar troughs to clark. Here stemflow accounted for about 40% of the incident rainfall; however, the canopy structure of these grasses was not described. Differences between the

the canopy structures of veld grass and wheat could account for the contrasting results.

Butler and Huband (1985) measured throughfall and stemflow in wheat using latex boxes which were installed within the crop. The leaf area index was about 3. Interception obtained from the difference between rainfall and throughfall included that water held in the canopy and that which evaporated during rain. Values of interception obtained were plotted against rainfall as shown in Fig.2.6 and the plot shows that interception increases as rainfall increases.

Table 2.1 Precipitation and ground rainfall record during the respective experimental period studied for corn, (After Hayness, 1940).

	Year	(mm)	
Rainfall	1937	181	
	1938	326	
	1939	176	
Total		683	
Canopy penetration	1937	123	
	1938	231	
	1939	126	
Total		480	
Stemwater	1937	30	
	1938	81	
	1939	45	
Total		156	
Number of observations			51
Total interception including stemwater as % of rainfall			6.9
Total interception excluding stemwater as % of interception			29.7

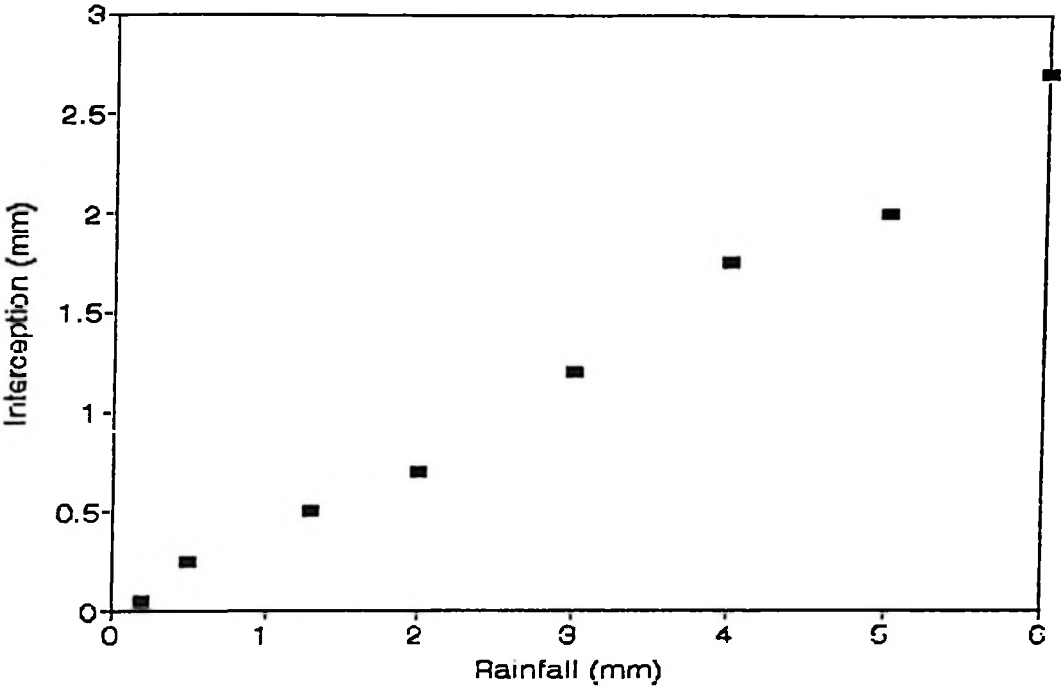


Figure 2.6 Interception plotted against rainfall for wheat (After Butler and Huband, 1985).

Results for grasses have been presented mainly by Clark (1940). They ranged considerably higher than for other types of vegetation. For example andropogon gerardi vitman (big blue stem) of 100% density, the percent interception loss was from 50 to 63 percent of a storm of 1.27 mm. Since stemflow was ignored these values are undoubtedly too high.

Throughfall under vegetation is not uniform and samples must be collected over a large enough area to be representative of the crop (Reynolds & Layton, 1963). In cereals throughfall may arise from rain falling directly through gaps in the canopy or from water which drops from leaves.

In dry climates the effect of stemflow is of significant importance to plants because light rainfall is concentrated within their root zones. On a smaller scale the effect has been shown to be important for drought resistance in tall crop plants like maize (Glover and Gwynne 1962). Stemflow carries amounts of nutrients to the bases of individual plants that are too large to be ignored (Herwitz, 1986b)

2.4 Available models

Interception is usually measured indirectly as the difference between gross (above the canopy) and net (below the canopy) rainfall. The latter is calculated by summing the total throughfall and stemflow (Kittredge, 1948; Rothacker, 1963; Rutter, 1963; Helvery & Patrick, 1965; Zinke, 1967; Hutchinson et al.,1981). From the established relations it is possible to develop estimates of the budgetary terms in the form of linear regression equations that are of practical value to the forest and water manager.

Numerous empirical models have been presented during past and recent years, but only few of these have been comprehensively compared and tested against independent field data. Eriksson and Grip (1978) made a comparison of interception models. The interception process was described in six models: HEJMDAL (Hansen, 1979), CANOPY (Halldin et al., 1979), SIM5T/12 (Gash et al., 1979), SOIL (Jansson and Halldin, 1979). ETFOREST (Jensen, 1979) and WATREG (Item, 1979). The models were compared with respect to process description and simulation results. On a seasonal basis all models except CANOPY, seemed to produce reasonable results which coincided with earlier precipitation-throughfall measurements in the Scots pine stand (aged 120-150 years). The earlier measurements established the interception loss through evaporation of intercepted precipitation in the forest canopy to about 20%

of the summer's precipitation in the test stand. The divergence of CANOPY from the rest was believed to be due to a non-optimal choice of parameters in the drip process retaining too much water in the canopy.

Despite considerable research, it is not yet possible to predict the amount of rainfall that will be intercepted by a forest canopy nor the pattern of throughfall distribution below the canopy from a knowledge of its physical characteristics (Stanhill, 1970). The amount of interception (INTCEP) must be calculated for each stand from measurements of above-canopy rainfall (P), stemflow (S) and throughfall (T) using the following equation:

$$INTCEP = P - (T + S) \qquad (3)$$

The threshold value of P above which T commences is nearly always less than that at which S commences. Therefore, the storage capacity of the canopy (C) can be derived from the slope and intercept of a linear regression of T on P using data of individual storms or, more usually, individual days of precipitation (Stanhill, 1970). Thus

$$C = a/b \quad \text{where} \quad T = b * P - a \qquad (4)$$

and

a = intercept

b = slope of the line

Leornard (1965) worked on interception in forest areas and suggested that gross interception loss can be expressed in terms of mm water per unit ground projected area (after Horton, 1919). He presented interception as follows:

$$INTCEP = C + LAI * Ea * t \qquad (5)$$

where:

INTCEP = total interception (mm)

C = storage capacity of vegetation

LAI = the ratio of evaporating surface area to its projected area on the ground

Ea = rate of evaporation from plant surfaces (mm/day)

t = rainfall duration (day)

Using an exponential term to take into account the total rainfall Merriam (1960) derived the following relationship:

$$INTCEP = C * (1 - EXP\,[-P/C]) + LAI * Ea * t \qquad (6)$$

in which P = total precipitation and the other variables are as defined earlier.

Then Belmans et al. (1983) proposed the equation of the form:

$$INTCEP = u * Sc * P^{(v-w*P)} \qquad (7)$$

where:

INTCEP = flux rate of interception (daily)

Sc = ground cover fraction

u,v,w = regression coefficients for predicting interception in SWATER (Soil Water Balance Simulation Model).

Although equation (5), (6) and (7) cannot estimate instantaneous interception rate, these three models can estimate total interception.

Rutter et al. (1971, 1972) developed an equation to predict interception rate in forests and is expressed as:

$$i = (1 - q) * r - EXP\ (a + b - C_t) \qquad (8a)$$

$$Dr = EXP\ (a + b - C_t) \qquad (8b)$$

where:

i = interception rate (mm/h)

C_t = depth of water on the canopy at time t

q = fraction of rainfall passing the canopy without being intercepted.

r = rainfall intensity (mm/h)

Dr = drainage rate

a,b = fitted parameters.

Aston (1979) tested the model of Rutter et al. (1971,1972) in Australia and found that it gave unsatisfactory results. However, Bathurst et al. (1986) while using the equation in the SHE model have found that the equation works satisfactorily under conditions of a completely wetted canopy ($C_t > C$). But the equation can be modified by introducing the ratio C_t/C, so that it can be used fully to wetted canopy. Thadei (1992) argues that the Rutter et al. (1971, 1972) was strictly developed for estimating interception in forests and it is unlikely that it can also be used for simulating interception in a cropped area.

Measured interception has often been expressed as a function of gross rainfall in empirical linear regressions of the form:

$$INTCEP = a + b * P \qquad (9)$$

where:

INTCEP = interception loss (mm)

P = gross rainfall (mm)

a,b = constants

The implicit assumptions in this approach were re-examined by Gash (1979) and he demonstrated that the constant 'b' is equal to the ratio of evaporation rate to rainfall rate during a storm. Over extended periods total interception loss and rainfall amount are often highly correlated. The basis of the Gash analytical model is that mean evaporation and rainfall rates can be used to substitute for the actual values in each storm event. The Gash model predictions are insensitive to the canopy structure parameters but are strongly dependent on daily rainfall. Gash, Wright and Lloyd (1980) used the model on three coniferous forests in Britain and found a systematic divergence of up to 20% from measured interception losses at two of the sites, but a close agreement at the third. But this divergence is substantiated by the fact that their measured interception was subject to a possible error of up to 17%. Jarvis et al. (1988) tested the Gash model on sitka spruce in Scotland and expressed interception loss as a percentage of annual rainfall for the period 1970-1979. They found that interception loss increases from an average of 36% at 1000 mm rainfall to around 40% at 500-700 mm rainfall. They recommend the Gash model to be useful for applied research.

Very few investigations of rainfall interception by grass and crops have been carried out (Clark, 1940; Hayness, 1940; Burgy and Pomeroy, 1958 and Merriam, 1961). These investigations measured interception and regressed with total rainfall to get equations for estimating interception. Thus no reliable equation was obtained from their studies. However, De Jong and Cameron (1979) have represented total interception as a function of daily rainfall and days after planting using the following relationship:

$$INTCEP = 0.03 * DAYS * P/(0.5 * P + 1.5) \qquad (10)$$

where:

INTCEP = total interception (mm)
P = total rainfall (mm/day)
DAYS = days from planting

Patwardhan et al. (1990) used this equation to estimate interception in predicting effective rainfall. He found that this equation is very useful for estimating total interception although it has a problem when it comes to the estimation of instantaneous interception rate.

2.5 Determination of evapotranspiration (ETo)

Reference crop evapotranspiration (ETo) can be determined directly through measurement or indirectly through calculations (correlation methods) using empirical formulae. The Penman-FAO modified equation (FAO,1984) was adopted for this study because ETo was not directly measured. Climatic data included measured air temperature and sunshine, cloudness or radiation, wind speed and humidity. The relationship representing mean values over a given period is

$$ETo = c * [W * Rn + (1 - W) * f(U) * (ea - ed)] \qquad (11)$$

where:

ETo = reference crop evapotranspiration in mm/day
W = temperature-related weighting factor
Rn = net radiation in equivalent evaporation in mm/day
f(U) = wind-related function
(ea-ed) = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mbar
c = adjustment factor to compensate for the effect of day and night weather conditions

Vapour pressure must be expressed in mbar but if ed is given in mm Hg, multiply by 1.33 to find mbar. For a given mean temperature ea is read from tables.

The wind function is defined as:

$$f(U) = 0.27 * \left(1 + \frac{U}{100} \right) \qquad (12)$$

where U is 24-hr wind run in km/day at 2 m height. This expression is valid when ea-ed is expressed in mbar.

(1-W) is a weighting factor for the effect of wind and humidity on ETo. Values of (1-W) as related to temperature and altitude are given and read from a table (FAO,1984).

The weighting factor (W) is due to the effect of radiation on ETo. Values of (W) as related to temperature and altitude are given and read from a table (FAO, 1984).

Net radiation (Rn) is the difference between all incoming and outgoing radiation. Rn can be calculated from solar radiation or sunshine hours (or degree of cloud cover), temperature and humidity data.

The method is generally valid for humid climates. To better take into account arid conditions an adjustment factor (c) is used. The variables considered are maximum relative humidity (RHmax), solar radiation (Rs), windspeed (Uday) and the ratio Uday/Unight. A table is then used to read the value of (c) (FAO, 1984).

2.6 Determination of ETcrop

Crop evapotranspiration (ETcrop) is related to reference crop evapotranspiration (ETo) by a crop coefficient (kc) to account for the effect of the crop characteristics on crop water requirements (FAO, 1984). ETcrop can then be found by:

$$ETcrop = kc * ETo \qquad (13)$$

General climatic conditions, especially wind and humidity are considered in the estimation of kc values. FAO (1984) describes the steps that are to be followed in order to estimate the kc values at different stages of plant growth.

Due to limitations of time and budget constraint in this research only models (5), (6), (9) and (10) were evaluated. The other models demand more parameters to be measured which was not possible as can be clearly seen in the following chapter on materials and methods.

3. METHODOLOGY

3.1 Introduction

The functions used to describe interception contain two parameters that give the process a physical basis. These are canopy density and the maximum interception storage capacity. With the knowledge of these parameters the amount of interception of rainfall by vegetation can be estimated. To measure rainfall interception for agricultural crops, rainfall may be measured above the crop or by an adjacent standard raingauge placed near the study area to determine the gross rainfall and in gauges installed within the crop field to determine throughfall. Water running down the plant stalks can be diverted into collection containers by means of a funnel like collar sealed to the stem by wax. Leaf area index has a direct bearing on rainfall interception and its measurement, therefore, is of significant importance. If evapotranspiration is not directly measured its estimation requires the use of climatic data on temperature, windspeed, sunshine hours, radiation and humidity. Collected data on gross and net precipitation (throughfall plus stemflow) is useful in establishing maximum storage capacity of the agricultural crop under study. The study area is described with respect to its location, climatic conditions and soil type. Problems encountered during data collection and the reasons leading to such problems are briefly explained.

3.2 Description of the study area

3.2.1 Location

The study was carried out in Kabanana, a peri-urban area in Lusaka, Zambia. The specific site was plot No.2952 M, one of the Kabanana farm plots along Kabanana road located between 28.4°E and 28.6°E, and 15.1°S and 15.3°S, (Fig.3.1 and Fig.3.2). The area was chosen because safety of the equipment was guaranteed and most importantly it facilitated an interaction between the farmer and the researcher. The mean height is about 1070 m above sea level.

3.2.2 Climate

Although Lusaka is within the tropics, its climate is modified by altitude and distance from the Indian ocean which lies some 830 km away. As can be seen from Appendix 1, the rainy season is from November to March. The highest amount of rainfall is in the month of January and averages 222 mm. Annual rainfall averages 803 mm. The rainfall is relatively reliable with 80 percent of the average likely to be recorded in three out of four years. Fig. 3.3 shows the distribution of rainfall in Lusaka. Temperatures are moderate. The average maximum temperature for the warmest month (October) being 31.2°C and the average minimum temperature for the coldest month (July) is 9.6°C. Lusaka is quite windy and persistent winds from the east are the most significant.

3.2.3 Land use and vegetation

The natural vegetation of Lusaka area originally had been the dry deciduous woodland called miombo although very little remains in the vicinity of the city where it has been cleared for cultivation and charcoal burning.

Miombo is dominated in this area by Brachystegia and Julbernardia species,respectively, however there is munga in some pockets; a more open savanna woodland characterised by Accacia Terminalia and Combretum species.

3.2.4 Soils

The predominant rock is a quartz-muscovite schist on the chunga formation. The soils are deep and well drained with high permeability. They are sandy loam, or loamy sand and the soils in this series have a fairly low base saturation and the acidity ranges from pH 4.6 to 6 (Van Beek, 1986). They are therefore suited to a wide range of crops and will produce high yields under proper fertilizer appication and good management.

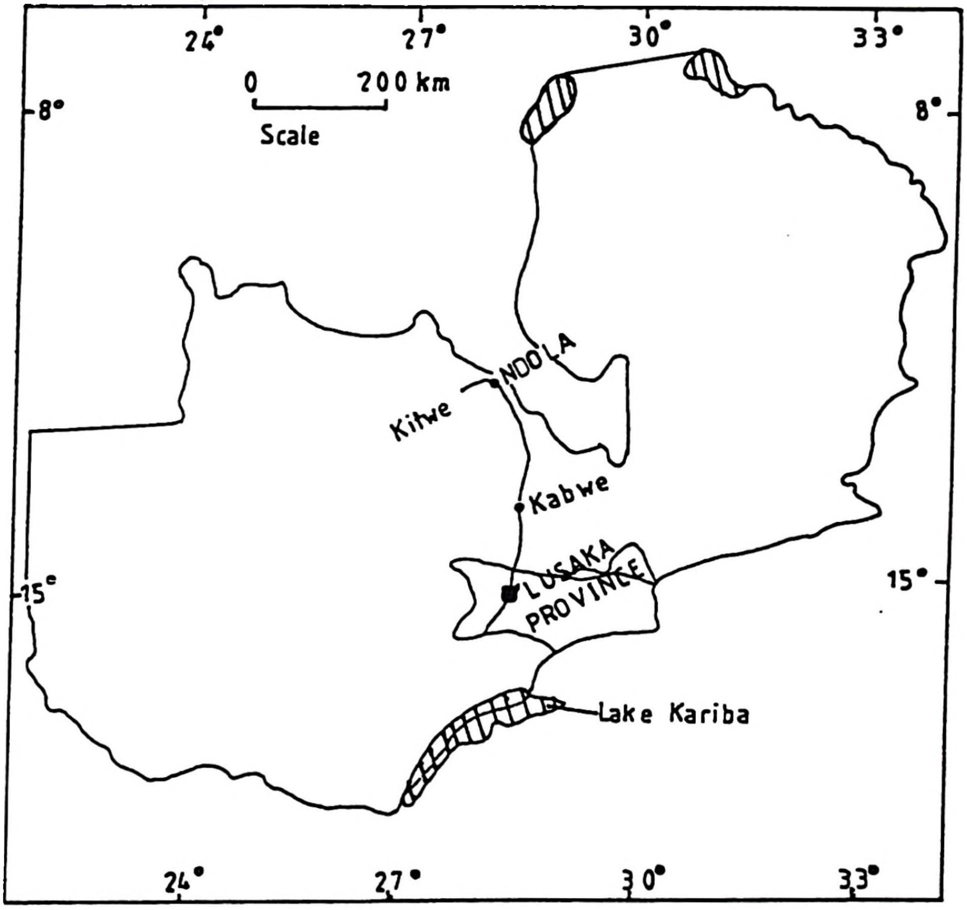


Figure 3·1 Location of Lusaka in Zambia

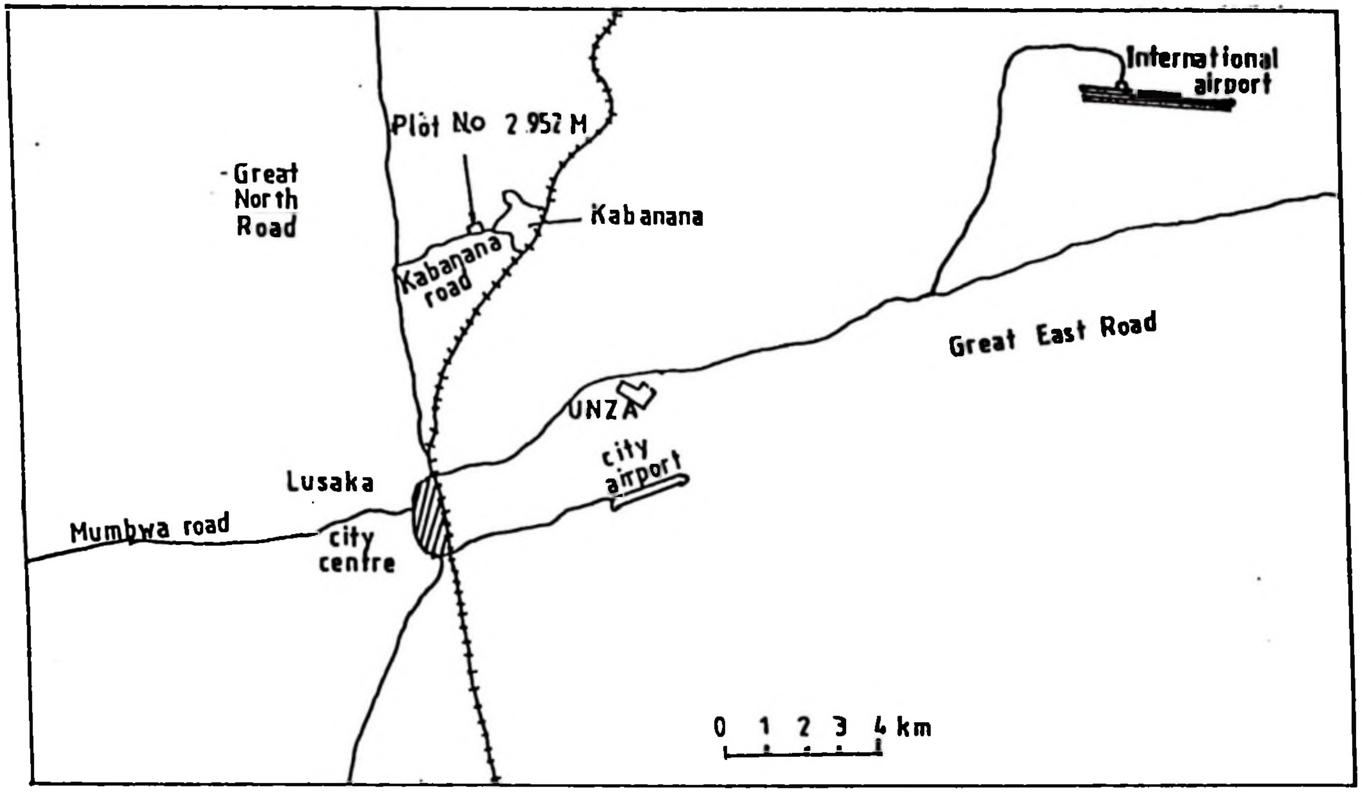


Figure 3·2 Location of Kabanana plot No 2 952M

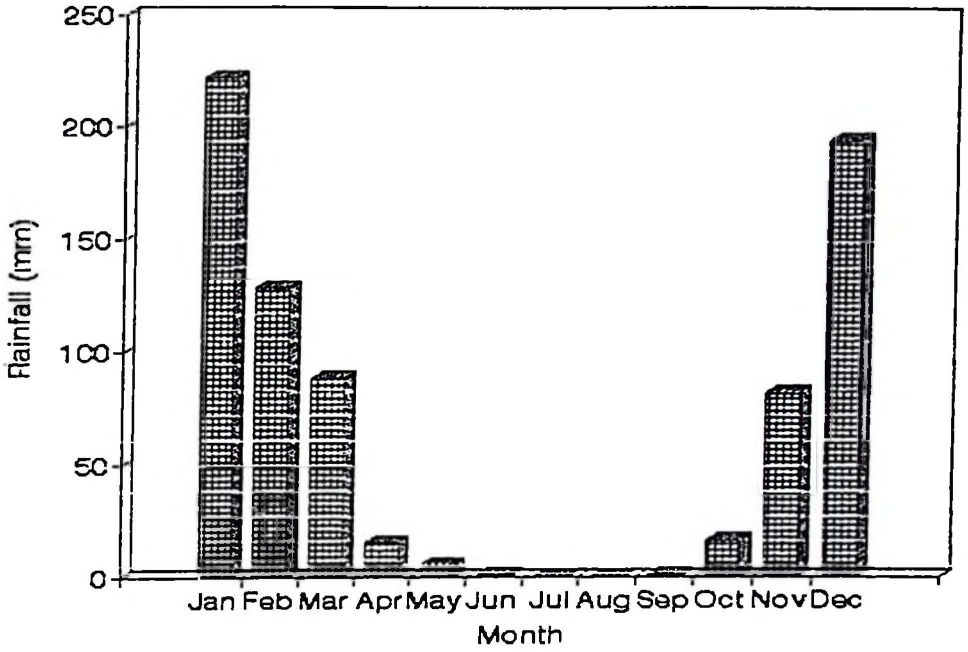


Figure 3.3 Normal distribution of rainfall for Lusaka (Based on data from Van Beek, 1986).

3.3 Experimental Procedure

3.3.1 Crop grown and fertilizers used

A 100 m * 100 m plot was cultivated but the middle portion of 40m * 40m was used for conducting the study. This was particularly done to ensure that there was stability of conditions in the study area. On December 2nd, 1993 the Zambian maize variety mm604 was sown. The plant spacing was 90 cm x 18 cm. This spacing was used because it was the standard, according to the farmers of the area, recommended for the type of soil and seed used. At two weeks old basal dressing fertiliser (X-compound) was applied. One month later urea was applied as a top dressing fertiliser. The experimental plot was kept weed free for the entire season.

3.3.2 Measurement of rainfall interception

Interception measurements started when the maize crop reached a height of 30 cm. Haynes (1940) recorded measurable quantities of interception when corn reached a height of 91.44 cm but in this case a lower figure was chosen so that De Jong and Cameron's equation (1979) could be tested because in this equation the number of days after planting is a significant variable. Twenty raingauges were randomly installed in the maize field. The 40 m * 40m study area had 43 rows. The spacing between rows was 90 cm. To achieve an unbiased installation of the 20 raingauges in the study area the sampling method after Boyd et al. (1981), was used: a sample (n) is to be chosen such that the sampling fraction (n/N) is at least equal to or greater than 5 percent. Therefore 100 possible positions were identified out of which 20 positions were installed with a raingauge at each position. Installation was done in such a way that the opening of the raingauge was directly under the leaves of the maize plant. One raingauge was installed in an open place near the field to measure gross rainfall. Rainfall was measured after each rainfall event, however, if it rained during the night rainfall was measured the following day. Measurements normally involved recording rainfall from the raingauge in the open space and those installed under maize. During the storms of very high intensity a few raingauges in the maize field recorded more rainfall than the one in the open space. This was due to more water flowing down the stem but dripping at a pronounced drip-point of the stem and leaf joint and, thereby finding its way into the raingauge.

3.3.3 Measurement of Stemflow

Funnel-like collars were installed the same day the raingauges were installed and the same process of random selection of points like that used during installation of raingauges was also followed. This was done by installation of the funnel on the maize stem just below the last bottom leaf of the maize plant. A small hole at the base of the funnel provided a connection with an 8mm plastic tube. The tube acted as a channel to the 2.5 litres water collecting plastic containers (Fig. 3.4). Wax was used to seal any possible leakage of stem water once it falls on the funnel so that all the water finds its way through the tube to the container. Stemflow was measured volumetrically and the amounts subsquently converted to millimetres of water by dividing them by projected crown area (after Freise 1936). During the early stages of the experiment when the funnels were closer to the ground a very heavy rainfall with high intensity splashed the soil particles into the funnels and blocked flow of stem water through a few tubes. Such raindrop impact from rainfall with a very high erosivity index were otherwise a rare occurrence. During the early stages of data collection when the plant stem was increasing its diameter the funnels were detached and refixed to the same plant but at a point slightly above the first one.This was done to avoid restriction of the stem growth at the point of attachment.

3.3.4 Measurement of foliage cover

Estimation of percent foliage cover was made by measuring the amount of light penetrating the canopy and striking the ground . The measurements were taken at noon when the sun was directly overhead since this technique is not suitable for cloudy or windy days (Elwell and Wendelaar, 1977). This involved laying sheets of paper under the plant and sunlight areas traced out and later measuring them by using a planimeter. These areas (lit areas) so obtained when subtracted from the total area gave shadow cover which was expressed as a percentage of total area to give an estimate of percent foliage cover.

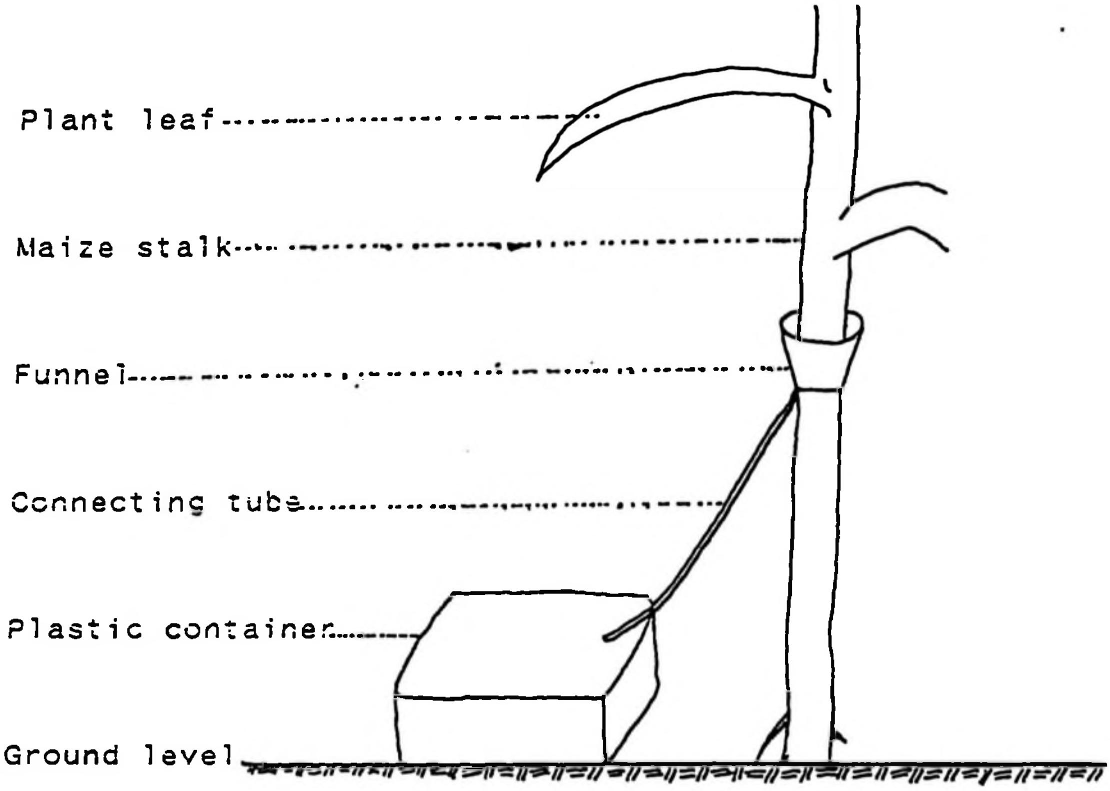


Figure 3.4 Arrangement of equipment for stemflow collection

3.3.5 Measurement of leaf area Index

A planimeter was used to measure the area of the leaf. The method was destructive in that it involved cutting the maize plant from the base. The area shaded by the plant at noon was determined before cutting the plant. All the leaves were carefully cut from the maize stem and each leaf had its area determined using a planimeter. After the leaves had been cut the stem also had its area determined. Leaf area index was then calculated as the area of one side of the leaves including that of the stem divided by the area shaded by the plant at noon. The leaf area index was measured approximately after every 10 cm gained in height during growth.

3.3.6 Data from meteorological station

Climatic data of air temperature, sunshine hours, radiation, wind speed and humidity was collected from the nearby University of Zambia meteorological station located 5.7 km from the study area (Fig.3.2) This data was required for the estimation of evapotranspiration through calculations using FAO-Penman modified equation (Eqn. 11). The estimated reference crop evapotranspiration was used to calculate the crop evapotranspiration (ETcrop) referred to as ETmaize. The method suggested by FAO (1984) was used to determine the crop coefficient (kc) for maize at different stages of the plant growth.

3.3.7 Determination of maximum storage capacity

To estimate maximum storage capacity the methods suggested by Stanhill (1970) and Hamilton and Rowe (1949) were followed. Both methods use the data on gross and net rainfall collected from the study area during the measurement of rainfall interception.

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion with particular attention to the two specific objectives. The first part deals with measured rainfall interception. Then meteorological variables for the period from December 1993 to March 1994 are presented. The results of crop evapotranspiration, leaf area index, stemflow, throughfall and the estimated maximum storage capacity are discussed. Rainfall interception is presented in the form of graphs and relationships. The second part deals with model evaluation to see whether the selected models agree with the collected data. Expected interception loss from each of the four models was calculated. The results were then plotted against the observed interception loss and a 45 degrees angle straight line was fitted on the graph to see if at all there was an equal distribution of points on both sides of the line. A further evaluation of the models was done by using a T-test and the results are as presented.

4.2. Climatic variables

The temperatures for the period from December 1993 to March 1994 were slightly warmer than the mean averages of the period from 1941 to 1966 presented by Van Beek (1986). Sunshine hours were between 6.2 and 7.2 hours/day. These were also slightly higher than the averages presented by the Meteorological Department in 1971.The windspeed averaged 134.5 km/day. Unfortunately the southern part of the country which includes Lusaka region showed drought tendencies. During the time of data collection there were 33 rainfall events. A frequency distribution analysis of the 33 rainfall events was done by grouping the data into 1 mm intervals. The results of this frequency analysis is shown in Fig 4.3. For most of the days rainfall amounts were never above 9 mm. It is surprising to note that a monthly total of only 5.9 mm was recorded in March. Under normal circumstances March experiences a monthly total of around 88 mm. The rainfall amounts were below the normal averages presented by the Meteorological Department. These changes in the climatic variables could mostly be attributed to drought situation experienced in the southern part of the country. Table 4.1 shows monthly averages of temperature, sunshine hours, windspeed and rainfall. However, daily values are indicated in appendices 2 to 5. Graphical representations of temperature and rainfall are as shown on Fig.4.1 and Fig.4.2 respectively.

4.3 Crop evapotranspiration

The calculated crop evapotranspiration (ETmaize) is related to the reference crop evapotranspiration (ETo) which was calculated based on the data as obtained from the University of Zambia meteorological station. Data from the University of Zambia meteorological station was supposed to be recorded on a daily basis but in some cases the data was incomplete. Weekend values and values on some other few occasional days were missing. The ETo values that were of particular importance were those obtained for the days that had rainfall. If on a particular rainy day there was no corresponding ETo value , then the recorded variables used to calculate ETo appearing on the two days: one before and the other after the day of interest, were averaged and the resulting variables were used to calculate ETo. Average ETo increased progressively from an average of 3.79 mm/day in December, 4.78 mm/day in January, 4.82 mm/day in February to 5.48 mm/day in March. The ETo values based on the data from the University of Zambia are as shown in appendix 7, 8 and 9.

The crop evapotranspiration (ETmaize) values in appendix 11 were obtained from the ETo values using equation 13.

The kc (crop coefficient) values were obtained by following the procedure described by FAO (1984). Procedures for selection of kc values take into account the crop characteristics, time of planting or sowing, stages of crop development and general climatic conditions. Therefore, in order to come up with the crop coefficient curve presented on Fig. 4.4, the ETo at the initial stage of planting and the average recurrence interval of significant rain were considered. Then the growing season was subdivided into four stages, namely, initial stage, crop development stage, mid season stage and late stage. Windspeed and humidity were other factors that were considered. The available tables and figures were then referred to in order to select the kc initial, kc midseason and kc end of season. From Fig. 4.4 it can be seen that the initial kc was 0.4, the kc for mid season was 1.05 and the kc at the end of season was 0.5.

Table 4.1 Meteorological parameters expressed as monthly averages.

Month	Temperature max	°C min	mean	Windspeed km/day	Sunshine hours/d	Rainfall mm
December	28.3	18.2	23.2	134.6	6.5	72.3
January	27.0	18.2	22.6	136.0	6.2	128.7
February	27.5	18.1	22.8	129.5	7.0	89.5
March	29.7	18.7	24.2	138.0	7.2	5.9

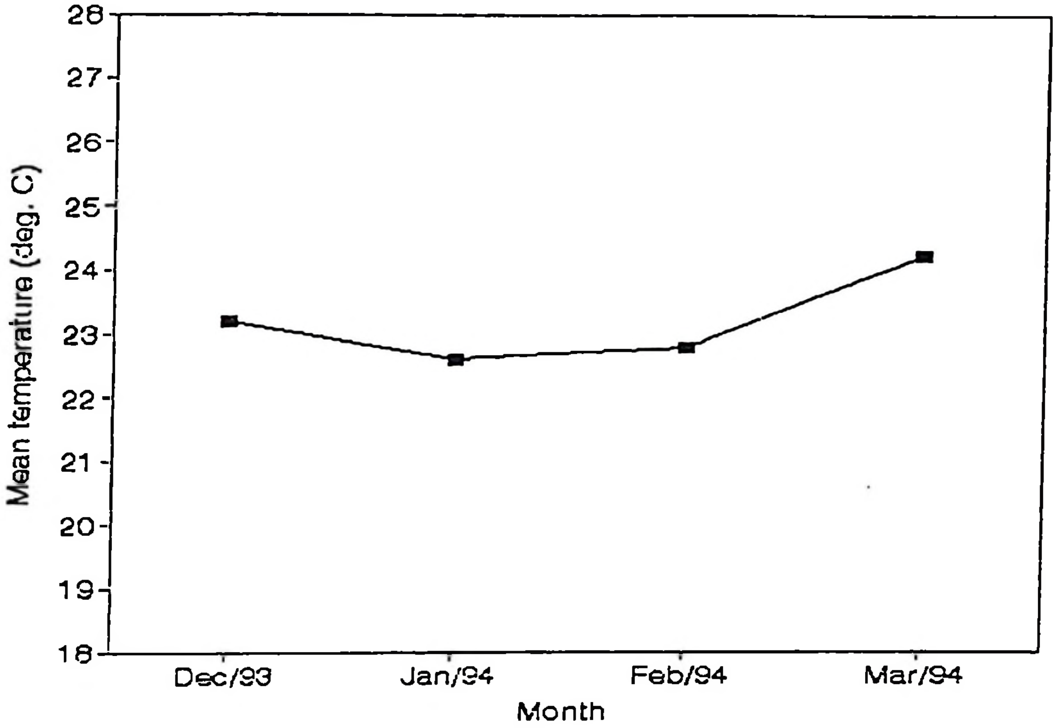


Figure 4.1: Mean temperature values for December, January, February and March.

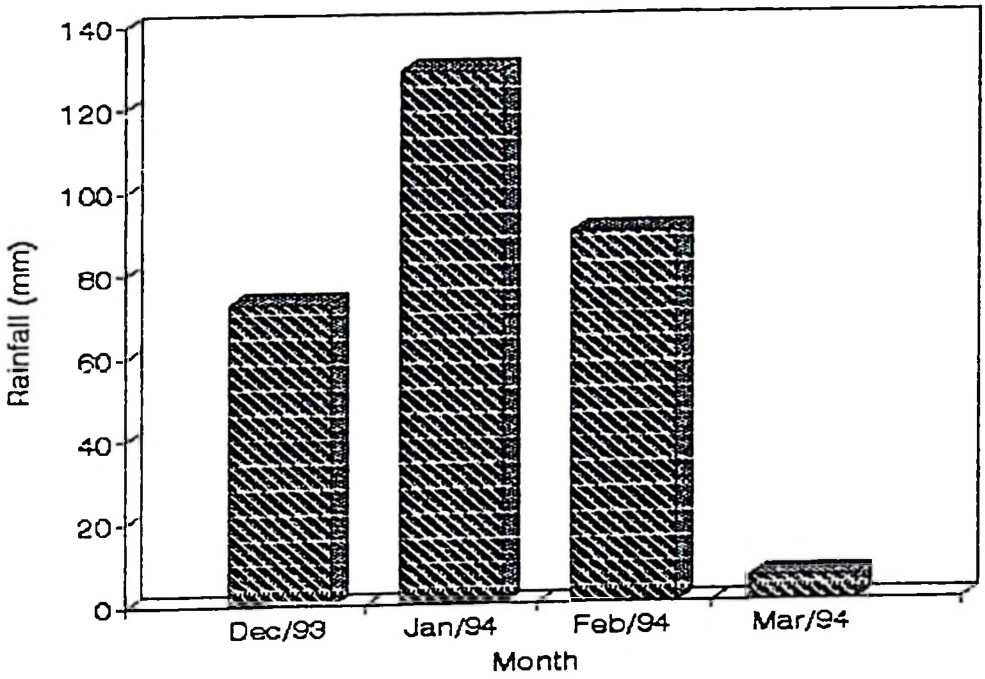


Figure 4.2: Monthly totals of rainfall for December, January, February and March.

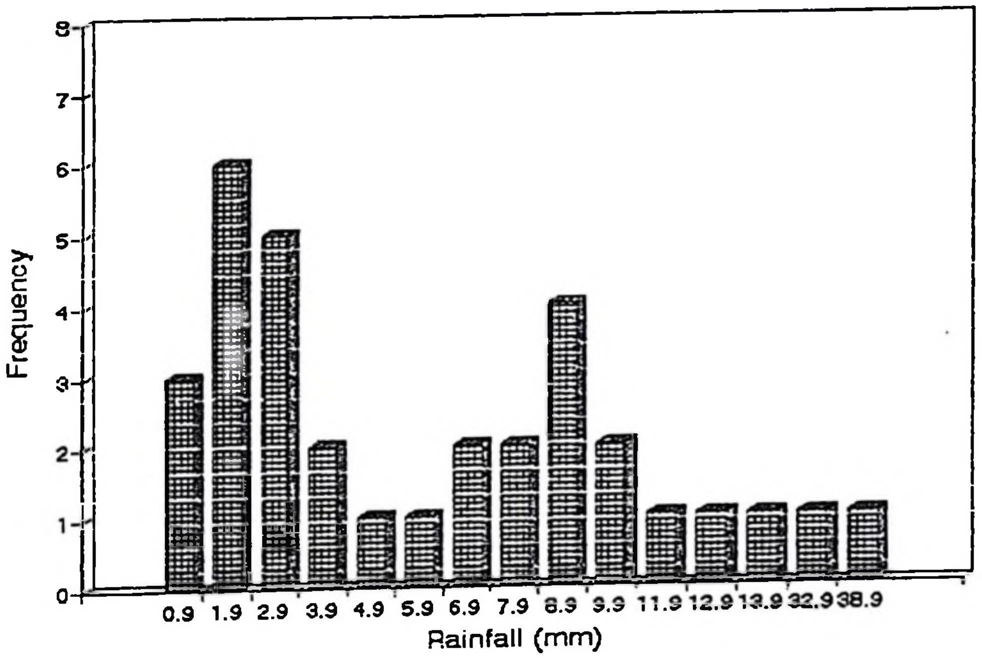


Figure 4.3: Frequency distribution of the 33 rainfall events

4.4 Leaf area index (LAI)

The leaf area index was 1.5 when the first measurements were taken at 30 cm height of the maize plant. The foliage cover at this time was around 38%. As can be seen from appendix 9 the leaf area index increased as the maize height and foliage cover increased. Fig. 4.5 shows the relationship between LAI and foliage cover. At maximum LAI the foliage cover was around 78% and the maize plant had reached an average height of 2.3 m. The maximum LAI was 3.1. After this stage the leaves were mature enough and did not bring about any further increase in foliage cover. Thus when measurements were done on 13th March 1994 foliage cover had reduced to 70% and the LAI was 2.3. The trend in the values of both leaf area index and foliage cover show similarity to those of corn measured by Haynes (1940).

4.5 Throughfall and stemflow

To show whether the collected data on throughfall and stemflow were statistically relevant and related to the 33 recorded events of gross rainfall, a regression analysis of the mean values was done. Both mean values of stemflow and throughfall were regressed on gross rainfall. Table 4.2 and

Table 4.3 show the details of the regression analysis. Both results show a high coefficient of determination, R-squared, of 89% and 99%, respectively. Therefore the mean values of both stemflow and throughfall were very highly correlated to rainfall.

Table 4.2: **Regression analysis showing the relationship betwwen stemflow (S) and gross rainfall (P).**

Fitted equation : $S = 0.0959 + 0.1609 * P$

Std. error of slope : 0.0099

R-squared : 0.8949

Table 4.3: **Regression analysis showing the relationship between throughfall (T) and gross rainfall (P).**

Fitted equation : $T = -0.5692 + 0.8119 * P$

Std. error of slope : 0.0124

R-squared : 0.9928

In appendix 11 throughfall is abbreviated as 'T' and it is in mm. The values shown are the mean values for each rainfall event. Stemflow is abbreviated as 'S' in appendix 11. A rainfall event of 0.2mm did not bring about any stemflow. Stemflow values were converted to equivalent cm by dividing the volumetric measurement of stemflow (which was measured in cm^3) by the basal area of the maize plant and the divident was subsquently converted from cm to mm. Table 4.4 reveals that throughfall for the entire period was 163.5 mm representig 73% of the total rainfall. Stemflow was 39.1 mm representing 17.4% of the total rainfall. The throughfall values are within the range of those measured by Haynes (1940) on corn where interception loss resulting from throughfall (excluding stemflow) accounted for 29% of total rainfall. Stemflow from measurements conducted by Haynes (1940) accounted for 23% of the total rainfall and do not differ much from the measured 17.4% for the maize crop. However interception studies on forests show little or no stemflow at all (Rutter et al.,1971; Willis et al.,1975; Gash and Stewart, 1977 and Roberts et al.,1982). This difference is expected because the branches of forest trees are widely spreading and their barks are scally thereby absorbing most of the stemflow. The leaves of the maize plant are smooth and broad, and descend steeply towards the stem joint. They are therefore more suited to tapping rainfall and transporting it as stemflow. Most of the interception loss in forests result from the difference between throughfall and gross rainfall. Rakhmanov (1962) revealed that broad leaved forests intercept about 15-25% of the annual rainfall. The value of 17.4% for maize (interception excluding stemflow) lies within this range. The data presented by Baver (1956) show that 23% of rainfall was intercepted by corn.

Table 4.4: Summary of interception values for the months of January, February and March.

Month	P(mm)	S(mm)	T(mm)	T+S (mm)	P-T	P-(T+S) (mm)	%INTCEP
January	128.7	19.7	96.7	116.4	32.0	12.3	9.6%
February	89.5	18.9	62.1	81.0	27.4	8.5	9.5%
March	5.9	0.5	3.8	4.3	2.1	1.6	27.0%
Total	224.1	39.1	163.5	201.7	61.5	22.4	
Percent		17.4%	73%	90%	27.4%	10%	

Since stemflow values were not measured in Baver's experiment,the value is close to the 17.4% measured from the maize plant when stemflow is excluded. Stemflow in veld grass measured by Beard (1962) accounted for 40% of the incident rainfall. This is too large and the difference in the canopy structure of veld grass could probably account for the difference.

4.6 Rainfall interception loss

It is important to note that interception loss refers to the difference between gross rainfall (P) and net rainfall, throughfall plus stemflow (T+S). Appendix 11 and appendix 12 provide results of interception loss both in terms of mm and as a percentage of total precipitation for the 33 rainfall events. The results show that percent interception ranged from as low as 3% to as high as 100%. Table 4.4 is a summary for the three months. For the 33 rainfall events total rainfall (P) was 224.1 mm. Total interception loss for the period, P-(T+S), amounted to 22.4 mm representing 10% of total rainfall. However, interception without stemflow (P-T) accounted for as much as 27.4% for the whole period. This, therefore means that stemflow (S) alone accounted for 17.4% of the total rainfall.The amount of water which flowed down the stem was considerably large. The various relationships concerning the process of interception are discussed below.

4.6.1 Interception loss and gross precipitation

To make a better comparison, interception loss (INTCEP) was regressed on gross rainfall (P). The details of the fitted equation are on appendix 14. The fitted equation is then plotted and the fitted line is shown on Fig.4.6. The coefficient of determination R-squared on appendix 13 was about 47% and therefore a straight line is probably not the best way of presenting these results. An exponential curve on Fig.4.7 shows a meaningful outlook. Interception loss increased exponentially but gradually diminished such that any further increases in rainfall brought about little or no further interception loss at all. The exponential increase of interception loss as gross rainfall increases was also reported by Linsley et al. (1949), Merriam (1960) and Seppanen (1964). When interception loss is expressed as a percentage the opposite happens. Percent interception loss decreased exponentially when rainfall increased but only gradually such that further increases in rainfall did not result in a further decrease in percent interception loss. This relationship is illustrated on Fig.4.8. However, when log values of percent interception loss are plotted against log values of gross rainfall the results showed a straight line as a line of best fit (Fig. 4.9). The exponential decrease of percent interception loss was also reported by Calder and Newson (1979) when they analysed results obtained from the experiments of Law (1956), Rutter (1963), Leyton et al. (1967), Gash and Stewart (1977) and Courtney (1978). Table 4.4 shows that the average interception loss for the season was about 10% of gross precipitation. The seasonal interception loss of about 10% of gross rainfall is close to the results for corn of 7% shown by Haynes (1940). However,this result of 10% interception loss differs from the interception loss values measured from forest canopies which range from 15% to as much as above 40% (Rakhmanov, 1962; Bringfelt and Harsmar, 1974; Miller et al., 1976; Gash and Stewart, 1977; Calder and Newson, 1979 and Roberts et al., 1982). This difference could be attributed to the magnitude of stemflow which has been shown to be of considerably high magnitude on a maize plant resulting in low interception values. Rainfall of less than 1.5 mm were almost totally intercepted. But for rainfall of more than 1.5 mm, less than 31% was intercepted. Infact rainfall of more than 5 mm only 5-9% of the incident rainfall was intercepted. Results from forest interception studies report values of 2 to 5 mm of rainfall to be almost completely intercepted (Delfs, 1965). Since stemflow measurements were reported from rainfall of more than 0.76 mm (Willis et al., 1975) and yet most of it could be absorbed by the bark of the tree, it is possible to completely intercept 2-5 mm of rainfall in forest canopies. But stemflow is a significant component in the maize interception process and this could probably account for the big difference.

4.6.2 Interception loss and leaf area index (LAI)

As the maize plant grew it increased both in girth and height. The size and length of the leaves also increased. To show the effect of LAI on interception loss it was logical to consider rainfall amounts of about the same magnitude received on different days corresponding to different LAI. Therefore rainfall of between 7 and 9 mm (any rainfall amount with high frequency could have been chosen) were regressed on leaf area index. Details of the fitted line are shown in appendix 14. The relationship is illustrated on Fig.4.10. Interception loss increased as leaf area index increased. This relationship was explained by Leonard (1965) that the interception loss which is related to canopy storage capacity is dependent on leaf area index. Hutchinson and Roberts

(1981) demonstrated this relationship by showing that branch storage capacity increases as the branch interception area increases.

4.6.3 Stemflow and leaf area index

The water referred to as stemflow came from the rainfall that was intercepted mainly by the leaves of the maize plant (to a lesser extent the stem also intercepts some rain). Rainfall was intercepted by the leaves, flowed down the leaf after the leaf had attained its maximum storage capacity, up to the stem leaf joint, then it flowed down the maize stem to be referred to as stemflow. To show the effect of leaf area index on stemflow rainfall of about the same magnitude were taken. In this particular case stemflow values resulting from rainfall amounts of between 7 and 9 mm were regressed on leaf area index. Details of the fitted line are presented in appendix 14 and the relationship is illustrated in Fig.4.13. As leaf area index increased stemflow also increased. Hutchinson and Roberts (1981) have also shown that branch storage capacity increases as the branch interception area increases. Since stemflow on a maize plant mainly originates from the water falling on the leaves, it is equally expected that stemflow has to increase as leaf area index increases.

This is as shown on Fig. 4.14.

4.6.4 Throughfall and leaf area index

When rainfall was falling part of it was intercepted by the leaves of the maize plant. One component of the intercepted rainfall flowed down the stem to become stemflow and the other dropped off the leaves to become part of throughfall. The other component of throughfall is one whereby the rainfall is not intercepted at all until it reaches the ground surface. As the maize plant grew the leaves also grew in size and the interception area grew because the leaf area index had increased. Throughfall amounts resulting from gross rainfall of between 8 and 9 mm were regressed on canopy density and details of the fitted line are presented in appendix 16. The relationship of throughfall and leaf area index is illustrated on Fig.4.12. There is an inverse relationship. Throughfall decreased as leaf area index increased. As explained above concerning the experiment by Hutchinson and Roberts (1981), an increase in branch interception area leads to an increase in foliage cover. When foliage cover increases it means that there is little room left for throughfall and consequently throughfall decreases as canopy density increases.

4.6.5 Maximum storage capacity

The maximum storage capacity or canopy saturation value (C) was obtained by regressing net rainfall (T+S) on gross rainfall (P). The details of the fitted line are shown in Appendix 16. There was a very high correlation (99%) of net precipitation to gross rainfall amounts with a standard error of about 0.5%. When net rainfall was plotted against gross rainfall the resulting point of intercept on the x-axis was the canopy saturation value (C). This is shown on Fig.4.11. The canopy saturation value was therefore found to be 0.5 mm. Hamilton and Rowe (1949) used this procedure in their experiments and gave a range of values considered to be reasonable canopy saturation values. They gave a range of 0.25-9.14 mm. The value of 0.5 mm as canopy saturation value for maize falls within this range.

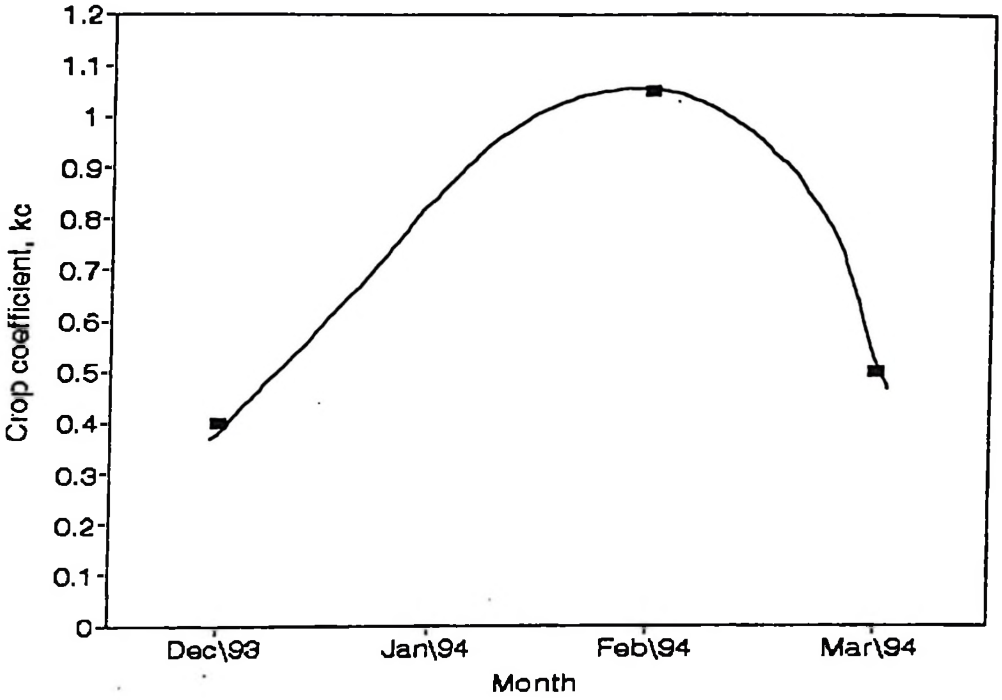


Figure 4.4 Crop coefficient curve for the maize crop

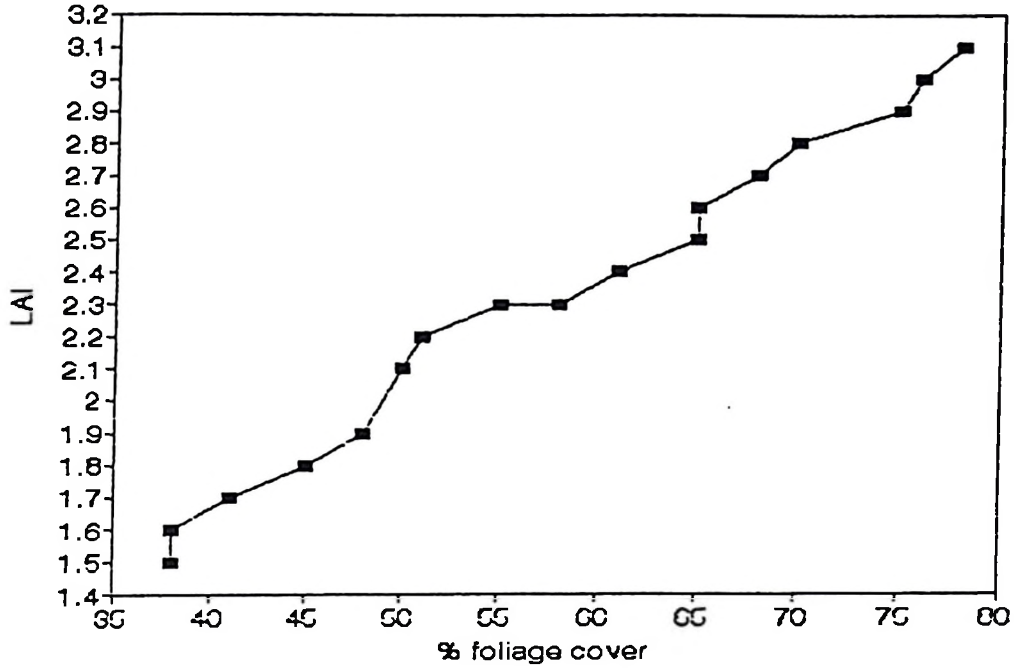
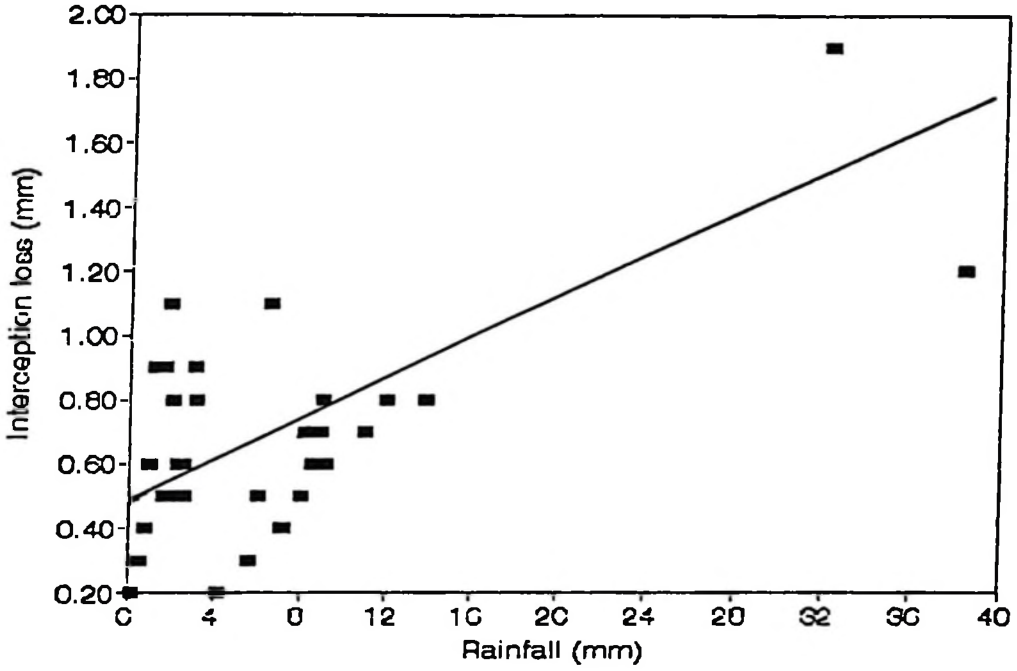
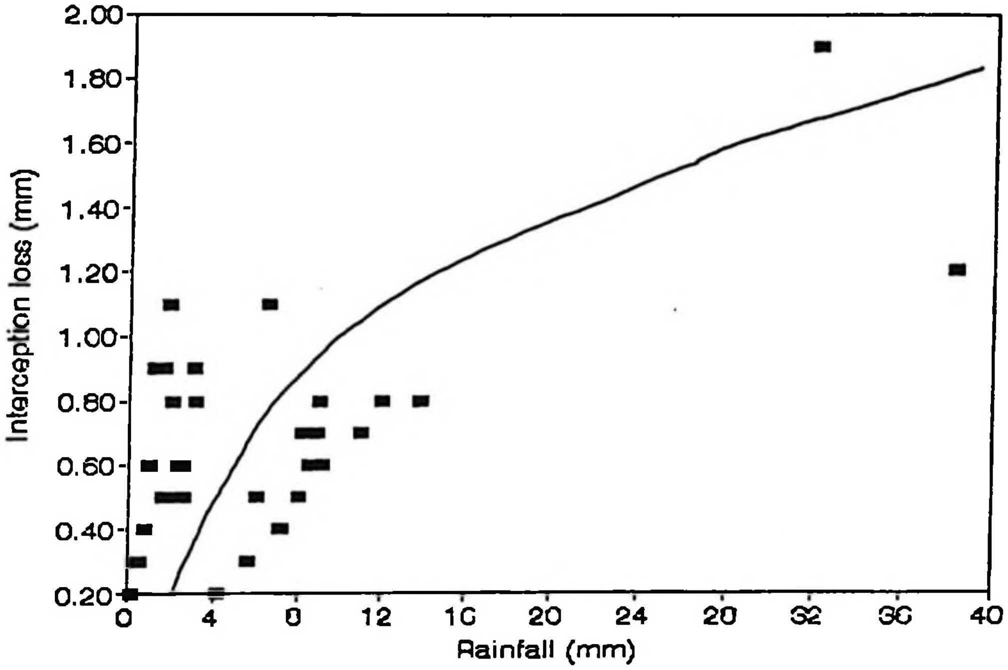


Figure 4.5 Relationship between foliage cover and leaf area index



Key: ■ Data points ——— Line of regression

Figure 4.6: Relationship between interception loss and gross rainfall



Key: ■ Data points ———fitted curve

Figure 4.7 Relationship between interception loss and gross rainfall.

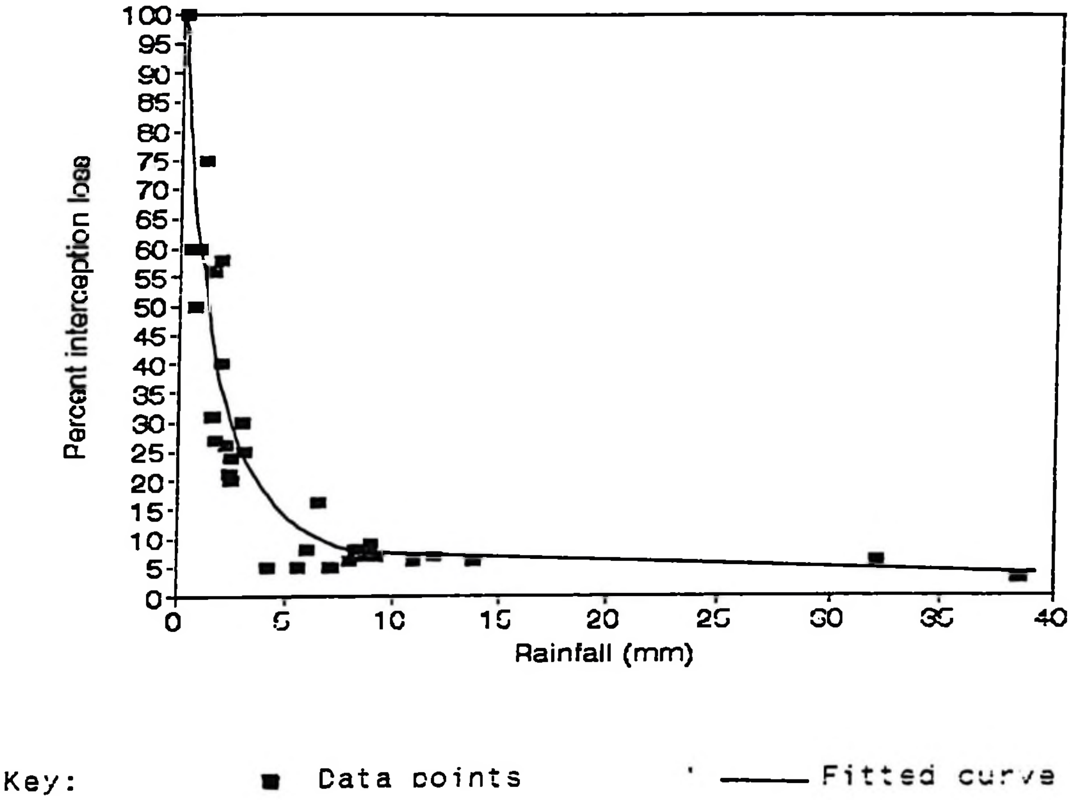
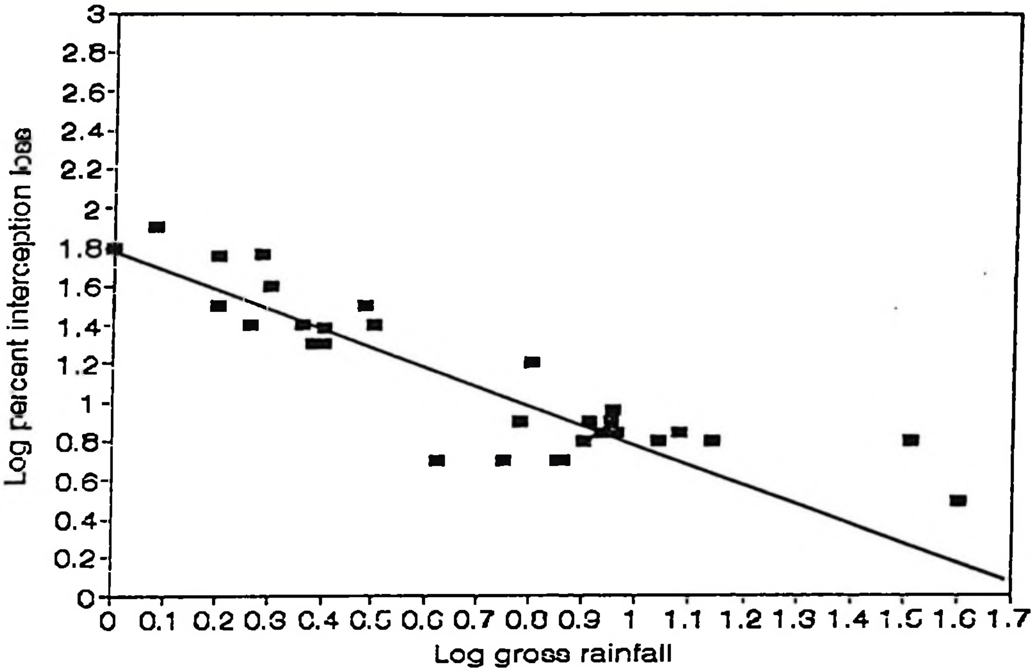
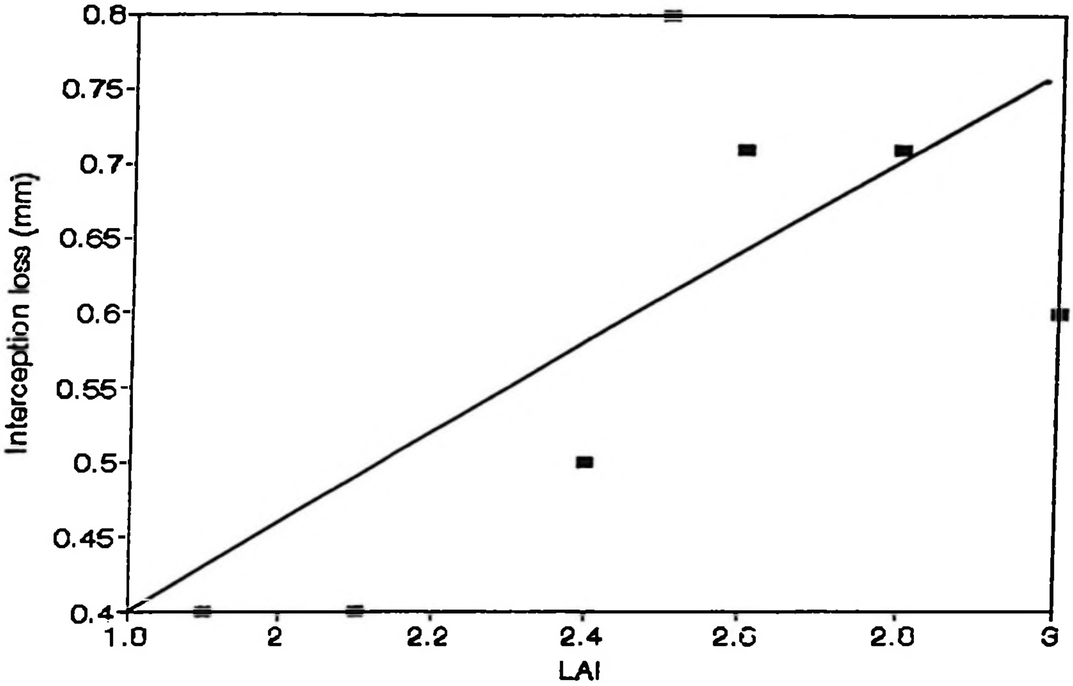


Figure 4.8 Relationship between percent interception loss and gross rainfall.



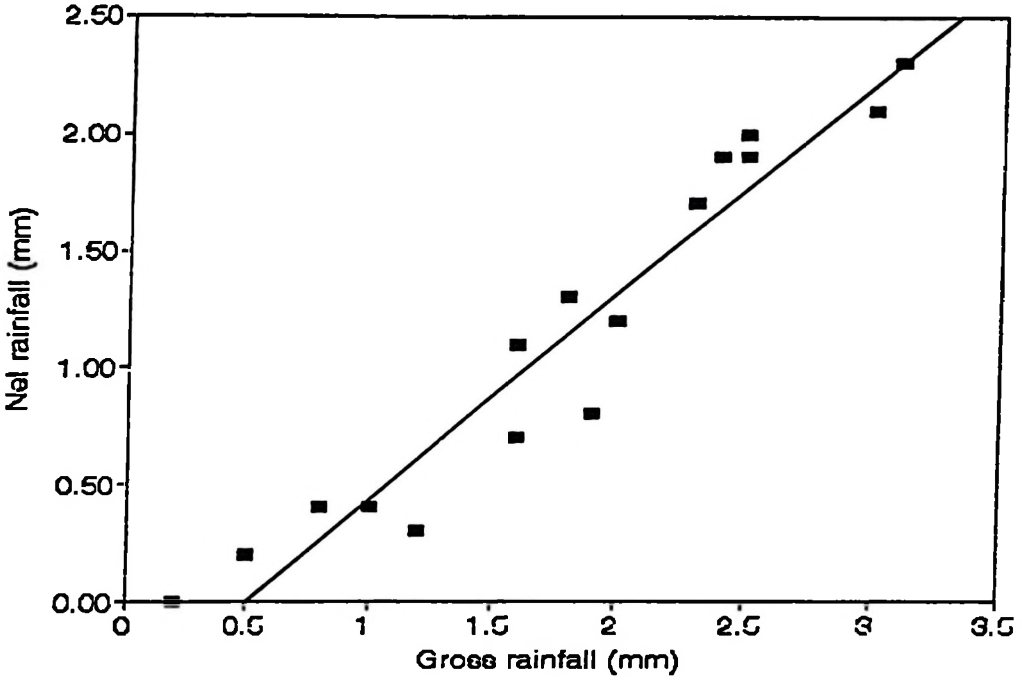
Key: ■ Data points ——— Regression line

Figure 4.9 Relationship between log values of percent interception loss and log values of gross rainfall



Key: ■ Data points ——— Regression line

Figure 4.10 Variation of interception loss with leaf area index



Key: ■ Data points ————Regression line

Figure 4.11 Relationship between net rainfall and gross rainfall showing canopy saturation value as the intercept on the x-axis (0.5mm).

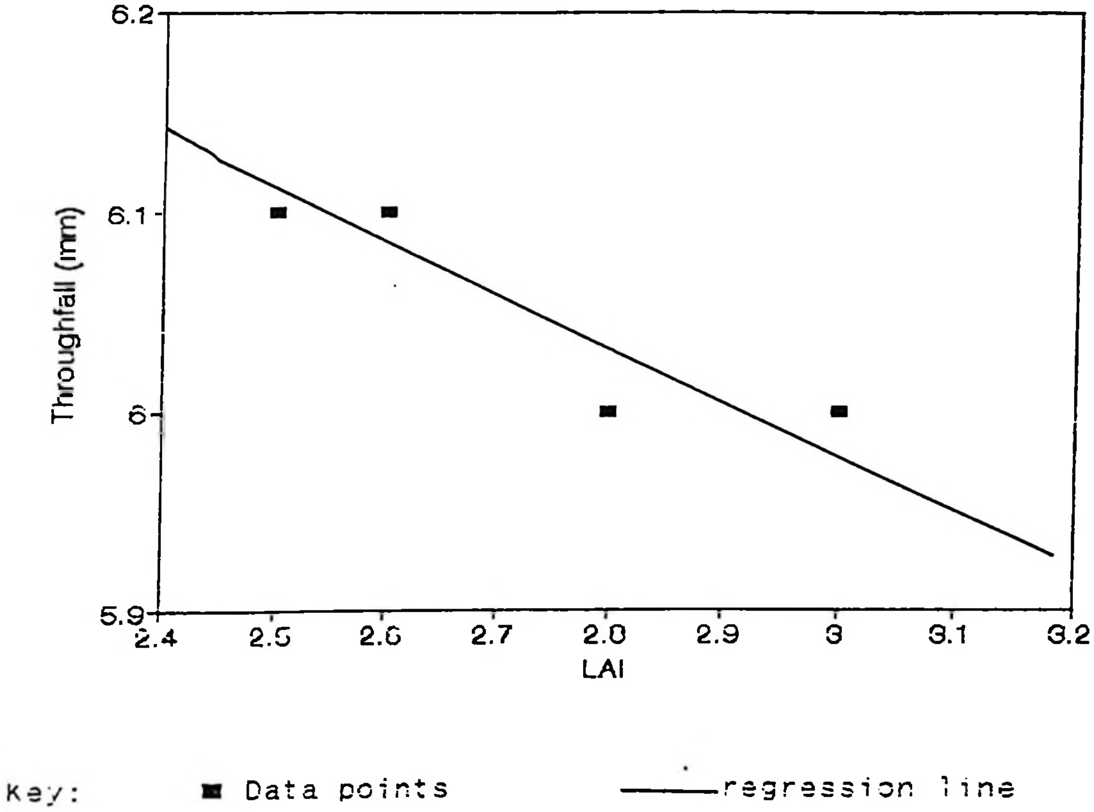
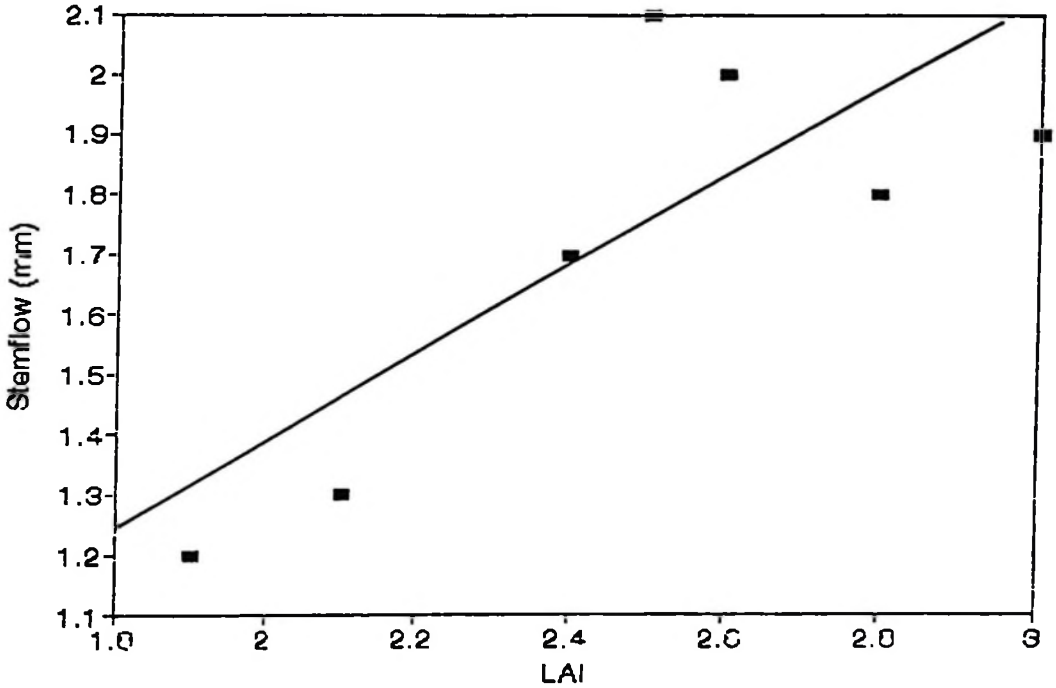


Figure 4.12 Relationship between throughfall and leaf area index



Key: ■ Data points ———Regression line

Figure 4.13 Relationship between stemflow and leaf area index.

4.7 Model evaluation and validation

The models that were evaluated are models (5), (6), (9) and (10) and they are now presented in the following order as:

Model 1: $INTCEP = C + LAI * Ea * t$

Model 2: $INTCEP = C * (1 - EXP[-P/C]) + LAI * Ea * t$

Model 3: $INTCEP = a + b * P$

Model 4: $INTCEP = 0.03 * DAYS * P/(0.5 * P + 1.5)$

To evaluate the models, interception predicted by each model were calculated using the measured parameters (eg C, LAI, ETcrop for Ea, P, DAYS and t). The sample size in each case is 33 because there was a total of 33 rainfall events. These interception values are presented in appendix 18. The mean interception values as predicted by each of the four models were calculated. Table 4.5 is a summary of the interception for each of the models. From table 4.5 it can be seen that only model 3 gave the same percent interception (10%) as that of the measured one. The interception values were analysed by plotting the calculated interception from each model against the observed interception. A line was fitted such that any point along this line gave the same value for either calculated interception or observed interception to see the distribution of points on either side of the line. A T-test was carried out to test the significance of the difference between the means (the mean from the observed data and one from the expected interception loss for each of the four models). The null hypothesis was that there was no significant difference between the means.

The results for model 1 showed that almost all the points were above the fitted line. The model overestimated most of the points (Fig. 4.14). Therefore model 1 does not give a fair representation of the measured interception values. Appendix 19 shows the output of the t-test on the model. The predicted results showed a standard deviation of 73% and the pooled standard deviation was 56.5%. At 95% confidence interval the significance level of the model was 0%. Therefore the model was insignificant for the observed data. According to Leonard, (1965) this model is developed to express interception loss in terms of mm water per unit ground projected area. Table 4.5 shows that the average interception loss from this model is 19%. This value is within the range of what is expected from forest areas. But in most forest interception studies the contribution of stemflow to water captured by the ground projected area is in most cases too little (Kittredge, 1948; Rutter et al., 1971; Willis et al., 1975; Gash and Stewart, 1977 and Roberts et al., 1982). The results, on the contrary, show that stemflow contributed about 17.4% of the 27.4% water captured by the ground projected area under a maize plant (refer to Table 4.4). This probably is the reason why the model is invalid.

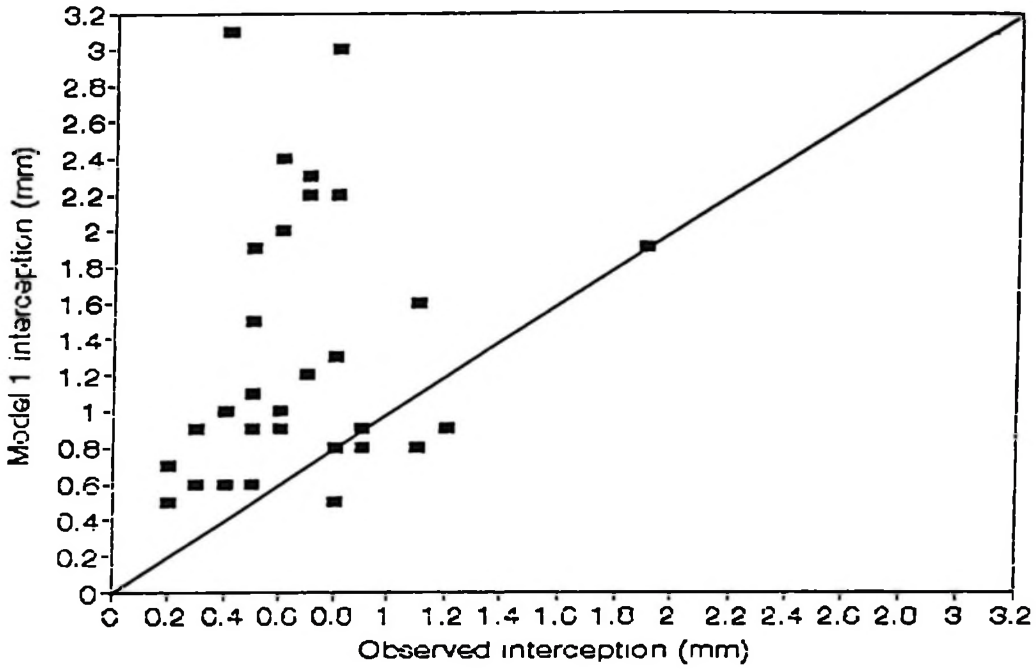
Fig 4.15 shows the distribution of points when the interception values predicted by model 2 were plotted against observed interception values. As for model 1, the observed values did not agree with the predicted ones. The model therefore, does not represent the measured interception values. Appendix 20 shows the results of the t-test on the model. The results on the model are not different from those of model 1. The standard deviation of the expected interception values is 74% and the pooled standard deviation is 57%. At 95% confidence interval the significance level of the model is 0%. Therefore the model is not suitable for prediction. The reason given for the invalidity of model 1 also applies here.

When interception values predicted by model 3 were plotted against observed interception values there was almost an equal number of points on either side of the fitted line (Fig. 4.16). Therefore model 3 fairly represents the measured interception values. This model is an empirical linear regression model and the implicit assumptions in this model were re-examined by Gash (1979). Appendix 21 shows the results of the t-test on the model. The mean standard deviation of predicted interception values was 22%. The pooled standard deviation was 28%. At 95% confidence interval the model was 93% significant. The predicted interception by this model agreed well with the observed data. The data on the interception for maize showed that interception loss and gross rainfall were correlated (see appendix 13). Gash (1979) found that over extended time total interception loss and rainfall are often highly correlated. Gash et al. (1980) used the model and found that the model predictions are insensitive to canopy structure but strongly dependent on daily rainfall. Jarvis et al. (1988) found a similar relationship and recommended the model as useful for applied research.

The interception predicted by model 4 did not agree with the observed data. The distribution of points when predicted and observed interception were plotted showed a concentration of points on one side of the fitted line (Fig 4.17). Appendix 22 shows the output of the t-test on the model. The standard deviation of the interception values was very high (97%). The pooled standard deviation was also high (73%). At 95% confidence interval the significance of the model was 0%. This meant that the model did not agree with this kind of observed data. This model is developed to represent total interception loss as a function of daily rainfall and days after planting meaning interception loss is expected to increase with an increase of the number of days after planting. Indeed this is true even from the observed data but Table 4.5 shows that this model yields an average interception loss of 30%. This value falls within the interception loss range available for some of the studies on agricultural crops (Baver, 1956) which range from 23-50%. In these results (Baver, 1956) stemflow measurements were not done. The water flowing down the stalks of the maize plant was significantly high. It can therefore be argued that the constants in De Jong and Camerons model, (1979) were derived to suit a certain range of interception values suiting most of the agricultural crops where the amount of stemflow is not as large as that of the maize plant.

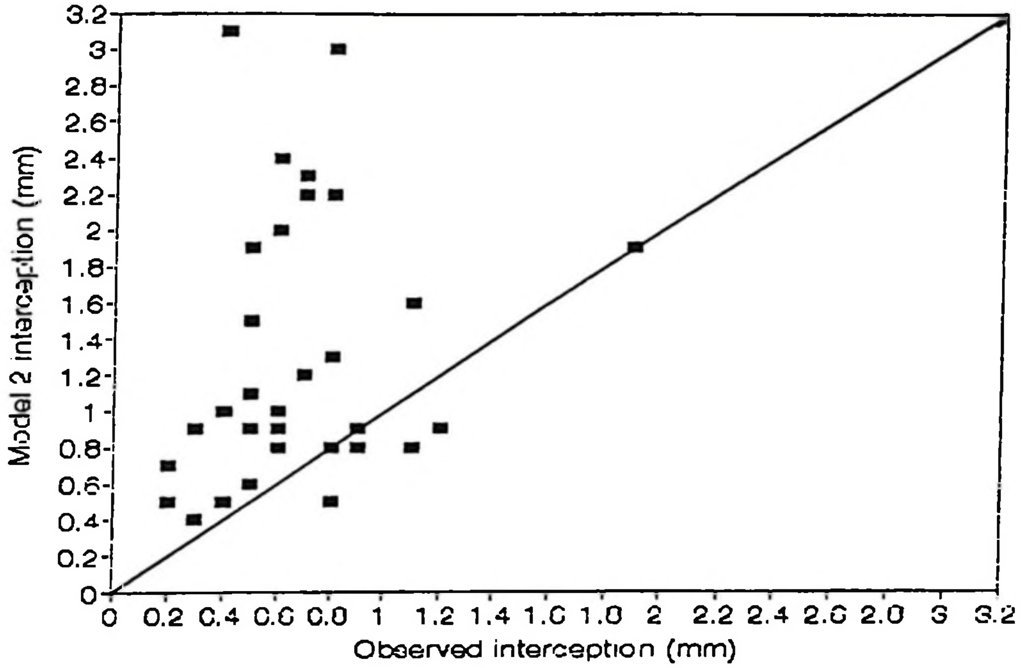
Table 4.5 Summary of the measured and predicted interception for the models.

	Measured (mm)	Model 1 (mm)	Model 2 (mm)	Model 3 (mm)	Model 4 (mm)
Mean	0.66	1.29	1.28	0.65	2.04
Total	21.70	42.50	42.10	21.50	67.20
% INTCEP	10%	19%	19%	10%	30%



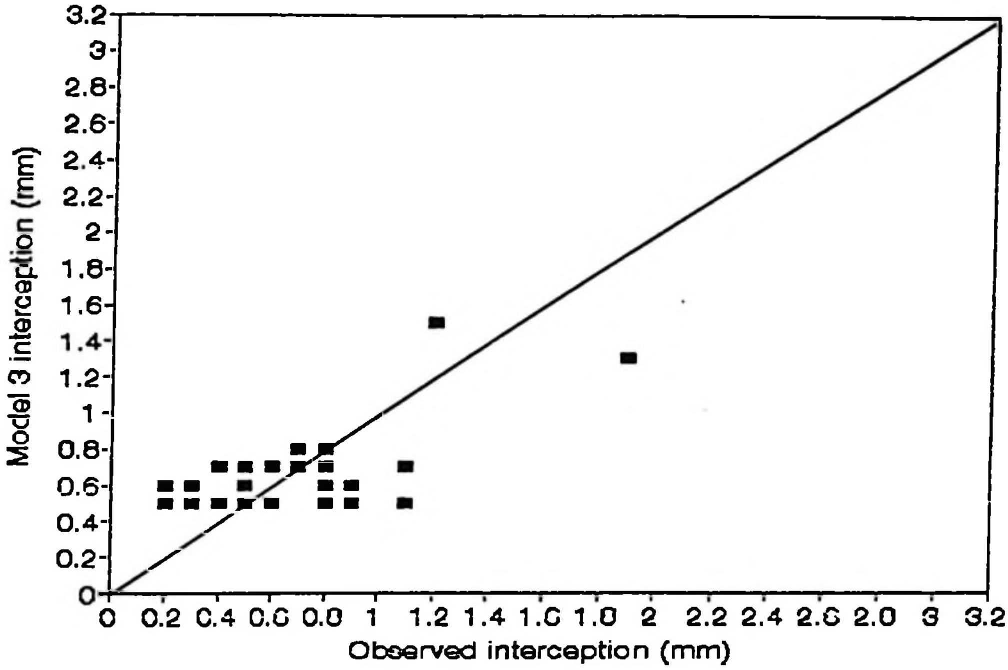
Key: ■ Data points ——— Fitted line

Figure 4.14 Position of the fitted line when model 1 interception values are plotted against observed interception values



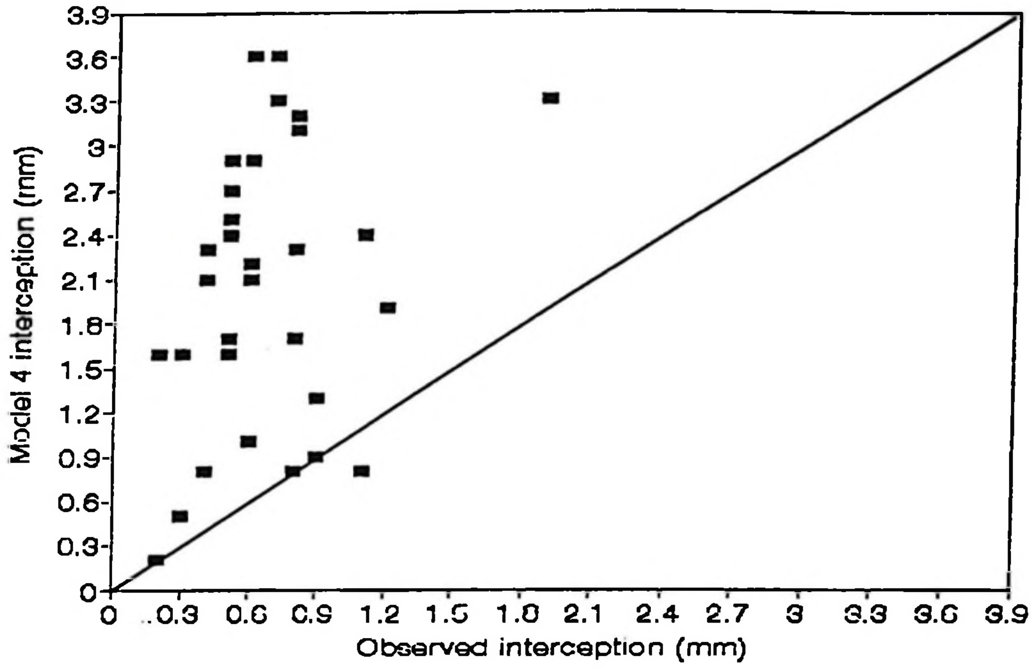
Key: ■ Data points ——— Fitted line

Figure 4.15 Position of the fitted line when model 2 interception values are plotted against observed interception values



Key: ■ Data points ——Fitted line

Figure 4.16 Position of the fitted line when model 3 interception values are plotted against observed interception values



Key: ■ Data points : ———Fitted line

Figure 4.17 Position of the fitted line when model 4 interception values are plotted against observed interception values

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study reveals that the mean temperatures and sunshine hours were slightly higher than normal for the 1993/94 growing season. The rainfall was also below the normal average leading to drought tendancies.

At a maximum LAI of 3.1 the Zambian maize variety mm603 had a foliage cover of about 78% and a height of 2.3 m. There was a high correlation of throughfall and stemflow to gross rainfall. Throughfall accounted for 73% of total rainfall. Throughfall decreased as canopy density increased. Stemflow accounted for about 17.4% of incident rainfall and it increased as canopy density increased. Stemflow was a significant component in the interception process.

About 10% of the gross rainfall was intercepted. The canopy of the maize plant intercepted 27.4% of the gross rainfall but the interception loss was reduced to 10% because a significant amount of the intercepted water flowed down the stem as stemflow. Rainfall of less than 1.5 mm were almost totally intercepted. As rainfall increased percent interception loss decreased.

The maximum storage capacity of the maize plant could be around 0.5 mm.

The models presented by Merriam (1960), Leonard (1965) and De Jong and Cameron (1979) were invalid. They could not be used to define interception loss in a maize plant. The large contribution by stemflow to the interception process, thereby lowering the percent interception loss, was the main reason for the invalidity of the three models. The model adopted by Gash (1979) was valid because it was insensitive to canopy structure and was simply a linear regression of interception loss on gross precipitation.

5.2 Recommendations

In view of the discussion above the following are the recommendations:

(a) Before adopting any of the models developed to represent rainfall interception loss, it is advisable to calibrate the model so that any changes that would suit the given situation can be made.

(b) It is highly recommended that further research be done to develop a model that describes interception in a broader context. This entails that measurable parameters should not only be limited to canopy saturation value, leaf area index and crop evapotranspiration but also leaf surface configuration and branching patterns. These two need a thorough representation because they have a direct influence on stemflow.

(c) It is recommended that further research of interception for crops be carried out.

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7. APPENDICES

Appendix 1: A Summary of Climatic Statistics for Lusaka based on Lusaka City Airport Records for 1941-1966. (After Van Beek, 1986)

Month	Sunshine hours/day	Temperature °C			Windspeed (knots)	Rainfall (mm)
		max	min	mean		
July	8.7	22.7	9.6	16.2	7.7	0
Aug	9.6	25.4	11.7	18.6	8.5	0
Sept	9.7	28.9	14.7	21.8	8.9	1
Oct	8.7	31.2	17.8	24.8	7.6	16
Nov	6.9	28.7	17.8	23.3	5.7	82
Dec	5.5	26.5	17.3	21.9	4.7	194
Jan	5.1	25.8	17.2	21.5	4.1	222
Feb	5.2	25.8	17.1	21.5	3.7	129
Mar	6.9	26.1	16.3	21.2	6.3	88
Apr	8.5	26.3	14.0	20.2	7.2	15
May	9.0	24.6	12.2	18.4	7.1	5
June	8.9	22.8	10.2	16.5	7.8	1
Year	7.7	26.2	14.7	20.5	6.6	803

Appendix 2: Climatic variables for December based on the University of Zambia records for the year 1993 (Geography Department, University of Zambia,1994)

Date	Temperature (° C)				Wind speed km/day	Net radiation mm/day	Sunshine hours/day
	Max	Min	Dry	Wet			
13	30.6	16.4	20.1	19.4	110.4	5.1	7
14	23.0	16.4	22.4	19.0	129.6	4.8	6
15	25.6	15.6	24.1	19.0	168.0	4.6	6
16	29.6	18.4	24.1	19.0	148.8	2.5	6
17	29.4	19.0	26.4	21.0	108.0	4.6	7
18	29.4	18.6	29.4	19.0	122.4	2.5	6
20	30.4	18.0	24.1	20.1	132.0	6.8	7
21	29.0	19.4	24.1	19.4	96.0	2.5	6
22	27.3	19.4	24.1	21.0	165.6	4.6	7
23	28.6	19.4	21.0	19.0	182.4	1.3	7
27	29.4	16.4	26.1	22.0	108.0	4.8	6
28	28.6	19.0	25.1	21.4	153.6	4.2	7
29	26.4	19.6	25.4	21.6	103.2	2.5	6
30	28.6	19.4	26.4	22.0	156.0	5.1	7
Monthly mean	28.3	18.2	24.5	20.2	134.6	4.0	6.5

Appendix 3: Climatic variables for January based on the University of Zambia records for the year 1994 (Geography Department, University of Zambia, 1994)

	Temperature (° C)						
Date	Max	Min	Dry	Wet	Wind speed km/day	Net radiation mm/day	Sunshine hours/day
3	30.6	16.4	29.6	24.0	158.4	1.52	5
4	30.6	19.0	19.6	19.0	184.8	15.36	7
5	26.4	19.4	20.0	10.0	192.0	2.29	7
6	23.0	17.0	19.6	17.0	132.0	4.34	7
7	24.4	16.4	21.0	19.4	98.4	4.06	4
10	28.6	15.0	24.0	20.0	168.0	6.10	6
11	29.4	16.4	23.4	19.0	112.8	4.83	6
12	26.4	17.1	21.6	19.0	124.8	7.92	7
13	27.0	19.4	26.4	21.4	146.4	2.92	4
14	29.0	17.0	21.0	19.0	124.8	5.08	8
17	21.0	19.4	21.4	19.0	151.2	3.76	7
18	24.6	19.3	22.4	20.0	105.6	4.06	6
19	27.0	16.9	24.1	21.4	129.6	1.52	6
20	27.6	19.4	22.0	20.0	122.4	4.06	6
21	27.6	19.0	24.1	21.0	139.2	6.10	7
24	28.6	19.4	22.6	19.4	105.6	8.50	5
25	26.4	19.4	25.3	21.0	110.4	3.81	6
26	26.4	19.0	21.0	19.0	136.8	3.56	7
27	26.4	19.0	21.6	18.6	124.8	11.46	5
28	26.4	19.4	20.4	19.0	146.4	1.52	7
30	27.6	19.4	22.6	20.0	141.6	2.57	7
Monthly mean	27.0	18.2	22.6	19.3	136.0	4.99	6.2

Appendix 4: Climatic variables for February based on the University of Zambia records for the year 1994 (Geography Department, University of Zambia, 1994)

	Temperature (° C)						
Date	Max	Min	Dry	Wet	Wind speed km/day	Net radiation mm/day	Sunshine hours/day
1	26.4	19.4	24.3	21.0	158.4	6.10	6
2	27.3	19.4	22.0	20.5	127.2	4.58	6
3	27.1	19.4	22.0	20.6	129.6	4.06	8
4	26.4	16.4	23.0	20.0	144.0	7.50	8
7	28.6	19.0	21.4	19.0	132.0	6.10	7
8	27.0	19.4	20.0	16.4	156.0	2.94	8
9	27.0	18.0	21.0	20.0	146.4	3.56	7
10	24.6	19.3	24.1	20.3	153.6	2.50	6
11	26.4	18.4	21.4	19.0	194.4	5.08	7
14	27.0	15.0	24.1	21.0	115.2	12.49	7
15	25.4	19.0	25.0	23.0	115.2	5.09	5
16	29.6	16.4	24.1	21.0	105.6	6.17	6
17	29.6	18.0	24.1	20.4	84.0	4.57	7
18	28.6	16.4	25.0	21.0	98.4	4.66	6
21	29.4	18.4	23.4	19.0	100.8	7.57	7
22	29.4	19.0	21.4	19.0	177.6	4.06	8
23	26.0	19.2	17.0	17.0	76.8	4.32	8
28	27.6	15.0	22.6	19.4	115.2	3.78	4
Monthly mean	27.5	18.1	22.5	19.9	129.5	5.3	7

Appendix 5: Climatic variables for March based on the University of Zambia records for the year 1994 (geography Department, University of Zambia, 1994

Date	Temperature (° C)				Wind speed km/day	Net radition mm/day	Sunshine hours/day
	Max	Min	Dry	Wet			
1	26.4	16.0	24.3	19.6	129.6	9.14	6
2	27.6	19.4	24.1	19.0	158.4	6.10	7
3	27.0	19.4	24.0	18.0	103.2	2.54	7
4	27.6	19.4	24.0	21.0	105.6	4.57	8
7	26.1	16.4	23.6	18.4	112.8	9.14	6
8	29.4	15.6	25.4	19.0	168.0	4.57	7
9	30.6	16.4	27.0	20.1	122.4	2.54	8
10	30.5	17.0	24.5	19.0	160.8	5.08	6
11	31.0	16.4	27.0	21.0	184.8	6.10	8
14	30.6	16.4	26.4	21.0	151.2	2.54	7
15	31.6	18.6	26.1	20.4	110.4	6.10	8
16	30.0	19.4	20.1	18.6	112.8	4.57	7
17	30.6	17.6	21.4	19.0	148.8	2.54	7
18	30.1	19.4	24.1	19.0	153.6	6.10	8
28	34.4	24.0	26.4	19.0	127.2	5.08	6
29	33.0	26.4	21.0	16.4	148.8	5.08	8
30	29.4	19.0	25.4	19.0	136.8	6.60	7
31	29.4	19.0	24.1	19.0	148.8	6.10	8
Monthly mean	29.7	18.7	24.4	19.2	138	5.2	7.2

Appendix 6: ETo values for DEC 1993 based on data from the University o Zambia Meteorological station, Lusaka,1994

Date	C	W	Rn (mm)	(1- W)	f(U)	(ea-ed)	ETo(mm)
13	0.94	0.74	5.1	0.26	0.57	6.7	4.48
14	0.94	0.73	4.8	0.27	0.62	3.2	3.80
15	0.94	0.72	4.6	0.28	0.72	5.1	4.08
16	0.91	0.73	2.5	0.25	0.67	10.7	3.34
17	0.94	0.75	4.6	0.25	0.56	8.1	4.31
18	0.91	0.75	2.5	0.25	0.60	10.6	3.15
20	0.99	0.75	6.8	0.25	0.63	8.9	6.44
21	0.91	0.75	2.5	0.25	0.53	11.1	3.04
22	0.94	0.74	4.6	0.26	0.72	5.5	4.17
23	0.88	0.75	1.3	0.25	0.76	8.9	2.35
27	0.94	0.74	4.8	0.26	0.56	4.0	3.89
28	0.93	0.75	4.2	0.25	0.68	3.8	3.53
29	0.91	0.74	2.5	0.26	0.55	5.5	2.40
30	0.94	0.75	5.1	0.25	0.69	2.6	4.02
mean							3.79

Appendix 7: ETo values for January, 1994 based on data from the University of Zambia Meteorological Station, Lusaka, 1994

Date	C	W	Rn(mm)	(1- W)	f(U)	(ea- ed)	ETo(mm)
3	0.94	0.74	1.52	0.26	0.70	4.4	1.81
4	1.05	0.76	15.36	0.24	0.77	9.4	14.08
5	0.94	0.74	2.29	0.26	0.79	21.4	5.72
6	0.95	0.71	4.34	0.29	0.63	5	3.23
7	0.95	0.71	4.06	0.29	0.54	2.2	3.07
10	1.00	0.73	6.10	0.27	0.72	5	5.43
11	0.94	0.74	4.83	0.26	0.57	11.9	5.02
12	0.99	0.73	7.92	0.27	0.61	4.9	6.52
13	0.92	0.71	2.92	0.29	0.67	6.0	2.98
14	0.98	0.74	5.08	0.26	0.61	7.5	4.85
17	0.92	0.71	3.76	0.29	0.68	2.7	2.95
18	0.96	0.73	4.06	0.27	0.56	4.0	3.43
19	0.95	0.73	1.52	0.27	0.62	3.7	1.64
20	0.97	0.74	4.06	0.26	0.60	6.7	3.93
21	1.01	0.74	6.10	0.26	0.65	5.5	5.43
24	1.04	0.75	8.50	0.25	0.36	9.2	7.97
25	0.95	0.74	3.81	0.26	0.57	5.4	3.44
26	0.95	0.74	3.56	0.26	0.64	5.8	3.42
27	1.05	0.74	11.46	0.26	0.61	6.2	9.94
28	0.94	0.74	1.52	0.26	0.67	7.0	2.20
30	0.94	0.75	2.57	0.25	0.65	9.2	3.22
mean							4.78

Appendix 8: ETo values for FEB 1994 based on data from the University of Zambia Meteorological Station, Lusaka, 1994

Date	C	W	Rn(mm)	(1-W)	(fu)	(ea-ed)	ETo(mm)
1	0.99	0.74	6.10	0.26	0.70	5.8	5.51
2	0.95	0.74	4.58	0.26	0.61	7.1	4.29
3	0.94	0.74	4.06	0.26	0.62	6.6	3.82
4	1.02	0.72	7.50	0.28	0.66	3.4	6.79
7	0.99	0.75	6.10	0.25	0.63	8.0	5.78
8	0.93	0.74	2.94	0.26	0.69	11.3	3.91
9	0.95	0.73	3.56	0.27	0.66	5.1	3.33
10	0.93	0.73	2.50.	0.27	0.68	5.3	2.60
11	0.99	0.74	5.08	0.26	0.79	6.2	4.98
14	1.05	0.72	12.49	0.28	0.58	3.8	10.09
15	0.98	0.74	5.09	0.26	0.58	0.8	3.85
16	1.02	0.74	6.17	0.26	0.56	2.6	5.04
17	0.97	0.75	4.57	0.25	0.50	4.4	3.86
18	0.98	0.74	4.66	0.26	0.54	4.6	4.03
21	1.02	0.75	7.57	0.25	0.54	9.5	7.10
22	0.95	0.75	4.06	0.25	0.75	9.1	4.51
23	0.97	0.73	4.32	0.27	0.48	8.1	4.08
28	0.95	0.72	3.78	0.28	0.58	4.3	3.25
mean							4.82

Appendix 9: ETo for March, 1994 based on data from the University of Zambia Meteorological Station, Lusaka, 1994

Date	C	W	Rn(mm)	(1-W)	f(U)	(ea-ed)	ETo(mm)
1	1.05	0.72	9.14	0.28	0.62	6.0	8.00
2	0.99	0.74	6.10	0.26	0.71	10.2	6.33
3	0.91	0.74	2.54	0.26	0.55	11.2	3.17
4	0.94	0.74	4.57	0.26	0.56	6.4	4.05
7	1.03	0.72	9.14	0.28	0.57	6.5	8.00
8	0.94	0.73	4.57	0.27	0.72	8.7	4.73
9	0.91	0.74	2.54	0.26	0.60	9.0	3.26
10	0.98	0.75	5.08	0.25	0.70	11.7	4.79
11	0.99	0.75	6.10	0.25	0.77	8.0	6.05
14	0.91	0.74	2.54	0.26	0.68	7.5	2.92
15	0.98	0.76	6.10	0.24	0.60	12.0	6.24
16	0.94	0.76	4.57	0.24	0.57	10.6	4.63
17	0.91	0.75	2.54	0.25	0.67	9.1	3.12
18	0.98	0.76	6.10	0.24	0.68	12.3	6.51
28	0.97	0.79	5.08	0.21	0.61	18.8	6.23
29	0.97	0.80	5.08	0.20	0.67	28.6	7.66
30	0.99	0.75	6.60	0.25	0.64	11.3	6.70
31	0.98	0.75	6.10	0.25	0.67	11.1	6.31
mean							5.48

Appendix 10: Leaf area index (L.A.I.) at different plant stages

Date	L.A.I.	Folliage cover %	Maize height (cm)
January, 1994			
3	1.5	38	30
7	1.6	38	40
10	1.7	41	53
14	1.8	45	67
18	1.9	48	75
22	2.1	50	87
25	2.2	51	98
28	2.3	55	105
31	2.3	58	110
February			
4	2.4	61	120
8	2.5	65	140
11	2.6	65	150
17	2.7	68	162
20	2.8	70	178
24	2.9	75	190
30	3.0	76	200
March			
4	3.1	78	215
7	3.1	78	230
13	2.3	70	230

Appendix 11: Interception values for January.

Date	P(mm)	Duration of rain (hours)	T(mm)	S(mm)	T+S(mm)	P-T(mm)	INTCEP P-(T+S)	%INTCEP	ETo(mm)	kc	ETmaize (mm)
3	38.4	7.5	32.6	4.6	37.2	5.8	1.2	3%	1.81	0.50	0.91
4	2.0	0.62	1.1	0.1	1.2	0.9	0.8	40%	14.08	0.50	7.00
5	1.9	1.2	0.6	0.2	0.8	1.3	1.1	58%	5.72	0.60	3.43
11	5.6	2.2	4.6	0.7	5.3	1.0	0.3	5%	5.02	0.07	3.51
12	3.0	1.0	1.7	0.4	2.1	1.3	0.9	30%	6.52	0.70	4.56
13	1.6	2.2	0.6	0.1	0.7	1.0	0.0	56%	3.00	0.80	2.38
15	13.8	3.5	10.8	2.2	13.0	3.0	0.8	6%	3.90	0.80	3.12
16	4.2	1.2	3.4	0.6	4.0	0.8	0.2	5%	3.90	0.90	3.51
18	7.1	4.5	5.5	1.2	6.7	1.6	0.4	5%	3.43	0.90	3.09
19	0.2	0.2	0.0	0.0	0.0	0.2	0.2	100%	1.64	1.00	1.64
22	1.2	0.7	0.2	0.1	0.3	1.0	0.9	75%	6.70	1.02	6.83
23	7.2	4.3	5.5	1.3	6.8	1.7	0.4	5%	6.70	1.02	6.83
26	3.1	0.9	1.8	0.5	2.3	1.3	0.8	25%	3.42	1.03	0.52
27	6.5	1.3	4.2	1.2	5.4	2.3	1.1	16%	9.94	1.03	10.24
29	32.1	5.2	23.8	6.4	30.2	8.3	1.9	6%	2.71	1.04	2.82
30	0.8	0.3	0.3	0.1	0.4	0.5	0.4	50%	3.22	1.05	3.38
Month	128.7			19.7		32.0	12.3	10%			

Appendix 12: Interception values for February and March.

Date	P(mm)	Duration of rain (hours)	T(mm)	S(mm)	T+S(mm)	P-T(mm)	(INTCEP) P-(T+S)	%INTCEP	ETo(mm)	kc	ETmaize (mm)
FEBRUARY											
2	0.5	0.2	0.1	0.1	0.2	0.4	0.3	60%	4.29	1.05	4.50
3	8.0	3.5	5.8	1.7	7.5	2.2	0.5	6%	3.82	1.05	4.01
4	9.2	2.6	6.7	1.9	8.6	2.5	0.6	7%	6.79	1.05	7.13
5	12.0	3.8	8.6	2.6	11.2	3.4	0.8	7%	6.28	1.05	6.60
7	6.0	1.6	4.3	1.2	5.5	1.7	0.5	8%	5.78	1.05	6.07
8	9.0	4.0	6.1	2.1	8.2	2.9	0.8	9%	3.91	1.05	4.11
9	11.0	4.1	7.8	2.5	10.3	3.2	0.7	6%	3.33	1.05	3.50
13	8.9	2.2	6.1	2.0	8.1	2.8	0.7	8%	7.53	1.05	7.91
16	1.6	0.2	0.9	0.2	1.1	0.7	0.5	31%	5.04	1.05	5.29
17	1.8	0.3	1.1	0.2	1.3	0.7	0.5	27%	3.86	1.05	4.05
20	2.5	0.6	1.5	0.4	1.9	1.0	0.6	24%	5.56	1.05	5.84
21	2.3	0.5	1.4	0.3	1.7	0.9	0.6	26%	7.10	1.05	7.45
22	8.2	3.2	5.7	1.8	7.5	2.5	0.7	8%	4.51	1.05	4.74
27	8.5	3.1	6.0	1.9	7.9	2.5	0.6	7%	3.66	1.05	3.84
Month	89.5			18.9		27.4	8.4	9%			
MARCH											
2	2.5	0.6	1.8	0.2	2.0	0.7	0.5	20%	6.33	1.05	6.65
4	2.4	0.8	1.7	0.2	1.9	0.5	0.5	21%	4.05	1.03	4.17
13	1.0	0.9	0.3	0.1	0.4	0.7	0.6	60%	4.48	0.90	4.03
Month	5.9			0.5		1.9	1.6	27%			

Appendix 13: Details of the fitted line when interception loss is regressed on gross precipitation.

Fitted equation : INTCEP = 0.4733 + 0.0272 * P

Std. error of slope : 0.0052

R-squared : 0.4708

Appendix 14: Details of the fitted line when interception loss is regressed on leaf area index

---

Fitted equation : INTCEP = -0.1129 + 0.2827 * LAI

Std. error of slope : 0.1342

R-squared : 0.4702

Appendix 15: Details of the fitted line when stemflow is regressed on leaf area index

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Fitted equation : S = -0.0464 + 0.7124 * LAI

Std. error of slope : 0.2461

R-squared : 0.6262

Appendix 16: Details of the fitted line when throughfall is regressed on leaf area index

Fitted equation : $T = 6.697 - 0.2273 * LAI$

Std. error of slope : 0.0758

R-squared : 0.8305

Appendix 17: Details of the fitted line when net precipitation is regressed on gross precipitation

Fitted equation : $T+S = -0.4733 + 0.9728 * P$

Std. error of slope : 0.0052

R-squared :0.9991

Appendix 18: Observed interception loss and expected interception loss from the four models.

	Observed (mm)	Model 1 (mm)	Model 2 (mm)	Model 3 (mm)	Model 3 (mm)
	1.2	0.9	0.9	1.5	1.9
	0.8	0.8	0.8	0.5	0.8
	1.1	0.8	0.8	0.5	0.8
	0.3	0.9	0.9	0.6	1.6
	0.9	0.8	0.8	0.6	1.3
	0.9	0.9	0.9	0.5	0.9
	0.8	1.3	1.3	0.8	2.3
	0.2	0.7	0.7	0.6	1.6
	0.4	1.0	1.0	0.7	2.1
	0.2	0.5	0.5	0.5	0.2
	0.9	0.9	0.9	0.5	0.9
	0.4	3.1	3.1	0.7	2.3
	0.8	0.5	0.5	0.6	1.7
	1.1	1.6	1.6	0.7	2.4
	1.9	1.9	1.9	1.3	3.3
	0.4	0.6	0.5	0.5	0.8
	0.3	0.6	0.4	0.5	0.5
	0.5	1.9	1.9	0.7	2.3
	0.6	2.4	2.4	0.7	2.9
	0.8	3.0	3.0	0.8	3.2
	0.5	1.5	1.5	0.6	2.7
	0.8	2.2	2.2	0.7	3.1
	0.7	1.2	1.2	0.8	3.3
	0.7	2.3	2.3	0.7	3.3
	0.5	0.6	0.6	0.5	1.6
	0.5	0.6	0.6	0.5	1.7
	0.6	1.0	1.0	0.5	2.2
	0.6	0.9	0.9	0.5	2.1
	0.7	2.2	2.2	0.7	3.6
	0.6	2.0	2.0	0.7	3.9
	0.5	1.1	1.1	0.5	2.5
	0.5	0.9	0.9	0.5	2.4
	0.6	0.9	0.8	0.5	1.0
Mean	0.7	1.3	1.3	0.7	2.0
Total	21.7	42.5	42.1	21.5	67.2
%INTCEP	10%	19%	19%	10%	30%

Appendix 19: T-test output for model 1.

```
                   Observed INTCEP       Expected INTCEP
Sample size         33                    33
Minimum              0.2                   0.5
Maximum              1.9                   3.1
Range                1.7                   2.6
Mean                 0.65758               1.2879
Std. deviation       0.3279                0.72877

Pooled std. deviation                              0.565074
Difference between means                          -0.6303
Std. error of difference                           0.13911
Degrees of freedom                                64

95% confidence interval   -0.90821    to    -0.3524
t  value                                    -4.53

Significance level  for 2 sided test        0.00%
```

Appendix 20: T-test output for model 2.

```
                   Observed INTCEP      Expected INTCEP

Sample size         33                   33
Minimum              0.2                  0.4
Maximum              1.9                  3.1
Range                1.7                  2.7
Mean                 0.65758              1.2758
Std. deviation       0.3279               0.74037

Pooled std. deviation                             0.572566
Difference between means                         -0.61818
Std. of means                                     0.14096
Degrees of freedom                               64

95% confidence interval      -0.89977   to      -0.33659
t value                                         -4.39

                                                 Significance level
for two sided test           0.00%
```

Appendix 21: T-test output for model 3.

```
                   Obsreved INTCEP      Expected INCEP

Sample size         33                   33
Minimum              0.2                  0.5
Maximum              1.9                  1.5
Range                1.7                  1
Mean                 0.65758              0.65152
Std. deviation       0.3279               0.22097

Pooled std. deviation                            0.279593
Difference between means                         0.00606
Std. error of difference                         0.06883
Degrees of freedom                              64

95% confidence interval    -0.13145     to      0.14357
t value                                         0.09

Significance level for two sided test      93.01%
```

Appendix 22: T-test output for model 4.

```
                        Observed INTCEP    Expected INTCEP

Sample size              33                 33
Minimum                    0.2                 0.2
Maximum                  1.9                3.9
Range                    1.7                3.7
Mean                     0.65758            2.0364
Std. deviation           0.3279             0.97526

Pooled std. deviation                              0.727549
Difference between means                          -1.3788
Std. error of difference                           0.17911
Degrees of freedom                                64

95% confidence interval    -1.7366     to      -1.021
t value                                        -7.70

Significance level for two sided test             0.00%
```