ESTIMATION OF RAINFALL INTENSITY FOR POTENTIAL CROP PRODUCTION ON CLAY SOIL WITH IN-FIELD WATER HARVESTING PRACTICES IN A SEMI-ARID AREA

by

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Executive Summary

Motivation and aims

Development of informal settlements surrounding major cities in South Africa is by its very nature unplanned, so many of the normally carefully planned aspects of a city have not been met. The rapid urbanisation taking place in South Africa and accompanying low-income generation is partly to blame for the lack of food security in these informal settlement areas. A Water Research Commission (WRC) project entitled "Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water" (WRC Report No 878/1/00) has addressed the soil and agronomic aspects of water harvesting for use in crop production. However, several aspects have also been identified that appear to be weak links in the chain. The chain of logic is that the long-term rainfall data is used to generate an amount of runoff water per storm per area, which can then be channelled onto the productive land and used for crop production.

The theoretical relationships relating daily rainfall to rainfall intensity and runoff should be tested under the practical conditions of crop production in specific ecotopes. The beneficial manipulation of runoff is fundamental to the success of the water harvesting techniques, and rainfall intensity is a major factor in this respect. Because of rainfall variability, reliable evaluation of the production techniques being tested is best achieved with long-term data. The fact that long-term rainfall data is only available as daily total amounts seriously impairs the efficiency of the long-term crop modelling strategy because of the absence of the key information, i.e. long-term rainfall intensity data. This procedure can be used to predict runoff for water harvesting initiatives designed to stabilise food production in dry areas, i.e., in peri-urban and rural areas. If the method is to be transferred to other ecotopes, then similar daily rainfall amount to rainfall intensity to runoff relationships need to be developed with long-term daily rainfall data. If climate-crop models are to be used to perform a risk analysis with cumulative distribution functions from long-term data sets, then it is necessary to be able to convert the daily rainfall data into rainfall intensity data to generate an expected amount of runoff which would be an input into existing climate-crop models.

The specific objectives of this project are, therefore, as follows:

(a) to do statistical analysis of rainfall intensity and runoff data
(b) to test the various theoretical relationships particularly those previously identified as good in South Africa
(c) to generate rainfall intensity data from the historic record of daily rainfall, at selected benchmark ecotopes, and therefore the expected amount of runoff
(d) to conduct a risk analysis for water harvesting techniques at selected sites using a climate-crop model.

Rainfall and Runoff Analysis

Rainfall intensity data (peak rainfall intensity, event rainfall amount, event rainfall duration, and daily rainfall amount) at Glen (1992–2001) was used for statistical analysis, and compared with rainfall intensity data at Bloemfontein (1962–1992) and Pretoria (1966–1996). It was found that there were no differences in either daily or event amounts of rainfall between Glen, Bloemfontein and Pretoria weather stations, however, Glen had higher values for event rainfall duration and peak rainfall intensity than Bloemfontein and Pretoria. The relationships of peak rainfall intensity to event rainfall for Glen were analogous to those for Bloemfontein. Also, Pretoria had different relationships of intensity with amount from the other two locations. From the results, it is not possible to use these statistical relationships (r^2 = 0.2 to 0.8) with any confidence to estimate the rainfall intensity from the daily or event rainfall amounts in the historical record. With respect to seasonal variability, the rainy season has a tendency to have higher peak rainfall intensity and event rainfall amount, and lower event rainfall duration than the non-rainy season. Concerning rainfall-runoff processes, daily runoff data at Glen was analysed for relationships with daily rainfall amount. The amount of daily runoff at Glen is estimated to be 36 % to 41 % of the amount of daily rainfall, but as the amount of daily rainfall increased, the daily runoff-rainfall relationship was more variable. That is, the model could provide a good estimate at low rainfall amounts, but failed at high rainfall amounts. Consequently, it is not possible to employ this linear type model.

Rainfall Intensity Models

The area under the rainfall intensity curve (the Φ index) method provided acceptable daily runoff estimation from daily rainfall. This method may be used for estimating runoff from rainfall on different soil ecotopes by changing the index value used for final rate of infiltration. Concerning a deterministic model of rainfall intensity, stepwise regression techniques (with surface weather data) and artificial neural networks (ANN) (with meteorological satellite data) were used to develop a rainfall intensity model. However, the stepwise regression showed no relationships between rainfall intensity and the other meteorological factors. This indicates that it is difficult to estimate rainfall intensity from other daily surface meteorological data. In the ANN analysis, a strong relationship between rainfall intensity and wind speed at 700 hPa level was found, but some of the generated rainfall intensities were negative values. Thus, it is necessary to reconsider the methodology in future studies. Since rainfall intensity was not successfully modelled deterministically, using the hyetograph (Huff curve) method, a stochastic model of rainfall intensity was developed for Bloemfontein and Pretoria. The model was reasonably verified, and this model gave a variety of time distributions of rainfall.

Rainfall-Runoff-Yield Simulation

Using the Putu crop growth model together with deterministic runoff model, hyetograph (stochastic rainfall intensity) model and the area under the rainfall intensity curve model, the risk assessment of maize yield was carried out under several scenarios, including water harvesting / basin tillage / no-till / mulching (WHBM) and conventional total soil tillage (CT) production techniques. The potential strengths of the Putu crop growth model were demonstrated. A combination of the deterministic runoff model and the stochastic rainfall intensity model gave more flexible performance than the empirical runoff model (the area under the rainfall intensity curve model). The lower the initial soil water content at planting, the greater the yield difference between the WHBM and CT production techniques. With the low initial soil water content at planting, the WHBM production technique had up to 50 % higher yield compared to the CT production technique. Thus, the superiority of the WHBM production technique is clearly demonstrated. In addition, it is recommended that the risk analysis of crop yield be carried out using the Putu crop growth model in the combination model for the rainfall intensity – runoff processes. Although a satisfactory runoff estimation still needs to be improved, the value of the simulation technique has been shown.

Conclusions and recommendations

Two successful models for rainfall-runoff processes have been introduced to be used in crop model simulation: (i) the area under the rainfall intensity curve method and (ii) the combination of dimensionless hyetograph model and deterministic runoff model. It has been concluded that the latter is more useful than the former. This stochastic rainfall intensity model has been developed to provide long-term rainfall intensity values as applied in water harvesting projects. In addition, these results would then be available to the hydrologists to be used in peak rainfall intensity estimation (for food production) and soil erosion and water quality studies. This would greatly enhance the existing hydrological models and predictions.

However, the following recommendations for further studies are made:

(1) It is recommended to develop the Huff curve procedure further and to make it applicable to most parts of South Africa, particularly, to develop the Huff curve model for the highveld region, comparing the model for Bloemfontein and Pretoria (both the summer rainfall highveld).

(2) The runoff data estimated can become input into the Putu crop growth model. However, the model simulation runs have been carried out step by step. It is therefore recommended to develop a complete simulator for crop yield by linking the

combination of the stochastic rainfall intensity generator – the mechanistic runoff model to the crop model.

This project has provided opportunity for capacity building. E. Mukhala was exposed to statistical analysis of rainfall parameters, M. Tsubo was exposed to rainfall intensity modelling. J.J. Anderson worked on the risk analysis part of the project using the Putu crop growth model, and M. Olivier worked on the synoptic weather chart analysis used in the stepwise regression technique. This project provided them the opportunity to learn about rainfall analysis, rainfall modelling and crop simulation.

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Chapter 1
Introduction

1.1. Motivation

Development of informal settlements surrounding major cities in South Africa is by its very nature unplanned, so many of the normally carefully planned aspects of a city have not been met. The rapid urbanisation taking place in South Africa and accompanying low-income generation is partly to blame for the lack of food security in these informal settlement areas. The low and erratic rainfall also contributes to the fact that poor people cannot easily cultivate the land or are unfamiliar with alternative lower risk crop production techniques, so they do not consistently produce sufficient maize, the staple food crop. As much of South Africa has low and erratic rainfall, water is often a limiting factor for cultivation of food crops. However, if rainwater can be harvested and channelled to adjacent high potential land, then crops could be grown, despite the low rainfall. This type of water harvesting technique has been successfully used in rural areas in other parts of Africa, but a working model needs to be developed or identified for the unique agricultural situation in South Africa. Some of the unemployed people will also be able to work in the fields or find productive occupations connected to the farming activities. This may help to fulfil their basic needs and thus increase the general quality of life of the whole community.

A Water Research Commission (WRC) project entitled "Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water" (WRC Report No 878/1/00) has addressed the soil and agronomic aspects of water harvesting for use in crop production (Hensley *et al.*, 2000). However, several aspects have also been identified that appear to be weak links in the chain. The main one is the absence of long-term rainfall intensity data needed to make reliable predictions of runoff water per storm per area, which can then be channelled onto the productive land and used for crop production. This runoff water could be collected from the roofs of houses, roadways and surrounding natural areas. A theoretical relationship relating daily rainfall to rainfall intensity and runoff needs to be developed and tested under the practical conditions of crop production in the specific ecotopes. The beneficial manipulation of runoff is fundamental to the success of these techniques, and rainfall intensity is a major factor in this respect. Because of rainfall variability, reliable evaluation of the production techniques being tested is best with long-term data. The fact that long-term rainfall data is only available as daily total amounts seriously impairs the efficiency of the long-term crop modelling strategy because of the absence of the key information, i.e. long-term rainfall intensity data. This procedure could also then be used to predict runoff for water harvesting projects designed to stabilise food production in dry areas, i.e., in peri-urban and rural areas.

If the method is to be transferred to other ecotopes, then similar relationships of daily rainfall amount to rainfall intensity to runoff need to be developed with long-term daily rainfall data. If the climate-crop models are to be used to perform a risk analysis with cumulative distribution functions from long-term data sets, then it is necessary to be able to convert the daily rainfall data into rainfall intensity data to generate an expected amount of runoff. This project has enhanced the above procedures by providing an agro-hydrological approach to the prediction of the runoff water that will be available to feed into the agronomic trial plots. The questions to be answered are as follows:

(a) Can a model be found or developed by which rainfall intensity data can be reliably predicted from daily rainfall amount data?
(b) Will the predicted long-term rainfall intensity data for a particular site be capable in practice of predicting runoff from micro-catchments with reasonable accuracy?
(c) Assuming (i) and (ii) are successful, what possible increases in low yield could be expected from water harvesting systems?

1.2. Aims

The importance of having rainfall intensity data for planning purposes for agricultural development programs, particularly food security, cannot be overemphasised. It is important to constitute locally appropriate relationships between daily precipitation and runoff amounts, using statistical analysis and modelling. The information obtained could be used to facilitate prediction of rainfall intensity data from the vast amounts of historic daily precipitation data available, and to predict runoff for water harvesting from micro-catchments to stabilise food production in rural and peri-urban communities in South Africa. In order to answer the above questions, the specific objectives of this project are as follows:

(a) To do a complete analysis of the rainfall intensity and runoff data already collected during WRC projects by Hensley *et al.* (1997, WRC Report No 508/1/97; 2000, WRC Report No 878/1/00).

(b) To test the various theoretical relationships particularly those identified as good in South Africa in a WRC project by Smithers and Schulze (2000, WRC report No 681/1/00).

(c) To generate rainfall intensity data from the historic record of daily rainfall at selected benchmark ecotopes and therefore the expected amount of runoff.

(d) To conduct a risk analysis for water harvesting techniques at selected sites using a climate model.

1.3. Literature review

Terminology

In this kind of study, the use of appropriate terminology is of utmost importance. Terms used are defined for better understanding as a wide variety of definitions exist in the literature. Morin and Cluff (1980) define a rain-day as a 24-hour period beginning at midnight, during which a rainfall event occurred. The World Meteorological Organization (WMO) of the United Nations, Geneva, defines a rain-day with a 24-hour period as well, but from 08:00 am to 08:00 am the following day due to the standard manual measurement method. Once the measurement has been read on the following day, it is recorded on the previous days' date and this is referred to as 'booking back'. The WMO definition of a rain-day is followed in this work because most of the data is collected under the WMO agreed conditions for easier exchange of data with member countries. Disaggregation of rainfall will also be used in this research study and therefore an understanding of this term is necessary. Disaggregation can be defined as the breaking down of daily rainfall data into individual rainfall events in a day given only total amount of rainfall on that day.

Rainfall event: Rainfall events are defined as continuous precipitation, without a dry moment, separated by a length of time (usually less than 3 hours) with no precipitation before precipitation recommences for the following event (Restrepo-Posada and Eagleson, 1982). Depending on the rainfall pattern, more than one rainfall event may be recorded in a 24 hour period. A rainfall event can constitute several rainstorms. Breakpoint data are recorded when intensity changes, rather than on a fixed time step. A number of definitions of rainstorms have also been given in the literature. Huff (1967) defines a storm as a rain period separated from preceding and succeeding rainfall by 6 hours or more. Rain can be considered to fall at a rate that changes with time, but for specific time intervals, Δt_i, the intensity is considered to be constant, P_i. Morin and Cluff (1980) have defined a rainstorm as a group of rain segments where the breaks are less than 24 hours and therefore give the depth of the rainstorm, D_i, as explained by the following equation:

$$D_i = \sum_{j=1}^{i} P_j \Delta t_j \qquad (1.1)$$

where i is the number of time increments. With regard to time interval, the Morin and Cluff (1980) definition is not well defined but Calles and Kulander (1994) define a rainstorm as discrete precipitation events separated from the next rainfall event by more than 3 hours. This last definition will be used in this study.

Critical duration: The duration which separates events from preceding and succeeding rainfall is often called the critical duration. For example, Huff (1967) separated rainfall events by the critical duration of 6 hours while Calles and Kulander (1994) used 3 hours. Restrepo-Posada and Eagleson (1982) proposed 'the exponential method' to determine the critical duration. Although the critical duration may be determined for a specific location using the exponential method, the following empirical relationship (Equation 1.2), which is given by Restrepo-Posada and Eagleson (1982), can probably be used satisfactorily to determine a reasonable value for the specific location:

$$\frac{t_{b0}}{m_\tau} = 1523\left(\frac{m_{PA}}{m_\tau}\right)^{-1.59} \tag{1.2}$$

where t_{b0} is minimum time between independent storms (hours), m_τ is average length of rainy season (months), and m_{PA} is average seasonal precipitation (mm). Another method to determine the critical duration is called "the rank correlation method" (e.g., Grace and Eagleson, 1966). Bonta and Rao (1988) recommended using the exponential method in order to determine the critical duration. In this study, the critical duration of 3 hours has been used to separate rainfall events at Bloemfontein, Glen and Pretoria.

Rainfall intensity: Rainfall intensity is the rate at which rain falls per unit time. Rainfall intensity is measured using automatic recording instruments which include: tipping bucket and syphon type of rain gauges. Rainfall intensity information has always been a very important input in studies of water harvesting, infiltration, runoff and soil erosion. Few stations in South Africa have measured rainfall intensity data sets for more than 10 years, although many stations (about 170) now have at least 10 years of measured data (Smithers and Schulze, 2000). On the other hand, records of 100 years or more in length of daily rainfall data are commonly available in many developing countries, including South Africa.

Ecotope: Each homogenous piece of land has a unique combination of climate, terrain form and soil characteristics, which is described as an ecotope: e.g., Glen/Bonheim, Glen/Swartland and Khumo/Swartland ecotopes (MacVicar *et al.*, 1974; Cited in Hensley *et al.*, 2000, pp. 9). The first part of the name refers to the geographical location, and therefore provides preliminary information about the climate, and the second part of the name describes the soil component of the ecotope in terms of the form name. Each of three natural resources, i.e., climate, topography and soil, have characteristics which have a major influence on the productivity of the system as a whole. According to Hensley *et al.* (2000), an ecotope is also defined conceptually by expanding the soil-plant-atmosphere system spatially to those points in the landscape where there is a significant change in any of these three factors.

Rainfall-runoff processes

Overland flow or surface runoff is water which travels over the ground surface to a channel (Linsley *et al.*, 1982). Runoff is normally expressed as a volume per unit of time and may also be expressed as a depth equivalent over a catchment, i.e., mm/day, month or year (Ward, 1975). According to Ward (1975), factors affecting runoff can be differentiated between those factors which combine to influence the total amount of runoff over a period of several years and those factors which combine to influence the distribution of runoff in time over a period of one year or less.

The most effective influence on the total amount of runoff is the long-term balance between the amount of water gained by a catchment area in the form of rainfall and the amount of water lost from that catchment area in the form of evapotranspiration. This relationship between annual totals of rainfall and evapotranspiration is modified by rainfall distribution and vegetation cover. The second group of factors affecting the total amount of runoff consists of aspects of the structure of the catchment area. The main factor is the size of the catchment area because it determines the total amount of rainfall caught. This effect may be dependent on the prevailing climatic regime. That is, in a region where potential evaporation exceeds rainfall, a large catchment as well as a small one will have very little runoff, while in a region where rainfall exceeds potential evaporation, the larger the catchment area, the greater the runoff amount. The slope, soil and rock type also indirectly influence the total amount of runoff. In general, high annual runoff is expected from steeply sloping areas having thin soils and impermeable rocks.

The duration of rainfall is also important in relation to the hydrologically responsive areas of a catchment, especially, flat, low-lying areas. The importance of rainfall duration changes with the size and nature of the catchment. The time relationship between rainfall and runoff is greatly influenced by the distribution of rainfall over catchment areas. That is, an amount of rainfall which is uniformly distributed over the whole of a catchment has lower intensites and therefore produce less quickflow than the same amount of rainfall on a small part of the catchment. Catchment factors affecting the distribution of runoff in time include topography, geology, soil, vegetation and drainage network. The shape of the catchment area is known to affect runoff through its effects on flood intensities. The slope of the catchment area may affect the relative importance of predominantly vertical movement of water by means of infiltration and the predominantly lateral movement of water by means of interflow and overland flow. Concerning the influence of soil type on infiltration and therefore runoff, open-textured sandy soils tend to be associated with higher infiltration than fine-grained, closely compacted clay soils, and sandy soils therefore tend to generate less quickflow. In addition, the total effect of vegetation on runoff is comprised of its individual effects on interception, evapotranspiration and soil water movement (Ward, 1975).

Rainfall intensity is an important factor in determining the proportions of the rainfall which go to overland flow, interflow and groundwater flow in the hydrological cycle. Rainfall intensity information is one of the major inputs in the determination of soil erosion and runoff on various soil types and slopes. This information is lacking at most data collection centres resulting in estimations being made for input data. Development of water harvesting programmes to sustain agricultural production for food security in semi-arid areas requires this information for planning and implementation. While efforts are being made to make rainfall intensity data available, infiltration capacity data of different soil types is also important and must be readily available to facilitate the calculation of water flow. The decrease in infiltration rates is caused by the formation of crusts due to direct impact of raindrops on the soil surface resulting in overland surface flow of water (Morin and Cluff, 1980). The formation of crusts is influenced by wetting and drying cycles and crop and vegetation cover (Connolly, 1998). Favourable conditions that allow runoff to take place include: rainfall intensity being higher than infiltration rate, and satisfaction of the maximum surface storage and retention. Infiltration, surface storage and retention are parameters that are dynamic in nature (Morin and Cluff, 1980).

Empirical relationships for rainfall-runoff processes

Estimating runoff from rainfall measurements is very much dependent on the time interval being considered (Shaw, 1988). The relationship on a basis of short duration (i.e., hours) is more complex than that for an annual basis. The simplest method for estimating runoff from rainfall is a locally determined linear regression analysis. For example, Hensley *et al.* (2000) measured runoff on a 1 % slope no-till crusted surface and found the following relationship for two ecotopes (Glen/Bonheim and Glen/Swartland) at Glen during the three rain seasons 1996/1997, 1997/1998 and 1998/1999:

$$RO = 0.473RF - 2.168 \qquad (1.3)$$

where RO is the amount of runoff (mm) per rainfall event and RF is the amount of rainfall (mm) per rainfall event. Du Plessis and Mostert (1965) measured annual runoff at Glen from 1937 to 1955, and reported the fraction of measured annual runoff to rainfall was 32 % for a no-till soil. Their ecotope consisted of a Tukulu form soil with 15 % clay in the topsoil, situated on a 5 % slope (Zere, 2003). Hensley *et al.* (2000) reported that annual runoff calculated using the above equation was 25 % of annual rainfall during the same period. The difference in the ratio of runoff to rainfall between the runoff studies at Glen might be explained by the difference in the slope or character of the soil surface.

Another simple type of runoff model is the rainfall-excess models. One of them is referred to as the infiltration index. The simplest infiltration index is called the Φ index, defined as the rate of rainfall above which the amount of rainfall equals the amount of runoff (Linsley *et al.*, 1982; Shaw, 1988), as follows:

$$\Phi = \frac{IF}{t} = \frac{RF - RO}{t} \tag{1.4}$$

IF is total infiltration, *t* is time during which rainfall intensity exceeds infiltration capacity rate, *RF* is total rainfall corresponding to *t*, and *RO* is runoff. This method assumes a constant loss rate from the beginning of the rainfall event. Moreover, the infiltration index including a soil surface detention is called the W index, as follows (Linsley *et al.*, 1982):

$$W = \frac{IF}{t} = \frac{RF - RO - SD}{t} \tag{1.5}$$

where *SD* is surface retention. When the infiltration capacity is maximum and soil retention rate is very slow under very wet conditions, the W index is almost equal to the Φ index. It is clear that these indices must be calibrated under each variation in the condition of soil surface and for each soil texture.

Another rainfall-excess model is the Soil Conservation Service (SCS), United States Department of Agriculture (USDA), curve number method (USDA-SCS, 1985). This method has been used in most water balance models of soil-crop systems (Connolly, 1998). The model is given by:

$$Q = \frac{(RF - I_a)^2}{[(RF - I_a) + S]} \tag{1.6}$$

where Q is runoff (inches), RF is rainfall (inches), S is potential maximum retention after runoff begins, and I_a is all losses before runoff begins. I_a includes water retained in surface depressions, vegetation interception, evaporation and infiltration, and may be assumed to be 0.2S for agricultural watersheds. S (inches) is calculated by:

$$S = \frac{1000}{CN} - 10 \qquad (1.7)$$

where CN is curve number ($30 < CN < 100$). CN is dependent on hydrological conditions, soil type, land use, vegetation, and crop pattern.

Deterministic models of rainfall-runoff processes

Although a more realistic dynamic model of the runoff process has been introduce by many scientists, for many years, several simple infiltration theories, including Green-Ampt, Horton, Philip and Holtan infiltration equations, have been employed to model the runoff process (Ward, 1975; Hillel, 1980; Linsley *et al.*, 1982; Shaw, 1988). These theories consider average conditions over an entire catchment area. Surface runoff is generated where and when rainfall intensity exceeds the rate at which water can enter the soil. The Green-Ampt and Philip equations are approximate theory-based infiltration models, but the Horton and Holtan equations are empirically based infiltration models (Hillel, 1980). The infiltration rate, I_t (mm/hr), equations are as follows:

Green and Ampt (1911):

$$I_t = I_F + \frac{a}{CI} \qquad (1.8)$$

I_F: the final infiltration rate

A: a constant

CI: the cumulative amount of water infiltrated at the time t from the beginning of rainfall

Horton (1940):

$$I_t = I_F + \left(I_I - I_F\right)\exp\left(-kt\right) \qquad (1.9)$$

I_I: the initial infiltration rate

k: a constant

Philip (1957):

$$I_t = I_F + \frac{s}{2} t^{-1/2} \tag{1.10}$$

s: a constant

Holtan (1961):

$$\begin{aligned} I_t &= I_F + a(M - CI)^n && \text{when} \quad 0 \le CI \le M \\ I_t &= I_F && \text{when} \quad CI > M \end{aligned} \tag{1.11}$$

a: a constant

M: a constant (the water storage capacity of the soil above the first impeding stratum)

n: a constant

Morin and Benyaminy (1977): Following the Horton infiltration theory, the actual infiltration equals the infiltration capacity, defined as the maximum rate at which water can enter the soil at a particular point under a given set of conditions, only when the supply rate (rainfall intensity) equals or exceeds the infiltration capacity. The infiltration capacity depends on soil type, soil water content, organic matter, vegetation cover and season. Based on the Horton infiltration theory, Morin and Benyaminy (1977) introduced an exponential relationship of the infiltration capacity to cumulative rainfall, instead of time from the beginning of rainfall, in a semi-arid area, as follows:

$$I_t = I_F + (I_I - I_F)\exp(-\gamma P t) \tag{1.12}$$

where γ is the soil factor (determined by the stability of the soil surface aggregate to the reorientation of soil particles by the impact of the raindrops), P is rainfall intensity, and t is the time elapsed from the beginning of the rainfall event, and therefore, P multiplied by t gives the cumulative amount of rainfall from the beginning of the rain event.

Stochastic models of rainfall intensity

In the past, daily rainfall data was adequate as input data in cropping systems, runoff and soil erosion models, but due to the advancement in model development, detailed rainfall data like rainfall intensity are now required (Connolly *et al.,* 1998). The utilisation of available daily records would be enhanced once methods are available to reliably convert daily rainfall data into breakpoink data. One of the methods is a disaggregation model. Daily rainfall is disaggregated into a number of rainfall events by deriving the characteristics (amount, duration and starting time) and then time-varying intensity for each event. For example, Srikanthan and McMahon (1985) developed a model to simulate 6-minute rainfall from annual rainfall in Australia. This model requires 20 years measured rainfall intensity data to parameterise hourly and 6-minute rainfall components.

Woolhiser and Osborn (1985) introduced a dimensionless hyetograph method for generating rainfall intensity within rainfall events. Using the dimensionless hyetograph method, Hershenhon and Woolhiser (1987) developed a model for disaggregating daily rainfall into a number of individual rainfall events in a day. The starting time, duration and amount of each event are simulated using rainfall on the day and on the preceding and following days. Similarly Connolly *et al.* (1998) introduced a stochastic model for disaggregating daily rainfall into multiple rainfall events on a day for a semi-arid region. The model simulates time-varying rainfall intensity within each day. The model was designed to be parameterisable with a relatively short rainfall record (5 years), and then to be able to disaggregate long-term daily records into break point rainfall, preserving the characteristics of the record from which the parameters were derived. Multiple rainfall events in a day are represented, and for each event, rainfall amount and duration, peak intensity, time to peak rainfall intensity, starting time and temporal pattern are simulated.

Water harvesting

According to Pacey and Cullis (1986), the principle of collecting and using precipitation from catchment areas is referred to as rainwater harvesting, or more generally water harvesting. Water harvesting includes not only rainwater at the point where it falls, but also rainwater from stream flow in creeks and gullies. Rainwater collected from short or small catchments is distinguished between external catchments (runoff farming) and within-field catchments (micro-catchments). The former refers to systems where strips of catchment area alternate with cultivated plots inside the field boundary, while the latter refers to systems where runoff is applied directly to growing crops without any deep inundation, bunds and spillways. External catchment systems often have slope lengths greater than 50 – 150 m while micro-catchment systems have short slope lengths within cultivated plots.

Many studies on water harvesting have been reported worldwide, e.g., Cater and Miller (1991), Hensley *et al.* (2000), Wiyo *et al.* (2000), and reviewed by Boers and Ben-Asher (1982), Pacey and Cullis, (1986) and Gould and Nissen-Petersen (1999). In South Africa, attention has been paid to in-field water harvesting for the last decade at Glen (Hensley *et al.*, 2000). Hensley *et al.* (2000) introduced a no-till type of micro-catchment and basin tillage covered by mulch. They carried out field trials of maize production systems during three growing seasons (1996/1997, 1997/1998 and 1998/1999) and showed its yield advantages from the water harvesting technique, compared with a conventional total tillage production technique. In their study, one of the growing seasons had no maize yield with the conventional production technique because of poor distribution of rainfall during the growing season. However, the water harvesting technique gave some maize yield (132 kg/ha) because of the mulched basin micro-catchment, which could have provided more water to the crops.

In arid and semi-arid climatic regions of the world, it is important to analyse crop productivity and water harvesting because those areas have been facing water scarcity and therefore food insecurity. Although many types of water harvesting techniques have been reported, however, field experiments for assessing those systems are very expensive and laborious. As a result, several models of water harvesting and comprehensive models of rainfall-runoff-yield systems have been developed (Gould and Nissen-Petersen, 1999; Young *et al.*, 2002). For example, Young *et al.* (2002) introduced the comprehensive model simulator “Parched-Thirst.” This simulator generates 5 min rainfall intensity from an assured rainfall intensity distribution (if no data of rainfall intensity is available), estimates runoff using the water balance model for both runoff-producing and receiving areas, and then predicts crop growth and yield. Therefore, it is possible to assess risk of crop production with water harvesting techniques (Sanchez *et al.*, 1995).

Chapter 2
Statistical Analysis of Rainfall and Runoff Data

2.1. Rainfall analysis

Statistical analyses have been used to analyse climatological data in many parts of the world. In South Africa, statistical analyses were employed in the early 1990's in a similar research conducted by the Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) in Potchefstroom. The research objectives were to characterise rainfall intensity during different types of storms and to describe relationships between rainfall intensity and other parameters, such as raindrop size, event rainfall amount and duration, and piecewise linear regression analysis was utilised in the research. The motivation of this research was that rainfall intensity is an input in runoff and soil erosion models used worldwide. With better knowledge of rainfall intensity during different kinds of storms, the influence on runoff could be determined. Even though extremely important, the research was discontinued.

In studying rainfall intensity, it is important to know long-term distribution of monthly rainfall amounts. As shown in Figure 2.1, February, followed by January and March, has the highest mean monthly rainfall amount at weather stations located at Glen (Glen Agricultural College; 28º57´S, 26º20´E, 1304 m) and Bloemfontein (29º06´S, 26º18´E, 1354 m). At Pretoria (25º44´S, 28º11´E, 1330 m), January, followed by November and December, has the highest mean monthly rainfall. Months which have less then 30 mm of mean monthly rainfall are May, June, July, August and September at all locations. From those monthly rainfall patterns, the rainy season for both locations can be defined as a period from October to April. The average total amount of rainfall during the rainy season is 491 mm for Glen, 483 mm for Bloemfontein and 617 mm for Pretoria. Glen has an equivalent annual amount of rainfall to Bloemfontein (567 mm and 559 mm, respectively), however, Pretoria (667 mm of annual rainfall) has about 15 % higher annual rainfall than the other two locations.

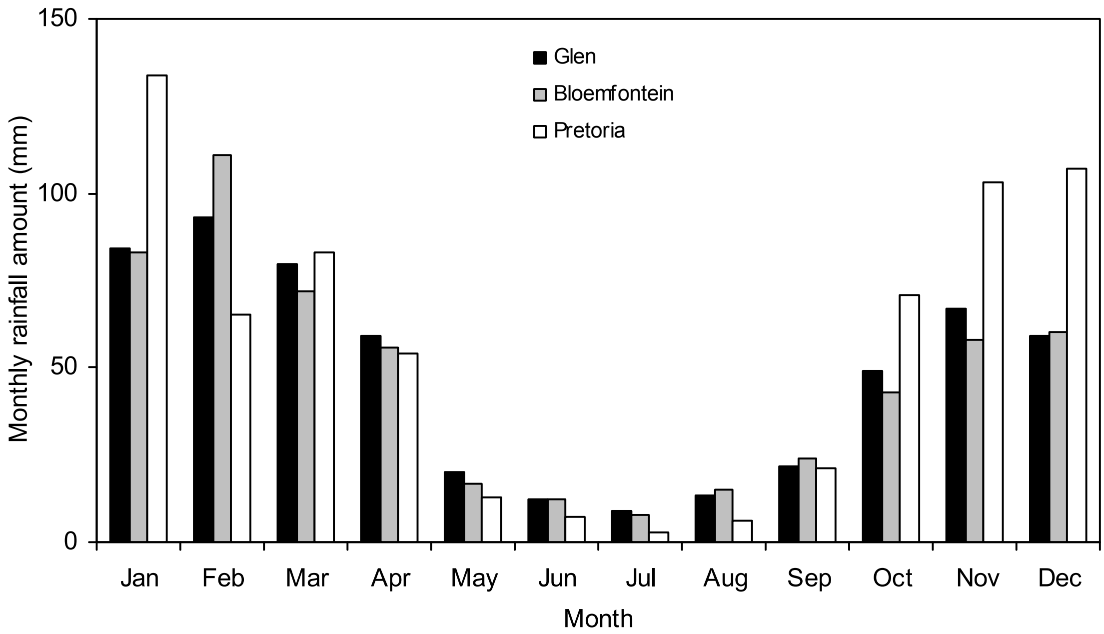


Figure 2.1. Long-term mean monthly rainfall at Glen, Bloemfontein and Pretoria (1961–1990).

In this study, rainfall intensity data at Glen from 1992 to 2001 were used for statistical analysis: 339 rain days (data of daily rainfall amount) and 401 rainfall events (data of peak rainfall intensity, event rainfall amount and event rainfall duration). Most of the data was collected during a period from October to April (87 % of all data). Rainfall was measured and recorded using a tipping bucket rain gauge and a datalogger. The data of only 1 tip per rainfall event was excluded due to no measurement of the starting time at the beginning of each rainfall event. Rainfall intensity data throughout the years from 1962 to 1992 for Bloemfontein and from 1966 to 1996 for Pretoria, which was recorded by a siphon type gauge (Bloemfontein: 3128 events and 2549 rainy days; Pretoria: 2676 events and 2503 rainy days) was also analysed.

Means and standard deviations of the rainfall data (data sets of rain days) for Glen, Bloemfontein and Pretoria are shown in Table 2.1. For all months, Glen had 8, 27 and 35 % larger values than Bloemfontein in rainfall event amount, event rainfall duration and

Table 2.1. Means and standard deviations of rainfall data at Glen, (1992–2001) Bloemfontein (1962–1992) and Pretoria (1966–1996) (based on the data sets of rainy days only).

Location	Factor	Season*	Mean	Standard deviation
Glen	Daily rainfall (mm)	All months	6.1	8.7
		Rainy	6.4	9.0
		Non-rainy	4.4	2.1
	Event amount (mm)	All months	5.2	8.2
		Rainy	5.4	8.5
		Non-rainy	3.9	5.7
	Event duration (min)	All months	163	187
		Rainy	162	191
		Non-rainy	170	160
	Peak intensity (mm/min)	All months	0.386	0.499
		Rainy	0.402	0.498
		Non-rainy	0.275	0.498
Bloemfontein	Daily rainfall (mm)	All months	6.7	9.7
		Rainy	7.1	10.0
		Non-rainy	4.9	7.7
	Event amount (mm)	All months	4.8	7.8
		Rainy	5.1	8.0
		Non-rainy	3.8	6.8
	Event duration (min)	All months	128	185
		Rainy	126	177
		Non-rainy	145	216
	Peak intensity (mm/min)	All months	0.285	0.504
		Rainy	0.309	0.536
		Non-rainy	0.173	0.275
Pretoria	Daily rainfall (mm)	All months	6.7	10.0
		Rainy	7.0	10.3
		Non-rainy	4.3	6.8
	Event amount (mm)	All months	6.0	9.2
		Rainy	6.2	9.4
		Non-rainy	4.1	6.4
	Event duration (min)	All months	130	186
		Rainy	129	186
		Non-rainy	137	178
	Peak intensity (mm/min)	All months	0.374	0.772
		Rainy	0.392	0.800
		Non-rainy	0.215	0.421

* Rainy season: from October to April (including January, February, March, April, October, November and December); Non-rainy season: from May to September (including May, June, July, August and September).

peak rainfall intensity, respectively. Similarly, Glen had 6, 29 and 30 % larger values in rainfall event amount, event rainfall duration and peak rainfall intensity, respectively, for the rainy season and 3, 17 and 59 % for the non-rainy season than Bloemfontein. However, Bloemfontein had slightly (10 % for all seasons, 11 % for the rainy season and 11 % for the non-rainy season) larger daily rainfall amounts than Glen. Concerning localisation, Pretoria had higher rainfall event amount (10 % on average) than Glen while Glen had greater rainfall event duration (23 % on average) and daily rainfall (7 % on average) than Pretoria. However, peak rainfall intensity at Glen was similar to Pretoria.

It is necessary to identify the distribution of rainfall data sets. This helps in applying the correct methodology for analysing probability curves. The rainfall intensity data at Glen and Bloemfontein was observed to have a skew distribution. In this case, non-symmetric distribution functions may be employed for describing the data, such as the gamma distribution. The gamma probability density function on x is given by:

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} \exp\left(-\frac{x}{\beta}\right) \qquad x > 0, \alpha > 0, \beta > 0 \tag{2.1}$$

where α is the shape parameter and β is the scale parameter, and $\Gamma(\alpha)$ is the gamma function, which has a useful property as follows:

$$\Gamma(\alpha + 1) = \alpha\Gamma(\alpha) \tag{2.2}$$

The two parameters can be estimated from the mean, $E(x)$, and variance, $V(x)$(method of moments):

$$E(x) = \alpha\beta \tag{2.3}$$

$$V(x) = \alpha\beta^{2} \tag{2.4}$$

For $\alpha \leq 1$, the probability density function is an exponential distribution while for $\alpha > 1$, the probability density function is a non-symmetrical bell shaped distribution. As the α increases, the probability density function varies from a highly non-symmetrical distribution with large positive skewness to a broad and flat bell shaped distribution. The height of the probability density function decreases as β increases.

The parameters α and β for daily rainfall amount, peak rainfall intensity, event rainfall amount and event rainfall duration for all months, the rainy season and the non-rainy season were estimated, as shown in Table 2.2. Generally, in all seasons and the rainy season, Glen was analogous in both of the parameters α and β for daily rainfall amount and event rainfall amount to Bloemfontein and Pretoria, while Glen had greater α and smaller β values than the other locations in the non-rainy season. For event rainfall duration, the shape parameters for all months, the rainy season and the non-rainy season were greater in Glen than in Bloemfontein and Pretoria, but Glen had smaller scale parameters than the other locations. For peak rainfall intensity, there were greater α and smaller β in all months and the rainy season at Glen than at Glen and Pretoria while Bloemfontein had greater α and smaller β in the non-rainy season than the other location.

The gamma probability density curves for daily rainfall amount, event rainfall amount, event rainfall duration and peak rainfall intensity at Glen, Bloemfontein and Pretoria are presented in Figure 2.2. With the excepting of the density curve for event rainfall duration at Glen in the non-rainy season, the probability densities decreased exponentially as the x-axis values increased since the parameter α was less than one. In other words, probabilities of getting small and great x-axis values tended to be high and low, respectively. In general, the probability curves for all seasons were similar to those for the rainy season, but different from those for the non-rainy season.

Table 2.2. The shape and scale parameters (α and β, respectively) of the gamma probability density function for Glen, Bloemfontein and Pretoria.

Location	Factor	Season*	Daily rainfall (mm)	Event amount (mm)	Event duration (min)	Peak intensity (mm/min)
Glen	α (shape)	All months	0.500	0.399	0.759	0.598
		Rainy	0.504	0.400	0.720	0.652
		Non-rainy	0.598	0.466	1.131	0.305
	β (scale)	All months	12.3	13.0	215	0.646
		Rainy	12.7	13.5	225	0.617
		Non-rainy	7.3	8.3	150	0.901
Bloemfontein	α (shape)	All months	0.482	0.384	0.489	0.321
		Rainy	0.507	0.400	0.504	0.322
		Non-rainy	0.402	0.316	0.453	0.396
	β (scale)	All months	13.9	12.6	264	0.888
		Rainy	14.1	12.6	250	0.931
		Non-rainy	12.2	12.1	321	0.437
Pretoria	α (shape)	All months	0.450	0.420	0.490	0.235
		Rainy	0.462	0.428	0.479	0.240
		Non-rainy	0.402	0.399	0.594	0.260
	β (scale)	All months	14.9	14.2	265	1.593
		Rainy	15.1	14.4	269	1.632
		Non-rainy	10.7	10.2	231	0.826

* Rainy season: from October to April (including January, February, March, April, October, November and December); Non-rainy season: from May to September (including May, June, July, August and September).

The Chi-Square Goodness-of-Fit Test was carried out to compare the observed values, including event rainfall amount and duration, peak intensity and daily rainfall, with the expected values. The data was categorised into 10 groups. All two-tailed P values are shown in Table 2.3. In all locations, the P values for the non-rainy season were greater than 0.05, indicating not statistically significant difference. This means that the gamma distribution describes distributions of the event rainfall amount, the event rainfall duration and the peak rainfall intensity as well as the daily rainfall amount. In contrast, there were significant differences in peak rainfall intensity for all months and the rainy season (p value < 0.05). There were significant differences in the daily rainfall, the event rainfall amount and the event rainfall duration for all months and the rainy season at

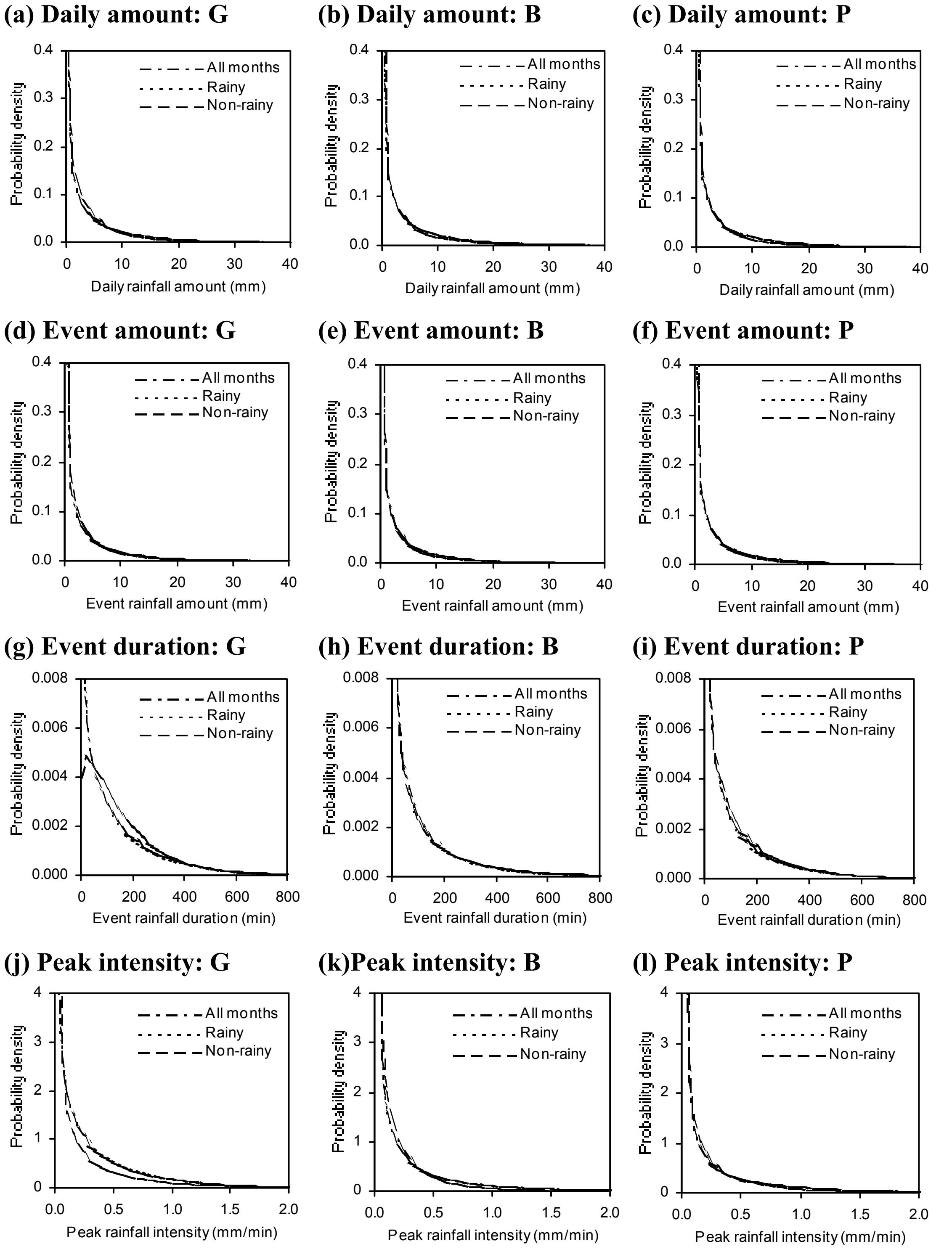


Figure 2.2. The gamma probability density functions for daily rainfall amount, event rainfall amount and duration, and peak rainfall intensity at Glen (G), Bloemfontein (B) and Pretoria (P).

Table 2.3. The Chi-Square Goodness-of-Fit Test (the two-tailed P values) for the gamma probability density function for Glen, Bloemfontein and Pretoria.

Location	Season*	Daily rainfall (mm)	Event amount (mm)	Event duration (min)	Peak intensity (mm/min)
Glen	All months	0.6154	0.1904	0.8138	0.0017
	Rainy	0.6400	0.2338	0.6000	0.0412
	Non-rainy	0.4020	0.3683	0.8610	0.5610
Bloemfontein	All months	0.5590	0.6670	0.9218	0.0001
	Rainy	0.9713	0.1093	0.9162	0.0005
	Non-rainy	0.6509	0.9354	0.1191	0.6713
Pretoria	All months	0.0319	0.0001	0.0235	0.0001
	Rainy	0.0278	0.0001	0.0124	0.0001
	Non-rainy	0.4329	0.1402	0.7141	0.7496

* Rainy season: from October to April (including January, February, March, April, October, November and December); Non-rainy season: from May to September (including May, June, July, August and September).

Pretoria, but no difference was found at Glen and Bloemfontein. From the results, it can be concluded that the gamma probability density function can describe data distribution of daily rainfall, event rainfall amount and duration, and peak rainfall intensity, but may not describe peak rainfall intensity for rainy season.

From the gamma cumulative distribution functions for daily rainfall amount, as shown in Figure 2.3, there were the probabilities of 25, 50 and 75 % of receiving the daily rainfall amount of less than 0.5, 2.8 and 8.1 mm, respectively, at Glen; 0.6, 2.9 and 8.8 mm at Bloemfontein and 0.5, 2.8 and 8.7 mm at Pretoria in all months, as shown in Table 2.4. It can be rephrased that the probabilities of obtaining more than 0.5, 2.8 and 8.1 mm at Glen, 0.6, 2.9 and 8.8 mm at Bloemfontein and 0.5, 2.8 and 8.7 mm at Pretoria were 75, 50 and 25 %. At all locations, the rainy season had similar values in daily rainfall amount to all months, however, the non-rainy season had lower values than all months. This tendency was also found for event rainfall amount (Table 2.4).

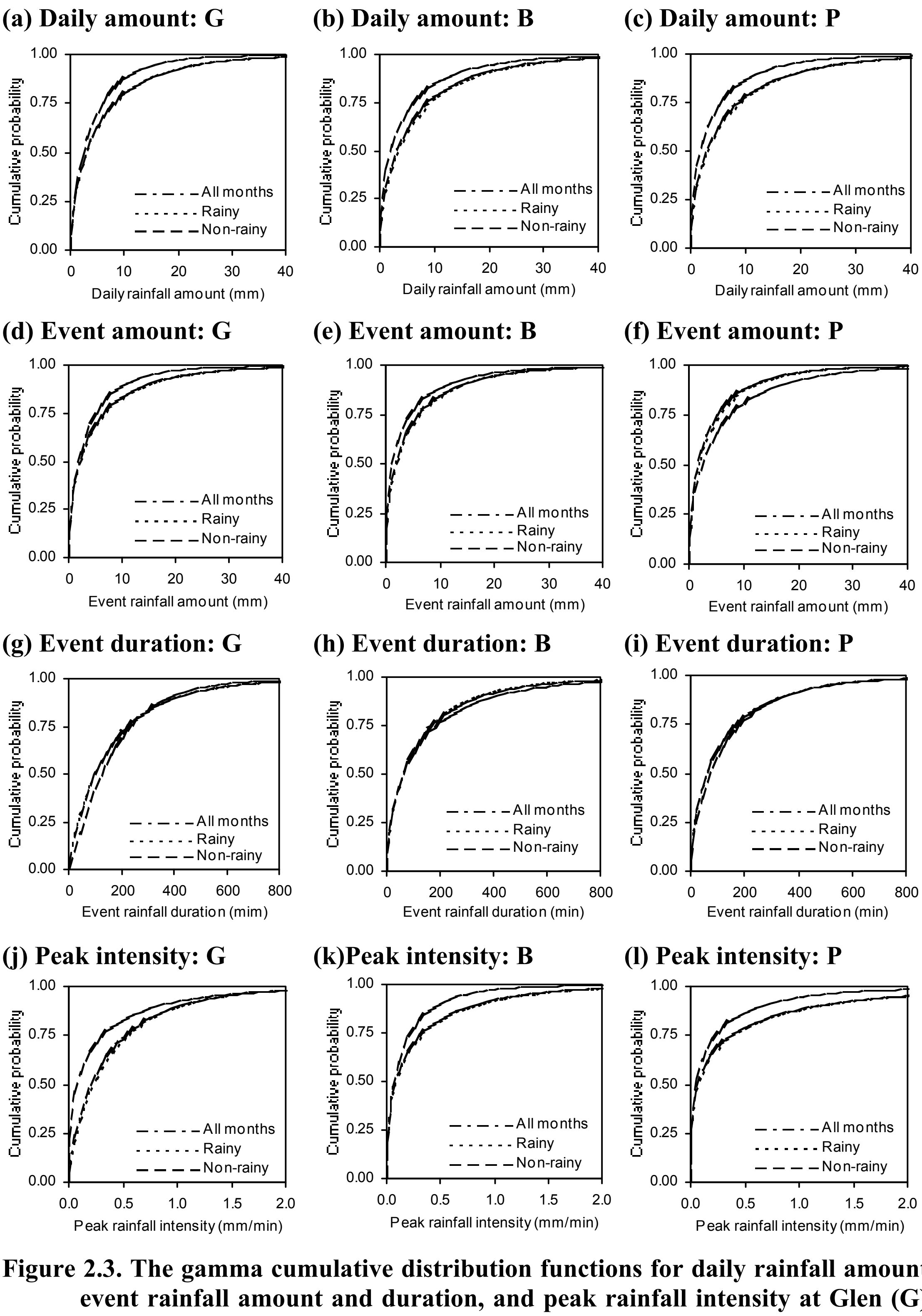


Figure 2.3. The gamma cumulative distribution functions for daily rainfall amount, event rainfall amount and duration, and peak rainfall intensity at Glen (G), Bloemfontein (B) and Pretoria (P).

Table 2.4. Daily rainfall amount, event rainfall amount, event rainfall duration and peak rainfall intensity at three probability levels (25, 50 and 75 %) of the gamma cumulative distribution functions for Glen, Bloemfontein and Pretoria.

Location	Factor	Season*	Probability level		
			25 %	50 %	75 %
Glen	Daily rainfall (mm)	All months	0.5	2.8	8.1
		Rainy	0.6	2.8	8.2
		Non-rainy	0.6	2.3	5.9
	Event amount (mm)	All months	0.3	1.9	6.5
		Rainy	0.3	2.0	6.8
		Non-rainy	0.3	1.6	5.1
	Event duration (min)	All months	34	99	225
		Rainy	31	96	223
		Non-rainy	55	123	235
	Peak intensity (mm/min)	All months	0.056	0.203	0.524
		Rainy	0.067	0.224	0.550
		Non-rainy	0.007	0.069	0.316
Bloemfontein	Daily rainfall (mm)	All months	0.6	2.9	8.8
		Rainy	0.7	3.3	9.5
		Non-rainy	0.3	1.8	6.2
	Event amount (mm)	All months	0.3	1.7	6.0
		Rainy	0.3	1.8	6.4
		Non-rainy	0.1	1.0	4.5
	Event duration (min)	All months	12	58	170
		Rainy	13	58	167
		Non-rainy	12	60	189
	Peak intensity (mm/min)	All months	0.008	0.077	0.335
		Rainy	0.009	0.081	0.360
		Non-rainy	0.010	0.062	0.218
Pretoria	Daily rainfall (mm)	All months	0.5	2.8	8.7
		Rainy	0.6	2.9	9.1
		Non-rainy	0.3	1.6	5.4
	Event amount (mm)	All months	0.4	2.3	7.6
		Rainy	0.4	2.4	7.9
		Non-rainy	0.2	1.5	5.1
	Event duration (min)	All months	13	58	171
		Rainy	12	56	169
		Non-rainy	19	72	186
	Peak intensity (mm/min)	All months	0.003	0.057	0.376
		Rainy	0.003	0.063	0.398
		Non-rainy	0.003	0.041	0.229

* Rainy season: from October to April (including January, February, March, April, October, November and December); Non-rainy season: from May to September (including May, June, July, August and September).

Concerning event rainfall duration, there were the probabilities of 25, 50 and 75 % of rainfall for a time period of less than 34, 99 and 225 min, respectively, at Glen, less than 12, 58 and 170 min at Bloemfontein and less than 13, 58 and 171 min at Pretoria in all months, and both rainy and non-rainy seasons had similar results to all months (Table 2.4). As shown in Table 2.4, probabilities of obtaining the peak rainfall intensity of more than 0.056, 0.203 and 0.524 mm/min at Glen, 0.008, 0.077 and 0.355 mm/min at Bloemfontein and 0.003, 0.057 and 0.376 mm/min at Pretoria were 75, 50 and 25 % in all months, respectively. Data from all months had equivalent values in peak rainfall intensity to the rainy season, but greater values than the non-rainy season at all locations as the rainy season data dominates the data set. Also, there were no differences in either daily or event amounts of rainfall among Glen, Bloemfontein and Pretoria, however, Glen had higher values in event rainfall duration and peak rainfall intensity than Bloemfontein and Pretoria.

2.2. Relationships of rainfall intensity with event rainfall

Data sets of event rainfall at Glen (1992–2001; 401 data points), Bloemfontein (1962–1992; 3128 data points) and Pretoria (1966–1996; 2676 data points) were used to analyse relationships of peak rainfall intensity with event rainfall amount and duration. The data were classified into three levels: (i) Duration ≤ 60 min, (ii) 60 min < Duration ≤ 180 min, and (iii) Duration > 180 min. Figures 2.4, 2.5 and 2.6 show relationships between peak rainfall intensity and event rainfall amount at three classes for all months, the rainy season and the non-rainy season, respectively. In all classes of event rainfall duration, peak rainfall intensity positively correlated with event rainfall amount at all locations. Moreover, as the duration increased, rates of peak rainfall intensity to event rainfall amount (slopes of the equations given in Figures 2.4, 2.5 and 2.6) decreased, implying that peak rainfall intensity was negatively correlated with event rainfall duration.

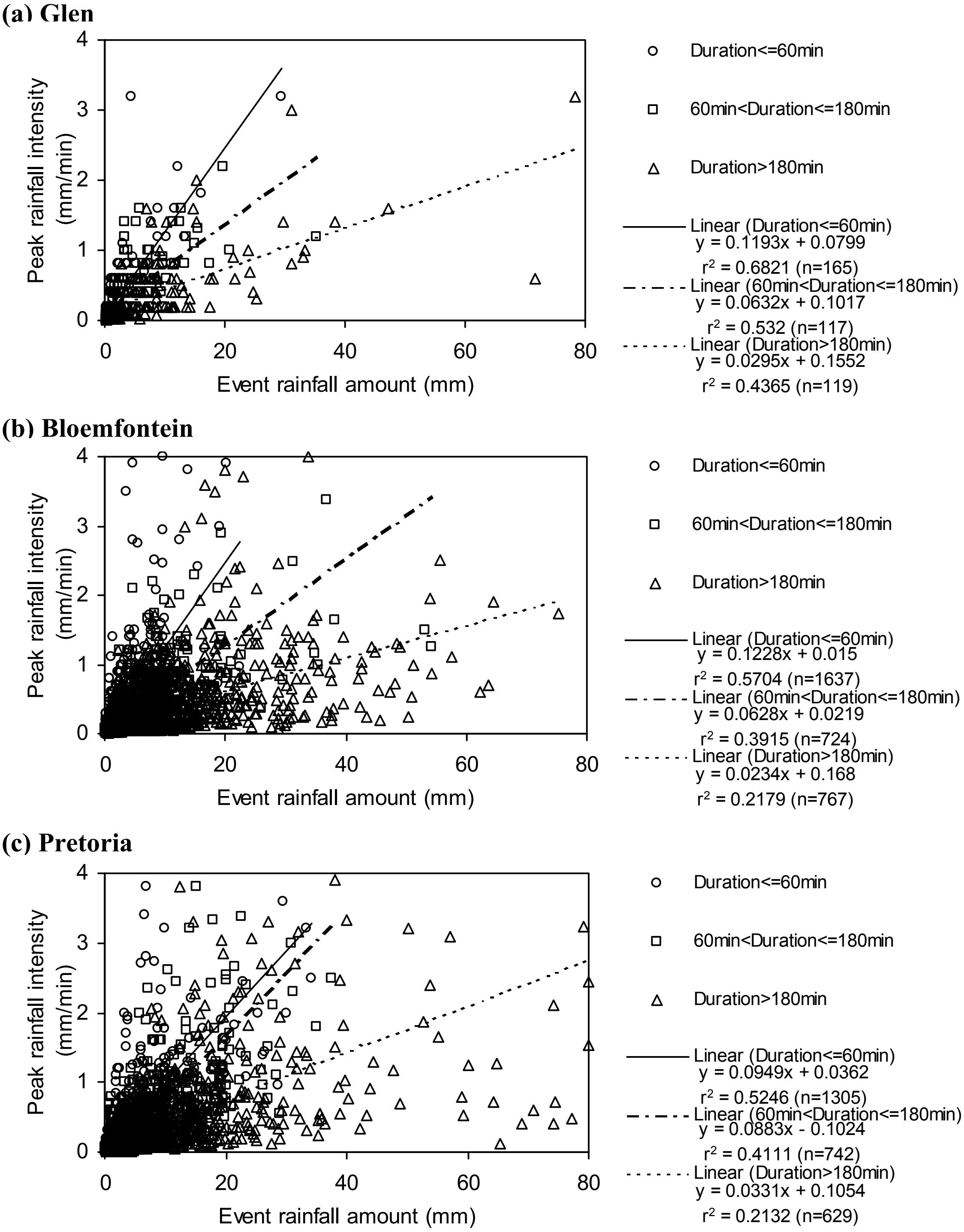


Figure 2.4. Relationships of peak rainfall intensity with event rainfall at Glen, Bloemfontein and Pretoria for all months.

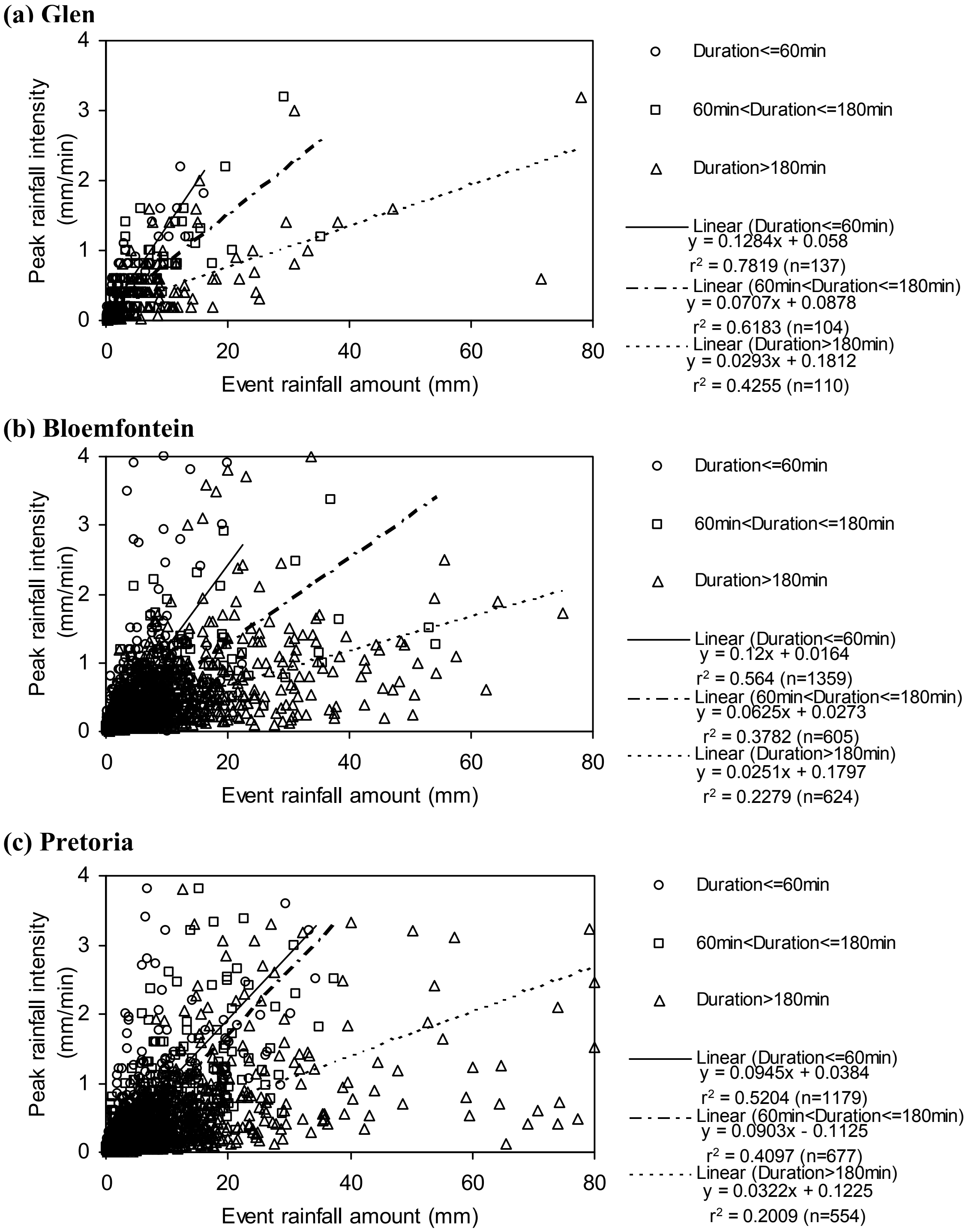


Figure 2.5. Relationships of peak rainfall intensity with event rainfall at Glen, Bloemfontein and Pretoria for the rainy season (ONDJFMA).

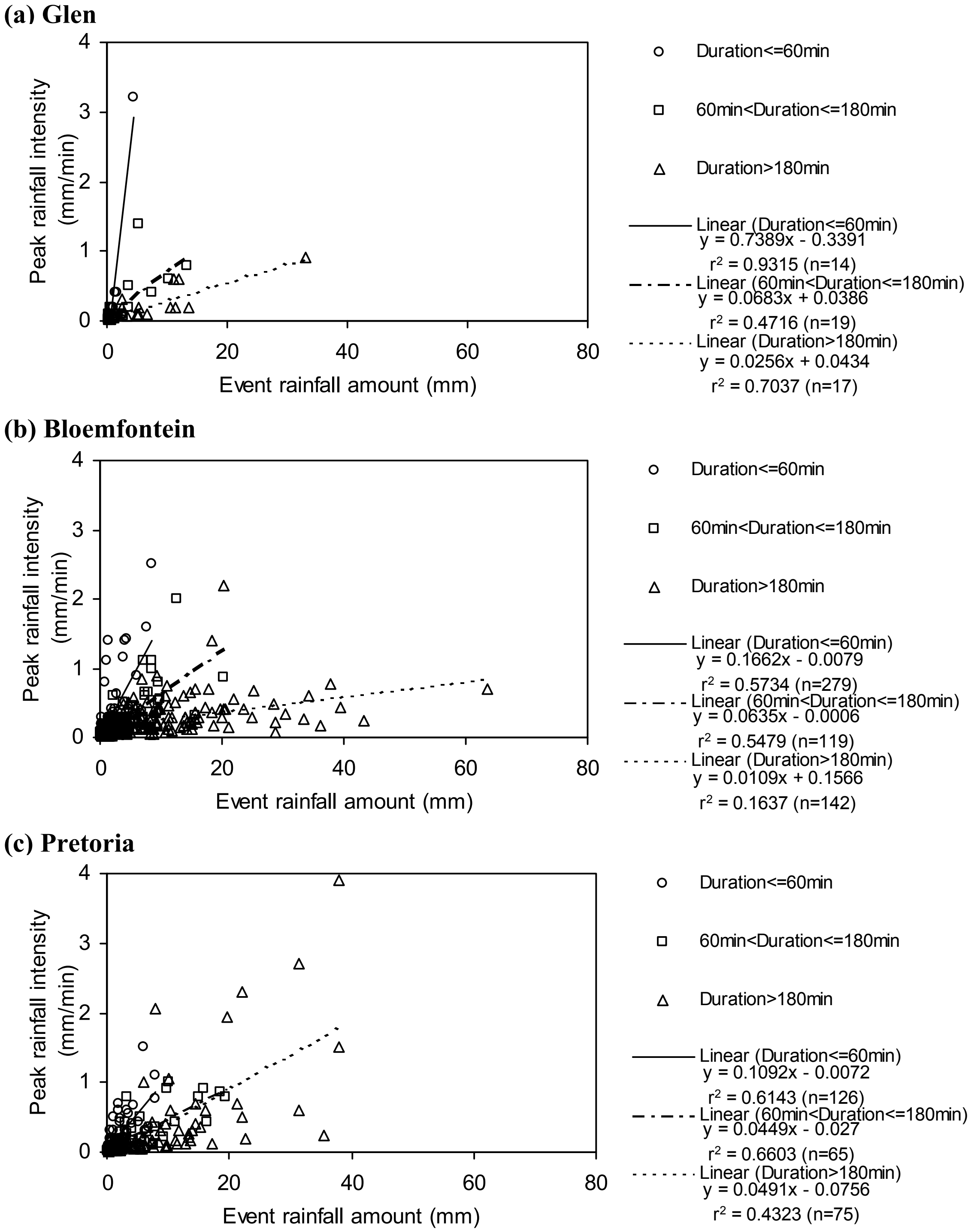


Figure 2.6. Relationships of peak rainfall intensity with event rainfall at Glen, Bloemfontein and Pretoria for the non-rainy season (MJJAS).

The relationships of peak rainfall intensity with event rainfall for Glen were analogous to those for Bloemfontein in all months and the rainy season. However, in the non-rainy season, the relationships for Glen were different from those for Bloemfontein in the duration classes Duration ≤ 60 min and Duration > 180 min, although there was a similar relationships of peak rainfall intensity with event rainfall amount between locations in the duration class 60 min < Duration ≤ 180 min (Figure 2.6). Concerning locality, Pretoria had slightly different relationships of peak rainfall intensity with event rainfall amount and duration from Glen and Bloemfontein.. The r-square for all months and the rainy season are between 0.2 and 0.7 and between 0.2 and 0.8, respectively, so it is not possible to use these equations with any confidence to estimate the rainfall intensity from the daily/event rainfall amount from the historical record, especially at the long event rainfall duration (Duration > 180 min).

The monthly rainfall data was averaged, and the mean monthly peak rainfall intensity was plotted against the mean monthly event rainfall amount and duration, as shown in Figures 2.7 and 2.8. From the fitted lines shown in Figures 2.7 and 2.8, the higher the event rainfall amount, the greater the peak rainfall intensity, in contrast, the higher the event rainfall duration, the smaller the peak rainfall intensity. Thus, peak rainfall intensity was positively and negatively correlated with the amount and duration of event rainfall, respectively. With respect to seasonal variability, the rainy season (October–April) has a tendency to have higher peak rainfall intensity and event rainfall amount, and lower event rainfall duration than the non-rainy season (May–September). The rainy and non-rainy seasons were distinctly different for the Bloemfontein data set (Figure 2.8).

The linear equations for the relationships of peak rainfall intensity with the amount and duration of event rainfall are as follows:

$$P_{\max} = \begin{cases} 0.0509RF + 0.1192 & \text{Glen} \\ 0.0694RF - 0.0616 & \text{Bloemfontein} \\ 0.0662RF - 0.0311 & \text{Pretoria} \end{cases} \qquad (2.5)$$

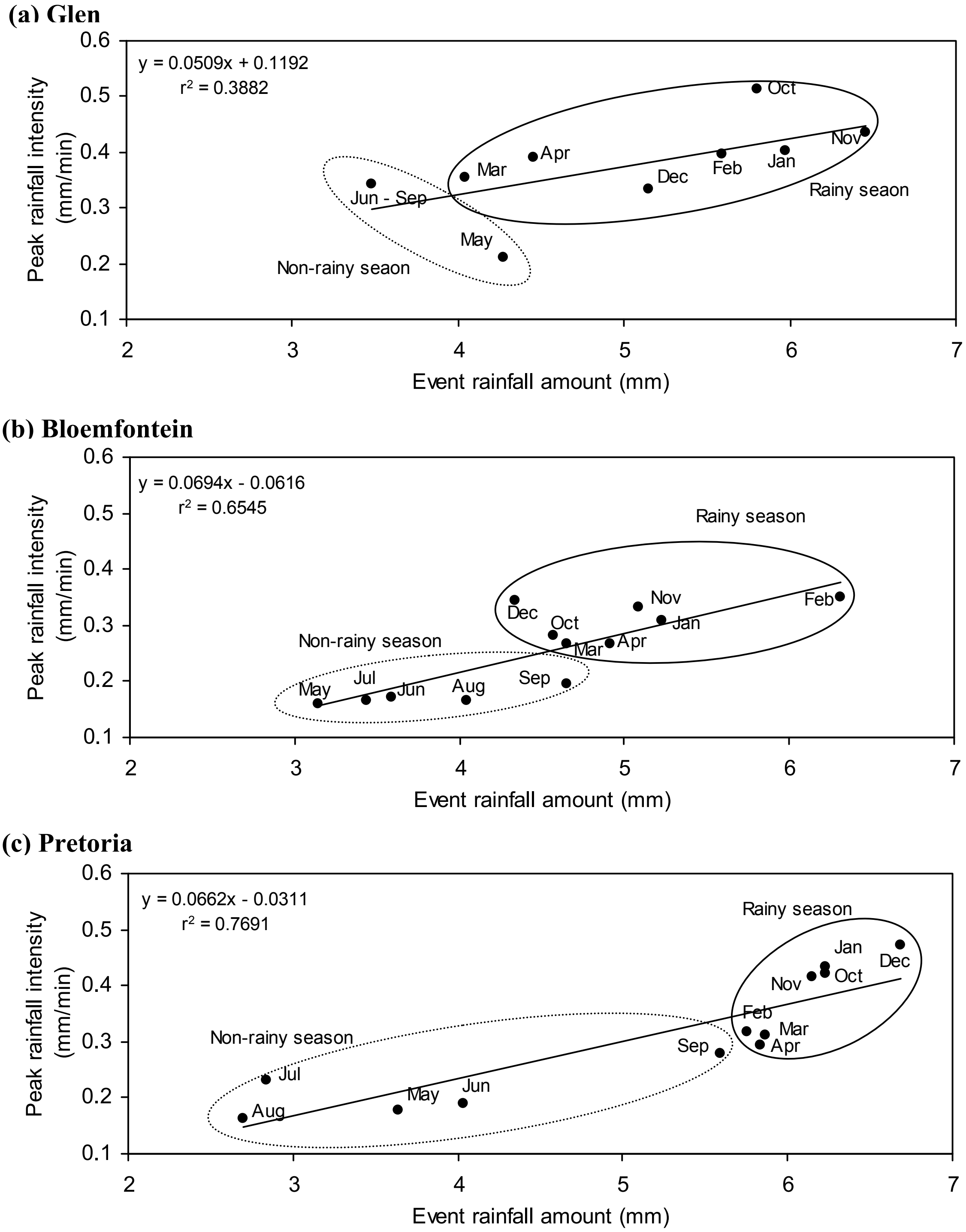


Figure 2.7. Relationships of mean monthly peak rainfall intensity with the monthly mean event rainfall at Glen, Bloemfontein and Pretoria (linear equations are for data sets for all months).

(a) Glen

(b) Bloemfontein

(c) Pretoria

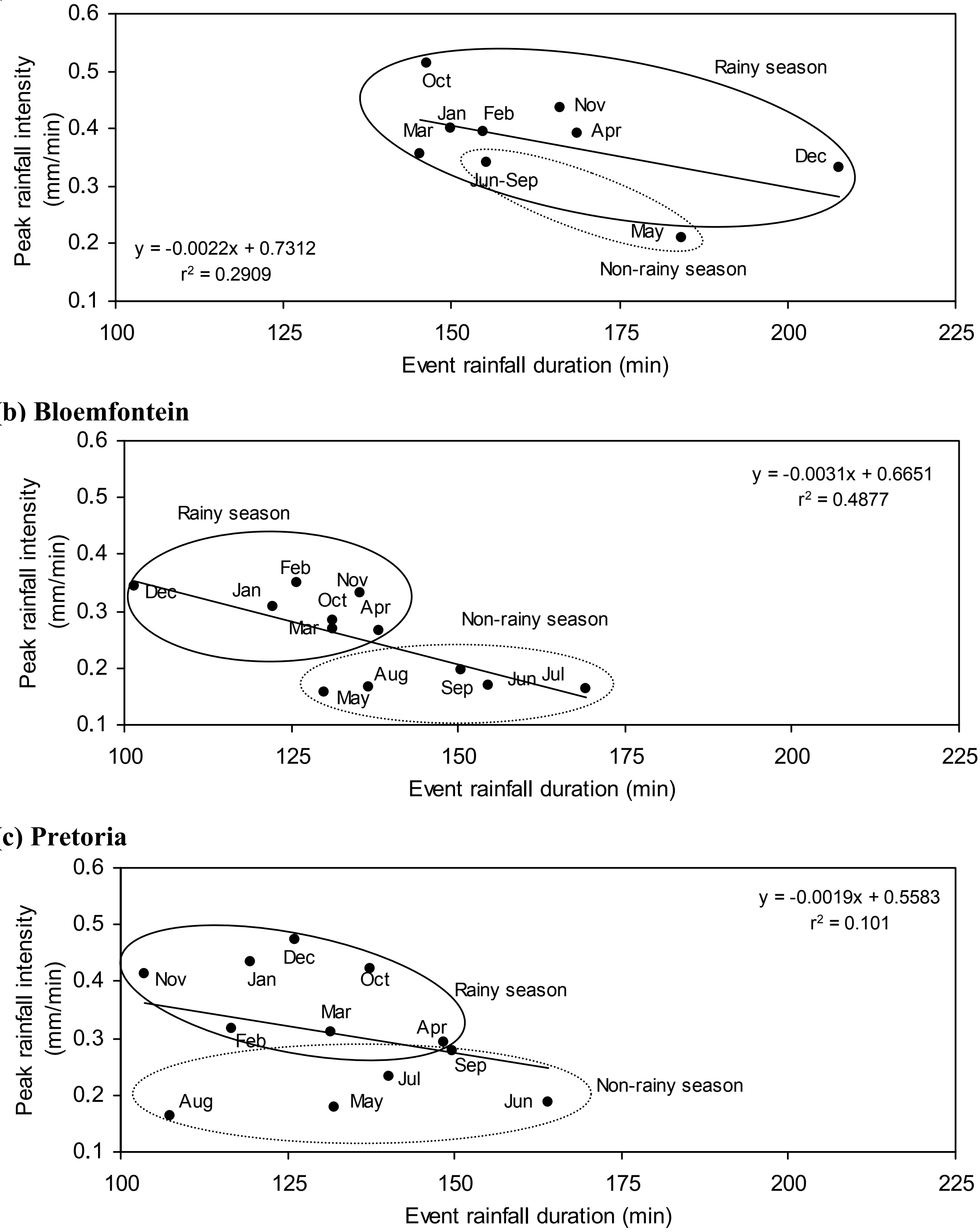


Figure 2.8. Relationships of mean monthly peak rainfall intensity with the monthly mean event rainfall duration at Glen, Bloemfontein and Pretoria (linear equations are for data sets for all months).

$$P_{\max} = \begin{cases} -0.0022t + 0.7312 & \text{Glen} \\ -0.0031t + 0.6651 & \text{Bloemfontein} \\ -0.0019t + 0.5583 & \text{Pretoria} \end{cases} \quad (2.6)$$

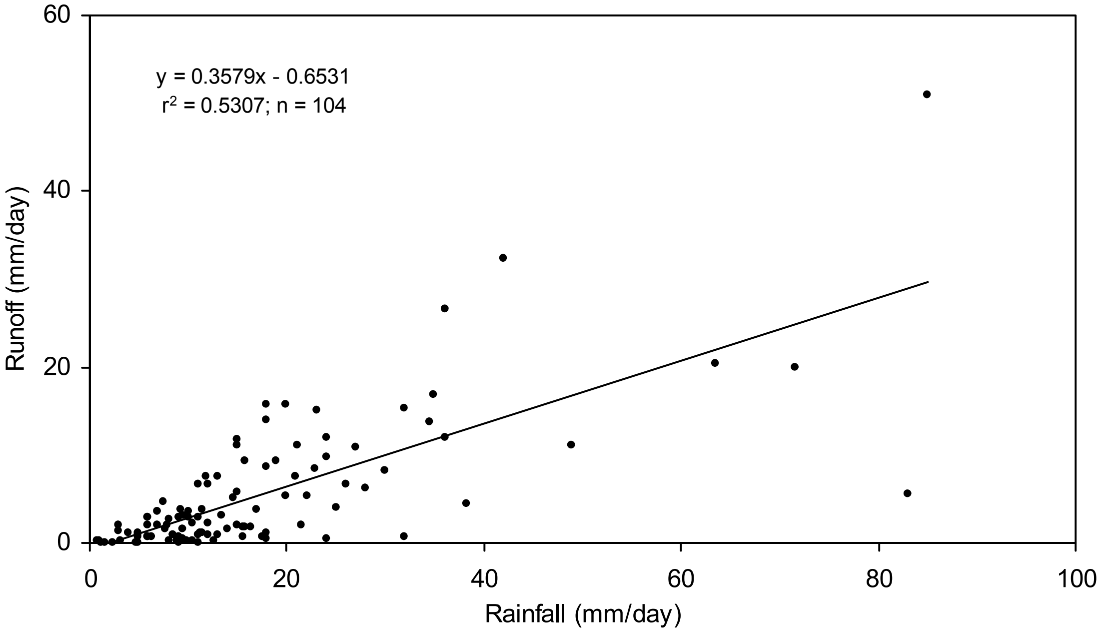
where P_{max} is peak rainfall intensity, *RF* is the amount of rainfall, and *t* is the duration of rainfall. The r-square for the relationships of the rainfall intensity with event amount and duration are between 0.4 and 0.8 and between 0.1 and 0.5, respectively. Thus, it is not possible to use these equations to estimate the rainfall intensity from the rainfall event amount or duration.

2.3. Relationships between rainfall and runoff

Daily runoff data at Glen (104 data points for the Glen/Bonheim benchmark ecotope and 124 data points for the Glen/Swartland bechmark ecotope) from 1996 to 2001 were analysed for a relationship with daily rainfall, excluding the data when it rained but no runoff was recorded. Runoff measurements were taken on 3 m wide × 20 m long runoff plots (1 % slope) (Hensley *et al.*, 2000). The mean and standard deviation of daily runoff for Glen/Bonheim (5.4 ± 7.5 mm) were equivalent to those for Glen/Swartland (5.4 ± 7.6 mm). Relationships between rainfall and runoff for Glen are shown in Figure 2.9. In both ecotopes, there was a moderate linear relationship between runoff and rainfall. Ignoring the intercept of the equations given in Figure 2.9, the amount of daily runoff for Glen/Bonleim is estimated to be 36 % of the amount of daily rainfall. Similarly, daily runoff for Glen/Swartland was 41 % of daily rainfall. However, as the amount of daily rainfall increased, the daily runoff was widely scattered. That is, the model could provide a good estimate at low rainfall amounts, but could not at high daily rainfall amounts.

In both Glen/Bonheim and Glen/Swartland, when daily rainfall was less than 2 mm, almost no daily runoff was measured. For reassessment, the runoff data was classified into two levels of daily rainfall amounts: (i) Rainfall ≤ 2 mm and (ii) Rainfall > 2 mm. The mean of daily runoff was 0.1 mm for both ecotopes when Rainfall ≤ 2 mm,

(a) Glen/Bonheim



(b) Glen/Swartland

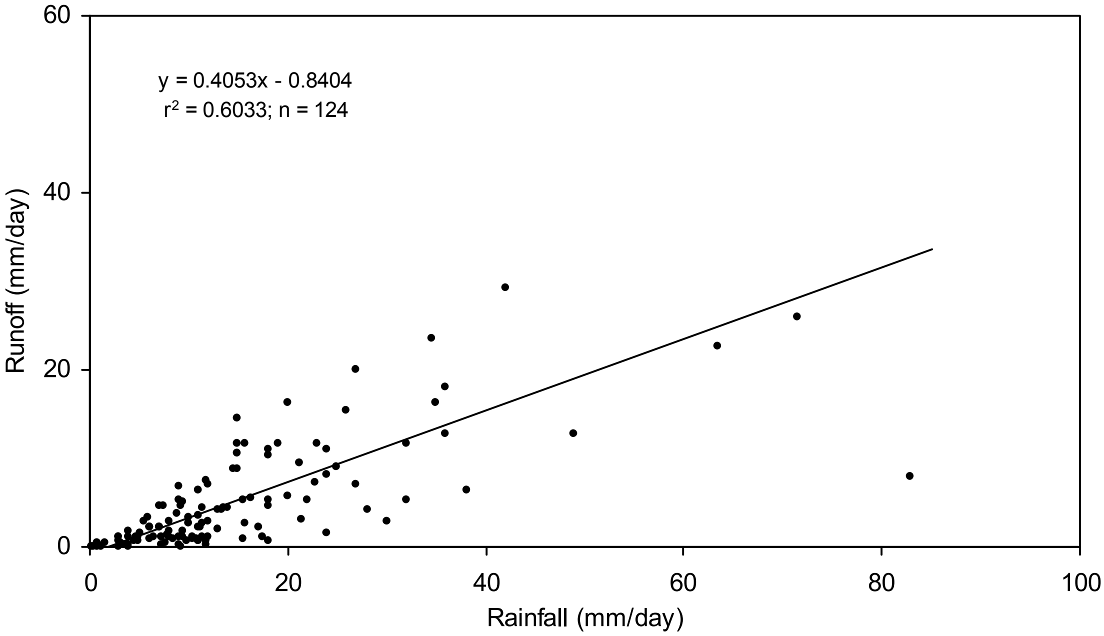


Figure 2.9. Relationships between daily rainfall and runoff at Glen.

suggesting that runoff can be perhaps ignored if daily rainfall ≤ 2 mm. When Rainfall > 2 mm, mean and standard deviation of daily runoff was 5.7 ± 7.6 mm for Glen/Bonheim and 5.7 ± 7.7 mm for Glen/Swartland. There were also moderate linear relationships between runoff and rainfall (r^2 = 0.52 for Glen/Bonheim and r^2 = 0.59 for Glen/Swartland). The ratio of runoff to rainfall was 36 % for Glen/Bonheim and 41 % for Glen/Swartland, which was exactly equal to the above results found with the complete data set.

Although the simple linear model could be used to estimate the daily amount of runoff from the daily amount of rainfall, it may be better to estimate runoff from rainfall intensity, as modelled by Morin and Cluff (1980). However, rainfall intensity data is not obtainable from most South African weather stations. So, this linear method could not be used. Therefore, in the following chapter (Chapter 3), further studies on modelling rainfall intensity-daily rainfall relationships have been carried out.

Chapter 3
Predicting Rainfall Intensity from Daily Rainfall Amount

3.1. The area under the rainfall intensity curve

The main challenge of this project is "to generate rainfall intensity information and then to estimate runoff." There are two procedures to model rainfall-runoff processes. As a direct method, the amount of runoff may be simply estimated from the amount of rainfall above a specified intensity, while the other method has two steps: (i) rainfall intensity information generation and (ii) runoff estimation from rainfall intensity (e.g., Morin and Cluff, 1980). In this chapter, the following methods for generating rainfall intensity are presented:

(a) The area under the rainfall intensity curve method
(b) Stepwise regression techniques (with surface weather data)
(c) Artificial neural networks (with meteorological satellite data)

The theory of the area under the rainfall intensity curve method is the same as that of the Φ index method. As mentioned in Section 1.2 (in Chapter 1), the area under the rainfall intensity curve (P_i) is defined as the amount of rainfall (mm) with rainfall intensity that is greater than a given i value (mm/hr), which is equivalent to the amount of runoff. For example, let i = 6 mm/hr, P_6 is the sum of X for each time period in Figure 3.1. This is perhaps a better method than the simple rainfall-runoff regression.

Figure 3.2 shows an example of measured rainfall intensity over time for a particular event at Glen. Rainfall was recorded between 22:30 and 0:30, and the daily rainfall and peak intensity were 12.4 mm and 1.4 mm/min (= 84 mm/hr), respectively. Daily rainfall (P_d) is defined as the amount of rainfall measured from 8:00 am of a specific day to 8:00 am of the following day. Concerning P_i, in Figure 3.2, for example, when rainfall intensity i is greater than 6, 18 and 54 mm/hr, then the values of P_6, P_{18} and P_{54} are 7.6, 4.8 and 0.6 mm, respectively.

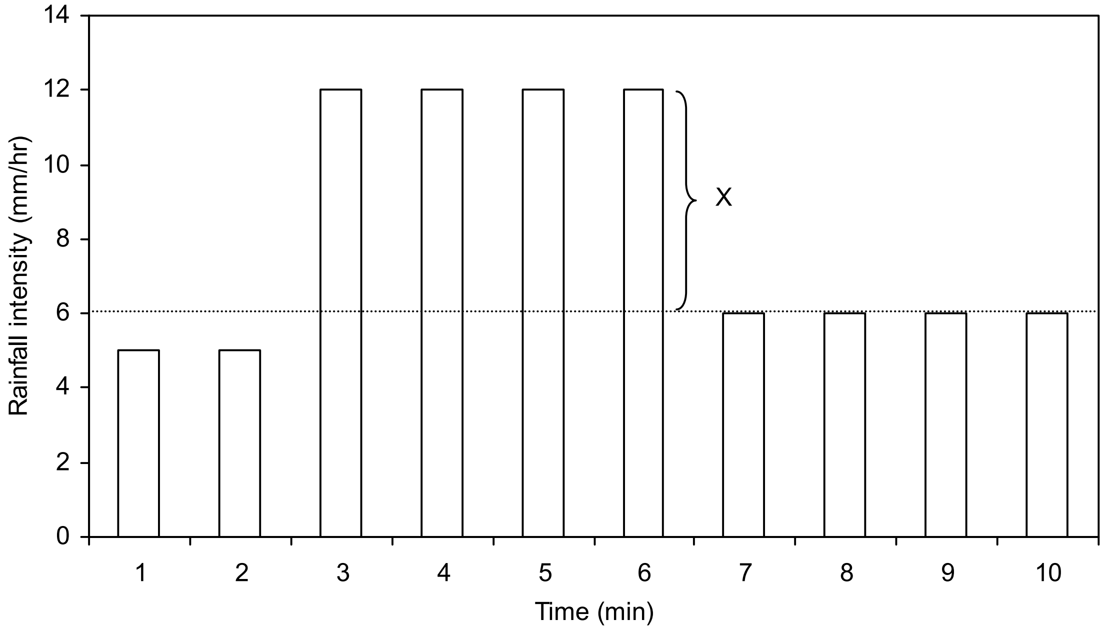


Figure 3.1. Plots of rainfall intensity indicating the threshold value of 6 mm/hr

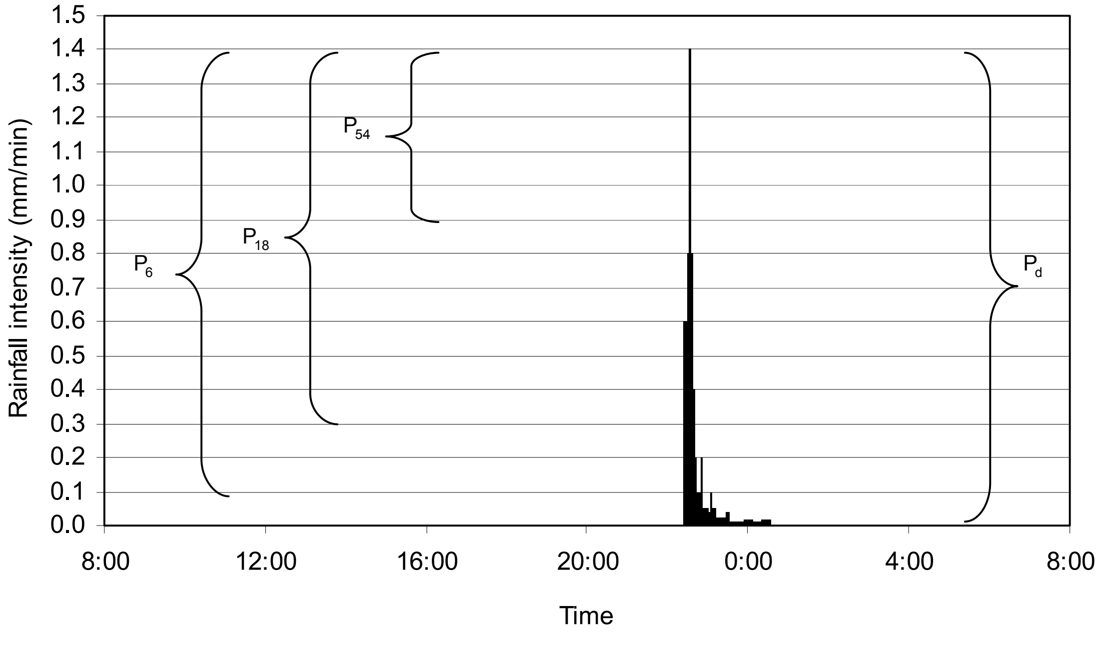


Figure 3.2. Measured rainfall intensity (mm/min) from 8am, 23 Jan., 1999 to 8am, 24 Jan., 1999 at Glen.

In the study by Hensley *et al.* (2000), it was found that the final infiltration rate for the Glen/Bonheim and Glen/Swartland benchmark ecotopes was 6 mm/hr. When rainfall intensity was greater than this rainfall intensity value and the soil was wet and saturated, then runoff occurred. The area under the rainfall intensity curve when rainfall intensity is greater than 6 mm/hr (0.1 mm/min), P_6 (mm) might be equivalent to the amount of runoff (mm). Moreover, the amount of minimum daily rainfall which might cause runoff was taken to be 8 mm because little runoff occurred at Glen when daily rainfall was less than 8 mm (Dr. Hensley, personal communication, 2002), although this threshold value was given 2 mm in Section 2.3 (in Chapter 2). Thus, the previous findings have suggested that the area under the rainfall intensity curve model probably estimates the amount of daily runoff from P_d when P_d is greater than 8 mm. Rainfall intensity data of seven locations on the highveld (272 data from 1992 to 2001), including Bethal (two ecotopes), Ermelo, Glen, Kroonstad, Petrusburg and Wolmaranstad was used to develop a relationship between P_6 and P_d for benchmark ecotopes on the highveld (Hensley *et al.*, 1997, 2000). The assumption is made that the rainfall intensity pattern across the highveld is reasonably homogeneous. A linear model, as shown in Figure 3.3, was found to be satisfactory. The coefficient of determination (r^2 = 0.73) was reasonably acceptable, enabling P_6 to be estimated from P_d, using the following equation:

$$P_6 = \begin{cases} 0 & P_d \le 8mm \\ 0.61P_d - 3.11 & P_d > 8mm \end{cases} \tag{3.1}$$

Daily runoff data for Glen from 1996 to 2001, which was collected by Dr. Hensley and his research team, was used to test the area under the rainfall intensity curve model for the Glen/Bonheim and Glen/Swartland ecotopes. Plots of the measured daily runoff from both ecotopes against P_6 are shown in Figure 3.4. The data scattered around 1:1 line between 0 and 60 mm, especially between 0 and 20 mm. The slope of the fitted line for both ecotopes (r^2 = 0.53 for Glen/Bonheim and r^2 = 0.60 Glen/Swartland) was 0.90, being close to 1:1 line. Root mean square error (RMSE), mean absolute error (MAE) and the index of determination (d), as shown in Figure 3.4, were 6.676 mm, 3.987 mm and

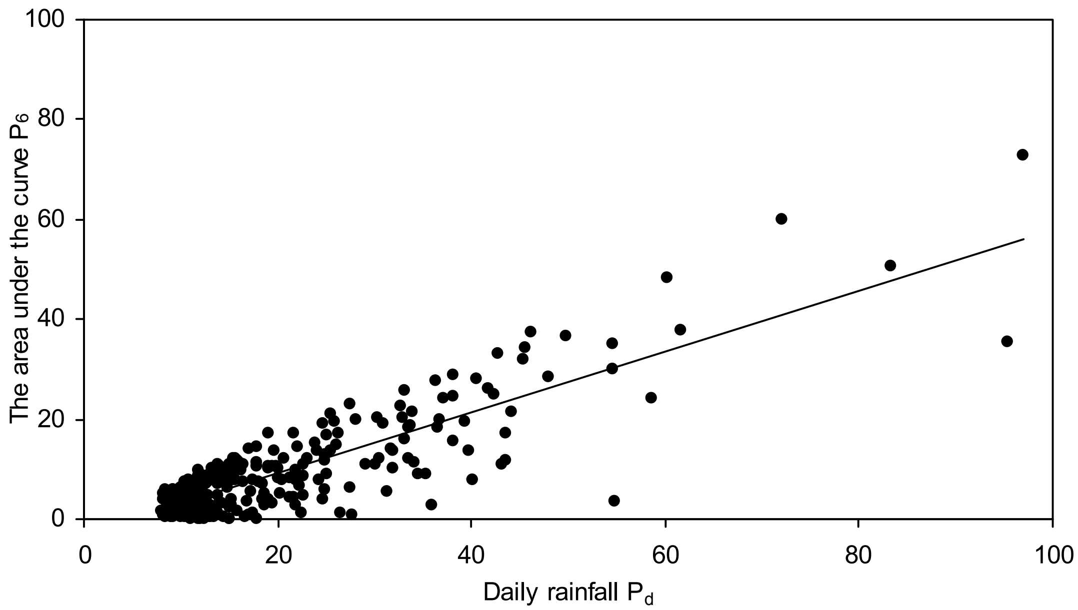
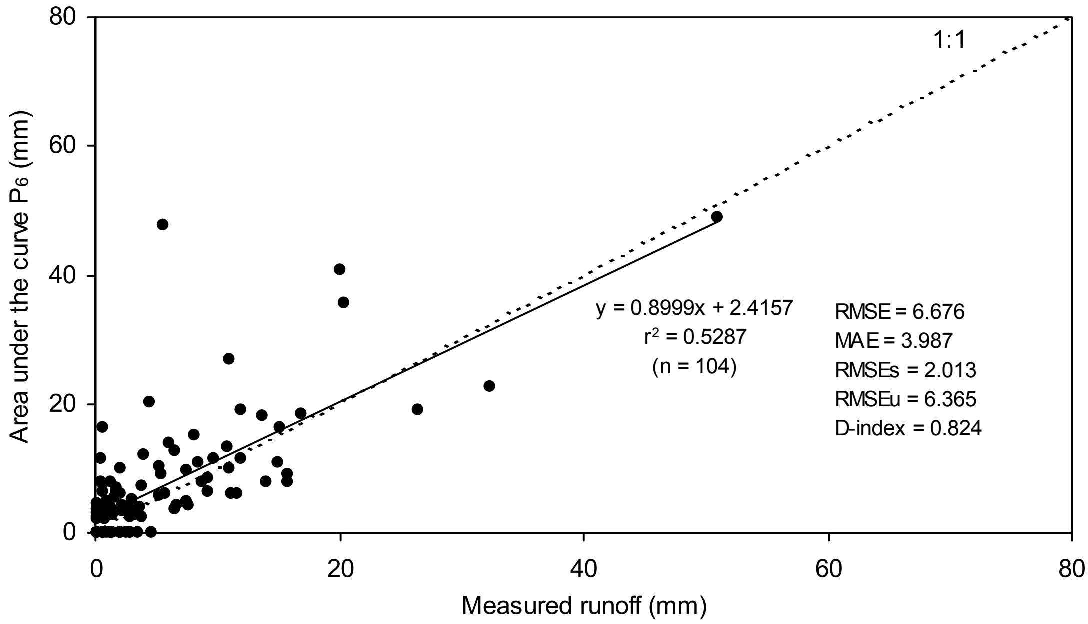


Figure 3.3. A linear relationship between P_6 and P_d for benchmark ecotopes on the highveld (daily rainfall >8 mm; 272 data of Hensley *et al.* (1997, 2000)).

0.824 for Glen/Bonheim and 5.704 mm, 3.436 mm and 0.867 for Glen/Swartland. Although RMSE and MAE gave slightly high values, d and RMSEs were acceptable values. From these statistics, it can be concluded that the area under the rainfall intensity curve model P_6 provides an acceptable daily runoff prediction for these two ecotopes.

Empirically and deterministically, if we consider the influence of weather information, such as solar radiation, temperature and wind speed, strongly link to the precipitation processes, this information can possibly be used in rainfall-runoff modelling. Daily-based weather data of Glen College and synoptic factors of Bloemfontein Airport (data at 14:00 South African Standard Time) were integrated in the simple linear model (the area under the rainfall intensity model P_6). Weather data factors included the diurnal range of maximum and minimum temperatures (*DT*) and the clearness index (*CI*), while synoptics factors included dew point, dry bulb and wet bulb temperatures (*Tdp*, *Tdb* and *Twb*, respectively) and eastward and northward wind speeds (*Wu* and *Wv*). Using the Glen rainfall intensity data, for example, the following equation was found:

(a) Glen/Bonheim



(b) Glen/Swartland

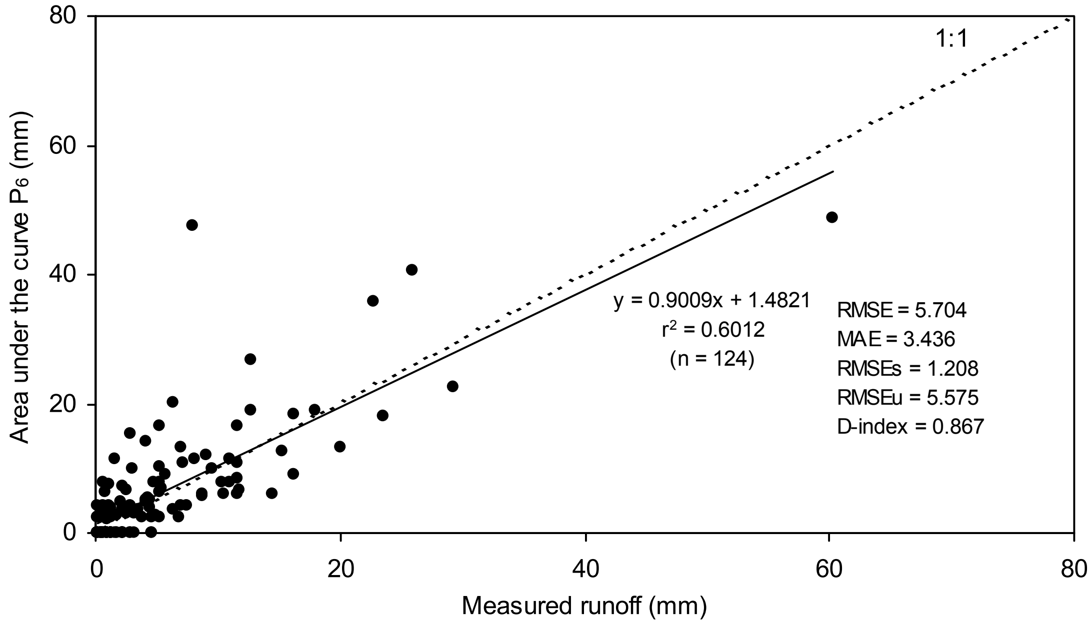


Figure 3.4. The measured runoff from Glen/Bonheim (a) and Glen/Swartland (b) against calculated P_6 area under the curve model of runoff for 1996 to 2001 data sets.

$$P_6 = 0.283P_d - 3.088 + P_d\left(0.035Tdp + 0.036Tdb - 0.058Twb\right) + P_d\left(0.013Wu - 0.003Wv\right) + P_d\left(0.014DT - 0.322CI\right) \quad (3.2)$$

The third, fourth and fifth components of the right-side of Equation 3.2 explain the effects of temperature, wind speed and daily energy-related factors, respectively, on P_d. Although the coefficient of determination ($r^2 = 0.79$) was slightly higher than that of the simple linear model, the simple linear model (Equation 3.1) was still preferred because of model simplicity, i.e., only using daily rainfall amount as input. Many other combinations of the variables also did not improve the accuracy of the model significantly.

3.2. Stepwise regression techniques

A stepwise regression analysis was carried out to model rainfall intensity factors. The factors included event rainfall amount, event rainfall duration and peak rainfall intensity, which are strongly related to daily rainfall and also to other meteorological factors, giving a distribution of a rainfall event. Several distributions of event rainfall are shown in Figure 3.5, assuming one peak rainfall intensity per rainfall event and that a basic shape of a rainfall event is a triangle. In Figure 3.5 (i) assuming constant peak rainfall intensity, then lower rainfall event duration gives less rainfall event amount, in contrast, longer rainfall event duration gives greater rainfall event amount. In Figure 3.5 (ii) assuming constant duration for a rainfall event, then the greater peak rainfall intensity, the greater event rainfall amount. In Figure 3.5 (iii) and (iv), slopes of the triangle tend to be arcs. Thus, if these three rainfall intensity factors are determined, the ideal shapes of event rainfall are described.

The Glen data of event rainfall intensity, including event rainfall amount (mm), event rainfall duration (min) and peak rainfall intensity (mm/min), from 1992 to 2001 (401 data) was used to perform a stepwise multiple linear regression analysis. All linear models include a daily rainfall variable. Weather data (daily-based data) factors of Glen College and synoptic factors at Bloemfontein Airport (data at 14:00 South African

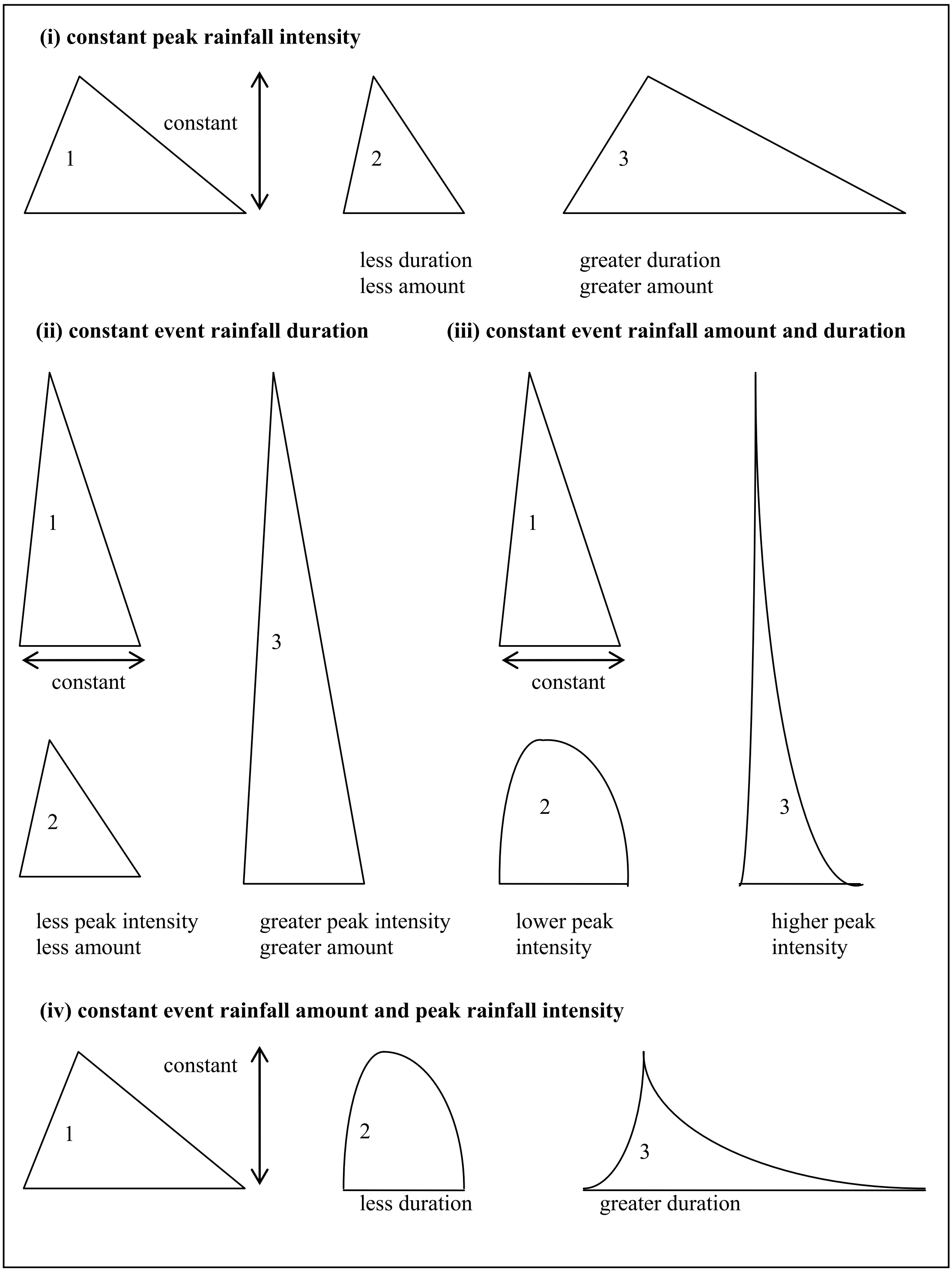


Figure 3.5. Possible shapes of rainfall events identified by event amount (area), event duration (x-axis) and peak intensity (y-axis).

Standard Time) were used. The weather factors included the diurnal range of maximum and minimum temperatures (*DT*) and the clearness index (*CI*), defined as the ratio of global to extraterrestrial solar radiation. The synoptics factors included dew point, dry bulb and wet bulb temperatures (*Tdp*, *Tdb* and *Twb*, respectively) and eastward and northward wind speeds (*Wu* and *Wv*, respectively).

As shown in Table 3.1, there were moderate relationships between event rainfall amount and model variables (daily rainfall and *CI*). However, r^2 for event rainfall duration and peak rainfall intensity was too low to accept the linear models. Thus, the shape of rainfall events could not be identified because there were no clear relationships between rainfall intensity factors and the other meteorological factors. Furthermore, after the daily synoptic charts were classified into several groups of high pressure positions or trough positions, the stepwise regression analysis was repeated, however, none of the models were improved explicitly. Similarly, in the stepwise multiple linear and interaction regression analysis (Table 3.2), there were no clear relationships between rainfall intensity factors and the other meteorological factors. Consequently, it was not possible to model the shape of rainfall events using the synoptic data or weather factors. In the next section, non-linear analysis of rainfall intensity was made with meteorological satellite data using a neural network technique.

Table 3.1. Summary of the stepwise multiple linear regression analysis*

Intensity factor	**Significant level**	**Weather variable**	**Synoptics variable**	**r^2**
Event amount	0.15	CI	None	0.599
	0.10	None	None	0.597
Event duration	0.15 and 0.10	CI	None	0.184
Peak intensity	0.15 and 0.10	CI	None	0.305

All models include a daily rainfall variable RF.

Table 3.2. Summary of the stepwise multiple linear + interaction regression analysis (at both 0.10 and 0.15 significant levels).

Intensity factor	**Daily rainfall, weather and synoptics variables***	r^2
Event amount	RF, Tdp×RF, Wv×RF, CI×RF, Wv×Wu	0.625
Event duration	RF, Twb×CI	0.186
Peak intensity	CI×RF, Wv×RF, Tdp×Wv	0.366

*RF-daily rainfall

3.3. Artificial neural networks

Artificial Neural Networks (ANN) are a network of many very simple processors ("units"), each possibly having a (small amount) local memory. Figure 3.6 shows a general structure of a single unit (Dawson and Wilby, 2001).

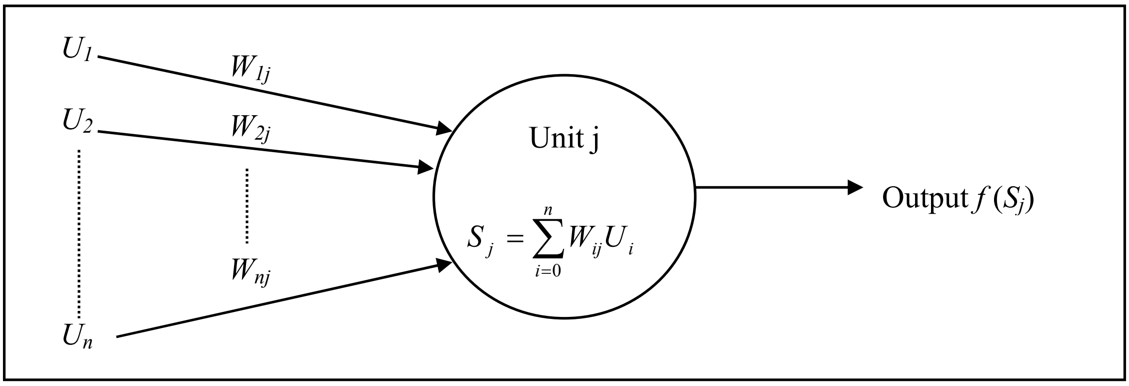


Figure 3.6. A structure of a single unit in artificial neural networks.

Each unit consists of a number of inputs, U_n, each input is linked by each weight, W_{nj}, and an output, $f(S_i)$, is computed on the basis of the weighted sum of all its inputs, S_j. The function $f(S_i)$ may be logistic sigmoid, linear, Gaussian or hyperbolic tangent functions. The logistic sigmoid function has mostly been used, as follows:

$$f(S_j) = \frac{1}{1 + \exp(-S_j)} \tag{3.3}$$

A multi-layer feed-forward, back propogation network type has been employed to model rainfall-runoff process, and the network consists of three or four connected layers of units, including input, hidden and output layers (Dawson and Wilby, 2001). The number of hidden layers and its units must be specified, and the best way to determine an appropriate number of units in the hidden layer is via trial and error. The network is trained by adjusting the weights that link its units. The training is applied with a training set of data, where the network is presented with a set of inputs and known associated outputs, and minimises ('learns') the error in its output for a given input and target output. It is important to ensure that the network is not over-trained. It is advisable to retain a portion of the data as a test data set, where, during the training process, the networks are tested on independent data without training taking place. When the point is reached where no improvement is found with respect to the test data, then further training would start to learn 'noise' or features that are not really present in the data.

ANN is a flexible mathematical structure that is capable of identifying a complex non-linear relationship between input and output data sets. The rainfall-runoff process is believed to be highly non-linear, time-varying, spatially distributed, and not easily described by simple models. ANN models have been found to be useful and efficient, particularly in problems for which the characteristics of the processes are difficult to describe using physical equations. So, ANN probably offers great opportunities for modelling rainfall intensity. ANN has been used in research similar to the present study and specifically with rainfall-runoff relationships (e.g., French *et al.*, 1992; Hsu *et al.*, 1995; Smith and Eli, 1995; Minns and Hall, 1996; Mason *et al.*, 1996; Shamseldin, 1997; Achela *et al.*, 1998; Dawson and Wilby, 1998; Sajikmar and Thandavesware, 1999; Tokar and Johnson, 1999; Dawson and Wilby, 2001).

Since rainfall events are strongly related to the upper levels of the atmosphere (e.g., 700 hPa level) data collected spatio-temporally by meteorological satellites, satellite data may be used as an input to estimate the amount of rainfall per unit time (rainfall intensity). The meteorological satellite data has become available over the last 20 years. In the ANN analysis presented here, the meteorological data included 700 hPa specific humidity (q700), 700 hPa temperature (t700), 700 hPa eastward wind velocity (u700) and 700 hPa northward wind velocity (v700). Each meteorological factor had 9 grid cell data (3 grid cells × 3 grid cells; Each grid cell = 2.5° × 2.5°) centered on Bloemfontein (29°S, 26°E) (Figure 3.7). It also had 8 data points during the current day and the previous day (2 days × 4 data per day, including 0:00, 6:00, 12:00 and 18:00 South African Standard Time), totally 72 units over space and time.

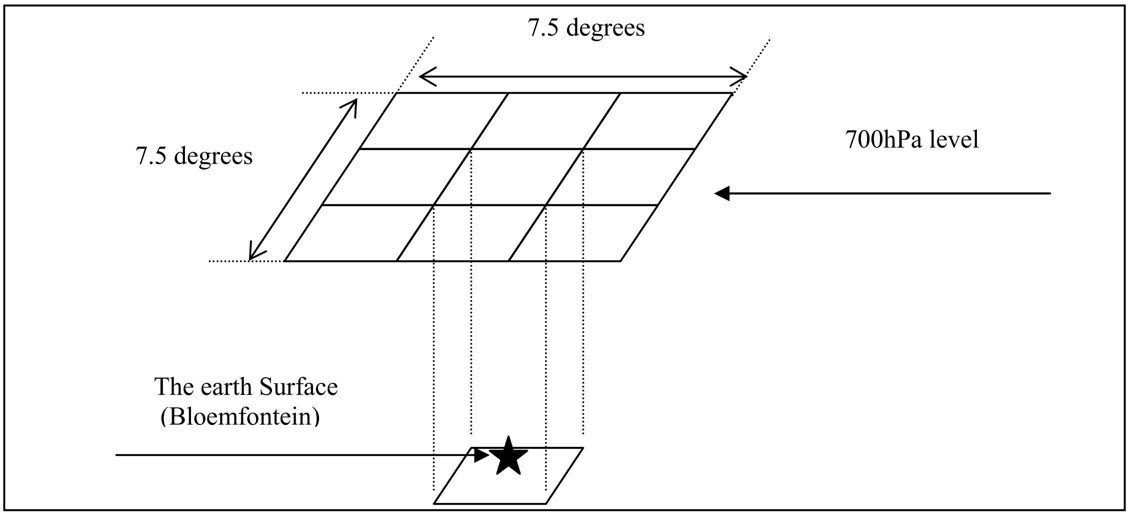


Figure 3.7. The three by three grid cells centred over Bloemfontein.

A general ANN structure used here is shown in Figure 3.8. The one- and two-hidden layer ANN structures were used to determine the best ANN structure for rainfall intensity modelling. The ANN output was the amount of rainfall per unit time, namely rainfall intensity. The amount of rainfall per 15 minutes was used in this study. The ANN analysis was made using the 2 days satellite data (as described above) and the Glen measured rainfall intensity data from 1996 to 1999 (98 data).

The one-hidden layer ANN analysis for daily rainfall (one output layer unit) was made in order to select useful meteorological factors from the four factors mentioned above (q700, t700, u700 and v700). Table 3.3 shows r^2 of the ANN analysis at five levels of hidden layer units. As the increased hidden layer units, r^2 of u700 and v700 were improved up to 0.97 and 0.99, respectively while those of q700 and t700 never resulted in a high value (always < 0.36). Therefore, it was decided that the rainfall amount per day could be better related to the wind velocities, u700 and v700, than the specific humidity and temperature, q700 and t700.

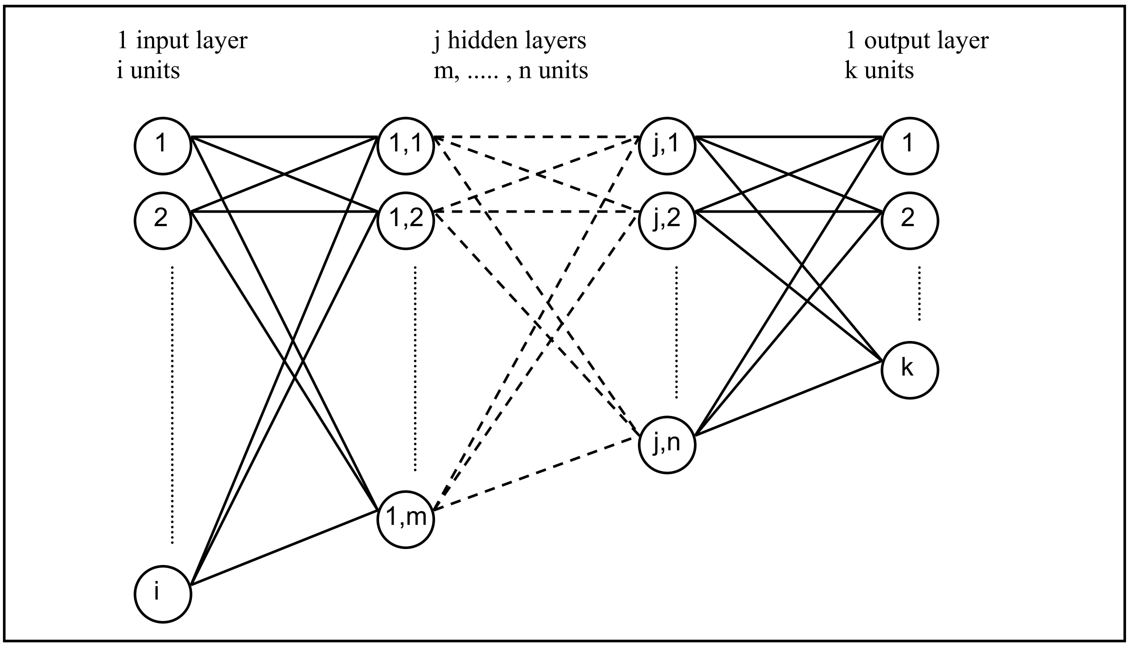


Figure 3.8. The ANN model structure with multiple hidden layers, as used with the satellite data.

Table 3.3. R-square values of the one-hidden layer ANN model for satellite data to predict Glen daily rainfall.

	Hidden layer units (% of input layer units)				
	0 (0 %)	36 (50 %)	72 (100 %)	108 (150 %)	144 (200 %)
q700	0.27	0.10	0.35	0.36	0.10
t700	0.27	< 0.1	< 0.1	< 0.1	< 0.1
u700	0.53	0.82	0.97	0.96	0.97
v700	0.64	0.99	0.99	0.99	0.99

The wind velocities (u700 and v700) were then chosen for the next ANN analysis. The input to be used in the ANN analysis was 72units (u700) + 72 units (v700) = 144 units. The ANN output was the amount of rainfall per 15 minutes, so the total output was 96 period units per day. Table 3.4 shows r^2 of the one-hidden layer ANN analysis. Similarly, the greater the number of hidden layer units included in the ANN, the higher the r-square values (0.98) became up to 288 hidden layer units. Then there was no further increase in r^2. As shown in Table 3.5, if the number of hidden layers was increased, it did not improve the r^2. Therefore, it was concluded that the best ANN structure had one hidden layer and 288 hidden layer units (200 % of the input layer units).

Table 3.4. R-square values of the one-hidden layer ANN model for wind velocities to predict 15 minute-based Glen rainfall intensity.

Hidden layer units (% of input layer units)						
0 (0 %)	72 (50 %)	144 (100 %)	216 (150 %)	288 (200 %)	360 (250 %)	432 (300 %)
0.82	0.86	0.86	0.93	0.98	0.98	0.99

Table 3.5. R-square values of the two-hidden layer ANN model for wind velocities to predict 15 minute-based Glen rainfall intensity.

		First hidden layer units (% of input layer units)			
		72 (50 %)	144 (100 %)	216 (150 %)	288 (200 %)
Second hidden layer units (% of input layer units)	72 (50 %)	0.67	0.84	0.83	0.91
	144 (100 %)	0.81	0.89	0.90	0.93
	216 (150 %)	0.84	0.87	0.91	0.94
	288 (200 %)	0.85	0.91	0.91	0.97

Rainfall intensity generation (millimeter/15minutes) was carried out using the best ANN model described above. Rainfall intensity for Glen was generated from 1980 to 2000. However, there was a problem with the generated data because the ANN model generated some negative value, as shown Table 3.6. In this case, a zero (0) was substituted for negative values (i.e., to truncate negative values at zero). For example, the calculated negative value (−0.1) of data set number 1 in the 30 minute column becomes zero (0), and of course, this agrees with the actual measured value (0). However, this procedure gave another problem; that is, actual daily rainfall was then not consistent with a daily rainfall sum from the generated rainfall intensities. Mostly the simulated daily value was greater than the actual daily value because each simulated rainfall which was originally a negative value had been increased by its absolute value to zero (0). Also, the procedure from data analysis to data generation was done on the basis of hourly rainfall, and results were similar to those based on 15-minute rainfall, although truncating negative value at zero maybe satisfied on a daily basis. Hence, the ANN model was not acceptable as a short-time rainfall intensity (e.g. mm/min) generator at the present time, but the ANN analysis showed good potential of modelling rainfall intensity if some of these process problems can be overcome in the future.

Table 3.6. An example of sets of calculated (Cal) and measured (Mea) rainfall per 15 minutes from the ANN analysis for Glen.

Data	15 min		30 min		45 min		60 min		75 min		90 min		105 min		120 min		135 min		150 min	
set#	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea	Cal	Mea
1	0.0	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	-0.3	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.0
2	0.0	0.0	-0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0
3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0
4	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.3	0.0	0.0	0.2	0.1	0.0
5	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.0
6	0.0	0.0	-0.2	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.1	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.1	0.0
7	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.3	0.0	-0.2	0.0	0.2	0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0
8	0.2	0.2	0.4	0.2	0.1	0.0	0.1	0.2	0.1	0.2	0.3	0.2	-0.1	0.2	0.0	0.2	0.1	0.2	0.2	0.2
9	0.2	0.2	0.2	0.0	0.2	0.2	0.2	0.4	0.1	0.2	0.1	0.2	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
10	0.1	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0
11	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0
12	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	-0.1	0.0
13	0.1	0.0	0.3	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.3	0.0	0.1	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0
14	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.3	0.0	0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
15	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	-0.1	0.0	-0.2	0.0	0.0	0.2	0.1	0.0
16	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	-0.2	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.1	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.1	0.0
18	0.2	0.0	0.3	0.2	0.2	0.0	0.2	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0
19	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.2	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.1	0.0
20	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
21	-0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.4	0.2	0.6	0.5	0.8	0.1	0.2	-0.1	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.3	0.0	0.2	0.6	0.0	0.2
23	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0
26	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
27	0.2	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.1	0.0	-0.4	0.0	0.1	0.0	0.3	0.0	0.2	0.0	0.2	0.0
28	0.4	0.2	1.4	2.2	0.5	0.6	0.2	0.0	0.2	0.2	0.1	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0
29	0.5	0.6	0.6	0.6	0.3	0.4	0.1	0.0	0.0	0.0	0.1	0.2	0.0	0.0	-0.1	0.0	0.1	0.2	0.0	0.0
30	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	-0.2	0.0	-0.1	0.0	-0.2	0.0
31	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	-0.1	0.0
32	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
34	0.3	0.6	0.3	0.2	0.4	0.6	0.4	0.6	0.6	1.0	0.7	0.6	0.6	0.8	0.8	1.2	0.8	1.6	0.9	1.8
35	0.1	0.0	0.2	0.0	0.3	0.0	0.2	0.0	0.3	0.0	0.4	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
36	-0.2	0.0	0.0	0.0	-0.2	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0
37	0.2	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.1	0.0
38	0.1	0.0	1.1	2.0	0.7	1.0	0.6	0.8	0.7	1.0	0.6	0.4	0.4	0.4	0.3	0.2	0.2	0.0	0.1	0.0
39	-0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.2	0.0
40	-0.2	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0
41	0.3	0.6	0.3	0.4	0.2	0.0	0.2	0.2	0.2	0.0	-0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	-0.1	0.0	-0.2	0.0	-0.2	0.0	-0.5	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
43	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0
44	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
45	0.1	0.0	0.2	0.0	0.2	0.2	0.1	0.0	0.1	0.0	-0.2	0.0	0.0	0.0	0.1	0.0	-0.1	0.0	-0.2	0.0
46	0.0	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0
47	0.0	0.0	-0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
48	0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0

3.4. Stochastic modelling

The area under the rainfall intensity curve method provided acceptable daily runoff estimation from daily rainfall, as a direct method. Also, this method may be used for estimating runoff from rainfall on different soil ecotopes by changing the value used for final rate of infiltration of water into soil. It has been shown estimation of daily runoff using the area under the rainfall intensity method is more reliable than that using the rainfall-runoff linear model in Section 2.3 (in Chapter 2). Although the area under the rainfall intensity curve model estimates daily runoff reasonably, a completely satisfactory runoff estimation still needs to be improved due to variability in runoff at high rainfall amounts, i.e., rainfall intensity-runoff modelling. However, long-term rainfall intensity data is not obtainable from most South African weather stations. In Sections 3.2 and 3.3, two methods of modelling rainfall intensity were introduced. The stepwise regression showed no relationships between rainfall intensity and the other meteorological factors (the weather data and the synoptics data). This indicates that it is difficult to estimate rainfall intensity factors from the other daily surface meteorological factors. In the ANN analysis, a strong relationship between rainfall intensity and wind speed at 700 hPa level was found, but it is still necessary to improve in data generation based on the ANN model. So, it may be necessary to reconsider the methodology in future studies.

As stated by Bonta (1997), the temporal variation of rainfall within a rainfall event is not predictable, so intensities would be generated stochastically. A simple stochastic model of rainfall intensity may be the decile probability model. Deciles have been defined as probability ranking, or classes, calculated from historic records. In this system, rainfall intensity can be evaluated with a class. For example, if a rainfall intensity value of say 30 mm/hr in the month of January of in the whole year of period being dealt with is rated as DECILE 7 for a specific location, then 7 out of 10 years, the rainfall intensity will be equal to or less than that intensity. A programme will be written to generate random numbers between 1 and 10. Once a number between 1 and 10 is generated, the programme takes that number as a decile number and pick the corresponding intensity value and allocates it on that particular day. The programme places a value of zero where the daily rainfall is zero. The disadvantage of this method is that constant intensities are generated, although rainfall intensity varies. So, it is difficult to predict runoff from rainfall intensity generated by this model.

As another stochastic model, an existing daily rainfall disaggregation model by Connolly *et al.* (1998) has great potential for application in South Africa. They developed a model for disaggregating daily rainfall into multiple events on a day. The model simulates time-varying intensity within each day. The model is simple to apply and makes use of model components from literature and develops others from Australian rainfall conditions. The model has been tested by comparing its reproduction of the statistical characteristics of measured rainfall in Australia. The model is designed to be parameterisable with a relatively short rainfall record (5 years), then to be able to disaggregate long term daily records into break point rainfall. The model software produced by Dr. Connolly has several programs that: derive parameter values from measured breakpoint records, then use the derived parameters to disaggregate the daily records. Multiple events on a day are represented, and for each event the duration, rainfall amount, time to peak intensity, peak intensity, starting time and temporal pattern are simulated. The model is stochastic, that is it incorporates a random component and generates different output each run of rainfall intensity generation. The disaggregation model program was sent to the team by Dr. Connolly for use in this project, however, data generation of rainfall intensity was never successful, so the method could not be successfully tested under South African conditions.

As introduced by Woolhiser and Osborn (1985), a stochastic model of rainfall intensity using hyetograph is potential for application in South Africa. Hence, in the following chapter (Chapter 4), this stochastic model for generating rainfall intensity has been explained.

Chapter 4
Modelling Rainfall Intensity within a Storm

4.1. Dimensionless hyetograph

In hydrological engineering, rainfall intensity information is often needed to analyse and develop water resources systems. Few stations in South Africa have measured rainfall intensity data of more than 10 years, although some stations (about 170 stations) now have at least 10 years of measured data (Smithers and Schulze, 2000). On the other hand, records of 100 years or more in length of daily rainfall data are commonly available in many developing countries, including South Africa. In the areas where little rainfall intensity data is available, therefore, having design storms is of importance in solving hydrological and agro-hydrological problems.

Huff (1967) investigated relationships between the fraction of the cumulative rainfall amount from the start of rainfall to the total rainfall amount (the dimensionless amount, x) and the fraction of the cumulative rainfall duration from the start of rainfall to the total rainfall duration (the dimensionless duration, y). Figure 4.1(a) shows examples of original hyetographs with varying amount and duration. Figure 4.1(b) shows the new patterns once the amount and duration has been standardised against the amount and total length of rainfall duration, thus depicting the random pattern curves. Another example of dimensionless hyetograph is reported by Adamson (1981). The relationships of the dimensionless values were expressed in terms of probability because of the great variability in the characteristics of temporal distribution of rainfall from event to event.

The dimensionless hyetograph intersections on the y axes for each interval in x of a given value (e.g., 0.02 in this study) are sampled and plotted at nine specific percentiles: i.e., 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 % (Bonta, 1997). These frequency curves (the dimensionless mass curves of different percentiles) are referred to as "Huff Curves." Figure 4.2 shows Huff curves by quartile type (including both Bloemfontein and Pretoria data; see Section 4.2.). Bonta and Rao (1987; 1989) and Bonta (1997) further studied Huff curves, investigating the effects of several factors on the development of Huff curves. They compared Huff curves for summer and winter at different locations on continental USA (640 km apart) and found seasonal variability in Huff curves, but non-location dependence across the central USA.

(a) original hyetographs (b) dimensionless hyetographs

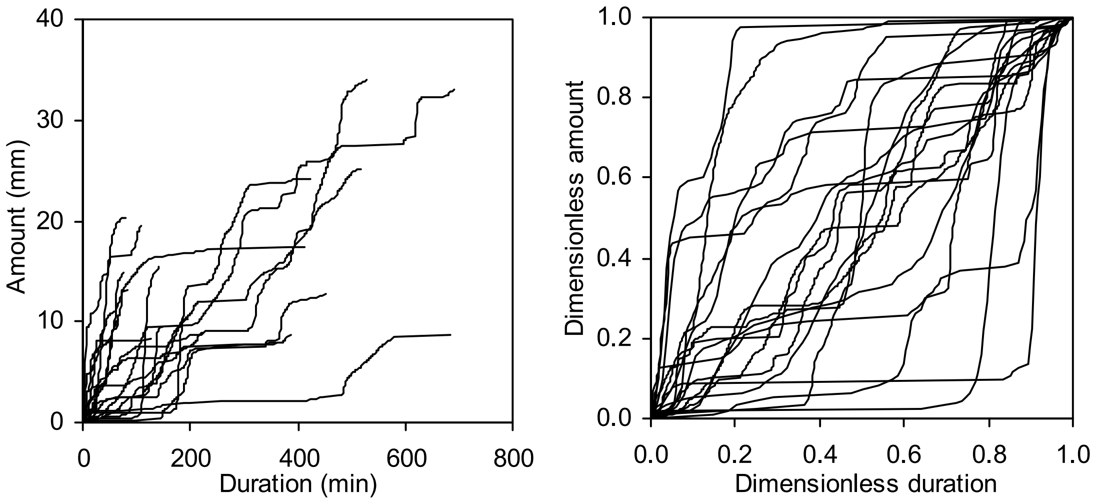


Figure 4.1. Hyetographs (19 sample rainfall events at Glen).

Once rainfall intensity is characterised in a particular location where long-term data of rainfall intensity is not obtainable, long-term rainfall intensity data can be generated. As stated by Bonta (1997), the temporal variation of rainfall within a rainfall event is highly variable and therefore not predictable, so the data would be generated stochastically. Woolhiser and Osborn (1985) proposed a stochastic model of rainfall intensity using the hyetograph. Thereafter, several scientists developed similar stochastic rainfall intensity models (e.g., Garcia-Guzman and Aranda-Oliver, 1993; Koutsoyiannis and Foufoula-Georgiou, 1993; Robinson and Sivapalan, 1997). One of the most important characteristics of those models is that a dimensionless hyetograph forms its basis. In this modeling, any continuous probability density functions in a range from zero to one can be used to describe the distribution of the increment process, z, of the dimensionless amount of rainfall, y at a given dimensionless duration, x.

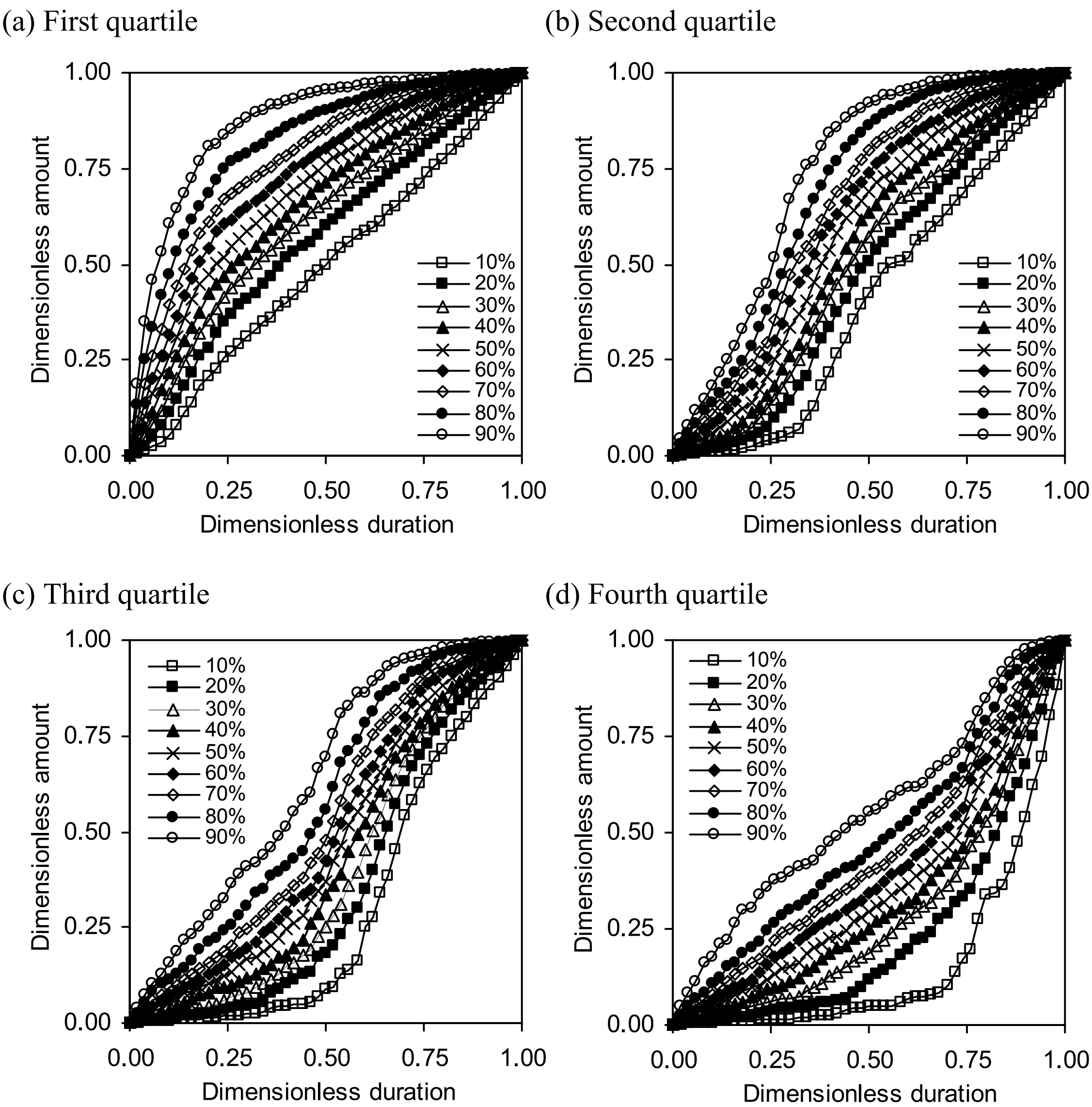


Figure 4.2. Huff curves for both Bloemfontein and Pretoria.

4.2. Rainfall intensity data

Rainfall intensity data for 30 years from the Bloemfontein weather office (29º06´S, 26º18´E, 1354 m) from 1962 to 1992 and the Pretoria weather office (25º44´S, 28º11´E, 1330 m) from 1966 to 1996 were used to develop Huff curves and the stochastic rainfall intensity model. Bloemfontein is approximately 500 km away from Pretoria, but both locations are on the highveld as seen from similar altitudes. The intensities were recorded with a siphon type automatic recording raingauge. The intensity data included 1780 and 1733 rain days for Bloemfontein and Pretoria, respectively, which each have daily rainfall ≥ 1 mm. The data which had daily rainfall greater than 8 mm were selected (representing 38 % and 40 % of the total rain days for Bloemfontein and Pretoria, respectively). Rainfall events were defined to be separated by a dry period of at least 3 hours in which no rain fell. These selection criteria gave 536 rainfall events for Bloemfontein and 631 rainfall events for Pretoria.

Within the data, one event per day was occurred on 476 days while those with more than one event per day consisted of only 31 days in Bloemfontein, thus, 94 % of the event rainfall data belonged to one rainfall event per rain day. Pretoria had 581 days for one event per day and 25 days for two events per day. Thus, 96 % of the event rainfall data belonged to the set of one rainfall event per rain day. The rainfall event duration varied from 14 min to 1940 min (from 0.2 hours to 32.2 hours) in Bloemfontein and from 7 min to 2580 min (form 0.1 hours to 43.0 hours) in Pretoria. 97 % and 94 % of the event rainfall data for Bloemfontein and Pretoria, respectively, fell within the range between 30 min and 1440 min (one day). Therefore, event rainfall could be assumed to be almost equal to daily rainfall for these Bloemfontein and Pretoria data.

Rainfall events were classified into four groups, depending on whether peak intensity occurred in the first, second, third or fourth quarter of the rainfall event period (Huff, 1967) for the rainy and non-rainy seasons. The rainy season for both locations was defined as a period from October to April, in which months have less then 30 mm per month. Table 4.1 shows event numbers by quartile type and season. Approximately, a half of the data was classified into the first quartile type of storms while the second quartile type of storms had 20 to 25 %. There was no difference between the data distribution in the third and the fourth quartile types (13 % to 15 %). Similar results were reported by Bonta and Rao (1987): 37–39 % for the first type, 20 % for the second type, 22–24 % for the third type and 17–21 % for the fourth type in Ohio, U.S.A. However, Huff (1967) reported 30 %, 36 %, 19 % and 15 % in Illinois, U.S.A. As another example, Garcia-Guzman and Aranda-Oliver (1993) found approximately 25 % in each quartile type in southern Spain. Thus, the distribution of peak rainfall intensity within storms is perhaps dependent on the main type of rainfall received in each region (i.e., convective storms, frontal rain, orographic uplift, etc.).

Table 4.1. Event numbers by quartile type and season.

Location†	Quartile	Season‡	
		Rainy	Non-rainy
Bloemfontein 536 events	First	229 (42.7%)	34 (6.3%)
	Second	98 (18.3%)	16 (2.9%)
	Third	67 (12.5%)	15 (2.8%)
	Fourth	65 (12.1%)	13 (2.4%)
Pretoria 631 events	First	292 (46.3%)	15 (2.4%)
	Second	143 (22.7%)	9 (1.4%)
	Third	80 (12.7%)	6 (0.9%)
	Fourth	77 (12.2%)	9 (1.4%)

The percentages of the data in parentheses
† Bloemfontein: 29º06´S, 26º18´E, 1354 m; Pretoria: 25º44´S, 28º11´E, 1330 m
‡ Rainy season: Oct, Nov, Dec, Jan, Feb, Mar, Apr; Non-rainy season: May, Jun, Jul, Aug, Sep

4.3. Analysis of Huff curves

It is important to know whether seasons and locations affects Huff curves (or rainfall intensity distributions) because this information can be used to develop the stochastic rainfall intensity model in the next section (Section 4.4). So, in this section, seasonal and geographical variability in Huff curves was analysed. Although there was little data for the non-rainy season for Bloemfontein and Pretoria (see Table 4.1), Huff curves were compared between the rainy season (October – April) and the non-rainy season (May – September) and between Bloemfontein and Pretoria.

Figure 4.3 shows Huff curves by quartile type for the rainy season and the non-rainy season at 10, 50 and 90 percentiles. There were some discrepancies in Huff curves between seasons. In the first and second quartile types, the non-rainy season had lower dimensionless amount than the rainy season at all dimensionless duration except 90 percentile curves of the second quartile type. In the third and fourth quartile types, 50 percentile curves for the rainy season were similar to those for the no-rainy season, and 90 percentile curves for the rainy season depicted slightly higher values than those for the non-rainy season, however, at 10 percentile the rainy season showed lower values than the rainy season. This implies than the rainy season had wider ranges of hyetograph types than the non-rainy season. Figure 4.4 gives a comparison of Huff curves by quartile type for Bloemfontein and Pretoria at 10, 50 and 90 percentiles. Some slight differences were found between Bloemfontein and Pretoria Huff curves. In the first quartile type, Huff curves for Pretoria were slightly higher than those for Bloemfontein. In the third and fourth quartile types, the dimensionless amount at Bloemfontein was fractionally higher than that at Pretoria, especially at middle range dimensionless duration. Compared with seasonal variability of Huff curves, less variation due to locality was found between Bloemfontein and Pretoria.

The Kolmogorov-Smirnov Test for two samples is concerned with the agreement between two sets of observed values (two empirical cumulative distributions), and the null hypothesis is that the two groups are the same (Keeping, 1962). Using this test, Huff curves were statistically compared between locations and between seasons. Since the number of rainfall events for the non-rainy season is small, only the 50 percentile Huff curve was compared between seasons at each location. Table 4.2 shows the D statistics (the maximum vertical deviation between two curves; the maximum difference in cumulative function) with corresponding P values for the seasonal variability. Compared with Pretoria, Bloemfontein had lower values of the D statistic. The second quartile type of Huff curves at Pretoria had the highest difference (D = 0.2353) between seasons, followed by the first and third quartile types at Pretoria. From the p-values, it has been concluded that there were no statistically significant differences between seasons at either location (P > 0.1).

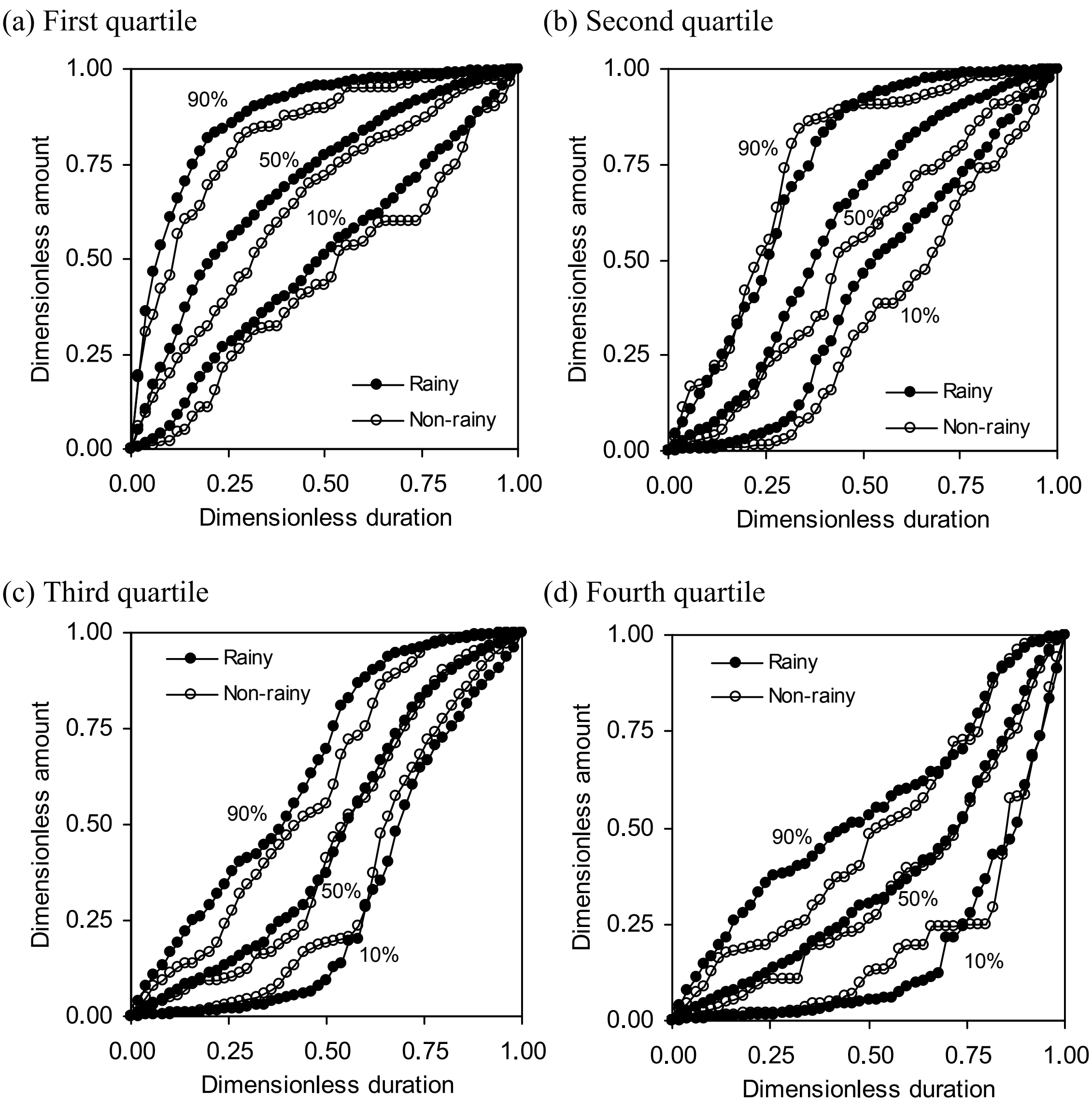


Figure 4.3. Comparisons of Huff curves for the two seasons both locations (rainy season vs non-rainy season) (10, 50 and 90 percentiles).

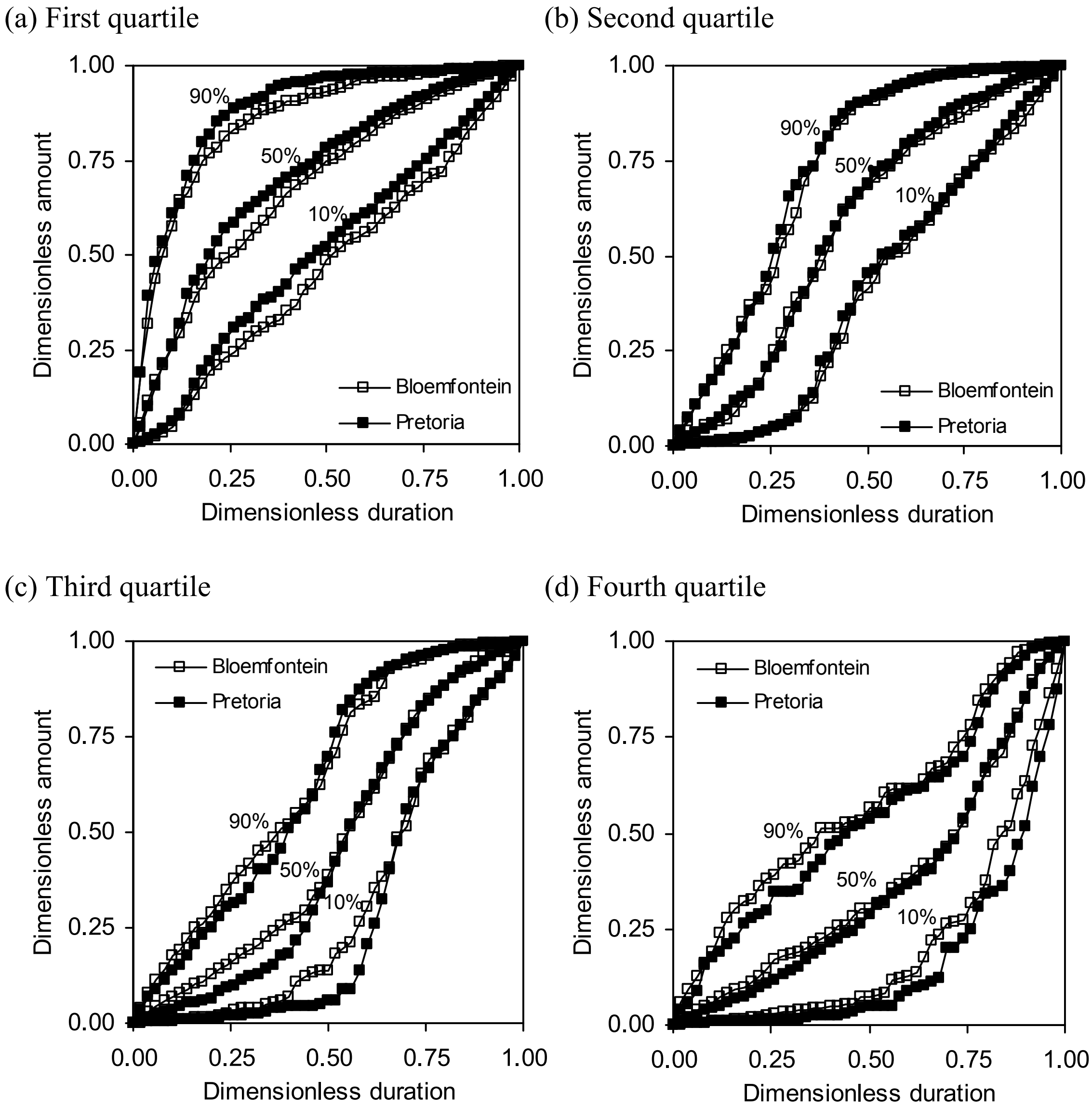


Figure 4.4. Localisation (Bloemfontein vs Pretoria) of Huff curves (10, 50 and 90 percentiles).

Three percentiles (10, 50 and 90 %) of Huff curves were compared between locations (Table 4.3). The data sets included both the rainy season and non-rainy season data because there was no significant difference in Huff curves between seasons. The second quartile type of Huff curves had small values in the D statistic, compared with the other three quartile types, indicating the second type of Huff curves were close to each other, as shown in Figure 4.4. As all the p-values were greater than 0.37, so Huff curves for Bloemfontein did not differ significantly from those for Pretoria. Therefore, the combined data set could be used to represent a wide area of the South Africa Highveld.

Table 4.2. The Kolmogorov-Smirnov Test for the seasonal variability of 50 % Huff curves (the rainy season versus the non-rainy season)‡ of Huff curves.

Location†	Quartile	D statistic	P value
Bloemfontein	First	0.0980	0.958
	Second	0.1569	0.521
	Third	0.0588	1.000
	Fourth	0.1765	0.371
Pretoria	First	0.2157	0.163
	Second	0.2353	0.101
	Third	0.1961	0.251
	Fourth	0.0784	0.996

† Bloemfontein: 29º06´S, 26º18´E, 1354 m; Pretoria: 25º44´S, 28º11´E, 1330 m
‡ Rainy season: Oct, Nov, Dec, Jan, Feb, Mar, Apr; Non-rainy season: May, Jun, Jul, Aug, Sep

Table 4.3. The Kolmogorov-Smirnov Test for the localisation (Bloemfontein versus Pretoria)† of Huff curves.

Quartile	Percentile	D statistic	P value
First	10	0.0980	0.958
	50	0.0784	0.996
	90	0.1765	0.371
Second	10	0.0392	1.000
	50	0.0588	1.000
	90	0.0392	1.000
Third	10	0.1569	0.521
	50	0.1176	0.850
	90	0.0588	1.000
Fourth	10	0.1765	0.371
	50	0.0784	0.996
	90	0.1176	0.850

† Bloemfontein: 29º06´S, 26º18´E, 1354 m; Pretoria: 25º44´S, 28º11´E, 1330 m

4.4. Model development

A dimensionless hyetograph is not dependent on either rainfall event amount or duration. Using this advantage, a stochastic model of rainfall intensity was developed using the dimensionless hyetograph method. Within a rainfall event, the amount of rainfall in a period between x_{i-1} min and x_i min, P_i (namely, rainfall intensity), is given by:

$$P_i = \frac{Y(y_i - y_{i-1})}{X(x_i - x_{i-1})} \qquad i = 1,2,\cdots,n \qquad (4.1)$$

where X is the total duration of event rainfall (min), Y is the total amount of event rainfall (mm), y_i is the fraction of the cumulative event amount at a given time from the starting time of rain to the total event amount (the dimensionless amount of rainfall events), x_i is the fraction of the cumulative event duration from the starting time of rain to the total event duration (the dimensionless duration of rainfall events), and n is the number of steps in which rainfall intensity is divided (the nth step or increment). The start point (x_0, y_0) and the end point (x_n, y_n) of the dimensionless hyetograph are equal to the point (0, 0) and the point (1, 1). The other points fulfill $x_i > x_{i-1}$ in a range between x_0 and x_n ($0 < x_1 < x_2 < \cdots < x_{n-1} < 1$) and $y_i > y_{i-1}$ in a range between y_0 and y_n ($0 < y_1 < y_2 < \cdots < y_{n-1} < 1$), as the order statistics (Garcia-Guzman and Aranda-Oliver, 1993).

As introduced by Woolhiser and Osborn (1985), the increment process of the dimensionless amount at a given interval of the dimensionless duration, z_j ($0 < z_j < 1$), is used in this study, as follows:

$$z_j = \frac{y_j - y_{j-1}}{1 - y_{j-1}} \qquad j = 1,2\cdots,n-1 \qquad (4.2)$$

The intervals of 0.1 and 0.05 mean the ten- and twenty-increment processes, respectively, of the dimensionless amount.

For depicting a complete dimensionless hyetograph from y_0 to y_n, the probability density function of the beta distribution may describe the distribution of the increment process of dimensionless amount for any j, $f(z_j)$, as follows:

$$f(z_j) = \frac{\Gamma(\alpha_j + \beta_j)}{\Gamma(\alpha_j)\Gamma(\beta_j)} z^{\alpha_j -} (1-x)^{\beta_j - 1} \tag{4.3}$$

where α_j and β_j are the shape parameters ($\alpha_j > 0$ and $\beta_j > 0$). For any j, z_j is stochastically chosen using the cumulative distribution function. The parameters α_j and β_j are estimated from the mean $E(z_j)$ and the variance $V(z_j)$:

$$E(z_j) = \frac{\alpha_j}{\alpha_j + \beta_j} \tag{4.4}$$

$$V(z_j) = \frac{\alpha_j \beta_j}{(\alpha_j + \beta_j)^2 (\alpha_j + \beta_j + 1)} \tag{4.5}$$

In addition, the gamma probability density function, $f(X)$, (see Equation 2.1) is used to describe the distribution of the total duration of event rainfall, and X is also stochastically chosen using the cumulative distribution function, $F(X)$.

Figure 4.5 shows the gamma cumulative probability curves for the total duration of rainfall events at Bloemfontein and Pretoria. From these distribution functions, the probabilities of 25, 50 and 75 % of it raining for the time period (X) is 150, 285 and 480 min at Bloemfontein and 85, 200 and 400 min at Pretoria. If the number of steps of the increment process is constant, rainfall events have variable time periods of the interval at which the dimensionless amount changes. In contrast, if the time period of the interval is constant, the number of steps of the increment process is variable. For example, if the interval is 30 min, the probability levels of 25 % (X = 150 min), 50% (X = 285 min) and 75 % (X = 480 min) give the 5, 10 and 16 step increment processes of the dimensionless amount, respectively, if the interval is 15 min, the probability levels of 25, 50 and 75 %

give the 10, 19 and 32 step increment processes, respectively, and if the interval is 60 min, the probability levels of 25, 50 and 75 % give the 3, 5 and 8 step increment processes, respectively. Thus, the number of steps of the increment process is dependent on the interval chosen.

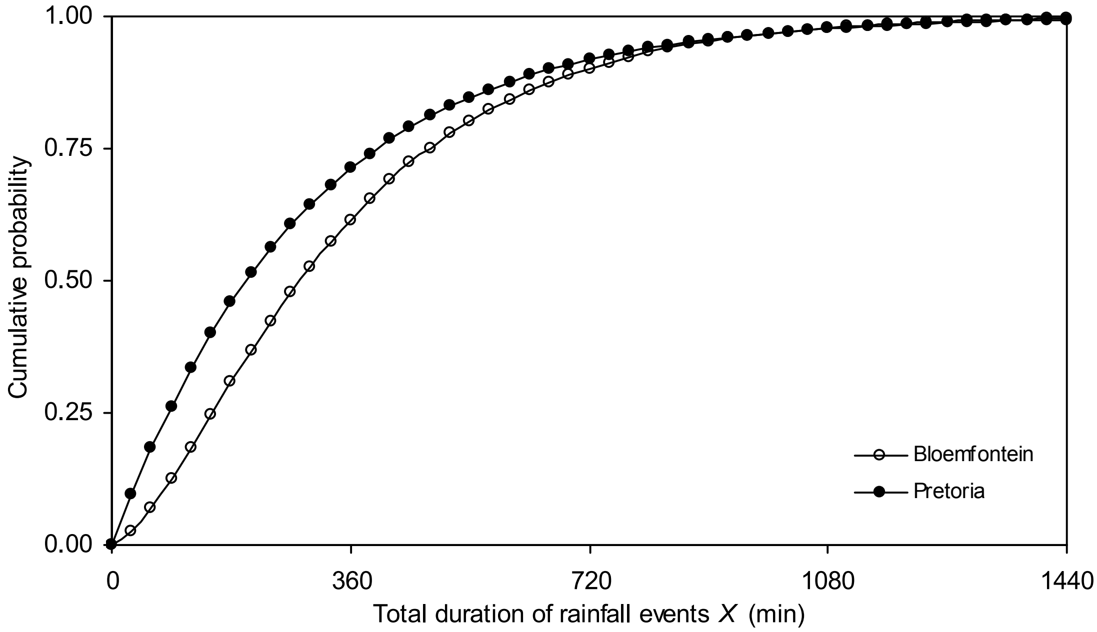
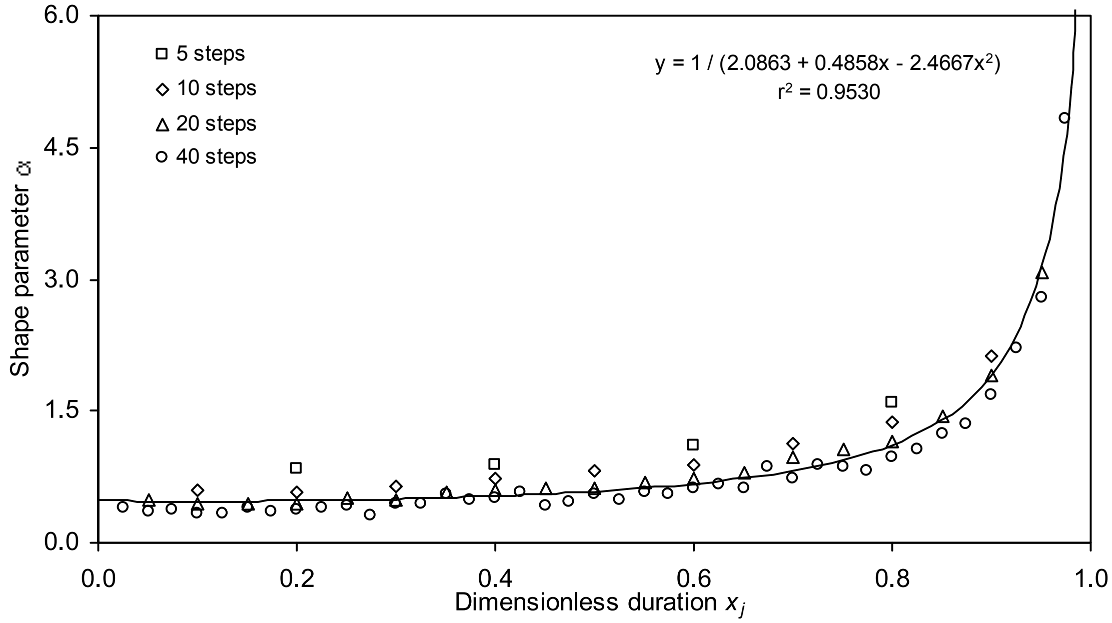


Figure 4.5. The gamma cumulative distribution function of the rainfall event duration. Parameters of the gamma probability density function: the shape parameter α = 1.65, the scale parameter $\beta = 212$ for Bloemfontein; $\alpha = 1.02$, $\beta = 282$ for Pretoria).

The minimum and maximum event duration was set to 30 min and 1440 min, respectively. Rainfall amount per a half hour (which could change the number of steps of the increment process from 1 to 48; the variable steps of the increment process) was simulated. For determining the parameters α_j and β_j for the variable steps of the increment process, the five, ten, twenty and forty step increment processes of the dimensionless amount were analysed as these four types of the increment processes can be representative of the number of steps from 1 to 48. Figure 4.6 shows plots of α_j and β_j against the dimensionless duration x_j. Good relationships were found between the

(a) Bloemfontein



(b) Pretoria

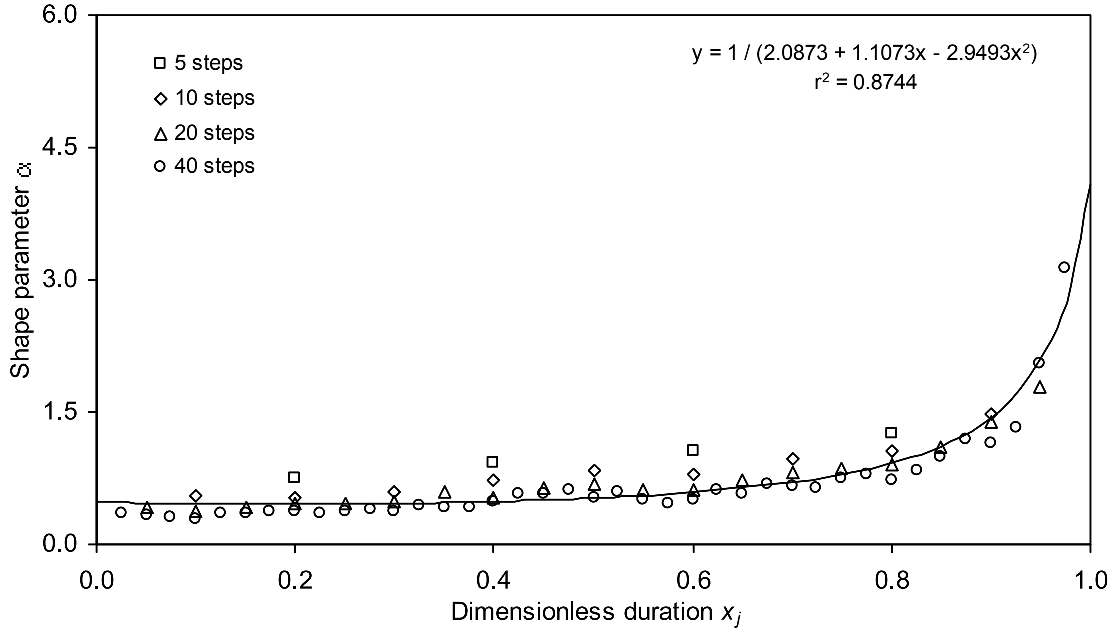


Figure 4.6. Shape parameter α of the beta probability density function for the increment process.

parameters and the dimensionless duration for all steps, fitting a reciprocal quadratic curve (R^2 >0.96). The relationships for the parameter α_j were similar, so one curve was fit for each location (r^2 = 0.95 for Bloemfontein; r^2 = 0.87 for Pretoria). However, there are differences in the parameter β_j between the ranged steps, as shown in Figure 4.7. As the number of steps increased, the parameter β_j also increased at all x_j. Similar results were found in the study by Woolhiser and Osborn (1985). In addition, variable α_j and β_j parameters gave the skewness of the beta distribution for the increment process, which was varied in the range of dimensionless duration between 0 and 1, as shown in Figures 4.8 and 4.9.

Note that the parameter α_j is not dependent on the step number of the increment process (see Figure 4.6), but that the parameter β_j is (see Figure 4.7). Woolhiser and Osborn (1985) reported the parameter β_j might be dependent on the previous increment process z_{j-1}. They assumed that there was a linear relationship between successive increments, i.e.,

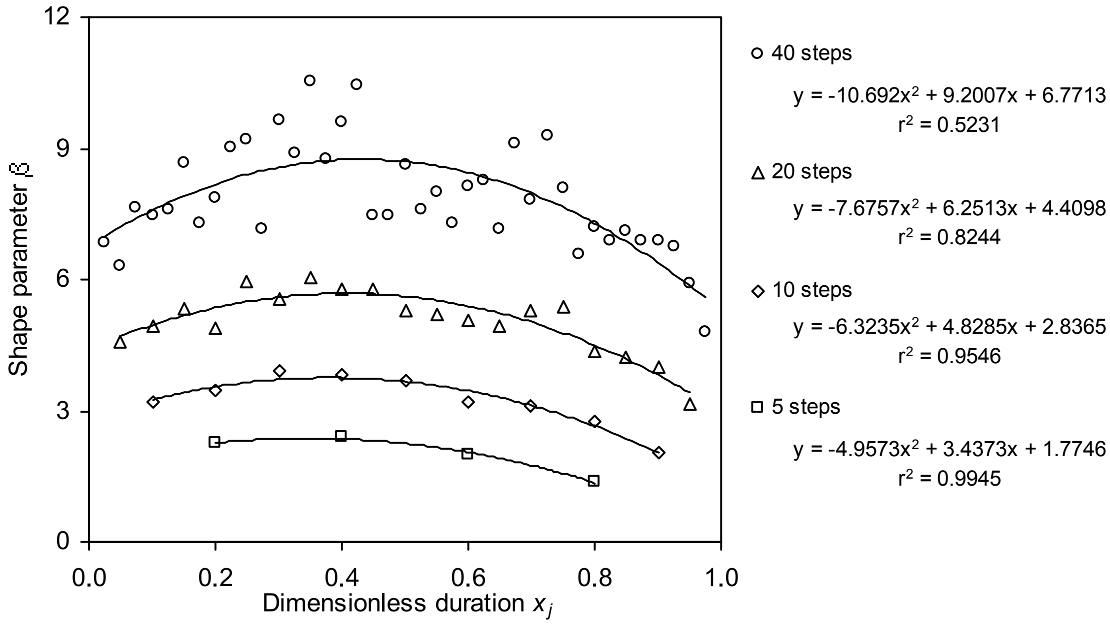
$$z_j = a_j + b_j z_{j-1} \qquad (4.6)$$

where a_j is the intercept and b_j is the slope, equated the right hand-sides of this linear equation and Equation 4.4 (the mean of the beta distribution), and solved for β_j, as follows:

$$\beta_j = \alpha_j \left(\frac{1}{a_j + b_j z_{j-1}} - 1 \right) \qquad (4.7)$$

However, the linear relationships between successive increments (Equation 4.6) was not strong enough to use Equation 4.7 (for the ten-step increment process, $0.11 < r^2 < 0.27$ for Bloemfontein and $0.12 < r^2 < 0.25$ for Pretoria). Woolhiser and Osborn (1985) also reported low r^2 between 0.14 and 0.41 for the ten-step increment process.

(a) Bloemfontein



(b) Pretoria

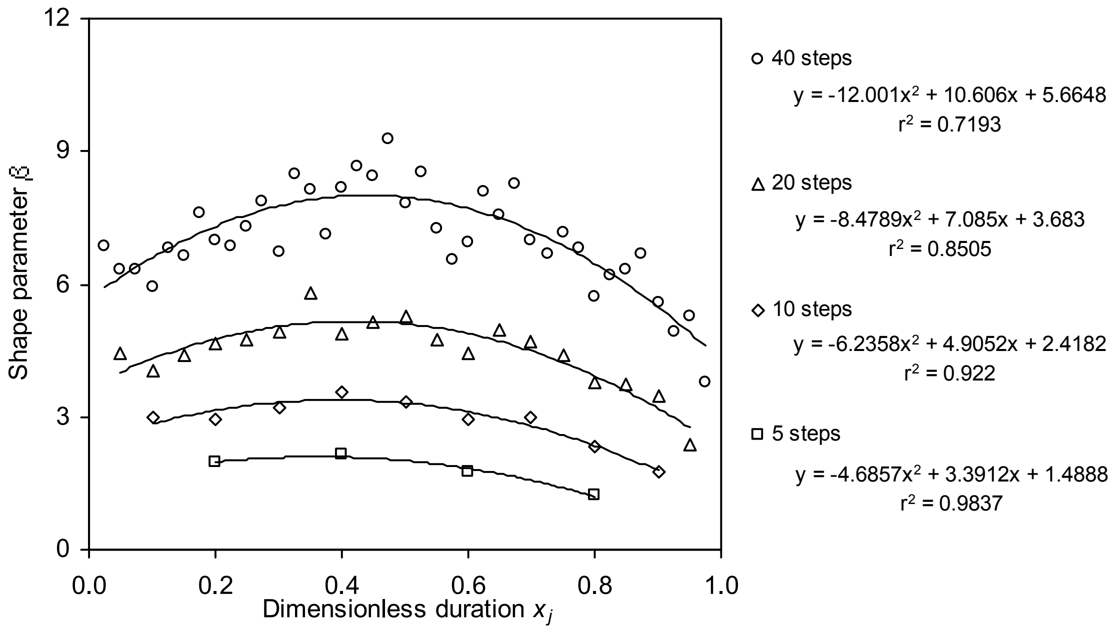


Figure 4.7. Shape parameter β of the beta probability density function for the increment process.

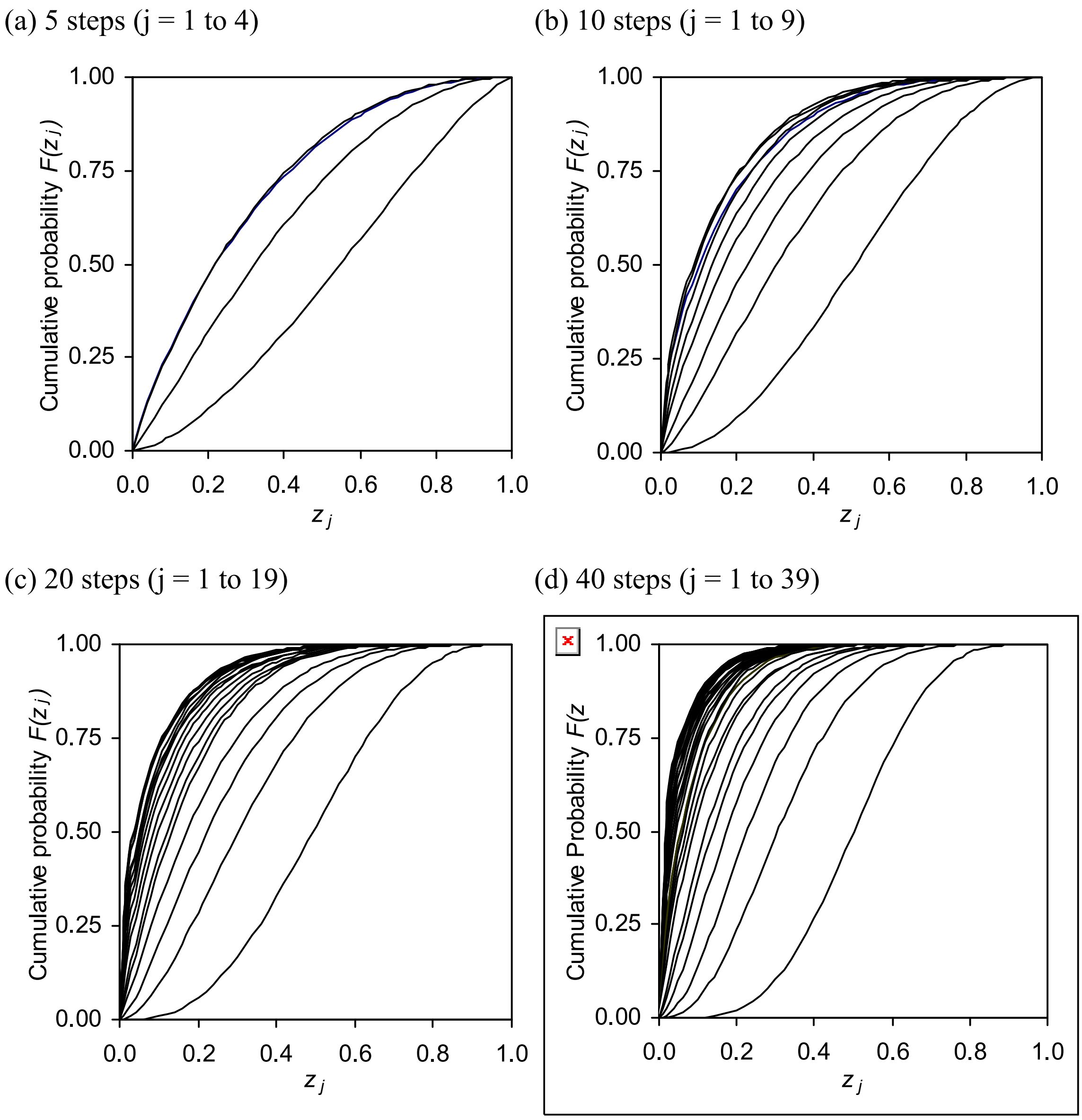


Figure 4.8. The beta cumulative probability curves for the increment process at Bloemfontein.

Figure 4.10 shows relationships between the number of steps and the coefficients of the quadratic equations given in Figure 4.7. There were quite good relationships between them for all coefficients. Therefore, in this study, the coefficients of the quadratic equations for the parameter β_j were determined from equations given in Figure 4.10, and then the parameter β_j for the various increment process was estimated using those coefficients of the quadratic equations.

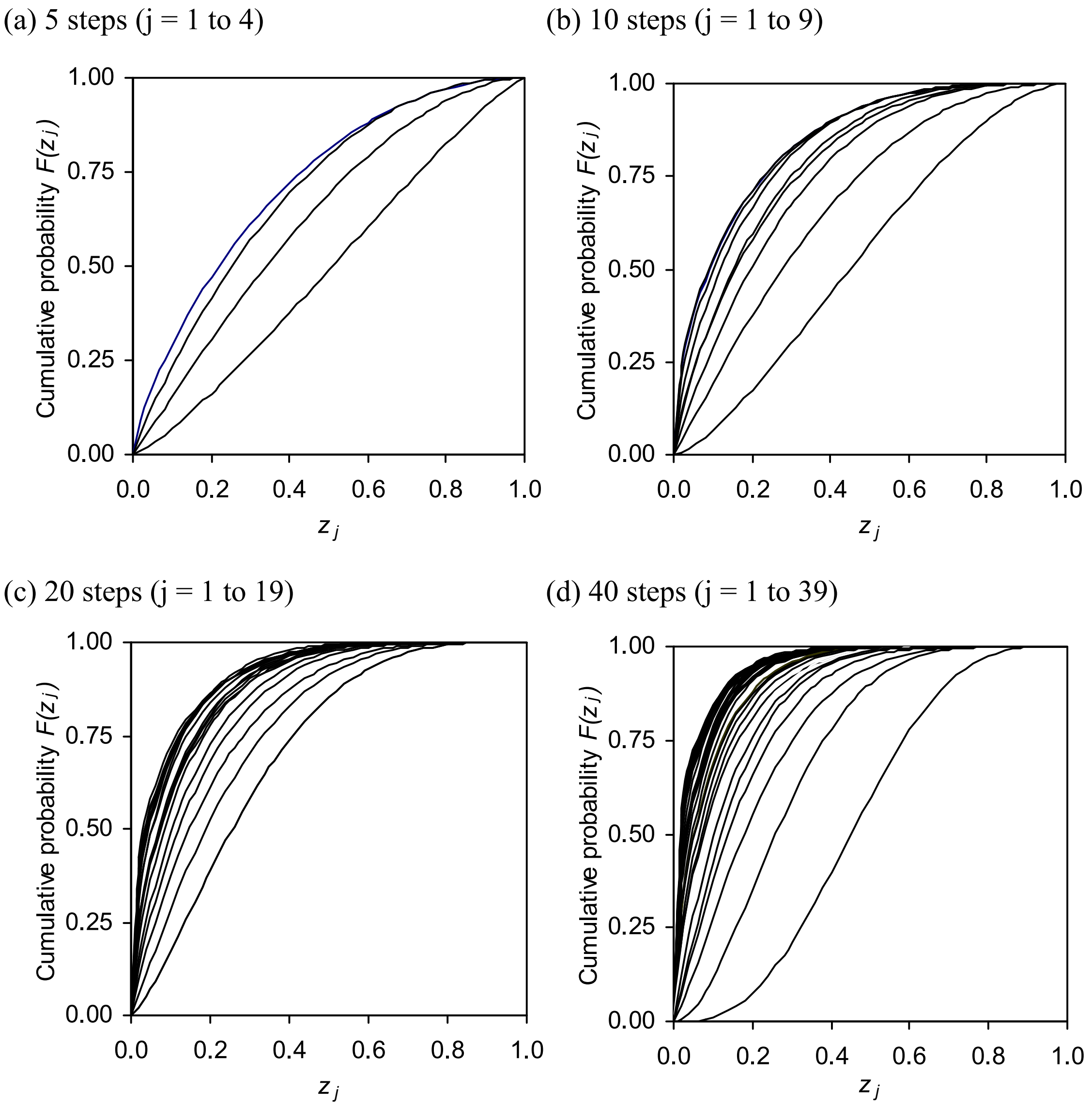
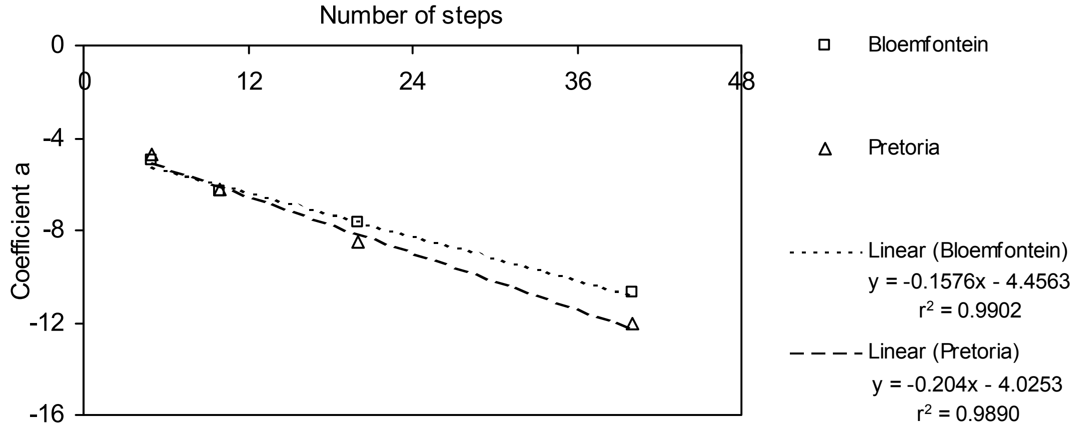
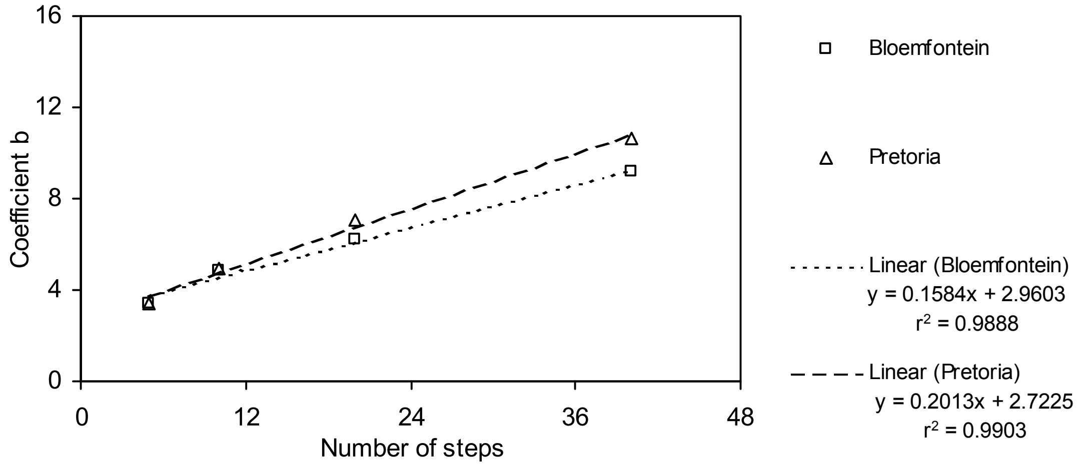


Figure 4.9. The beta cumulative probability curves for the increment process at Pretoria.

(a) Coefficient a



(b) Coefficient b



(c) Coefficient c

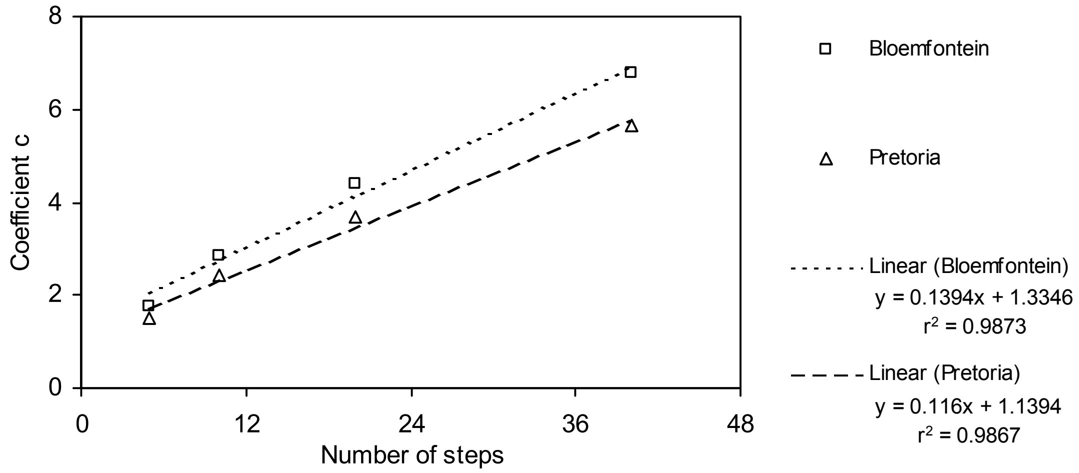


Figure 4.10. Coefficients of the 2nd order polynomial equation ($y = ax^2 + bx + c$) for the parameter β of the beta probability density function.

As this is a stochastic model, model verification against real data provides insufficient points due to it being a small sample of the population. Therefore, for model verification, two criteria were used to compare measured and generated hyetographs: maximum intensities by quartile type and Huff curves. The generated hyetographs data had the same number of rainfall events and event duration as the measured ones. As shown in Table 4.4, the first quartile type of the generated data had lower percentages than that of the measured data, especially for the Bloemfontein data. This resulted in higher percentages of the generated data in the third and fourth quartile types.

Table 4.4. Percentages of rainfall events by quartile type (measured and calculated).

Location†	Quartile	Measured	Generated
Bloemfontein	First	49	35
	Second	21	23
	Third	15	21
	Fourth	15	11
Pretoria	First	48	40
	Second	24	15
	Third	14	22
	Fourth	14	23

† Bloemfontein: 29º06´S, 26º18´E, 1354 m; Pretoria: 25º44´S, 28º11´E, 1330 m

The dimensionless hyetographs (Huff curves) at three percentiles (10 %, 50 % and 90 % levels) for the generated and measured rainfall intensity data were compared, sampling the dimensionless hyetograph intersections at y axes for each interval in x of 0.02 (the same procedure as in Section 4.3). Figures 4.11 and 4.12 show some discrepancies in the 90 percentile curves of the generated and measured dimensionless hyetographs in all quartile types. There was not much difference for the 10 and 50 percentile curves between the measured and generated hyetograhps. The percentile curves of the generated dimensionless hyetographs were similar in shapes to those of the measured dimensionless hyetographs, however, the former was less variable than the latter because the generated 90 percentile curves had lower values than the measured ones at all dimensionless duration. This implies that at very early dimensionless duration, the model developed in this study could not reproduce maximum rainfall intensities at the same frequency as occurred in the measured data sets. The measured and generated Huff curves were compared using the Kolmogorov-Smirnov Test. In general, the 90 percentile curves ($D > 0.24$, $P < 0.11$ for Bloemfontein; $D > 0.16$, $P < 0.52$ for Pretoria) had higher D statistics

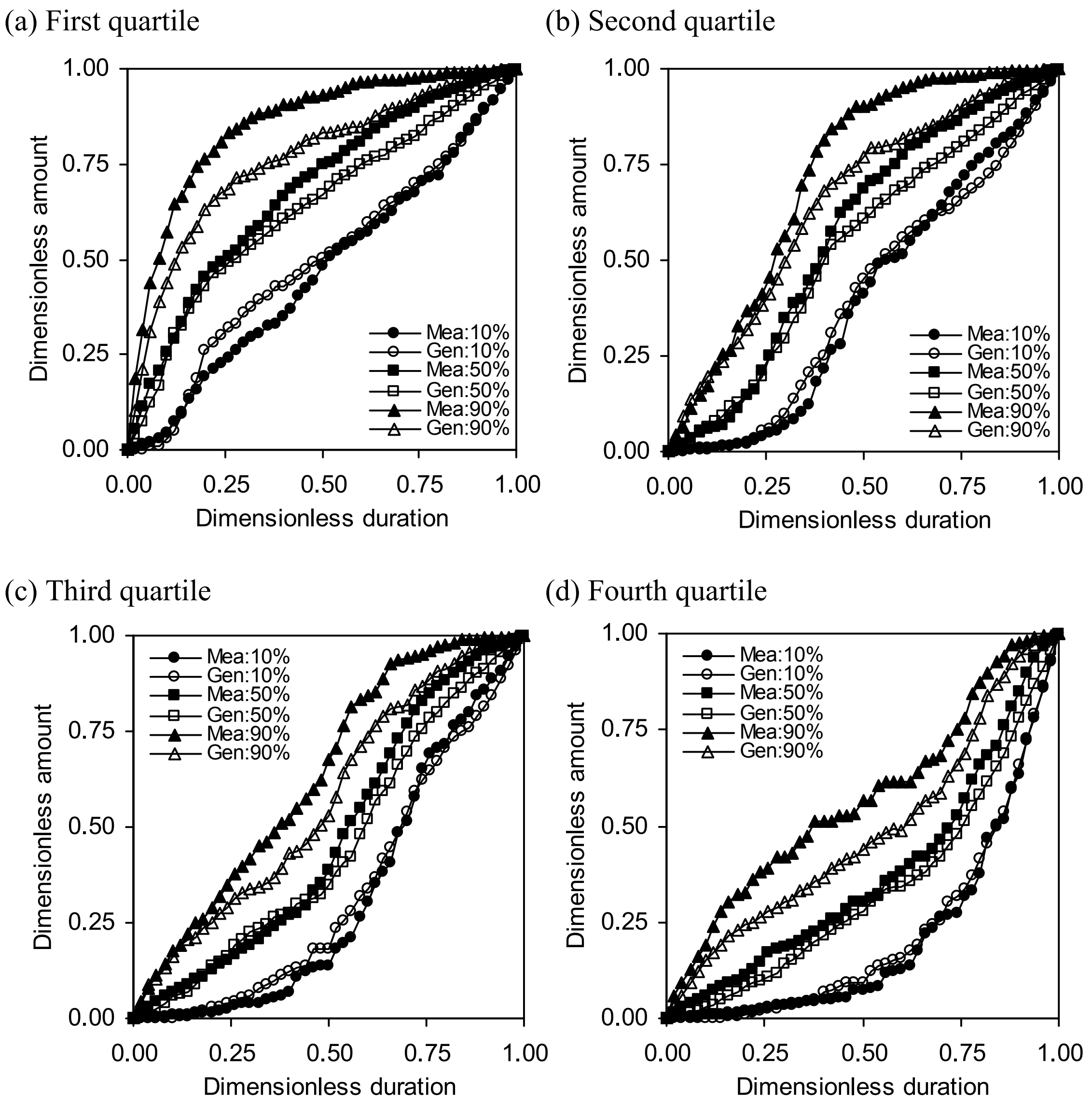


Figure 4.11. The 10, 50 and 90 percentile curves of the measured and generated dimensionless hyetographs for the Bloemfontein data. Mea: measured data; Gen: generated data.

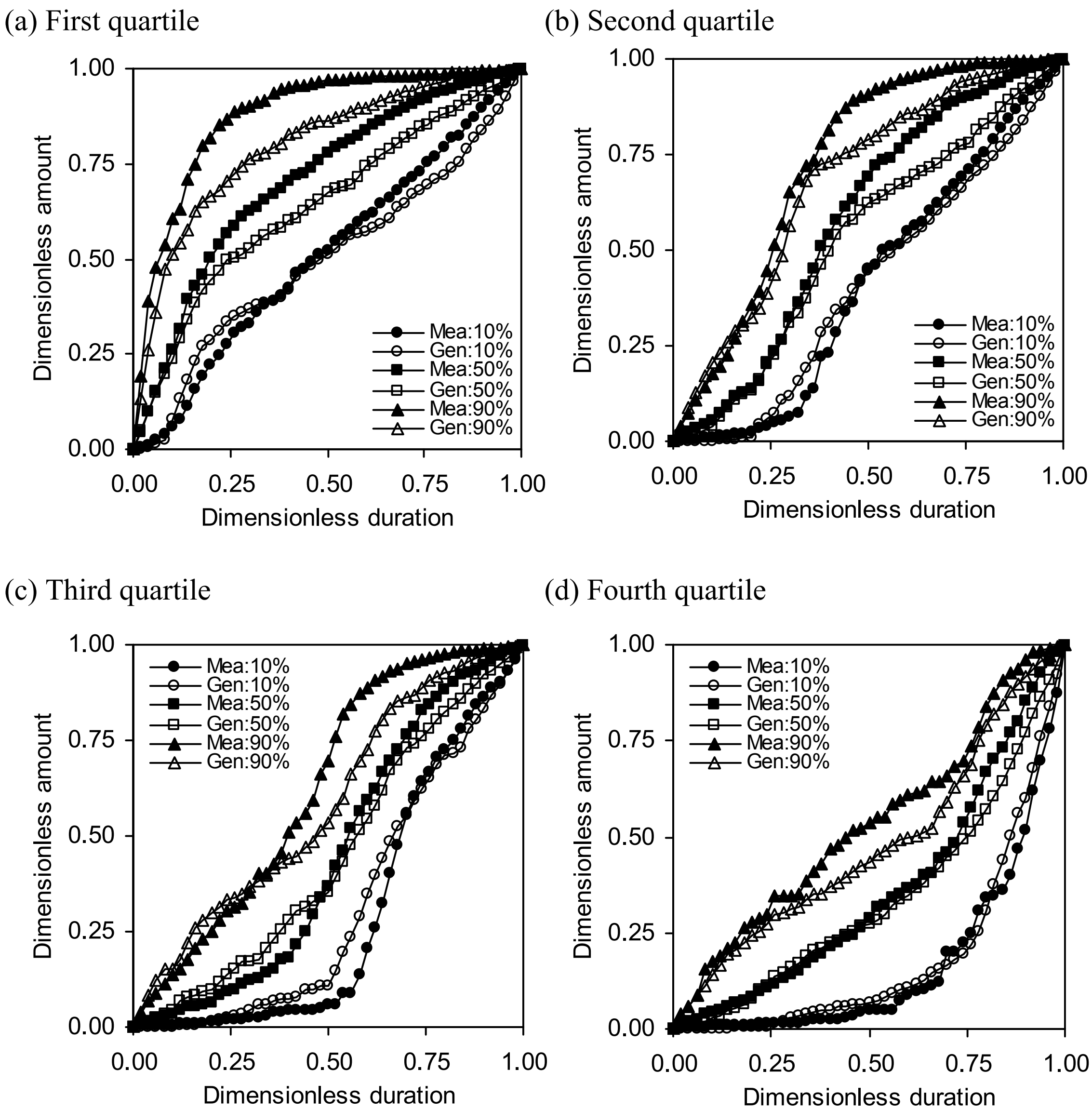


Figure 4.12. The 10, 50 and 90 percentile curves of the measured and generated dimensionless hyetographs for the Pretoria data. Mea: measured data; Gen: generated data.

and lower P values than the other percentile curves (D < 0.14, P > 0.52 for Bloemfontein; D < 0.18, P > 0.37 for Pretoria), as shown in Table 4.5. At both locations, statistically significant difference was only found for the 90 percentile Huff curves of the first quartile type (P < 0.01).

Table 4.5. The Kolmogorov-Smirnov Test for the model verification (measured versus generated) of Huff curves.

Location	Quartile	Percentile	D statistic	P value
Bloemfontein	First	10	0.1176	0.850
		50	0.1373	0.690
		90	0.3137	0.010
	Second	10	0.0588	1.000
		50	0.1373	0.690
		90	0.2549	0.060
	Third	10	0.0980	0.958
		50	0.0784	0.996
		90	0.1569	0.521
	Fourth	10	0.0980	0.958
		50	0.0784	0.996
		90	0.2353	0.101
Pretoria	First	10	0.0784	0.996
		50	0.1765	0.371
		90	0.3529	0.002
	Second	10	0.0980	0.958
		50	0.1765	0.371
		90	0.2157	0.163
	Third	10	0.1765	0.371
		50	0.0980	0.958
		90	0.1569	0.521
	Fourth	10	0.1569	0.521
		50	0.0588	1.000
		90	0.1961	0.251

Garcia-Guzman and Aranda-Oliver (1993) reported generated and measured hyetographs at Almería (36°50′N, 2°32′W), Córdoba (37°51′N, 4°51′W) and Lanjarón (36°55′N, 3°27′W) in Spain. They showed that their model accurately reproduced percentages of storms by quartile type and at three percentile (10, 50 and 90 %) curves of dimensionless hyetographs. The model developed in this study was less accurate than their model. Moreover, Garcia-Guzman and Aranda-Oliver (1993) carried out a simulation study on dimensionless hyetograph generation, changing the shape parameters α and β. They found that the first quartile type had a highest percentage of rainfall events by quartile type, followed by the second quartile type when $\alpha > \beta$, in contrast the forth percentile type showed the highest percentage when $\alpha < \beta$. Thus, determining the shape parameters α and β is critical to this type of stochastic modelling.

Nevertheless, the model developed for Bloemfontein and Pretoria still provides various patterns of rainfall intensities. Although the method for determining the shape parameters α and β should be improved, it is concluded that the model can be reasonably acceptable. Concerning locations, Huff curves for Bloemfontein were not different from Pretoria, as shown in Section 4.3. The reciprocal quadratic equations for the parameter α, the quadratic equations for the parameter β, and the coefficients for the quadratic equations for the Bloemfontein data were quite similar to those for the Pretoria data. These suggest that one dimensionless hyetograph model can be used for generating rainfall intensities at both Bloemfontein and Pretoria, and possibly for all of the summer rainfall highveld region.

4.5. Concluding remarks

In this chapter, the distribution of rainfall intensities within rainfall events was investigated using Huff curves, and compared with respect to locations and seasons. The dimensionless hyetogroaph model was developed for the central high plateau of South Africa. Two areas, Bloemfontein (29ºS, 26ºE) and Pretoria (25ºS, 28ºE) have been chosen because they represent the northern and southern areas of maize production in South Africa. In the next chapter, maize production with water harvesting at Glen (28º57´S, 26º20´E, 1304 m; 30 km away from Bloemfontein) has been simulated and assessed. In the simulation study, generated rainfall intensity data has been used to estimate runoff. Figure 4.13 shows Huff curves for Glen, which are similar to those for Bloemfontein, based on the measured data. There were no significant differences in Huff curves between Glen and Bloemfontein (D statistics < 0.12; P values > 0.85). Therefore, the dimensionless hyetograph model for Bloemfontein has been used to generate rainfall intensities at Glen.

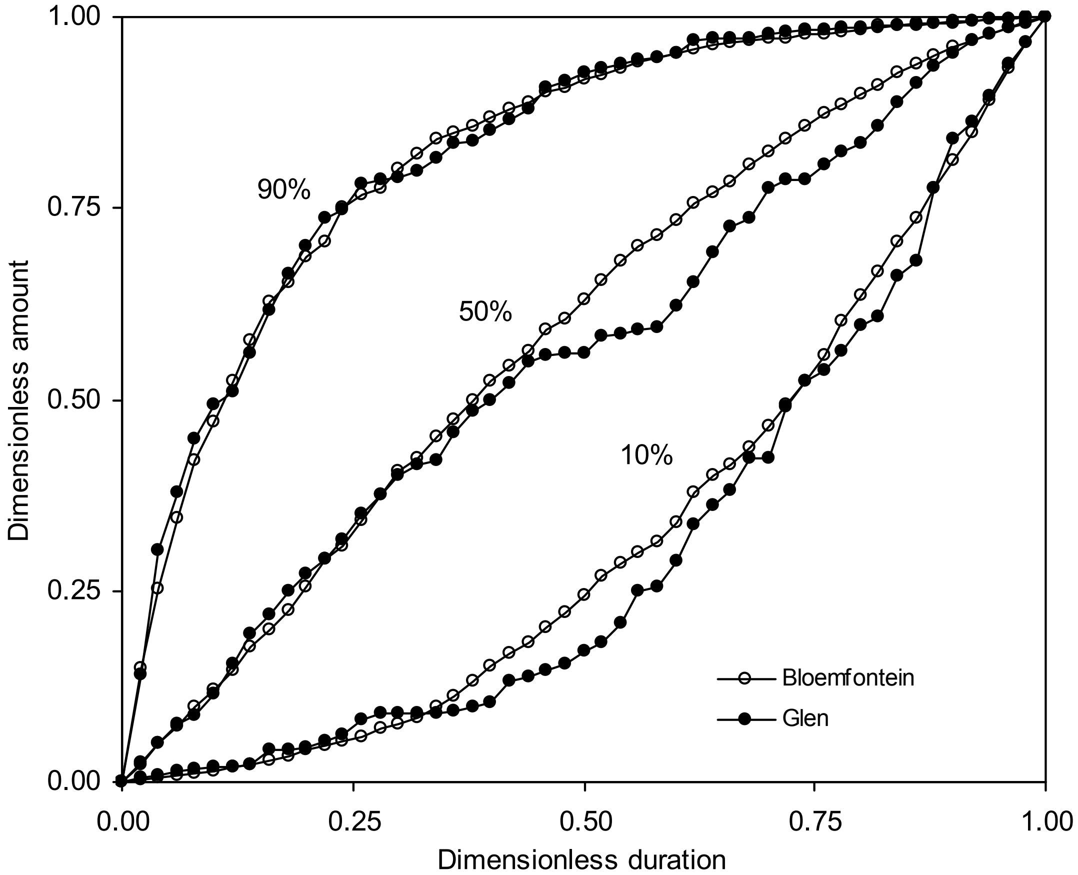


Figure 4.13. Huff curves (from measured data) for Glen and Bloemfontein for all quartile types.

Chapter 5
Quantifying Risk for Different Crop Production Techniques

5.1. Background information

In semi-arid climate zones, the factor most limiting agricultural production is the water resources. For the last two decades, attention has been paid to traditional techniques of water harvesting, especially in dryland crop production (Boers and Ben-Asher, 1982; Hensley *et al.*, 2000). Hensley *et al.*, (2000) reported on a water harvesting technique using a combination of a no-till type of micro-catchment, and basin tillage covered by mulch (WHBM), as shown in Figure 5.1, in a Water Research Commission (WRC) project entitled "Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water" (WRC Report No 878/1/00). The WHBM production technique has been demonstrated to be advantageous in field experiments (on-station and on-farm experiments), compared with a conventional total soil tillage (CT) production technique.

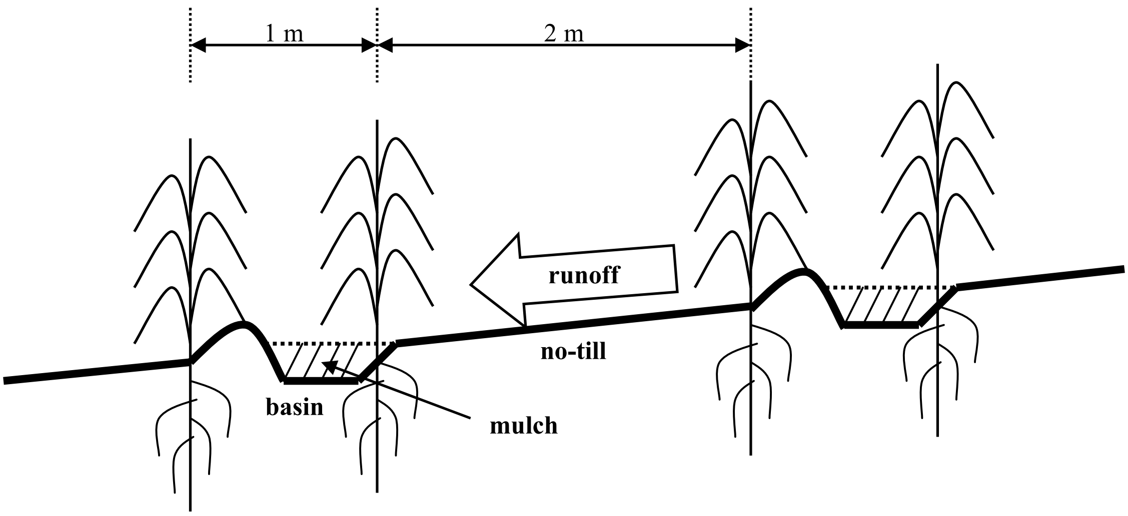


Figure 5.1. A diagrammatic representation of the water harvesting / basin tillage / no-till / mulching production technique (after Hensley *et al.*, 2000).

In order to quantify risk for different production techniques, crop growth modelling, normally run on a daily basis, can be used as an analytical tool. However, an estimation of daily runoff may be a prerequisite for the analysis. In general, subtracting runoff from rainfall gives effective rainfall water available for conventional crop production, while adding water from a runoff area to rainfall gives additional water which can be used by crops in water harvesting crop production. Thus, for the WHBM technique, the effective rainfall is made up of the measured rainfall plus twice the runoff. This is to try and simulate the runoff from the 2 m no-till section which will infiltrate into the soil in the 1 m wide basin section. For the CT technique, the effective rainfall is taken as the measured rainfall minus the runoff. Modelled comparisons of long-term crop production with these different production techniques have seldom been carried out because of lack of reliable runoff information. Therefore, in order to quantify risk for different production techniques using crop growth models, an estimation of runoff is a prerequisite to calculating the effective rainfall under different systems.

The simplest method for estimating daily runoff is the linear regression of daily rainfall to daily runoff (see Section 2.3 in Chapter 2); however, this method sometimes leads to excessive errors in the estimated runoff because soil characteristics are ignored. In Section 3.1 (in Chapter 3), a daily runoff model related to rainfall intensity was introduced: namely, the area under the rainfall intensity curve model (AUC). This model has reasonably estimated the daily amount of runoff under specific soil and climate conditions. Concerning a deterministic model of rainfall-runoff processes, the amount of rainfall per unit time (generally an hour or a minute), termed rainfall intensity, is often needed to run the model (e.g., Morin and Cluff, 1980). Importantly, this runoff model includes soil characteristics, such as soil texture and conditions of soil surfaces. However, long-term data of rainfall intensity is not available although daily rainfall has been observed at many South African weather stations. There are, however, some stochastic models to disaggregate daily rainfall into rainfall intensity (e.g., Woolhiser and Osborn, 1985) and stochastically generated data of rainfall intensity can be acceptable for rainfall intensity-runoff modelling in quantifying risk for long-term crop production systems.

Many crop growth models have been developed and tested worldwide: e.g., CERES-Maize (Jones and Kiniry, 1986); Putu-any crop (de Jager *et al.*, 2001); and SOYGRO (Wilkerson *et al.*, 1985) for soybeans, and SWAMP (Bennie *et al.*, 1997). The Putu crop growth model was developed under South African semi-arid conditions and demonstrated an acceptable degree of reliability in simulating crop yields. Therefore, in this study, the crop growth model "Putu", which means maize porridge in Zulu, developed by Prof. J. M. de Jager of the Department of Agrometeorology, University of the Orange Free State, South Africa (currently, Department of Soil, Crop and Climate Sciences, University of the Free State) was employed to assess risk of maize yield, as it was developed under South African semi-arid conditions (de Jager *et al*., 2001). The Putu crop growth model describes the proportionate limitation on growth due to each of the climatic variables for each day of the growing season (de Jager *et al*., 2001). A major advantage of the model is its subroutine structure, and each of the operations is undertaken in an independent subroutine, so modellers may alter any subroutines and introduce routines from other models (de Jager *et al.*, 2001). The model is written in Quick Basic and a version in C-language is also available.

5.2. Rainfall-runoff-crop production modelling

The schematic diagram of the model flow for rainfall-runoff-crop production processes is shown in Figure 5.2. Firstly, rainfall intensity data is stochastically generated using the dimensionless hyetograph method, i.e., Woolhiser and Osborn (1985) type model, Secondly, runoff is estimated using a deterministic runoff model, i.e., Morin and Cluff (1980) model. Thirdly, crop yield is predicted using a climate-crop growth model, i.e., Putu crop growth model (de Jager *et al.*, 2001). An alternative modelling flow is the estimation of runoff from daily rainfall using the rainfall-runoff linear relationship (e.g., the area under the rainfall intensity curve model, AUC) and then prediction of crop yield using a climate-crop growth model. Thus, crop production risk for different production techniques was quantified using these comprehensive modelling techniques.

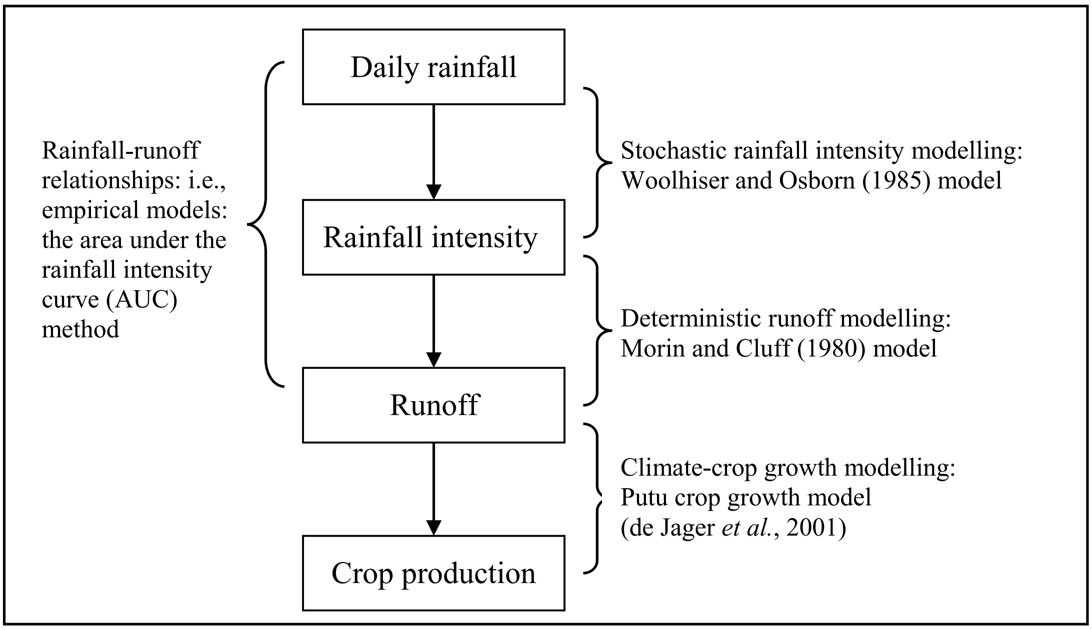


Figure 5.2. The modelling flow of rainfall-runoff-crop production processes.

The Putu crop growth model simulation was undertaken in two states, either energy limited growth or water limited growth (de Jager *et al*., 2001). The energy limited growth model is based on the expo-linear crop growth equation by Gourdriaan and Monteith (1990). The total above-ground standing dry mass, W, is calculated as follows:

$$W = (C_m/R_m)\ln\{1+\exp[\mathrm{R_m}(t-t_b)]\} \quad (5.1)$$

where C_m is maximum crop growth rate, R_m is maximum relative growth rate, t_b is lost time which determines the position of the curve on the time-axis. and t is time after emergence.

The water limited growth is modeled using relationships between biomass and the ratio of transpiration, T, to atmospheric vapour pressure deficit, D, and W is calculated as follows (Tanner and Sinclair, 1983):

$$W = kT/D \tag{5.2}$$

where *k* is transpiration coefficient. In the next section, the runoff model employed in this study is described.

5.3. Evaluation of rainfall-runoff models

In this study, three runoff models were employed to estimate the amount of effective rainfall for the WHBM and the CT production techniques (as an input of the Putu crop growth model). The runoff models used include the Putu runoff submodel (PUTURO), the area under the rainfall intensity curve model (AUC), and the combination model of the dimensionless hyetograph model based on Woolhiser and Osborn (1985) and the deterministic rainfall intensity-runoff model by Morin and Cluff (1980) (WOMC).

PUTURO: The threshold linear model of daily rainfall (RF) and runoff (RO) processes (de Jager *et al.*, 2001)

$$RO = \begin{cases} 0 & RF \le 15 \\ 0.05RF & 15 < RF \le 25 \\ 0.1RF & 25 < RF \le 50 \\ 0.2RF & RF > 50 \end{cases} \quad \text{mm/day} \tag{5.3}$$

AUC: The area under the rainfall intensity curve model (see Section 3.1 in Chapter 3).

$$RO = \begin{cases} 0 & RF \le 8 \\ 0.61RF - 3.11 & RF > 8 \end{cases} \quad \text{mm/day} \tag{5.4}$$

WOMC: The generated data of rainfall intensity for the variable steps of the increment process (see Section 4.4 in Chapter 4) was used to estimate runoff by a deterministic runoff model. In this study, the Morin and Cluff (1980) model was chosen because it is one of the most appropriate models of rainfall intensity-runoff processes for semi-arid regions.

There is an exponential relationship between the infiltration and rainfall intensity, as follows (Morin and Benyaminy, 1977):

$$I_t = I_F + (I_I - I_F)\exp(-\gamma Pt) \tag{5.5}$$

where I_t is the infiltration rate, I_F and I_I are the final and initial infiltration rates of the soil, γ is the soil factor (determined by the stability of the soil surface aggregate to the reorientation of soil particles, by the impact of the raindrops to form a crust), P is rainfall intensity, and t is the time elapsed from the beginning of the rainfall event. Morin and Cluff (1980) show that from Equation 5.5 it is possible to obtain, by substitution and integration, Equation 5.6 which makes it possible to compute the runoff of any storms, segment by segment, by means of Equation 5.8.

In what follows, since the model parameters was not calibrated, it was assumed that for the Glen/Bonheim ecotope, the initial infiltration I_I was 25 mm/hr (100 mm/hr for the Bloemfontein/Swartland ecotope) and the final infiltration I_F and the soil factor were 6 mm/hr and 0.2/mm, respectively. Figure 5.3 shows the infiltration rate curves for the Glen/Bonheim ecotope (Dr. Hensley, personal communication, 2002).

$$IF_k = I_F \Delta t_k + \frac{(I_I - I_F)}{-\gamma P_k}\left[\exp(-\gamma D_k) - \exp(-\gamma D_{k-1})\right] \tag{5.6}$$

where IF_k is the total infiltration of rain water into the soil over period k with rainfall intensity P_k, and D_k, is the amount of rainfall over period k (k = 1, 2,…, m: the number of the given periods per rainfall event) which is given by:

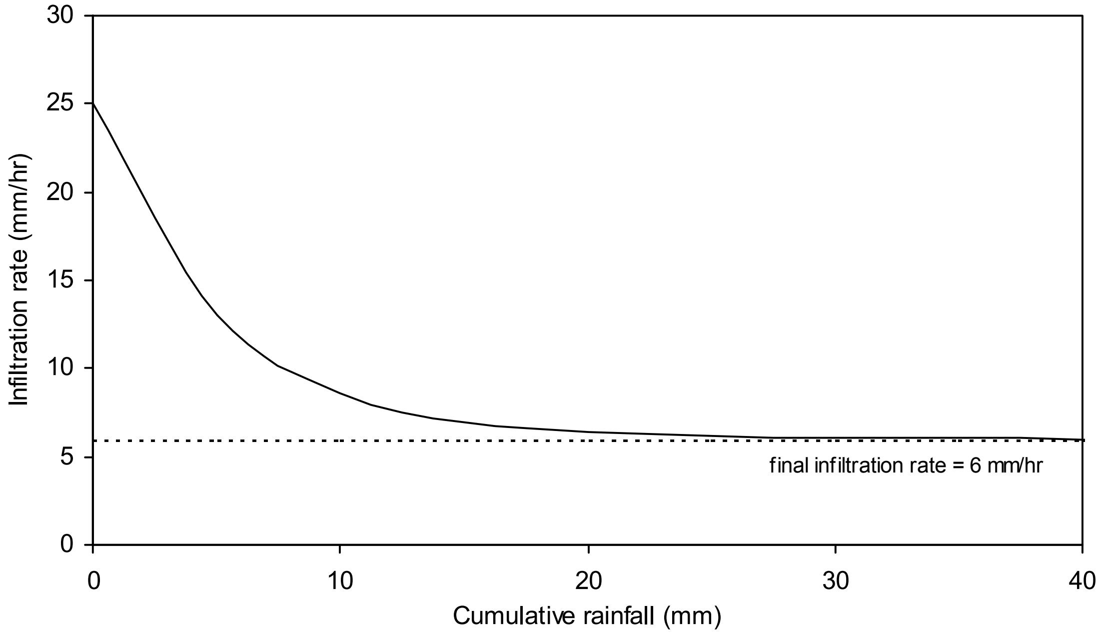


Figure 5.3. The infiltration rate curve for the Glen/Bonheim ecotope obtained using Equation 5.6 and the stated values for the various parameters (Dr. Hensley, personal communication, 2002).

$$D_k = \sum_{k=1}^{m} P_k \Delta t_k \qquad (5.7)$$

The runoff model computes the amount of runoff (RO_k,) in a time period from t_{k-1} to t_k (Δt_k) of any rainfall events, as follows:

$$RO_k = RF_k - IF_k - (SD_{\max} - SD_{k-1}) \qquad k = 1,2,\ldots,m \qquad (5.8)$$

where RF_k is the amount of rainfall, SD_{k-1} is storage and detention of soil surface water in the previous period Δt_{k-1}, and SD_{max} is maximum storage and detention of soil surface water. So, the total amount of runoff per rainfall event is the sum of runoff amounts in all m periods, as follows:

$$RO = \sum_{k=1}^{m} RO_k \tag{5.9}$$

Assuming that SD_{max} (Equation 5.8) was 0.025 mm and 5 mm for the runoff area of WHBM, and the whole land in the CT production technique, respectively, it is possible to calculate the total runoff into the basins from the no-till strip (Figure 5.1) in the WHBM treatment, and from the whole land in the CT treatment for any particular period for which rainfall data is available. Figure 5.4 shows the predicted results (using WOMC), and measured runoff on the CT runoff plot at Glen, showing the calculated runoff amount curve to be similar to the measured one.

Figure 5.5 presents predicted annual runoff`against annual rainfall on the Glen/Bonheim ecotope from 1937 to 1955, the period for which runoff at Glen was studied by du Plessis and Mostert (1965) on the Glen/Tukulu ecotope. Using linear regression analysis, the calculated runoff as a percentage of the annual rainfall, in the period was, 4 % for PUTURO; 33 % for AUC; using WOMC gave 31 % on the no-till strip of the WHBM production technique; using WOMC gave 10 % from the whole land using the CT production technique. As reported by du Plessis and Mostert (1965), the fraction of measured runoff to rainfall was 31.9 % for the no-till soil (equivalent to the no-till strip in the WHBM production technique), 10.3 % and 8.5 % for the prepared soils without and with maize plants, respectively (equivalent to the CT production technique). Long-term runoff estimated by PUTURO was considerably lower than that measured. AUC performed very well compared to the WHBM production technique – for which it was designed. WOMC accurately estimated long-term runoff for both production techniques, as the parameters are adapted for each production technique.

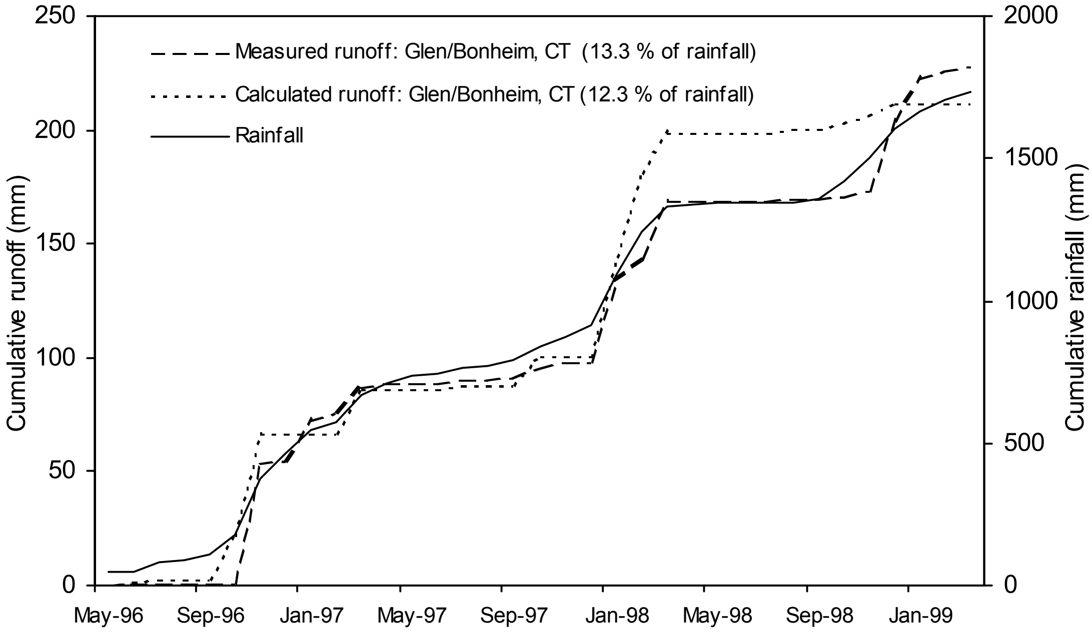


Figure 5.4. The cumulative amount of monthly rainfall, and measured and calculated runoff from May 1996 to March 1999 at Glen for the conventional tillage (CT) production technique.

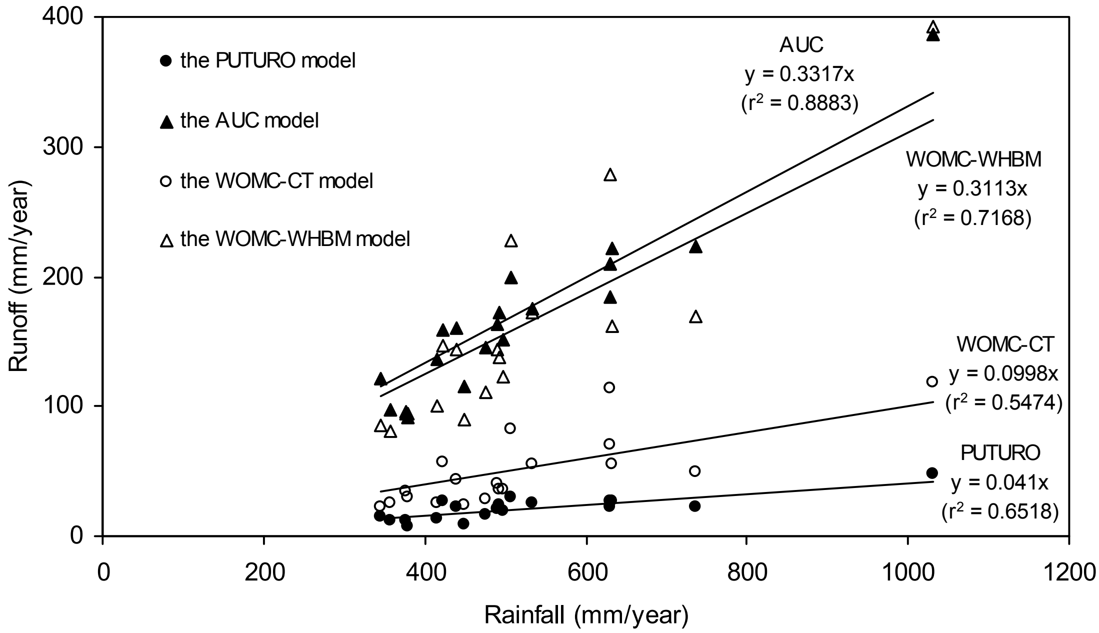


Figure 5.5. The calculated annual runoff against the measured annual rainfall from 1937 to 1955 at Glen.

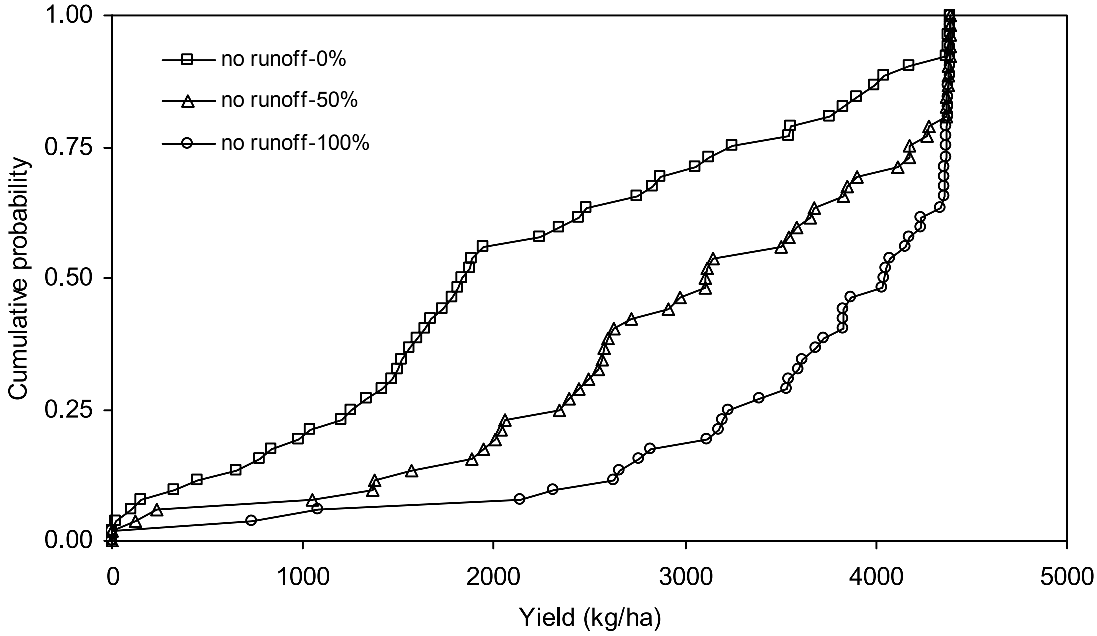
5.4. Risk analysis of maize yields

A problem which arises when making long-term simulations is that the water content at planting in each of the growing seasons in unknown. Another problem is that the models generally do not simulate the water balance well during fallow seasons. The result is that if one makes an uninterrupted long-term simulation including fallow periods, and starting with some assumed initial water content in the first year, the water content at planting in any particular years could be incorrect by a significant amount. This gives invalid results especially for semi-arid ecotopes where the initial water content in very important. In this study, an alternative strategy was employed. Long-term crop model simulations were run with a range of different initial root zone water content at planting each year. Maize cultivar, plant population and planting date were standardised and set to medium maturity, 12,000 plants/ha and the first of December, respectively. Scenarios of crop model simulation were as follows:

a) Ecotope: Glen/Bonheim, Bloemfontein/Swartland
b) Initial water content: empty (0 %), half (50 %), full (100 %)
c) Production technique: WHBM, CT

Simulations are carried out using rainfall data for the period 1951 – 2002. All results are shown in Figures 5.6, 5.7 and 5.8 which present the cumulative probability curves for simulated maize yields on the Glen/Bonheim and Bloemfontein/Swartland ecotopes. The curves explain probabilities of non-exceedance of (or less than) specific yields. For example, in Figure 5.6 (the simulated yields by Putu with no runoff), there was a probability of 50 % of producing less than 1833 kg/ha and 1805 kg/ha with empty initial soil water for the Glen/Bonheim and Bloemfontein/Swartland ecotopes, respectively, while 50 % of obtaining less than 4042 kg/ha and 3779 kg/ha, respectively, with full initial soil water. The simulated maize yields at the 50 % probability level for both ecotopes were summarised in Table 5.1. In general, there is no difference in yield potential between ecotopes.

(a) Glen/Bonheim



(b) Bloemfontein/Swartland

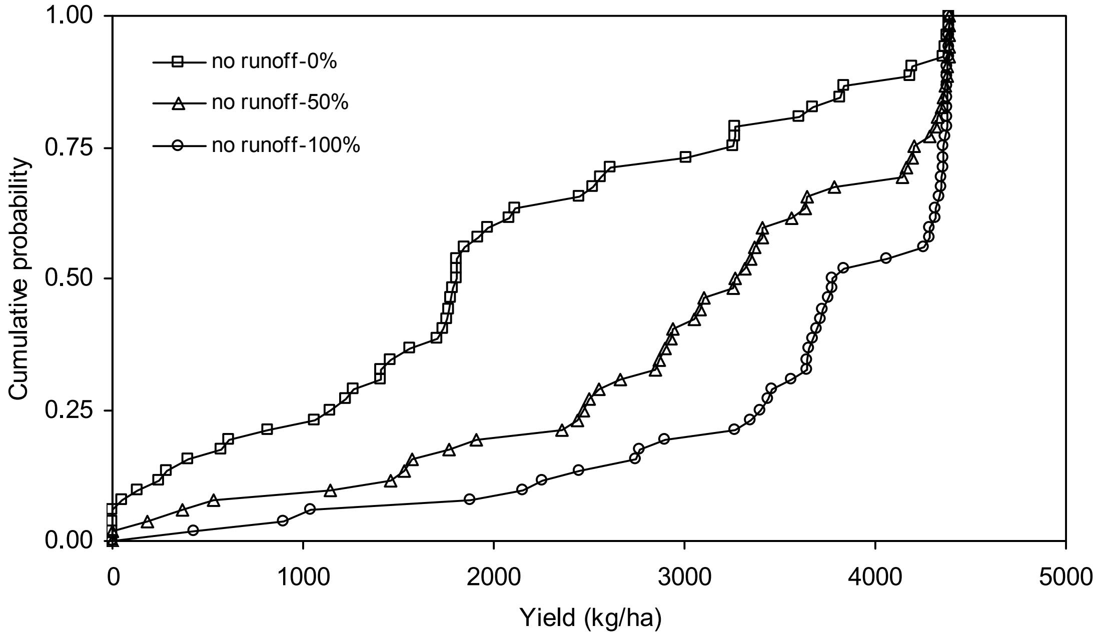


Figure 5.6. Cumulative probabilities of long-term (1951–2002) maize yields produced on the Glen/Bonheim and Bloemfontein/Swartland ecotopes with empty (0%), half (50%) and full (100%) initial soil water content regimes planted on the 1st of December, using the Putu crop growth model with no runoff.

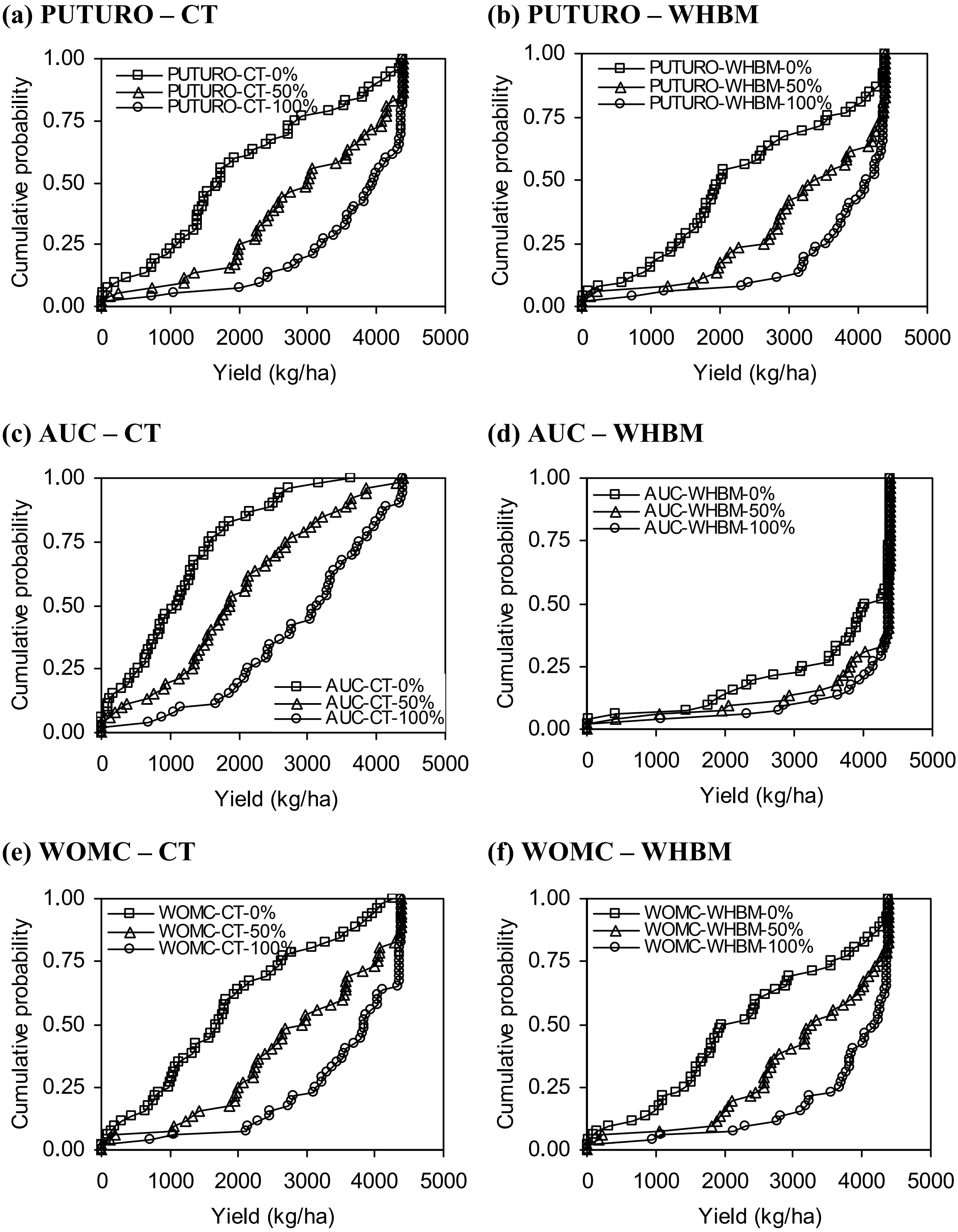
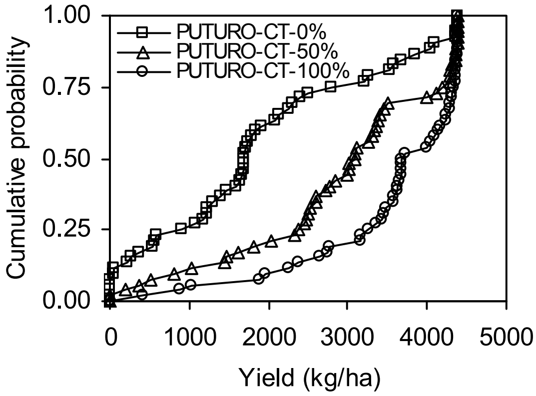
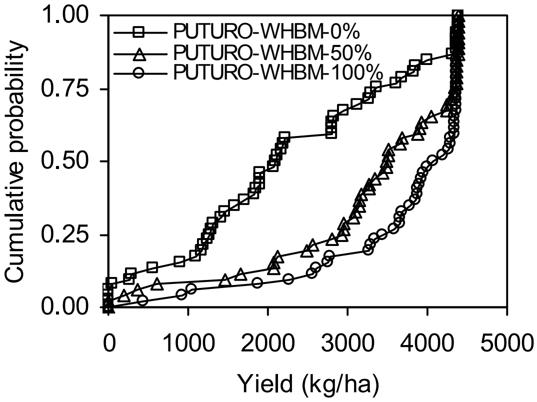


Figure 5.7. Cumulative probabilities of long-term (1951–2002) maize yields produced on the Glen/Bonheim ecotope with empty (0%), half (50%) and full (100%) initial soil water content regimes planted on the 1st of December, using the Putu crop growth model with different runoff calculations.

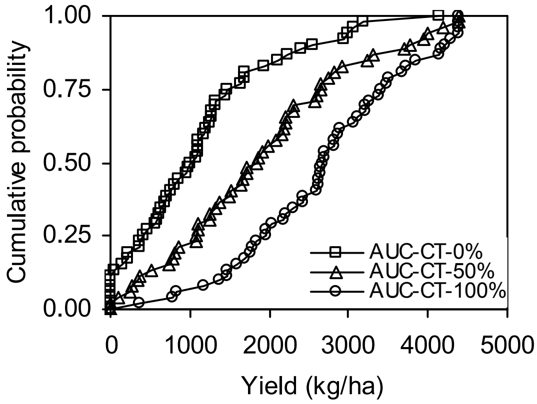
(a) PUTURO – CT



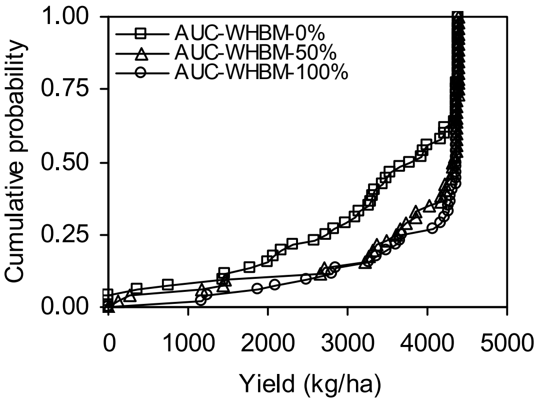
(b) PUTURO – WHBM



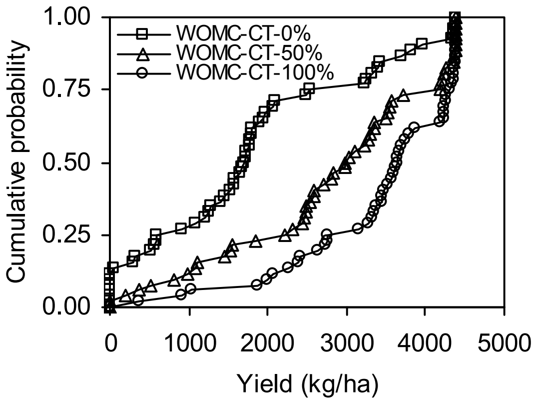
(c) AUC – CT



(d) AUC – WHBM



(e) WOMC – CT



(f) WOMC – WHBM

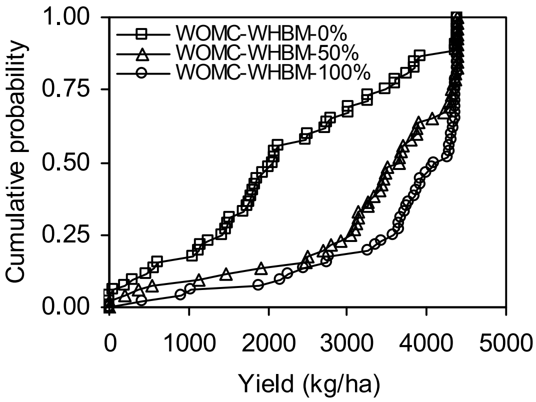


Figure 5.8. Cumulative probabilities of long-term (1951–2002) maize yields produced on the Bloemfontein/Swartland ecotope with empty (0%), half (50%) and full (100%) initial soil water content regimes planted on the 1st of December, using the Putu crop growth model with different runoff calculations.

Table 5.1. Simulated maize yields (kg/ha) at the 50 % probability level for the WHBM and CT production techniques on the Glen/Bonheim and Bloemfontein/Swartland ecotopes.

Ecotope	Runoff model	Production technique	Initial soil water		
			Empty	Half	Full
Glen /Bonheim	No runoff		1833	3106	4042
	PUTURO	CT	1701	2996	3949
		WHBM	2015	3370	4129
	AUC	CT	1101	1865	3128
		WHBM	4021	4371	4374
	WOMC	CT	1678	2940	3831
		WHBM	1971	3250	4179
Bloemfontein /Swartland	No runoff		1805	3267	3779
	PUTURO	CT	1695	3077	3687
		WHBM	2096	3498	4063
	AUC	CT	1010	1850	2668
		WHBM	3792	4323	4368
	WOMC	CT	1693	2984	3643
		WHBM	2069	3643	4103

PUTURO: the threshold linear model
AUC the area under the rainfall intensity curve model
WOMC: the dimensionless hyetograph model and the deterministic runoff model
CT: the conventional tillage production technique
WHBM: the water harvesting/no-till/basin/mulch production technique

With respect to initial soil water, the yields increased as the soil water at planting increased. Thus, as mentioned above, the importance of the soil water at planting was clearly demonstrated. Concerning the water harvesting technique, the Putu crop growth model (Putu) in combination of the AUC runoff model showed a large difference in yields between the WHBM and CT production techniques, compared with Putu with the other runoff models (Table 5.1). At the 50 % probability level, on average, for Putu with the AUC runoff model, the WHBM production technique had 3.7, 2.3 and 1.5 times higher yields than the CT production technique with empty, half and full initial soil water at planting, respectively. For Putu with the WOMC model, the WHBM production technique had 1.2, 1.5 and 1.1 times higher yields than the CT production technique with empty, half and full initial soil water at planting, respectively, while for Putu with the PUTURO model, the WHBM production technique had 1.5, 1.1 and 1.1 times higher yields than the CT production technique. Thus, the WHBM production technique is more advantageous than the CT production technique under water deficits at planting, but not under non-deficit water conditions at planting.

The difference in the simulated yield between production techniques among these crop simulations might result from the amount of runoff estimated by the models. Even though long-term measured runoff for the WHBM and CT production techniques was approximately 30 % and 10 % of rainfall, respectively (see Figure 5.5), the AUC runoff model calculated that runoff was 33 % of rainfall for both production techniques, on average, while the PUTURO model estimated 4 % of rainfall. In order to analyse the yield difference between those production techniques, the AUC and PUTURO models were used for estimating runoff for the WHBM and CT production techniques, respectively. On average, the WHBM production technique had 2.3, 1.4 and 1.1 times higher yields than the CT production technique with empty, half and full initial soil water at planting, respectively. In half and full initial soil water treatments, this result was similar to the result using the WOMC model. The similarity might be explained by analogous estimated runoff; that is, the WOMC runoff model estimated that long-term runoff was 10 % of rainfall for the CT production technique and 31 % of rainfall for the WHBM production technique (see Figure 5.5).

Another important analysis was made with respect to the effects of El Niño/La Niña on crop production. One of the indicators normally used to identify El Niño/La Niña episodes is the Southern Oscillation Index (SOI). The SOI is negative during El Niño episodes while the SOI is positive during La Niña episodes. This index has been used to investigate the influences of El Niño/La Niña on crop yields. Hammer and Muchow (1991) showed that there were remarkable differences in simulated sorghum (*Sorghum bicolor*) yield in Australia between years with SOI < -5 and SOI $> +5$ (SOI was averaged over August, September and October). They reported that with SOI < -5 the yield was lower at any cumulative probability level, compared with and SOI $> +5$.

In the present simulation study, the 3-month, September, October and November, average of the SOI was used to separate the simulated maize yield (planting at 1st December; harvest in March/April of the following year) into three categories: SOI < −5, −5 ≤ SOI ≤ +5, and SOI > +5. The cumulative probability curves for the simulated yield with these SOI ranges are presented in Figure 5.9 for the Glen/Bonheim ecotope and Figure 5.10 for the Bloemfontein/Swartland ecotope. With full initial soil water at planting, not much difference was found on cumulative probability curves among SOI classes in both CT and WHBM production techniques. This indicates that if there is adequate soil water initially, there is little effect of SOI on final yield. With empty and half initial soil water, at higher probability (yield) levels, the El Niño tendency years (SOI < −5) had lower yield potential than the La Niña tendency years (SOI > +5) in both production techniques. However, using the Kolmogorov-Smirnov Test, it was found that there was not statistically significant difference in the yield between the El Niño tendency years and the La Niña tendency years (D statistics < 0.27 and P values > 0.58 for the Glen/Bonheim ecotope; D statistics <0.41 and P values > 0.13 for the Bloemfontein/Swartland ecotope).

Concerning an advantage of in-field water harvesting, Table 5.2 shows the ratio of the yield for the WHBM production technique to the CT production technique for the El Niño and La Niña tendency years. On average (for both location and three probability levels), the yield for years with SOI < −5 with the WHBM production technique was 38, 29 and 13 % higher than the yields with the CT production technique for empty, half and full initial soil water at planting, respectively. This clearly shows the advantage of water harvesting during the drier El Niño years. Similarly, for years with SOI > +5, the WHBM production technique had 44, 22 and 11 % higher yield than the CT production technique. Thus, the superiority of the WHBM production technique is clearly demonstrated in both El Niño and La Niña years, particularly with little initial soil water at planting.

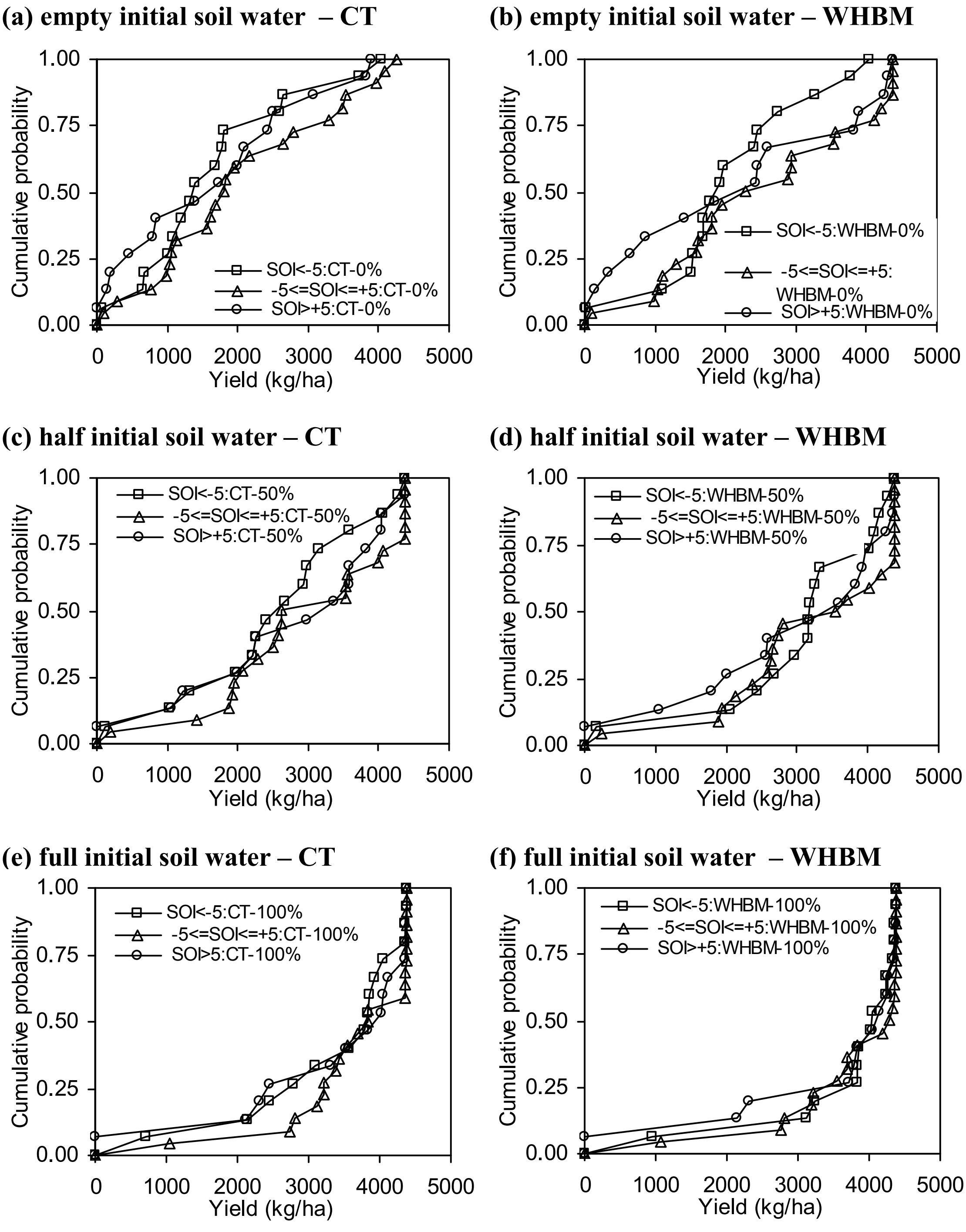
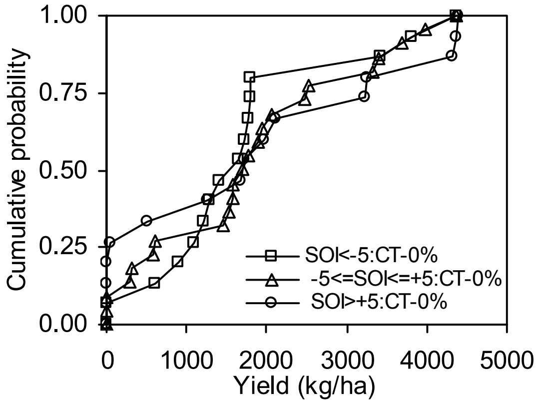
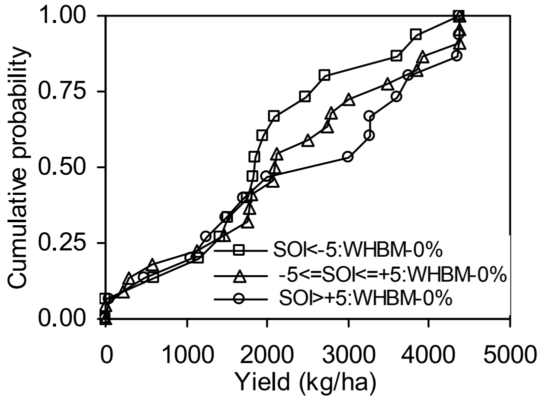


Figure 5.9. Cumulative probabilities of simulated long-term (1951–2002) maize yields produced on the Glen/Bonheim ecotope for SOI<–5, –5≤SOI≤+5 and SOI>+5, using the Putu crop growth model with the WOMC model.

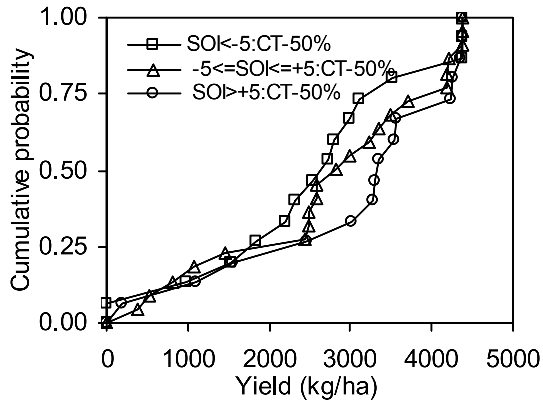
(a) empty initial soil water – CT



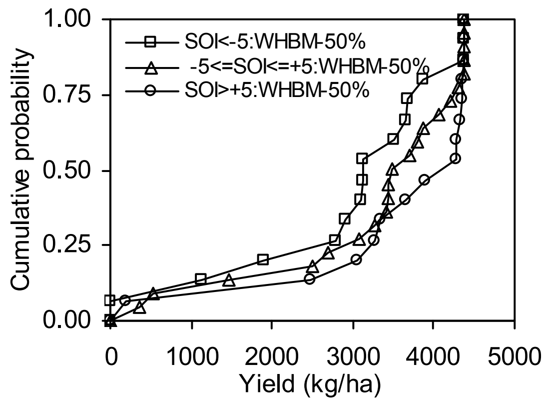
(b) empty initial soil water – WHBM



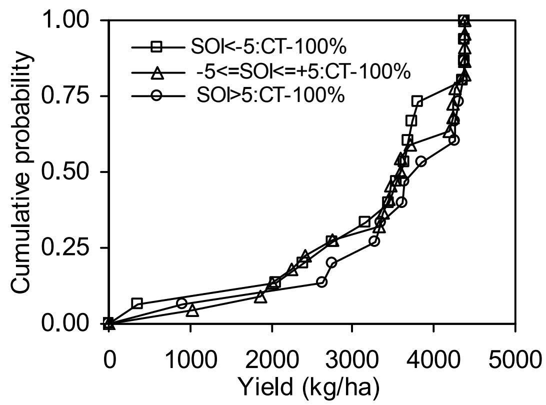
(c) half initial soil water – CT



(d) half initial soil water – WHBM



(e) full initial soil water – CT



(f) full initial soil water – WHBM

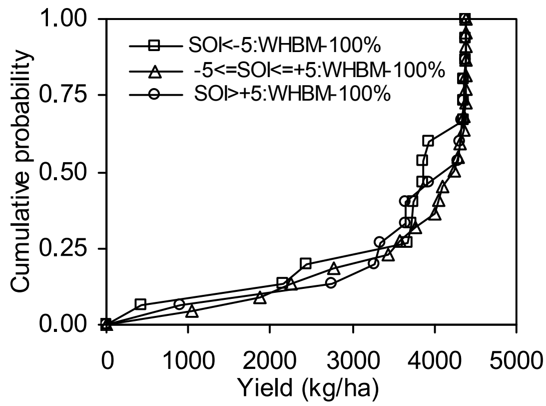


Figure 5.10. Cumulative probabilities of simulated long-term (1951–2002) maize yields produced on the Bloemfontein/Swartland ecotope for SOI<–5, –5≤SOI≤+5 and SOI>+5, using the Putu crop growth model with the WOMC model.

Table 5.2. The ratio of simulated maize yields for the WHBM production technique to the CT production technique for the El Niño tendency years (SOI < −5) and the La Niña tendency years (SOI >+5) at the 25, 50 and 75% cumulative probability level.

Location	SOI	Probability	Initial soil water		
			Empty	Half	Full
Glen	< −5	25 %	1.80	1.55	1.34
		50 %	1.37	1.25	1.06
		75 %	1.18	1.20	1.04
	> +5	25 %	1.52	1.19	1.27
		50 %	1.38	1.07	1.04
		75 %	1.42	1.07	1.04
Bloemfontein	< −5	25 %	1.28	1.40	1.19
		50 %	1.21	1.19	1.08
		75 %	1.45	1.14	1.07
	> +5	25 %	*	1.58	1.10
		50 %	1.48	1.23	1.10
		75 %	1.29	1.11	1.01

CT: the conventional tillage production technique.
WHBM: the water harvesting/no-till/basin/mulch production technique.
* the simulated yield with the CT production technique was extremely low (25 kg/ha), compared with the yield with the WHBM production technique (999kg/ha).

5.5. Concluding remarks

In this chapter, a framework for quantifying risk of maize production on clay soils under semi-arid conditions was presented. Long-term crop yields with different production techniques were assessed using crop simulation. Three processes (daily rainfall-rainfall intensity, rainfall intensity-runoff, runoff-crop yield) were simulated: i.e., rainfall intensity generation, daily runoff estimation and crop yield prediction. Using stochastically generated rainfall intensity and then deterministically estimated runoff, yield advantages of the in-field water harvesting production technique were clearly demonstrated through the crop simulation outputs. Although completely satisfactory runoff estimation and therefore rainfall intensity generation still need to be further developed, the value of the simulation technique employed has been shown.

Chapter 6
Conclusions and Recommendations

6.1. Conclusions

Three questions have been answered in this project; i.e. (i) can a model be found or developed by which rainfall intensity data can be reliably predicted from daily rainfall amount data?, (ii) will the predicted long-term rainfall intensity data for a particular site be capable in practice of predicting runoff from micro-catchments with reasonable accuracy?, and (iii) assuming the first and second questions are successful, what possible increases in low yield could be expected from water harvesting systems? Three studies were carried out to answer these questions (i) statistical analysis of rainfall and runoff data, (ii) estimating rainfall intensity from daily rainfall amount, and (iii) the application for risk analysis of crop yield.

In the statistical analysis, it was concluded that it would not be possible to use simple relationships between rainfall intensity and rainfall amount with any confidence to estimate the rainfall intensity from the daily/event rainfall amount from the historical record. Moreover, in rainfall-runoff relationships, the simple linear model could be used to estimate the daily amount of runoff from the daily amount of rainfall, but it has been concluded that it may be better to estimate runoff from rainfall intensity. However, rainfall intensity data is not obtainable from most South African weather stations.

Based on the above fact, four methods of modelling rainfall-runoff processes were introduced: (i) the stepwise regression techniques, (ii) artificial neural networks, (iii) the area under the rainfall intensity curve method and (iv) the hyetograph method. The stepwise regression showed no relationships between rainfall intensity and the other meteorological factors (weather data or synoptics data). In the ANN analysis, a strong relationship between rainfall intensity and wind speed at 700 hPa level was found, but it is still necessary to improve data generation based on the ANN model. Thus, data generation of rainfall intensity was not successful using the first two methods.

The area under the rainfall intensity curve method provided acceptable daily runoff estimation from daily rainfall, compared with the simple linear model of daily rainfall-runoff processes. In the dimensionless hyetograph method or the Woolhiser and Osborn (1985) model (stochastic rainfall intensity modelling), the model was reasonably validated for the purpose of generating the amount of daily runoff. This model should be used in combination with a deterministic runoff model. In this study, the Morin and Cluff (1980) model was combined with the hyetograph model and used to estimate runoff.

Two successful models for rainfall-runoff processes were employed for estimating daily runoff; that is, (i) the empirical runoff model (the area under the rainfall intensity curve model and the PUTURO runoff model) and (ii) the mechanistic runoff model combined with a stochastic rainfall intensity model (the Morin and Cluff runoff model). Using the Putu crop growth model, maize production was simulated under several scenarios, including the water harvesting / basin tillage / no-till / mulching (WHBM) and the conventional tillage (CT) production techniques. According to simulation outputs, the superiority of the WHBM production technique was clearly demonstrated, compared with the CT production technique. In some circumstances, small-scale developing farmers in semi-arid regions would be able to double their maize yields. Hence, it is recommended that the risk analysis of crop yield can be carried out using the Putu crop growth model in combination with the rainfall-runoff models used in this study.

Concerning rainfall intensity modelling, the Huff curve procedure has been developed to simulate the rainfall intensities in this project. This stochastic model has been developed to provide long-term rainfall intensity values as applied in agricultural water harvesting projects. In addition, these results would then be available to the hydrologists in South Africa to be used to estimate peak rainfall intensity for soil erosion and water quality studies. This would greatly enhance the existing hydrological models and predictions.

6.2. Recommendations

Crop simulation using the combination of a stochastic rainfall intensity model, a deterministic runoff model and a deterministic crop growth model can be useful for evaluating crop production with water harvesting techniques. It has been demonstrated in this study, and in fact, the model procedure which has been used in this study is reasonably acceptable. However, there are some important tasks which should be carried out in the future. One of the most important of these is to validate the stochastic Huff curve model under other South African climatic conditions. Another important task is to link by means of computer programming the rainfall intensity, runoff and crop yield models to form one comprehensive simulator. Hence, the following recommendations for further studies are made:

1. It is recommended to develop the Huff curve procedure further and to make it applicable to a larger area of South Africa, specifically, to develop the Huff curve model for highveld, compared with the model for Bloemfontein and Pretoria (both in summer rainfall highveld).

2. The runoff data estimated is able as an input for the Putu crop growth model. However, the model simulation runs have been carried out step by step, so it is recommended to develop a complete simulator for crop yield by linking the combination of the stochastic rainfall intensity generator – the mechanistic runoff model to the crop model.

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Appendices

(i) Summary of soil analytical data

Ecotope: Glen/Bonheim (Hensley *et al.*, 2000)

Horizon	A (veld)	A (profiel)	B1	B2	C	
Depth (mm)	0-300	300-400	400-550	550-800	800-1300	
Particle Size Distribution %						
c/g sand (2-0.5mm)	0.5	0.1	0.6	0.3	1.3	
m sand (0.5-0.25mm)	2.7	1.7	1.8	1.9	2.1	
f sand (0.25-0.106mm)	23.7	23.1	21.9	22.6	20.4	
v/b f sand (0.106-0.05mm)	16.6	19.5	20.0	19.4	17.1	
c/g silt (0.05-0.02mm)	4.9	5.1	7.3	6.8	5.7	
f silt (0.02-0.002mm)	4.8	4.4	4.5	7.1	14.3	
clay (0.002mm)	45.1	43.5	43.0	39.6	37.7	
Texture	Cl	Cl	Cl	ClLm	ClLm	
Chemical Analysis						
C %	0.85	0.57				
Plasticity index	33	21	33	29	28	
Resistance (ohm)	340	340	320	240	240	
pH H_2O	7.78	7.56	8.23	8.27	8.49	
pH KCl	6.50	6.11	7.06	7.36	7.60	
Exchangeable/Extractable Cations c mol+/kg soil						
Na	0.71	0.56	0.85	1.24	1.19	
K	0.80	0.65	0.55	0.62	0.58	
Ca	10.78	8.33	7.98	7.98	13.77	
Mg	11.24	12.22	11.53	11.94	8.86	
S value	23.53	21.76	20.91	21.78	24.40	
T value (CEC)	25.77	24.30	23.12	24.04	26.21	

Ecotope: Glen/Swartland (Hensley *et al.*, 2000)

Horizon	A	B1	B2	B3	B4	C
Depth (mm)	0-250	250-400	400-600	600-830	830-1000	1000-1300
Particle Size Distribution %						
c/g sand (2-0.5mm)	0.2	0.2	0.1	0.3	0.2	1.1
m sand (0.5-0.25mm)	2.2	2.0	2.0	1.9	1.7	2.6
f sand (0.25-0.106mm)	27.3	25.4	26.3	24.1	22.8	29.6
v/b f sand (0.106-0.05mm)	22.4	21.1	20.7	20.3	17.3	20.2
c/g silt (0.05-0.02mm)	4.7	3.1	5.4	2.8	4.1	4.9
f silt (0.02-0.002mm)	2.8	3.2	3.5	4.6	8.8	8.3
clay (0.002mm)	38.2	42.7	39.2	44.0	42.6	31.2
Texture	FiSaCl	FiSaCl	FiSaCl	FiSaCl	Cl	FiSaClLm
Chemical Analysis						
C %	0.53					
Plasticity index	22	27	28	33	34	22
Resistance (ohm)	1400	1400	1600	1400	1400	420
pH H_2O	6.46	7.44	8.14	8.94	9.14	8.92
pH KCl	4.97	6.08	6.52	7.26	7.54	7.57
Exchangeable/Extractable Cations c mol+/kg soil						
Na	0.19	0.33	0.54	0.51	0.96	0.94
K	0.78	0.55	0.49	0.39	0.76	0.77
Ca	5.89	6.04	6.59	4.86	14.82	15.72
Mg	7.61	8.41	11.20	6.80	13.69	11.03
S value	14.47	15.33	18.82	12.56	30.23	28.46
T value (CEC)	23.15	23.57	27.02	26.12	26.45	21.53

(ii) Summary of Huff curve data

All data (including both Bloemfontein and Pretoria and both the rainy season and the non-rainy season)

		Dimensionless duration								
Quartile	Percentile	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First	10	0.06	0.21	0.31	0.40	0.50	0.59	0.67	0.77	0.88
	20	0.11	0.28	0.41	0.51	0.60	0.68	0.76	0.84	0.93
	30	0.16	0.36	0.48	0.58	0.66	0.74	0.81	0.88	0.95
	40	0.22	0.42	0.53	0.63	0.72	0.79	0.85	0.91	0.96
	50	0.26	0.47	0.59	0.68	0.76	0.83	0.89	0.94	0.97
	60	0.31	0.54	0.65	0.73	0.80	0.87	0.92	0.95	0.98
	70	0.39	0.61	0.71	0.79	0.85	0.91	0.94	0.97	0.98
	80	0.47	0.68	0.79	0.86	0.90	0.94	0.96	0.98	0.99
	90	0.60	0.81	0.88	0.93	0.95	0.97	0.98	0.99	0.99
Second	10	0.01	0.02	0.06	0.22	0.43	0.52	0.64	0.76	0.87
	20	0.02	0.05	0.14	0.34	0.51	0.62	0.72	0.83	0.92
	30	0.02	0.07	0.21	0.41	0.57	0.68	0.76	0.86	0.94
	40	0.04	0.11	0.26	0.46	0.63	0.74	0.81	0.89	0.95
	50	0.06	0.14	0.33	0.54	0.69	0.78	0.86	0.91	0.96
	60	0.08	0.19	0.41	0.60	0.74	0.83	0.89	0.94	0.98
	70	0.11	0.24	0.47	0.65	0.80	0.87	0.93	0.96	0.99
	80	0.14	0.28	0.53	0.74	0.86	0.92	0.96	0.98	0.99
	90	0.18	0.38	0.67	0.84	0.92	0.96	0.98	0.99	1.00
Third	10	0.01	0.01	0.02	0.05	0.09	0.25	0.54	0.71	0.86
	20	0.02	0.03	0.05	0.10	0.18	0.35	0.63	0.78	0.90
	30	0.02	0.04	0.08	0.15	0.25	0.45	0.68	0.83	0.92
	40	0.04	0.08	0.12	0.18	0.34	0.52	0.72	0.85	0.93
	50	0.05	0.10	0.17	0.25	0.37	0.59	0.77	0.88	0.95
	60	0.07	0.13	0.20	0.29	0.42	0.65	0.80	0.91	0.96
	70	0.09	0.16	0.25	0.33	0.48	0.71	0.85	0.93	0.97
	80	0.11	0.21	0.31	0.41	0.56	0.78	0.90	0.96	0.98
	90	0.16	0.28	0.41	0.51	0.69	0.86	0.95	0.98	0.99
Fourth	10	0.01	0.01	0.02	0.03	0.05	0.07	0.10	0.34	0.54
	20	0.01	0.02	0.04	0.06	0.12	0.20	0.29	0.43	0.68
	30	0.02	0.05	0.06	0.12	0.18	0.28	0.36	0.52	0.74
	40	0.04	0.07	0.11	0.19	0.25	0.32	0.42	0.57	0.81
	50	0.05	0.10	0.15	0.23	0.29	0.37	0.46	0.66	0.85
	60	0.07	0.12	0.20	0.27	0.34	0.42	0.51	0.69	0.89
	70	0.08	0.16	0.25	0.32	0.40	0.48	0.58	0.75	0.92
	80	0.11	0.20	0.30	0.38	0.45	0.53	0.62	0.79	0.95
	90	0.18	0.30	0.40	0.48	0.55	0.62	0.69	0.85	0.97

Bloemfontein data (including both the rainy season and the non-rainy season)

		Dimensionless duration								
Quartile	Percentile	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First	10	0.05	0.19	0.28	0.35	0.49	0.56	0.65	0.72	0.87
	20	0.11	0.26	0.37	0.46	0.55	0.64	0.74	0.84	0.92
	30	0.16	0.33	0.45	0.54	0.63	0.72	0.81	0.87	0.94
	40	0.21	0.38	0.51	0.59	0.69	0.77	0.84	0.90	0.96
	50	0.26	0.45	0.55	0.66	0.75	0.81	0.88	0.93	0.97
	60	0.30	0.50	0.60	0.70	0.79	0.85	0.91	0.95	0.98
	70	0.38	0.58	0.68	0.75	0.83	0.90	0.93	0.96	0.99
	80	0.46	0.66	0.77	0.83	0.88	0.93	0.96	0.98	0.99
	90	0.57	0.77	0.86	0.90	0.93	0.96	0.97	0.98	0.99
Second	10	0.01	0.02	0.07	0.22	0.41	0.52	0.64	0.77	0.85
	20	0.02	0.05	0.14	0.31	0.50	0.62	0.71	0.83	0.92
	30	0.02	0.07	0.21	0.40	0.56	0.65	0.76	0.86	0.93
	40	0.04	0.09	0.27	0.45	0.62	0.73	0.80	0.89	0.95
	50	0.06	0.14	0.35	0.52	0.69	0.78	0.85	0.90	0.96
	60	0.08	0.18	0.39	0.61	0.73	0.83	0.88	0.93	0.97
	70	0.10	0.22	0.45	0.64	0.77	0.86	0.92	0.95	0.98
	80	0.13	0.26	0.49	0.73	0.83	0.92	0.95	0.97	0.99
	90	0.17	0.37	0.57	0.81	0.90	0.95	0.98	0.98	0.99
Third	10	0.01	0.02	0.04	0.07	0.14	0.31	0.52	0.72	0.86
	20	0.02	0.06	0.10	0.14	0.23	0.39	0.65	0.81	0.91
	30	0.04	0.09	0.13	0.17	0.29	0.47	0.70	0.83	0.93
	40	0.05	0.11	0.17	0.25	0.35	0.54	0.73	0.85	0.94
	50	0.07	0.13	0.19	0.27	0.39	0.58	0.77	0.88	0.96
	60	0.09	0.15	0.24	0.32	0.45	0.62	0.80	0.92	0.97
	70	0.10	0.17	0.26	0.36	0.48	0.69	0.84	0.93	0.98
	80	0.13	0.23	0.34	0.42	0.53	0.75	0.90	0.97	0.98
	90	0.18	0.29	0.42	0.52	0.67	0.84	0.94	0.98	0.99
Fourth	10	0.01	0.02	0.04	0.05	0.08	0.12	0.26	0.38	0.63
	20	0.01	0.03	0.05	0.09	0.17	0.28	0.32	0.47	0.71
	30	0.03	0.05	0.10	0.15	0.23	0.31	0.39	0.54	0.74
	40	0.05	0.09	0.14	0.21	0.27	0.33	0.43	0.57	0.81
	50	0.06	0.11	0.19	0.24	0.30	0.38	0.46	0.66	0.85
	60	0.08	0.14	0.22	0.29	0.37	0.42	0.52	0.69	0.91
	70	0.09	0.17	0.25	0.33	0.40	0.48	0.61	0.77	0.93
	80	0.12	0.22	0.31	0.39	0.46	0.54	0.64	0.80	0.96
	90	0.19	0.33	0.42	0.51	0.57	0.62	0.69	0.87	0.98

Pretoria data (including both the rainy season and the non-rainy season)

		Dimensionless duration								
Quartile	Percentile	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First	10	0.06	0.22	0.33	0.42	0.52	0.61	0.70	0.79	0.89
	20	0.10	0.31	0.44	0.54	0.63	0.70	0.77	0.85	0.93
	30	0.16	0.39	0.49	0.59	0.68	0.76	0.82	0.90	0.96
	40	0.22	0.45	0.56	0.65	0.74	0.80	0.86	0.92	0.97
	50	0.26	0.50	0.62	0.70	0.78	0.84	0.90	0.94	0.97
	60	0.32	0.57	0.68	0.75	0.82	0.88	0.93	0.96	0.98
	70	0.40	0.63	0.75	0.82	0.87	0.92	0.95	0.97	0.98
	80	0.49	0.70	0.80	0.87	0.91	0.95	0.97	0.98	0.99
	90	0.61	0.82	0.90	0.95	0.97	0.98	0.98	0.99	0.99
Second	10	0.01	0.03	0.06	0.23	0.45	0.55	0.65	0.76	0.89
	20	0.02	0.05	0.14	0.34	0.52	0.63	0.73	0.83	0.92
	30	0.03	0.08	0.21	0.41	0.59	0.70	0.76	0.86	0.94
	40	0.04	0.11	0.25	0.47	0.64	0.75	0.82	0.89	0.96
	50	0.06	0.14	0.32	0.54	0.69	0.79	0.88	0.92	0.97
	60	0.08	0.19	0.41	0.58	0.73	0.83	0.89	0.95	0.98
	70	0.11	0.23	0.47	0.65	0.80	0.88	0.93	0.96	0.99
	80	0.13	0.28	0.53	0.73	0.86	0.91	0.96	0.98	0.99
	90	0.17	0.36	0.65	0.81	0.91	0.95	0.98	0.99	0.99
Third	10	0.01	0.01	0.02	0.05	0.06	0.20	0.56	0.72	0.86
	20	0.01	0.02	0.03	0.07	0.13	0.32	0.63	0.78	0.90
	30	0.02	0.03	0.06	0.13	0.21	0.44	0.68	0.83	0.92
	40	0.03	0.04	0.08	0.15	0.30	0.52	0.72	0.85	0.93
	50	0.03	0.07	0.12	0.18	0.37	0.59	0.77	0.88	0.95
	60	0.05	0.10	0.15	0.25	0.41	0.66	0.79	0.91	0.96
	70	0.07	0.12	0.23	0.32	0.47	0.74	0.86	0.93	0.97
	80	0.10	0.16	0.27	0.38	0.58	0.80	0.89	0.95	0.98
	90	0.14	0.25	0.35	0.51	0.70	0.89	0.95	0.98	0.99
Fourth	10	0.01	0.01	0.01	0.03	0.05	0.09	0.20	0.34	0.52
	20	0.01	0.02	0.04	0.05	0.09	0.19	0.28	0.43	0.67
	30	0.02	0.05	0.06	0.13	0.17	0.23	0.35	0.54	0.77
	40	0.03	0.06	0.10	0.18	0.24	0.31	0.41	0.59	0.82
	50	0.04	0.08	0.14	0.21	0.29	0.37	0.46	0.67	0.85
	60	0.06	0.10	0.18	0.26	0.33	0.42	0.51	0.70	0.88
	70	0.07	0.14	0.23	0.32	0.39	0.48	0.56	0.74	0.90
	80	0.09	0.19	0.29	0.35	0.44	0.51	0.60	0.77	0.94
	90	0.17	0.28	0.35	0.47	0.54	0.61	0.66	0.84	0.96

The rainy season data (including both Bloemfontein and Pretoria)

		Dimensionless duration								
Quartile	Percentile	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First	10	0.06	0.21	0.32	0.40	0.51	0.60	0.68	0.79	0.88
	20	0.11	0.31	0.42	0.52	0.61	0.68	0.77	0.85	0.93
	30	0.17	0.37	0.49	0.58	0.67	0.75	0.82	0.89	0.95
	40	0.22	0.44	0.54	0.64	0.72	0.79	0.86	0.92	0.96
	50	0.26	0.49	0.60	0.69	0.77	0.84	0.89	0.94	0.97
	60	0.32	0.55	0.66	0.74	0.81	0.87	0.92	0.96	0.98
	70	0.40	0.62	0.73	0.80	0.87	0.91	0.94	0.97	0.99
	80	0.48	0.70	0.80	0.86	0.91	0.94	0.96	0.98	0.99
	90	0.61	0.81	0.89	0.93	0.96	0.97	0.98	0.99	0.99
Second	10	0.01	0.03	0.08	0.26	0.46	0.56	0.66	0.77	0.89
	20	0.02	0.05	0.15	0.36	0.52	0.64	0.73	0.84	0.93
	30	0.03	0.08	0.22	0.42	0.59	0.71	0.78	0.87	0.94
	40	0.04	0.11	0.26	0.48	0.65	0.75	0.83	0.90	0.96
	50	0.06	0.14	0.35	0.55	0.70	0.80	0.88	0.92	0.97
	60	0.09	0.19	0.41	0.61	0.74	0.84	0.90	0.95	0.98
	70	0.11	0.24	0.47	0.66	0.80	0.88	0.93	0.96	0.99
	80	0.14	0.28	0.53	0.74	0.86	0.92	0.96	0.98	0.99
	90	0.18	0.37	0.65	0.83	0.92	0.96	0.98	0.99	1.00
Third	10	0.01	0.02	0.02	0.05	0.09	0.29	0.55	0.72	0.86
	20	0.02	0.03	0.05	0.10	0.18	0.36	0.64	0.79	0.90
	30	0.02	0.05	0.09	0.15	0.27	0.46	0.68	0.83	0.92
	40	0.04	0.08	0.13	0.18	0.34	0.53	0.72	0.85	0.93
	50	0.06	0.11	0.17	0.26	0.37	0.59	0.77	0.88	0.95
	60	0.07	0.13	0.21	0.30	0.41	0.66	0.80	0.91	0.96
	70	0.09	0.17	0.26	0.35	0.48	0.72	0.86	0.93	0.97
	80	0.11	0.23	0.31	0.41	0.58	0.79	0.90	0.96	0.98
	90	0.17	0.29	0.41	0.52	0.70	0.88	0.95	0.98	0.99
Fourth	10	0.01	0.01	0.02	0.03	0.05	0.09	0.21	0.37	0.61
	20	0.01	0.03	0.05	0.06	0.12	0.21	0.32	0.47	0.70
	30	0.03	0.05	0.08	0.14	0.20	0.30	0.37	0.54	0.78
	40	0.04	0.08	0.12	0.19	0.26	0.32	0.42	0.58	0.82
	50	0.05	0.10	0.16	0.23	0.30	0.37	0.46	0.66	0.85
	60	0.07	0.12	0.20	0.28	0.35	0.42	0.51	0.69	0.89
	70	0.08	0.17	0.26	0.32	0.40	0.48	0.58	0.75	0.91
	80	0.10	0.21	0.30	0.39	0.44	0.53	0.62	0.78	0.94
	90	0.17	0.30	0.39	0.47	0.53	0.60	0.66	0.84	0.97

The non-rainy season data (including both Bloemfontein and Pretoria)

		Dimensionless duration								
Quartile	Percentile	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First	10	0.02	0.11	0.29	0.36	0.43	0.54	0.60	0.71	0.89
	20	0.08	0.21	0.33	0.45	0.54	0.62	0.72	0.81	0.90
	30	0.12	0.26	0.38	0.50	0.60	0.72	0.79	0.85	0.93
	40	0.16	0.30	0.45	0.58	0.67	0.75	0.81	0.88	0.95
	50	0.20	0.32	0.46	0.62	0.72	0.79	0.84	0.90	0.96
	60	0.28	0.41	0.54	0.66	0.75	0.81	0.87	0.93	0.97
	70	0.33	0.53	0.60	0.70	0.78	0.86	0.92	0.95	0.98
	80	0.38	0.62	0.68	0.74	0.82	0.90	0.94	0.96	0.99
	90	0.46	0.69	0.83	0.87	0.90	0.95	0.96	0.98	0.99
Second	10	0.01	0.02	0.08	0.26	0.39	0.47	0.68	0.78	0.93
	20	0.01	0.05	0.15	0.30	0.41	0.54	0.71	0.82	0.94
	30	0.03	0.14	0.18	0.36	0.51	0.61	0.74	0.85	0.95
	40	0.03	0.16	0.23	0.38	0.55	0.65	0.78	0.88	0.96
	50	0.09	0.23	0.31	0.53	0.62	0.74	0.80	0.91	0.98
	60	0.12	0.24	0.36	0.59	0.70	0.74	0.82	0.92	0.98
	70	0.19	0.28	0.55	0.73	0.77	0.78	0.85	0.93	0.99
	80	0.20	0.34	0.63	0.76	0.83	0.85	0.87	0.95	0.99
	90	0.26	0.55	0.86	0.90	0.91	0.93	0.97	0.98	1.00
Third	10	0.01	0.02	0.04	0.11	0.19	0.28	0.61	0.77	0.91
	20	0.02	0.03	0.07	0.12	0.21	0.39	0.70	0.81	0.94
	30	0.03	0.05	0.10	0.15	0.25	0.50	0.73	0.84	0.95
	40	0.05	0.07	0.10	0.17	0.34	0.53	0.74	0.86	0.95
	50	0.05	0.09	0.12	0.20	0.41	0.57	0.76	0.90	0.96
	60	0.05	0.11	0.18	0.27	0.45	0.62	0.77	0.92	0.97
	70	0.07	0.14	0.20	0.32	0.46	0.68	0.83	0.93	0.97
	80	0.09	0.15	0.24	0.32	0.49	0.73	0.88	0.95	0.99
	90	0.11	0.17	0.34	0.47	0.56	0.75	0.90	0.98	1.00
Fourth	10	0.01	0.02	0.02	0.05	0.12	0.20	0.24	0.25	0.58
	20	0.01	0.02	0.04	0.06	0.18	0.23	0.35	0.43	0.71
	30	0.02	0.03	0.05	0.10	0.20	0.24	0.39	0.53	0.73
	40	0.02	0.06	0.07	0.18	0.23	0.35	0.44	0.57	0.77
	50	0.03	0.08	0.11	0.20	0.26	0.39	0.45	0.63	0.81
	60	0.05	0.09	0.18	0.23	0.29	0.40	0.46	0.70	0.87
	70	0.06	0.11	0.19	0.25	0.37	0.47	0.56	0.74	0.94
	80	0.08	0.13	0.22	0.32	0.38	0.50	0.60	0.78	0.96
	90	0.13	0.19	0.25	0.35	0.48	0.54	0.67	0.81	0.98

(iii) Report on visit to USA for the project by Sue Walker

This report will highlight the visits made to researchers in USA that pertain to the WRC Rainfall Intensity Project and only mention the other contacts made.

1. Agronomy Meetings, Charlotte, North Carolina

A poster and oral paper were presented. The main purpose was to participate in the symposium arranged to honor Dr. Gaylon Campbell entitled "The Soil-Plant-Atmosphere Continuum: I. Gaps and Unresolved Issues – A Symposium in Honor of Gaylon S. Campbell'. Many researchers working in the soil-plant-atmosphere system attained. The CD is available with all the abstracts. The poster titled "Measurement of a Transpiration Efficiency Coefficient for Common Beans Using a Lysimeter" was the first time that data from WRC No. 307/1/95 was presented. The paper was concerned with "Resistance to Water Flow in Field-Grown Soybean and Wheat" which is vital to the partitioning of evapotranspiration into evaporation from tha soil and transpiration of the crop. Contact was also made with many researchers in the area of modelling agroclimatology and international agriculture. Unfortunately, due to the events of 11 September, the symposium on "Drought Mitigation in the Mediterranean Environment" was cancelled.

2. Water Resources Group, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta

Prof. Aris Georgakakos has an active group working on catchment hydrology with GIS and incorporating both crop modelling and socio-economic factors. This group has complete studies for Georgia and surrounding states and for the catchment of Lake Victoria in central Africa including Kenya, Uganda, Rwanda and Tanzania. At present they are busy applying the same technology to the whole of the Nile river catchment from the Ethiopian highlands and Lake Victoria through to Cairo. He was very interested in our application of ENSO in seasonal forecasting and the potential for cooperation projects is good.

3. North Applachian Experimental Watershed – US Department of Agriculture – Agricultural Research Service, Coshocton, Ohio

This catchment has many hydrological instruments and some measurements have been taken continuously for more than 60 years since late 1930. Dr. James V. Bonta is the research hydraulic engineer there. The most impressive thing was the 11 drainage lysimeters that are *in sisu* mounted in the catchment at the original slopes on the hillside. There is also one weighing lysimeter also on the hillside. Much runoff and groundwater data has been collected from these catchments both large and small. An accurate water balance has been measured on these watersheds for more than 60 years. He is also busy with a study to compare various rain gauges and try to eliminate the error due to wind drift and blow snow. He has set up a ground-truth rain gauge within a forest to compare the measurements.

The main reason I visited Dr. Jim Bonta was to learn about the "storm generator" he has constructed from all the rainfall intensity data from this experimental watershed. This storm generator first stochastically simulates storm occurrence – i.e. it identifies the "storms" and separates and/or groups the bursts of rainfall. Then it proceeds to synthesis the storm duration and storm depth. A critical duration being the minimum time is identified to separate storms one from another. The storm duration is then sampled from the frequency distribution that was constructed from the long-term data set. The amount of rainfall per storm is also from the distributions but conditional upon the storm duration as these two variables were found to have a statistical correlation.

Following this the with-in storm intensities can be synthesised using the Huff curves which summarise the natural with-in storm variability. All are converted to dimensionless for periods and amounts and duration. Then the specific period is sampled and the frequencies constructed for storm depths, so when this is repeated at many specific periods – a dimensionless mass curve of precipitation is constructed. The storm depth and duration are multiplied by the dimensionless mass curve to give a mass curve of actual time and depth of precipitation. Jim Bonta found that there was very little difference between the Huff curves for rain gauges close (500 m) or far (400 miles) from each other. This is across a region with similar weather patterns namely cold fronts and convective rainfall. He also investigated the variation in the Huff curves for different seasons and different numbers of rain gauges included.

This visit to Coshocton was most successful and the project team has already constructed some Huff curves from the Bloemfontein data.

4. Department of Civil and Environmental Engineering at Michigan Technological University in Houghton, Michigan

Dr. David Watkins has a project to predict and design storms breakpoint data for the whole Michigan State. The main approach they have made is first to identify homogenous rainfall regions. Following this, they have used *L*-moments analysis in a similar manner to Dr. J. Smithers. Much of this work is reported in the master's thesis entitled: "Development of Regional Rainfall Intensity-Duration-Frequency Estimates for the State of Michigan" by C.M. Trefry, Michigan Technological University, 2000.

5. USDA-ARS, Northwest Watershed Research Center, Boise, Idaho

Dr. Clayton Hanson and Dr. Greg Johnson (from USDA-Natural Resources Conservation Service, National Water and Climate Center, Portland, Oregon) are working on weather generators, and have constructed one called GEM (Generation of weather Elements for Multiple applications). Basically it was developed from a 30 year daily weather data set and uses statistical probabilities and mixed exponential equations together with the Fourier Series and Markov Chain. GEM covers the whole of the continental USA and many different climatic zones. It delivers a daily time series of climate data including precipitation amount, maximum and minimum temperature, mean dewpoint temperature, solar radiation and mean wind speed (http://www.nwrc.ars.usda.gov/models/gem). They are interested to introduce ENSO into the model to simulate those variations in a generated long-term data set. This weather generator will be tested with South Africa data and then adapted for use in Eritrea and Ethiopia where there are shortages of actual measured data sets. This was a most fruitful visit and I am most grateful to Dr. Johnston for meeting me in Idaho and we discussed plans for possible cooperative projects.

6. California Polytechnic State University, San Louis Obispo, California

Dr. David Keil is the Curator of the Robert C. Hoover Herbarium in the Biological Sciences Department at Cal Poly, San Louis Obispo. He teaches biogeography and plant ecology courses for undergraduate students. Many of the agrometeorology concepts are included in the biogeography curriculum. The influence of radiation together with the aspect of hills and valleys plays a large role on the distribution of the natural plants. There are many examples of the effect of climate on indigenous plant distribution. The progression of climate change may influence the distribution of the natural vegetation.

7. Conclusion

This visit to the USA was most beneficial for the WRC Rainfall Intensity project and in general for the Department of Agrometeorology, UFS. The approach taken by Dr. Jim Bonta to the storm generator (Huff curves) will be included in this project. The knowledge gained on the use of the weather generators will be put to good use in the Eritrean student projects.

Overall, the contacts made with USDA, universities and other organisations has encouraged us here at the Department of Agrometeorology that we are proceeding with research on issues that are still at the cutting edge of science in USA. Many of the contacts will be maintained and hopefully some combined cooperative projects will be able to be developed in the future.

USA Itinerary for S Walker for 19 Oct – 11 Nov 2001

Fri 19 Oct: Bloemfontein – Johannesburg – London

Sat 20 Oct: London – Chicago – Charlotte, North Carolina

Sun 21Oct – Thur 25 Oct: Agronomy Meetings, Charlotte, North Carolina

Fri 26 Oct: Georgia Tech., Atlanta, Georgia

Aris Georgakakos, Professor ageorgak@ce.gatech.edu

Director, Georgia Water Resources Institute, School of Civil and Environmental Engineering, Environmental Hydraulics and Water Resources Group, Group Leader Associate Chair for Research, Georgia Institute of Technology, 790 Atlanta Drive, Georgia Institute of Technology, Atlanta, Georgia 30332-0355 Tel: (404) 894-2240 Fax: (404) 894-2278 secretary: Janice Davis (404) 894-2217.

Mon 29 Oct – Tues 30 Oct: USDA-ARS-NAEW, Coshocton, Ohio

James V. Bonta, Ph.D., P.E. bonta@coshocton.com

Research Hydraulic Engineer, USDA – ARS, North Appalachian Experimental Watershed P.O. Box 488, State Route 621, Coshocton, OH 43812 Tel: (740) 545-6349 Fax: (740) 545-5125.

NAEW web page: http://www.ars-grin.gov/coshocton

Wed 31 Oct: Michigan Tech., Houghton, Michigan

David W. Watkins, Ph.D. dwatkins@mtu.edu

Assistant Professor, Dept. of Civil & Environmental Engrg, Michigan Technological University, Dow 870, Houghton, MI 49931-1295 Tel: (906) 487-1640 Fax: (906) 487-2943

http://www.civil.mtu.edu/~dwatkins

Thur 1 Nov – Fri 2 Nov: USDA-ARS, Boise, Idaho

Clayton Hanson, Ph.D. chanson@nwrc.ars.pn.usbr.gov

USDA-ARS, Boise, Idaho Tel: (208) 422-0711

Greg Johnson, Ph.D. gjohnson@wcc.nrcs.usda.gov

Applied Climatologist, USDA-Natural Resources Conservation Service, National Water and Climate Center, 101 SW Main St, Suite 1600, Portland OR 97204-3224 Tel: (503) 414-3017 Fax: (503) 414-3101 http://www.wcc.nrcs.usda.gov

Fri 2 Nov – Mon 5 Nov: Cal Poly., San Luis Obispo, California

David J. Keil, Ph.D. dkeil@calpoly.edu

Curator of Robert F. Hoover Herbarium, Biological Sciences Department, California Polytechnic State University, San Luis Obispo, CA 93407 Tel: (805) 756-2043 Fax: (805) 756-1419

Mon 5 Nov: San Luis Obispo, California – LA – London

Fri 9: Nov: London – Johannesburg

Sat 10 Nov: Johannesburg – Bloemfontein

(iv) Capacity Building

This project to generate rainfall intensity-runoff relationships from the daily weather data has provided opportunity for capacity building for the following people:

1. E. Mukhala worked on the project from January 1999 until February 2001, during which time he was exposed to statistical analysis of rainfall parameters and then he learnt how artificial neural networks function. This was completely different scientific experience compared to the type of project he had worked on previously.
2. M. Tsubo was provided a similar opportunity to expand his scientific abilities when he worked on the project from February 2001 until June 2002. He took the opportunity to learn about stochastic models and built the hyetograph model based on the statistical distribution.
3. J.J. Anderson worked on the risk analysis part of the project using the Putu crop growth model. Kobus will use this as a part of his PhD thesis in Agrometeorology in the Department of Soil, Crop and Climate Sciences at the University of the Free State.
4. M. Olivier worked on the synoptic weather chart analysis used in the stepwise regression technique. This provided her the opportunity to learn about the representation of surface meteorological data on a weather chart and its relationships to expected rainfall in the highveld region.

In addition, this project is linked to the Agricultural Research Council – Institute for Soil, Climate and Water research programme for water harvesting at Glen. Therefore, the Glen research team will use a modelling procedure that has been developed in this project for their research purposes.

(v) Research outcomes

Three scientific papers are submitted to the following journals:

Tsubo, M. and Walker, S. A stochastic model of rainfall intensity within a storm. Submitted to *Journal of Hydrology*.

Tsubo, M. and Walker, S. Huff curves for the highveld of South Africa. Submitted to *South African Journal of Science*.

Walker, S., Tsubo, M. and Hensley, M. Comparisons of risk for water harvesting under semi-arid conditions. Submitted to *Agricultural Water Management*.

Also, an oral paper was presented at the 2002 South African Society of Atmospheric Sciences (SASAS) meeting in Gauteng:

Tsubo, M. and Walker, S. The application of a stochastic model of rainfall intensity to estimate runoff. South African Society for Atmospheric Sciences (SASAS) Conference 2002, 26 - 27 August 2002, Centurion, South Africa.