RAINFALL CHARACTERISTICS FOR PLANNING MAIZE PRODUCTION IN SWAZILAND

BY

NHLONIPHO NHLANHLA NHLABATSI

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Faculty of Agriculture

University of Swaziland

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university. All facts and opinions have been distinguished and attributed to the respective sources.

.... Date 26 June 2000

N. N. NHLABATSI

This thesis has been submitted for examination with my approval as a University Supervisor

.... Date 26 June 2000

E.K. BIAMAH

DEDICATION

To my late father Sen. Mabalizandila Nhlabatsi, who was an ardent believer in education. "Dad, I will always remember and miss you. These are your fruits". To my daughter, Sonkhe Senanelo Nhlabatsi. This is for you. To my mother, Lozangcotho Nhlabatsi, brothers and sisters Badzelisile, Ncabile, Sihlangu and Bongiswa for their patience, support and encouragement throughout my studies.

To my girl-friend Nancy Carolyne Namenge, I thank you for being supportive, loving and moreover a shoulder to lean-on. "you have been with me, through the tides and I love you and always will".

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ABSTRACT

The estimation of missing climatic data was done using the arithmetic mean method. It is important to ascertain the homogeneity of any meteorological data before such data are used in any research work. To investigate whether the data sets were homogeneous or not, the mass curve method was employed.

Two graphical methods, the cumulative and the effective methods were used to determine the times of onset and cessation of the rains in the growing season for the four agro-ecological regions namely; Highveld, Middleveld, Lubombo Plateau and the Lowveld. The variability of rainfall throughout the country was investigated based on the mean and the standard deviation. Spectral analysis was done to see if there were cyclical rainfall events that recurred over time. These were done for both seasonal (≤ 1 year) and cyclical (> 1 year) variations. The water requirement satisfaction index (WRSI) was used to generate indices in the Highveld, which were then used to predict maize yields. Correlation and regression analyses were used to develop a model for predicting maize yields using the WRSI.

The cumulative rainfall method in all the four regions showed rains to begin between September and October and cease in April. The effective rainfall method on the other hand showed the effective rainfall season to be between October and March in three of the four regions The effective rainfall method in the Lowveld region indicated crop water requirements were always higher than the available soil water. Therefore, crop production without water stress in the lowveld can only be practised under irrigation. Therefore, all primary tillage operations should be complete by the fourth pentad of August, in readiness for planting. The effective rainfall method was found to be the most appropriate to use in agricultural production and planning in this study.

The variability and reliability of the rainfall in both space and time showed that the Highveld had the highest reliability and the Lowveld had the lowest variability. Spectral analysis showed that there are events that recur after 90 days, 35 days, 25 days, and 10 - 15 days. These cycles are a

manifestation of the Julian- Madden Cycle within the growing season. Cyclical variations of about 2 years (Quasi - Biennial Oscillation, QBO), 3 - 7 years (El-Niño/Southern Oscillation, ENSO) and longer than 10 years (sunspot or inter-decadal variability) were also observed. This can be confirmed by the generally observed recurrence of above normal (wet) and below normal (dry) events.

Correlation analysis showed that the yields were highly correlated to the WRSI indices. A linear regression model expressing yield in terms of the indices, had a coefficient of determination (r^2) of 54%.

A seasonal land management calendar for maize production was developed by this study; taking into account the most common seasonal tillage operations. This study has shown that primary tillage operations must be started well before (1-6 pentads) the onset of effective rainfall in order to optimize soil moisture and crop yields.

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LIST OF ABBREVIATIONS

ACZ	Agro-Climatic Zones.
C	Cessation
CEC	Cation Exchange Capacity
CSO	Central Statistical Office.
Cumrain	Cumulative Rainfall (mm/day)
DP	Dependable Precipitation.
ea	Saturation vapour pressure (mb)
ENSO	El-nino and the Southern Oscillation
ETp	Potential Evapotranspiration.
FAO	Food and Agriculture Organization
f(ed)	Effect of vapour pressure
f(u)	Wind related function
FYM	Farm yard manure
ISRIC	International Soil Reference and Information Centre
ITCZ	Inter-Tropical Convergence Zone
LAN	Limestone Ammonium Nitrate
mm/d	Millimetres per day
MoAC	Ministry of Agriculture and Co-operatives.
MoEPD	Ministry of Economic Planning and Development.
n	Actual observed sunshine hours
N	Maximum possible sunshine hours observed
NEWU	National Early Warning Unit
NMS	National Meteorological Services.
O	Onset
QBO	Quasi-Biennial Oscillation
R	Rainfall
Rainfall/d	Rainfall per day (mm/day)
RDI	Rainfall Distribution Index
Rn	Net radiation (MJ m^{-2} day^{-1})
Rnl	Net long wave radiation (MJ m^{-2} day^{-1})
Rs	Solar radiation (MJ m^{-2} day^{-1})
SAT	Semi Arid Tropics.
SNL	Swazi Nation Land
SO	Southern Oscillation
SR52	Indigenous maize cultivar in Swaziland
SSTs	Sea Surface Temperatures
T	Mean Temperature (°C)
TDL	Title Deed Land
U	24-hr wind run at 2 m height (miles/day)
u	24-hr wind run at 2 m height (km/day)
UNESCO	United Nations Educational; Scientific and Cultural Organization
UNICEF	United Nations International Childrens Emergence Fund
W	Weighting factor
WHC	Water holding capacity (mm)
WMO	World Meteorological Organization.
WRSI	Water Requirement Satisfaction Index

1. INTRODUCTION

1.1 General Background

Rainfall in Swaziland is primarily unimodal with one distinct crop growing season (September to April). During this period, approximately 75% to 80% of the total annual rainfall occurs. However, there can be drought in bad years. Hence the effectiveness of this rainfall for crop production is an important consideration when planning land preparation. Effectiveness of rainfall would depend amongst others, on the timeliness of tillage operations and subsequent conservation of the soil water.

According to Stewart and Harsh, (1982), expectations for adequate rainfall decline and evaporation rates increase with delayed onset of rains. Likewise an early onset of rains has a high probability of being followed by a long dry spell. An onset coming too late would be followed by a significantly shorter wet period than normal, and hence a high probability of crop failure.

The land tenure system in Swaziland is divided into two categories, namely:

1) Swazi nation land (SNL): This is land held in trust for the people by the King through the chiefs and covers a total of 80% of the land area.
2) Title deed land (TDL): This is commercial land or farms and covers 20% of the total land area.

Most people in SNL practice rain-fed subsistence farming. The major crop grown is maize, which is the nation's staple food. TDL farmers contribute more than 60% of the nation's foreign exchange earnings in sugar-cane, citrus, pineapple and forestry.

According to Michalczyk (1978), a statistical forecast of climatic conditions is relevant in that it enables one to determine what average operating conditions can be expected over a long period, thereby making it possible for the farmer to select his machinery in such a way as to avoid inordinate investment and, at the same time, acquire sufficient equipment to produce the highest possible yield through timely completion of work. Analyses of rainfall for effective land management are rather rare. The available analyses are either too general as with work done by geographers, or the statistical techniques are too sophisticated for the general user (Mutsaers, 1978).

The focus of this study is to provide baseline data for planning land management activities with emphasis on understanding the onset, cessation, effectiveness and variability of seasonal rains during the crop growing season in Swaziland. The rainfall data analysis is for a period of $\geq$ 30 years and was recorded in the Highveld, Middleveld and Lowveld zones of Swaziland.

1.2 Justification of Study

In Swaziland the amount of rainfall that falls at any given time has significant impact on soil productivity and crop production. Approximately 75 – 80% of rains fall between August and April.

Over the years, there have been discrepancies in terms of distribution, frequency, onset and cessation of rainfall during crop growing seasons. This has resulted in heavy losses in crop production. For example in 1992, there was a severe drought that swept through the whole country.

The Ministry of Agriculture and Co-operatives (MoAC, 1994) stated that there is need for forecasting annual and seasonal rainfall for the purposes of planning effective land management options. This study therefore seeks to answer the questions, when are the rains likely to start in any one crop growing season, and what are the rainfall variability indicators? Continued rainfall during harvest time, may cause heavy losses due to rotting and unworkable fields. It is therefore imperative that the cessation of the rains in any one growing season also be determined. In Swaziland, there is no research that has been carried-out to answer the above mentioned questions, which means that there is no statistical inference that can be used in advising farmers on planning for their tillage operations.

1.3 Objectives and Scope of Study

1.3.1 Objectives

Overall Objective

To analyse available climatological data for effective planning of maize production in Swaziland.

Specific Objectives

1. To determine the onset and cessation of the rains in a crop growing season.
2. To evaluate the variability and reliability of the seasonal rainfall.
3. To assess the effectiveness of rainfall to sustain maize crop productivity through the use of spectral analysis.
4. To predict crop yield using the Water Requirement Satisfaction Index (WRSI).
5. To identify the most suitable tillage operations for the different agro-climatic zones (ACZ) in Swaziland.
6. To develop a seasonal land management calendar for the different agro-climatic zones in Swaziland.

1.3.2 Scope of Study

This study was based on an analysis of available long-term rainfall data (>30 years) of the Mbabane, Malkerns and Big Bend Meteorological Stations in Swaziland. The three stations represent the Highveld, Middleveld and Lowveld agro-climatic zones respectively.

The analysis was specifically aimed at:- determining the onset and cessation of the rains; the reliability and variability of seasonal rainfall; the effectiveness of rainfall to sustain maize crop production; identifying the most suitable agricultural techniques for the different ACZs in

Swaziland; and develop a seasonal land management calendar for Swaziland. The results of this study are expected to assist in the planning of effective land management options in Swaziland.

1.4 The Study Area

The Kingdom of Swaziland is one of the smallest land locked countries in Africa with an area of 17364 km^2. There are four topographic regions, each of which runs from the North to the South and each has different climatic characteristics. The main agro-climatic zones are presented in Table 1 and Figure 1. Rainfall distribution is shown in Figure 2.

Table 1 *Main Agro-Climatic Zones in Swaziland (adapted from Carl Bro International, 1984).*

Regions	Area (km^2)	Percent (%)	Altitude (m)	Climate	Rainfall (mm)
Highveld	5,029	29	1300^+	Near Temperate	1000-2300
Middleveld	4,598	26	700^+	Intermediate	650-1100
Lowveld	6,416	37	200^+	Sub-tropical	500-900
Lubombo	1,321	8	600^+ (Ave)	Sub-tropical	650-1100

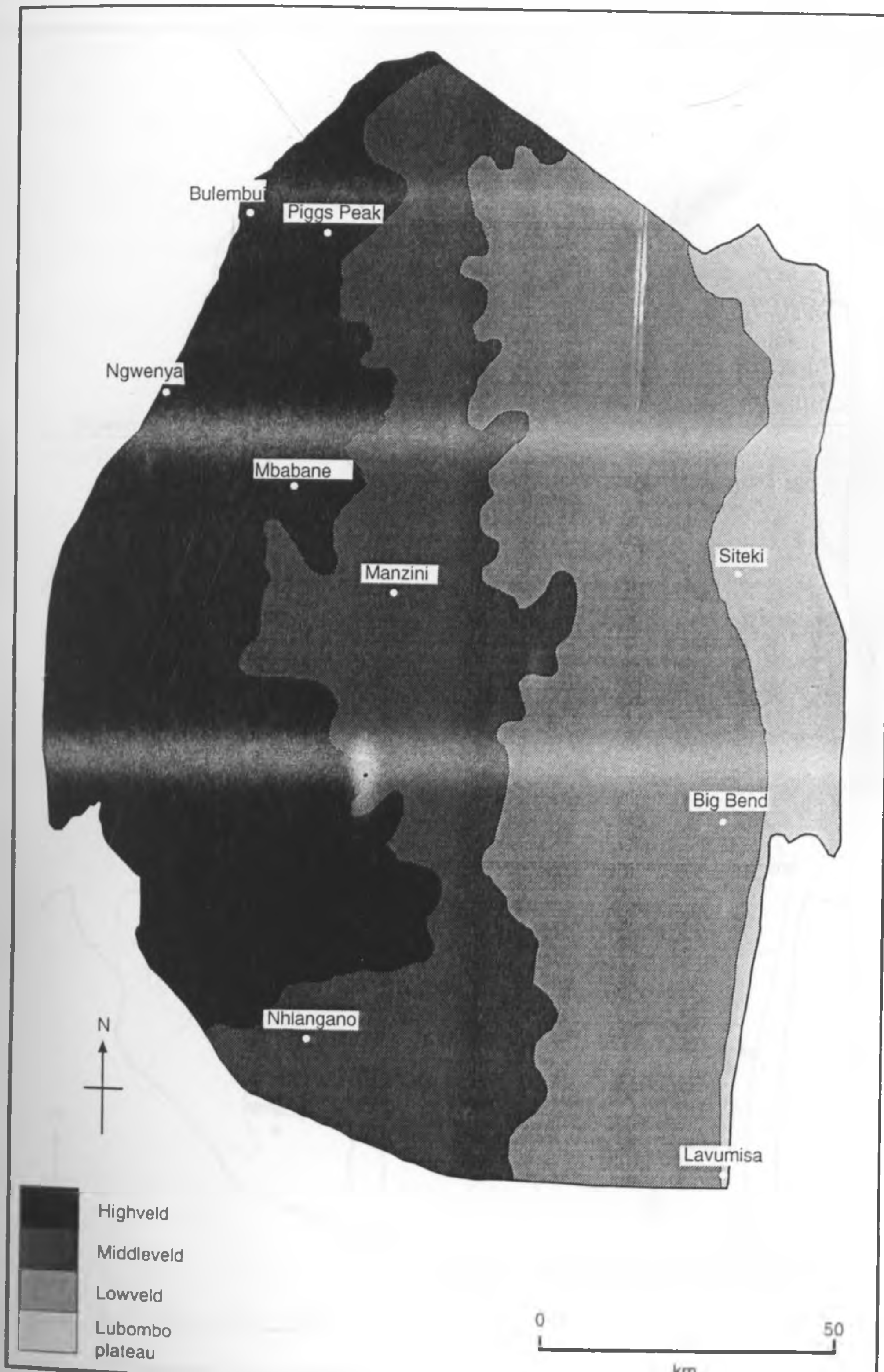

Figure 1 *Agro-climatic zones in Swaziland.*

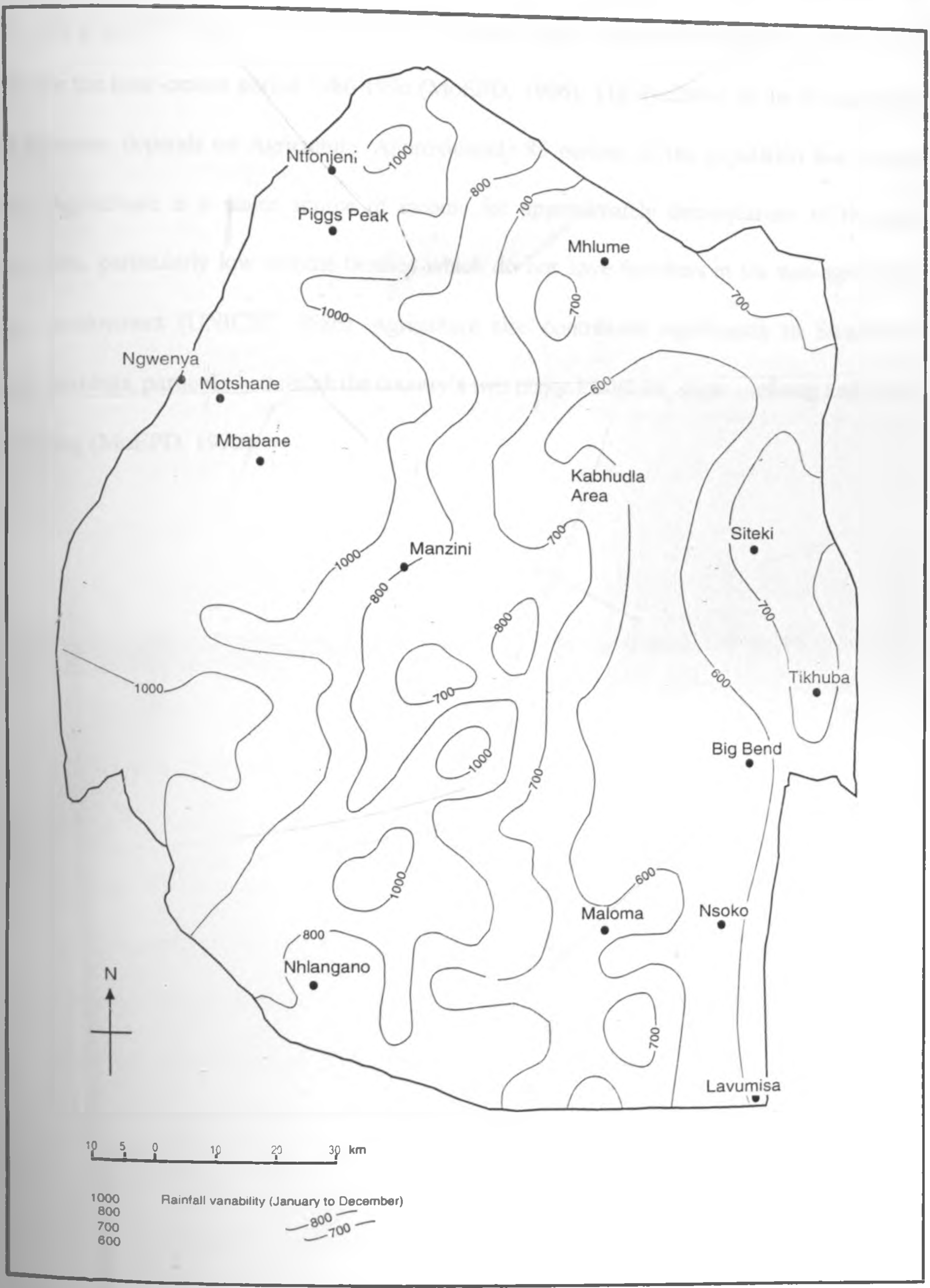

Figure 2 *Rainfall distribution in Swaziland.*

The last population census took place in 1996 and showed a total population of 800000. In 1986, the population was approximately 681000 which implies an average annual growth rate of 3.3% for the inter-census period 1986-1996 (MoEPD, 1996). The livelihood of the Swazi people and economy depends on Agriculture. Approximately 85 percent of the population live in rural areas. Agriculture is a major source of income for approximately three-quarters of the rural population, particularly low income families which do not have members in the non-agricultural wage employment (UNICEF, 1986). Agriculture also contributes significantly to Swaziland's export earnings, particularly through the country's two major industries, sugar - refining and wood-processing (MoEPD, 1992).

2. REVIEW OF LITERATURE

2.1 Rainfall and Soil Tillage Techniques

2.1.1 Rainfall Prediction

The importance of rainfall to agriculture cannot be over emphasized. It is one of the most limiting factors in crop production, especially in arid and semi-arid regions where most crop production is under rain-fed conditions. Rainfall, especially in the tropics, is unpredictable in time and space, and as such, farmers have been left to live with the limitations of the local climatic conditions (Kingamkono, 1997). Furthermore, knowledge of the rainfall regime is therefore an important prerequisite for agricultural planning.

There is a pressing need for timely information on present and future rainfall scenarios to develop strategies to reduce any adverse effects. A major concern for future agricultural production is the rate of climate change. If the change is gradual, farmers and society will have time to re-organise and adjust. Small changes in the mean climatic conditions may result in large changes in the frequency of climatic extremes, including heat waves, floods and droughts (Jagtab, 1995).

Despite the impressive advances in agricultural technology over the past 30 years, agricultural production is still dependent on weather and climate. Environmental and crop data are used to guide strategic decisions in planning agricultural systems such as design of irrigation schemes, choice of land-use and farming patterns, and selection of crops and animals, varieties, breeds, and farm machinery (WMO, 1981).

In the agricultural field, a statistical forecast of climatic conditions is relevant in that it enables one to determine what average operating conditions should be expected over a long period. This makes it possible for the farmer to select his machinery in such a way as to avoid inordinate investment and at the same time, acquire sufficient equipment to produce the highest possible yield through timely completion of work (Michalczyk, 1979).

Hills and Morgan (1981) state that a rainfall record can provide a wealth of guiding information for agriculturists, but only if the information generated can be used in solving operational problems.

Stern *et al.* (1981) observed that rainfall governs crop yields in the seasonally arid tropics and determines the choice of crops that can be grown. For an agriculturist, the important questions on rainfall are concerned with the start, end and length of the rainy season, the distribution of rainfall amounts throughout the year, and the risk of dry spells.

2.1.2 Soil Tillage Techniques

The primary objective of any tillage operation should be to optimize soil conditions such as bulk density, pore size distribution, temperature, consistency, soil water intake rate and moisture retention capacity for increased crop production through appropriate and timely seedbed preparation and weed control (Biamah et al., 1993).

Tillage practices are basically divided into traditional and modern techniques. Traditional tillage and residue management problems in Swaziland, include ridging, trash lines, stone lines, mulching, crop rotation, burying weeds and trash, fallowing and shift-cultivation. On the other hand, modern tillage practices include, contour bunds, infiltration ditches, protection channels, harvesting water from roads, erosion control wash-stops, Fanya juu terraces, compositing, strip cropping, control of grass, woodlots and panelling. Further more, Biamah (1988) concluded that small holder farmers were primarily interested in tillage practices that improve soil moisture, that do not involve high energy inputs that increase crop production.

2.2 Land Management

In the seasonally dry rain-fed semi-arid tropics (SAT), crop yields are low and variable from year to year (Virmani *et al.*, 1978). The instability of agricultural production is caused primarily by undependable rainfall. In any particular agro-climatic region, therefore, the aim of an inter-disciplinary farming systems research is to derive a set of practices for resource development, resource management, and utilisation, that will lead to substantial and sustainable increases in agricultural production while conserving and improving the region's resource base.

Crop yields are proportional to moisture availability and an optimum range of water is required for different crops according to their growth pattern, for maximum yield. Hargreaves (1975) has defined dependable precipitation (DP) as that amount of rainfall that could be received at a 75% probability.

Sarker and Biswas (1978) observe that it is well known that yield from any given crop-variety depends on the extent to which certain optimum conditions of rainfall and soil water supply, radiant energy, photoperiod, and temperatures are satisfied during different stages of crop growth. Weather can also indirectly affect crop production when weather situations:

a) Lead to the out breaks of pests and diseases of crops,
b) Interfere with timely agricultural operations and plant protection measures; and
c) Bring about deterioration in the quality of seed material held in storage. Hence, meteorological consideration becomes part of the realm of agriculture by its own right.

Meteorological studies and services can help bring about better agronomic practices in two broad ways. First, timely weather forecasts of a short and medium term would enable the farmers to adopt agricultural practices that minimise the adverse effects of weather and maximise its beneficial effects. Secondly, further scientific study of the interrelationship between crops and their environment would aid in the development of better varieties and in the proper choice of crops and farming practices. Agro-meteorological studies can also help long-term agricultural planning; by identifying regions of similar climate and delineating areas to different intensities of weather vagaries.

The physical capacity of the soil for water storage and the rates at which water can move into, out of, and within it has important effects on both the short-term and seasonal dynamics of the hydrologic cycle. The properties of the soil profile obviously affect its water retention, run-off, and drainage as well as the losses of water by evaporation and transpiration.

2.2.1 Classification of Swaziland Soils

Soil surveying in Swaziland started in the 1950s with the identification of fundamental soil units and subsequent classification by soil series (Kellogg et al., 1951; Murdoch, 1961; Murdoch, 1970; Greene, 1957). In order to introduce a reference framework for Swaziland soils, Murdoch classified his series according to the SPI legend (D'Hoore 1965).

Soil characterization in Swaziland has since been refined and correlated with the present FAO soil unit (FAO - UNESCO-ISRIC, 1988). Remmelzwaal and Masuku (1994) used the 10 soil units identified by Murdoch et al. (1966) and grouped them into four main categories namely:-

2.2.1.1 Highveld and Upper Middleveld Soils

Soils are characterized by intense weathering and leaching and with very deep soil formation (Ferrisols and Ferralitic soils). They have low Cation Exchange Capacity (CEC) clay and low base saturation of the exchange complex. FAO classification:- Ferralsols, and Acrisols.

2.2.1.2 Middleveld and Lowveld Soils

Soils are characterized by moderate weathering (Pseudopodzolic soils, Brown soils, vertisols, Halomorphic soils). They have a moderately high to high CEC clay and generally high base saturation, FAO classification : Vertisols, Planosols, Solonetz, Solonchaks, Lixisols, Luvisols and Phaeozems.

2.2.1.3 Transitional Soils

These soils are characterized by an advanced stage of weathering which has not progressed as far as the strongly leached soils of the first group, the main reason being that climatic conditions are less extreme (Fersialitic soils). These soils occur mainly in the transitional Middleveld and Lubombo zones; but also as remnants in the lowveld. CEC clay and base saturation are intermediate between the first two groups. FAO classification : Nitisols, Lixisols and Acrisols.

2.2.1.4 Azonal Soils

These soils are not related to physiographic zoning and occur in all regions of the country. They include shallow and hydromorphic soils (Raw mineral soils, weakly developed soils). FAO classification: Leptosols, Regosols, Gleysols and Fluvisols.

2.3 Calculation of Missing Rainfall Data

Methods have been recommended for the estimation of missing records in Meteorological times series by WMO (1966, 1986). Below is a brief description of the most commonly used methods.

2.3.1 Isopleth Method

In this method, missing climatic data are estimated using information from neighbouring stations. The first step involves the mapping of all available data for the period with the missing data at some location. Isopleths are then drawn and the missing values extrapolated from the magnitudes of two isopleths, one on either side of the station with the missing data.

The disadvantages of the method are that it requires a dense network of stations, which is not always available, and that it is very tedious and time consuming. This method is also more accurate over regions with homogeneous surface topography and climatic conditions. The advantage is that it is possible to include knowledge of physiographic relations, storm, tracks, storm types, and other factors when drawing the isopleths (Basalirwa, 1991).

2.3.2 Correlation Method

In this method, two aspects may be considered namely temporal correlation, and spatial correlation. In temporal Correlation, we try to establish if the variable with the missing data may be correlated with some other variable at the same locality over time, whilst in spatial correlation, we seek to establish if the variable may be correlated to other variables at other locations.

Once such a relationship has been established, regression analysis is then used to derive mathematical functions that can describe the relationship. The derived functions may then be used to estimate the missing data.

Simple linear relationships between the variable with missing data,(x_t)and a related parameter, (y_t), may be expressed as: -

$y_t = ax_t + b$..(1)

where a and b are coefficients to be estimated from available data. The next step involves the use of equation (1) to estimate y_t using x_t values.

2.4 Homogeneity (Quality Control) of Rainfall Data

A data set is said to be homogeneous if it is devoid of any spurious trends (Lavery *et al*, 1992). In other words, a homogeneous data set is one from a single population (Burrows, 1982). There are a number of factors, which introduce inhomogeneity (heterogeneity) in meteorological data. Most of these factors are described in detail by Mitchell (1953), WMO (1966, 1986), Burrows (1982), Ogallo (1987), Shepherd (1991) and Lavery *et a.l.* (1992). The most important of these factors are due to changes in:

i) observation techniques;

ii) the exposure of the instrument;

iii) location of the observation site; and

iv) the type of instrument.

Normally any meteorological (climatic) data series is composed of records that have been influenced by one or more of the above factors. The validity of studies, which utilise these data series, depend upon representativeness (homogeneity) of the data. Many investigations have therefore been carried out in many parts of the world to test the homogeneity of different data sets (Kohler, 1949; Shearman, 1975; Cornish, 1977; Craddock, 1977; Jones, 1980; Potter, 1981; Buishand, 1982; Burrows, 1982; Ogallo, 1982, Alexanderson 1986; Karl and Williams 1987; Vincent, 1990; Lavery *et al*, 1992). The techniques used in these investigations vary from simple mass curves to complex statistical tests (WMO, 1986).

In most parts of Africa, numerous studies have been undertaken in relation to the variability of rainfall. However, not much attention has been paid to the homogeneity of the data sets used (Matarira, 1990). The most notable effort has been the work of Ogallo (1982). Rodhe and Virji (1976) also carried out some simple homogeneity tests on East African data.

Quality control is important in order to detect any discontinuities in the data that may have occurred from un-natural influences like changes in observational schedules and methods, instrument changes, shifting stations sites, urbanisation, and other human processes (WMO, 1966; Basalirwa, 1979; King'uyu, 1994). Heterogeneity makes data not strictly comparable over long time periods and between different stations.

It is therefore important to ascertain the homogeneity of any meteorological data before it can be used in any study. Recommended homogeneity tests can be found in WMO (1966) for both relative and absolute homogeneity. Some of the most commonly used methods for data quality control are described below.

2.4.1 Correlation and Regression Methods

These methods use correlation and functional relationships between the variable x_t, being tested for homogeneity and another variable, y_t, which is known to be homogeneous. We first establish the degree of relationship between x_t and y_t using simple correlation analysis. The simple correlation coefficient, r, is given by: -

$$r = \frac{\sum (x_t - \bar{x})(y_t - \bar{y})}{\sqrt{\sum (x_t - \bar{x})^2 \sum (y_t - \bar{y})^2}} \qquad \text{.....(2)}$$

If r is statistically significant and subsets of variables x_t and y_t are known to be homogeneous, then for the homogeneous period, y_t may be expressed as a function of x_t using a linear relationship as in equation (1). The observed and computed values of y_t are then used to test the quality of the observations.

This method has one major disadvantage in that high correlation may not always lead to meaningful results as they might be due to seasonal effects on both x_t and y_t. Once the seasonal effects are removed, there may not be any significant correlation between x_t and y_t (WMO, 1986).

The method also assumes that samples of quality data were available for the development of the equation.

2.4.2 Wald – Walfowitz Method

This is a non-parameter (distribution free) method that is especially useful for testing the homogeneity of data against trend, bias, drift, oscillation, or a combination of these. This test does not require the data to be normally distributed and is based on the mean variances of the data as calculated from the means and variances of different samples of the same distribution. Details of the method can be found in Seigel (1956) and WMO (1966, 1986).

2.4.3 Absolute Homogeneity Test

This method is based on the concept of mass and residual mass curves. It involves comparing the differences between the series under test with only one other homogeneous series. The series will be a suitably described average of the series for the individual surrounding stations. This way, evidence of heterogeneity can be translated directly into definite information about the heterogeneity in the test series.

To derive the average series, different factors must be considered (Mitchell, 1961) like the density of reporting stations, the length of the record being investigated, the relative incidence of station relocations, and the climate uniformity over the area (WMO 1986). In this method, however, several stations situated within the same climatic zone and whose records are known to be homogeneous are chosen. A plot of the corresponding cumulative data of the station whose homogeneity is being tested is then plotted against the mean cumulative data of those of the reference stations. Heterogeneous records can be adjusted using the slopes of the curves. Details may be found in WMO (1966, 1986), King'uyu (1994), and Ogallo (1980, 1992).

2.4.4 The Cumulative Deviations Method

This method of cumulative proposed by Craddock (1979) and used by Burrows (1982), Buishand (1982) etc. has two major advantages namely;

i. It is easier for the user to recognise the significant turning points that mark changes in the relative rainfall amounts at the two stations from the minor fluctuations.

ii. When observations do not agree, with the mean conversion factor, it is easy to estimate from the graph what the factor should be.

The simple computational procedure in this method involves:

a) Determination of the mean annual rainfall $\bar{x}$ and $\bar{y}$ for the base and dependent stations respectively.

b) Determination of the mean conversion factor, C, assumed constant

$$C = \bar{y} / \bar{x} \qquad (3)$$

c) Computation of the deviations of the annual rainfall amounts for the dependent station from those estimated from the base station.

$$d_i = cx_i - y_i \qquad (4)$$

where d_i are the deviations, x_i the annual rainfall amounts for the base station, and y_i the annual rainfall amounts for the dependent station

d) Computation of the cumulative deviations

$$c_i = \sum_{i=1}^{i} d_i, \quad i=1 \ldots n \qquad (5)$$

e) Preparation of the time series graphs of the cumulative deviations against the years.

2.4.5 Bivariate Method for Detecting a Shift in Mean Precipitation

This is a technique developed by Maronna and Yohai (1978), recommended by WMO (1986), and also adopted by Potter (1981). This method not only detects shifts in the mean precipitation but also gives estimated magnitudes of change. The mathematical model for this technique is as follows: -

a) Generate two new series from the annual rainfall data.

$$x_i = 1/i \sum_{i=1}^{i} x_i ; \quad i=1......n \qquad ......(6)$$

$$y_i = 1/i \sum_{i=1}^{i} y_i \qquad ......(7)$$

b) Compute the variance sums of the two annual rainfall series x and y and their covariance sum.

$$S_x = \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad ......(8)$$

$$S_y = \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad ......(9)$$

$$S_{xy} = \sum_{i=1}^{n} (x_i - \bar{x})\,(y_i - \bar{y}) \qquad ......(10)$$

c) For each of the values in the series, compute:-

$$F_i = S_x - (x_i - \bar{x})^2 n_i / (n - i) ; \; I<n \qquad ......(11)$$

$$D_i[S_x(\bar{y} - y_i) - S_{xy}(\bar{x} - x_i)]n / [(n - i) F_i] \qquad ......(12)$$

$$T_i = [i(n - i) D_i^2 F_i] / [S_x S_y - S_{xy}^2] \qquad ......(13)$$

In this case the test statistic is T_i.

$$T_o = (T_i)_{max} \qquad ......(14)$$

Critical values of T_o computed by Maronna and Yohai (1978) and extended by Potter (1981) can then be used to test the significance of the maximum values of T_i at different confidence levels. Time series of T_i can then be prepared.

2.5 The Crop Growing Season

2.5.1 On-set of the Rains

The cumulative rainfall method in the determination of the start of the rains has been used widely by Alusa and Mushi (1974), Ilesanmi (1972) and Kingamkono (1997). The earliest possible start or end date of rains is taken as the date when the slope of the cumulative distribution of annual rainfall starts to change significantly. Another graphical presentation was used by Cocheme and Franquin (1967) and again by Franquin (1978) in establishing the crop growing season (Figure 3).

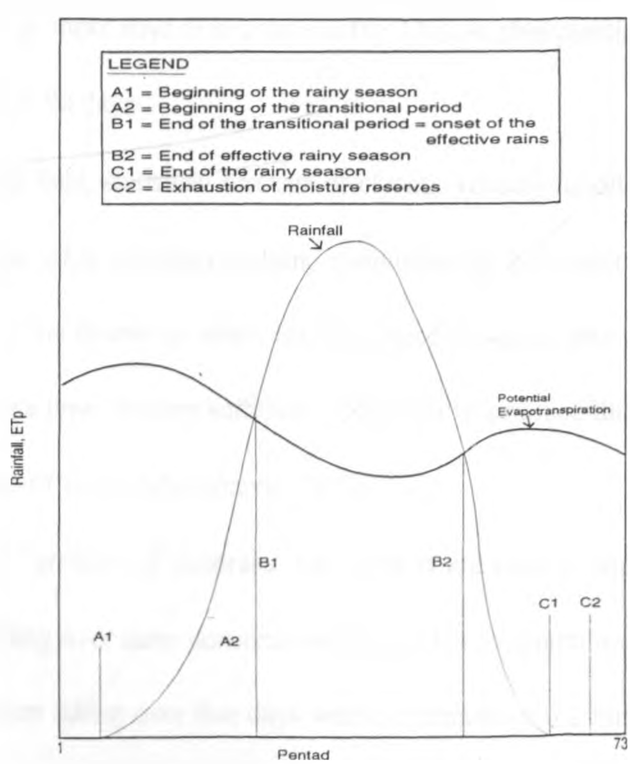

Figure 3. *Rainfall and potential evapotranspiration*

Kingamkono (1997) and Kassase *et al* (1992) took the start of the growing season to be the first occasion after an earliest possible date defined in the cumulative method, on which a running total of at least 20 mm was reached in 4-consecutive days with at least 2 days being wet, and that no dry spell of 10 days or more occurred in the following 30 days. The end of the growing season was taken as the first occasion after an earliest possible ending date on which fifteen consecutive dry days occurred. A day is considered dry if it had less than 0.85 mm of recorded rainfall. Such an amount is often insignificant in terms of its contribution to crops as it is usually lost through evaporation in a matter of hours (Buishand, 1977; Stern *et al*, 1982 and Nieuwolt, 1989).

Wanakwanyi (1992) defines a rainy day as a day with more than 0.85 mm of rain. The start of the growing season, for best yields in Swaziland, is defined as the first good rains of over 20 mm that fall in one or two consecutive days after the 1st August (Kay, 1988).

Stern (1990) observes that the start of the rains is denoted by the first day after the assumed date with more than 30 mm within a 5-day period of which at least 3 are rainy. Furthermore, there must be no dry spell of 7 or more days at any time in the 30 days after planting, and no dry spell of 10 or more days in the next 90 days.

In the agricultural field, statistical forecast of climatic (onset) conditions is relevant in that it enables one to determine what average operating conditions can be expected over a long period. This makes it possible for the farmer to select his machinery in such a way as to avoid inordinate investment and, at the same time, acquire sufficient equipment to produce the highest possible yield through timely completion of work (Michalczyk, 1979).

In the Northern Territory of Australia, two criteria are used to indicate sowing rains, a total of at least 50 mm falling over three consecutive days with a minimum on any one day of 2 mm and a total of a least 30 mm falling over five days with a minimum of 0.2 mm on each day. At the end of the season late rains can adversely affect grain quality and the incidence of a total of 10 mm over three days with a daily minimum of 0.2 mm should be examined (Mollah and Cook, 1996).

Stern *et al.* (1982) state that defining an event to mark the start of the rains is not easy, due to the intermittent and patchy nature of tropical rainfall. The event may be defined in different ways for different purposes. A definition may be based solely on rainfall amount. For instance, the planting date for Millet in Niger was observed to coincide with the first occurrence of 20 mm of rain over a two-day period (Davy *et al.*, 1976). Such a definition often gives rise to false onsets and various qualifying criteria have been added to overcome this difficulty.

Kowal and Knabe (1972) defined the start as the first ten-day period (dekad) with more than 25 mm, provided that rainfall in the next dekad exceeds half the potential evapotranspiration. The false start criterion used by Benoit (1977) was a dry spell of five or more days in the twelve days following the potential start.

2.5.2 Cessation of the Rains

The definition of the date of the end of the rains may depend on the particular application. In some studies (Gramzon and Henry, 1972) the end of the rainy season is defined as the last date on which a threshold amount is exceeded. Another possibility is to use the first occurrence of a long - dry spell after a specified date.

The definitions above are based solely on rainfall, but a measure of soil water-storage is needed to define more realistically the end of the period of growth. Stern *et al.* (1982) used a simple daily water balance instead. Two constants are chosen, soil moisture storage capacity (S), and daily evapotranspiration (E). A national daily water budget for the soil (Wn), is then evaluated, taking the value of (S) and zero respectively, as upper and lower limits, rainfall (R) as input and Evapotranspiration (E) as output. The water budget for day n is hence given as: -

$$W_n = W_{n-1} + R - E \quad \text{...}(15)$$

If the result is less than zero, it is set to zero, while if it is greater than (S) it is set to S (corresponding to a soil profile at field capacity). The end of the rains is then defined as the first day (after a pre-specified date, D) on which the value drops to zero, and this is recorded for each year on record.

Stern (1990) further states that the end of the rainy season can be defined as the first occasion that the water balance drops to zero after a pre-specified date.

Wanakwanyi (1992) considered the end of the growing season in Swaziland, Malkerns area as the first occasion after February when the soil water balance is less than 0.5 mm on a soil of average soil water holding capacity of 150 mm followed by fifteen consecutive dry days. A day is considered if it has less than 0.85 mm of recorded rainfall.

2.5.3 Duration of the Rains

This is a good measure of agricultural suitability. The length of the growing season is taken as the time between the start and end dates of the season. Furthermore, length of rains cannot be used as a standard or measure to judge the quality of the growing season. Rather the distribution over time should be used, and the length used as a guide in selecting long or short maturing varieties (Kingamkono, 1997).

Wanakwanyi (1992) argues that the start and end of the rains (growing season) are the most important agro-climatological parameters in agriculture. The cycle length of crops grown should be chosen such that it is shorter than the most likely length of the growing season. Planting early gives the crop a long growing season. The crop is established early and can better survive the droughts (dry spells) which are common in Swaziland in December and January. Early planted maize also suffer less from pests, diseases and weeds such as stalkborer, maize streak and witch weed.

Kingamkono (1997) asks whether it is the annual rainfall amount, or the length of the growing season that is truly descriptive of the quality of the growing season. The answer to this is neither, and he observes that a more appropriate use as an alternative for characterisation of the quality or suitability of a growing season of an area under crop production is the Rainfall Distribution Index (RDI). This is the ratio of the median annual rainfall to the length of the growing season.

Manning (1950) observed that a delay on the onset often handicaps arid areas, and there is therefore a real need in agriculture for knowledge not only of the average expected rainfall, but also of the limits within which this will lie.

According to Mutsaers (1978), an agriculturally useful analysis of rainfall within a growing season should consider both the amount and the distribution over the periods under study. Furthermore, rainfall distribution is of major importance to crops particularly during a drought sensitive period (e.g. maize at tasselling) and for any crop just after sowing.

Ngana (1993) points out that rainfall variability is a constraint to agricultural planning. Fluctuation of the onset of rains is also another disturbing factor. This state of fluctuation creates confusion to the farmers in terms of when to plant, because in semi-arid areas every drop of rain needs to be utilised. Berry *et al.*, (1972) reported that due to fluctuation of the onset of rains, farmers in the Dodoma District of Tanzania practised staggered planting. Therefore, analysis of rainfall characteristics may assist to minimise excessive costs in agricultural planning.

2.6 Trends and Recurrences of Rainfall

2.6.1 Auto Correlation and Spectral Analysis

The objective of this section is to examine the time series of the seasonal rainfall in Swaziland for any cyclic patterns. Ngana (1993) observed that an important guide to the properties of a time series is provided by a series of quantities called sample autocorrelation coefficients, which measure the correlation between observations at different time-lags. If a time series consists of some cyclic or periodic fluctuations, spectral analysis may be used to unveil them. If such cyclic patterns are identified in the series, prediction could be made about future rainfall situations.

Spectral analysis, sometimes called 'spectrum analysis', is therefore, the name given to methods of estimating the spectral density function, or spectrum, of a given time series.

Further more, King'uyu (1994) states that spectral analysis is the most modern method of determining the existence of any cyclic events. The methods, which have been used to compute the spectral estimates, include the auto correlation/auto covariance transform, the Fast Fourier Transform and the Maximum Entropy Method (Jenkins and Watts, 1968).

In the last century, research workers were essentially concerned with looking for 'hidden periodicities' in the data, but spectral analysis as we know it today is mainly concerned with estimating the spectrum over the whole range of frequencies. Bartlett (1966) and Tukey (1967) have been prominent in the development of modern spectral analysis that has a history of about thirty years, and the techniques are now widely used by many scientists.

Chatfield (1987) says that spectral analysis is essentially a modification of Fourier analysis so as to make it suitable for stochastic rather than deterministic functions of time. Fourier analysis (Hsu, 1967) is basically concerned with approximating a function by a sum of sine and cosine terms called the Fourier series representation.

Munk *et al* (1959); Craddock (1965); Roden (1966), Snodgrass *et al* (1966) and Mooers and Smith (1968) all concur that in agricultural meteorology and oceanography, spectral analysis is very useful.

2.6.2 El-Niño and the Southern Oscillation (ENSO)

The existence of cold surface water at the equator in the South Pacific and its influence on air above it, introduces two associated phenomena, the El Niño and the southern oscillation. Although the existence of the southern oscillation (SO) has been known since the 1920s, it has received particular attention in recent years because of its significance in atmospheric circulation and rainfall, not only in the Pacific but in much a wider dominant global climate signal for periods of a few months to a few years. Possible links with extreme events, particularly droughts and floods, have been the focus of much interest.

Rasmusson and Wallace (1983) and Wright (1985) all provide reviews of the basic characteristics of El Niño and SO (ENSO) and their significance, which has been demonstrated in recent years, with the plight of El-Niño.

Bjerknes (1969) reviews of the oscillation in atmospheric pressure between the East and West sides of the Pacific, the SO to be related to variations in rainfall and sea surface temperatures (SSTs) in the equatorial eastern Pacific, particularly anomalous warm temperatures off the Peruvian coast termed El Niño. The excessive cold water at the equator in the Pacific seems to prevent the ascent of trade-wind air, which therefore flows westward to the warm West Pacific and thus reducing the amount of rainfall in that region.

Lockwood (1984) furthermore states that trade-wind air accumulates moisture and is heated, taking part in large-scale ascent of warm air. In the Indonesian area this ascent leads to substantial rainfall and the latent energy release exceeds net radiation at the surface. The circulation between the east and west pacific is often termed the WALKER circulation.

Philander (1985) observed that in the eastern Pacific every year, a warm current moves south off Ecuador, displacing the cold surface waters off the South American coast. This feature is known as El Niño. From time to time, El Niño is much more intense and persistent than normal. SST rises along the Peruvian coast and the eastern equatorial Pacific may persist for more than a year and very heavy rain may occur over western South America. Recent occurrences include, 1972-73; 1976; 1982-83 and 1989-99. Philander refers to the complementary phase of El Niño, when low SSTs are experienced near the equator, as La Nina.

Ramage and Hori (1981), concluded that the prediction of El Niño events were more difficult than anticipated. Baker-Blocker and Bouwer (1984) examined occurrence over the period 1972 - 1976 using spectral analysis numerous periods between 2.3 and 37.1 years were found but it must be stressed that interpretation of results of such analysis is difficult. They suggested that large random pulses, perhaps of volcanic or solar origin, might act as triggers to shift the atmosphere between quasi-stable states.

2.6.3 Rainfall Reliability and Variability

Ogallo (1984) points out that although rainfall variability and change have important impacts on agricultural production, many human factors play a part. He contrasts the situation in some tropical Latin American countries and parts of Asia such as India where sound planning has increased food production resulting in technological innovations, reduced famines and deaths due to climatic variability, compared with that in other countries of these regions and also particularly countries of sub-Saharan Africa. In the latter, unstable economic, social and political systems, as well as constraints such as lack of skilled local human resources, fluctuations in markets and prices and a range of socio-economic factors have in many cases played a major role in declining agricultural production. This has highlighted the effects of climatic variability, particularly drought occurrence in drier regions.

Oguntoyinbo and Odingo (1979) showed how in East and West Africa, traditional systems in harmony with the physical environment were broken down by inappropriate land-use, socio-economic and technological changes. They point out that impacts tend to be greatest in more marginal areas, making communities particularly vulnerable to rainfall variability and effect of drought.

Michaels (1982) used a modelling approach to assess climatic sensitivity of high yielding variety 'green revolution' wheat in India and Mexico. Increased adoption of the high yielding 'package' led to a significant increase in yield sensitivity to important climatic factors including rainfall. Therefore, without any change in climatic variability, production became more variable. Furthermore, the effectiveness of rainfall must take into account a variety of characteristics, including storm size, intensity, frequency and time of occurrence as well as soil characteristics, vegetation, slope and evaporation rates as was done for this study.

Meher-Homji (1974), Dale (1959) and (Taylor and Tulloch, 1985) all agreed that seasonal distribution of rains should not be averaged if data is to give meaningful results in agriculture. They argue that the pattern of seasonal rainfall regimes is related to agricultural systems and water supplies.

Jackson (1991) observed that the use of monthly values of any kind to define seasonal regimes is suspect not only because rainfall conditions during short time periods are critical for agriculture but also because the onset and end of the wet season, either on average or for individual years, does not coincide with calendar months. This has led to the use of pentads (5 – day periods) to define rain seasons. Examples of this approach are the work of Gramzow and Henry (1972) for Central America, Ilesanmi (1972) for Nigeria and Ananthakrishnan and Rajagopalachari (1964) for India.

Torrance (1967) used pentads to examine the progress of the mean rainy season and variations in the length of the dry season in Central Africa. Furthermore Ananthakrishnan, Pathan and Aralikatti (1981) used pentads to study the northern advance of the Inter-tropical convergence zone (ITCZ) and onset of the summer monsoon rainfall for island stations in the Bay of Bengal. They found the onset dates to be earlier than those indicated on existing diagrams. For West Africa, daily rainfall models have been used to derive the probability distribution of the starting date of the rains by Stern, Dennett and Garbutt (1981).

Virmani (1975) defines the growing season in India as being made up of weeks with a 70 percent probability of receiving at least 10 mm per week and 'sowing rains' as more than 20 mm rain on not more than two consecutive days in such a week.

Oldeman and Frere (1982) used backward and forward accumulation of 10 – day totals to determine the onset and termination of the wet season. This was done for each year and then probabilities were assessed.

Keen and Tyson (1973), Fitzpatrick, Hart and Brookfield (1966) and Potts (1971) used spectral or harmonic analysis of mean monthly rainfall to define seasonal regimes.

2.7 Water Requirement Satisfaction Index

According to Kramer (1959) a water deficit occurs in the plant whenever transpiration exceeds water absorption. This may be due to the excessive water loss, reduced absorption or both. According to the degree of internal water deficit and its duration, one can distinguish between incipient, temporary and permanent wilting.

Shaw and Laing (1968) state that moisture stress does not affect all aspects of plant growth and development equally. Some processes are highly susceptible to increasing water stress, while others are far less affected. The final yield of the crop will be the integrated result of the effects of stress on growth, photosynthesis, respiration, on metabolic processes, reproduction, etc.

Slatyer (1967) observed that the amount of water in the plant is far higher than in the soil, and very small fluctuations, within very narrow limits, can interfere with active metabolism. For example in maize, an increase in water stress causes nitrate reductase activity to decline at a much greater rate than peroxidase activity (Todd, 1972). Almost all metabolic reactions are affected by plant water deficits.

Root growth-rate also decreases with increasing water stress. However, growth of the roots is less affected by water shortage than is that of the aerial parts, so that the overall shoot/root ratio is decreased (Peters and Runkles, 1967).

Growth is suspended during stress and resumed upon its elimination. The extent of the damage caused to the plants depends on their physiological age, the degree of water stress, and the species concerned (Gates, 1968). Generally, the organ growing most rapidly at the time of stress is the one most affected (Aspinall *et al*, 1964)

Kramer (1969) states that roots of plants subjected to water stress tend to become suberized on their tips and thereby lose part of their absorbing capacity. Furthermore, the effect of water stress on yield will depend largely on what proportion of the total dry matter produced is considered useful material to be harvested observed (Fisher and Hagan, 1965). When the harvested material consists of seeds and fruits, water stress affects the crop, the dry matter stored in the seeds or grain is mainly the result of photosynethesis that occurs after flowering (Thorne, 1966).

Peak water requirement in maize occurs during silking and tasselling periods. These periods are known to reduce grain yield more than at any other period (Denmead and Shaw, 1960; Volodarskij and Zienevic, 1960). The duration of the stress period is also an important yield determinant (Robins and Domingo, 1953). Indeed, there is a close relationship between yield and the percentage of rainfall over the growing season (Mota, 1959).

3. MATERIALS AND METHODS

3.1 Climatic Data

Mbabane, Malkerns and Big Bend, are the 3 meteorological stations that represent the four agro-climatic zones namely, the Highveld, Middleveld, Lowveld and Lubombo Plateau (Table 1). Another considerat on on the choice of the stations was the length and quality of the various data records obtained from the representative stations. It should also be noted that Lubombo Plateau and the Middleveld share the same agro-climatic characteristics (Lukando, 1993). Hence the Malkerns Station is representative of the two agro-climatic zones.

The data used in this study was obtained from the National Meteorological Services (NMS), the Ministry of Agriculture and Co-operatives (MoAC) and the Central Statistical Office (CSO) in Swaziland. The NMS provided daily rainfall, daily and monthly average temperatures, sunshine hours, maximum and minimum temperature, and wind speed data. The CSO provided the areas under maize production and annual yields and these records were compared with those from MoAC.

Since these data were original observations, they had to be checked for systematic errors. This check was done using an in built system for quality control and range validation that comes with the CLICOM programme. All the climatic data used in this study was in the CLICOM format.

3.2 Estimation of Missing Climatic Data

3.2.1 Arithmetic Mean Method

With this method, the ratio of long-term averages for two correlated locations is used to estimate the missing data using expressions of the form:-

$$x_t = \frac{\bar{x}}{\bar{y}} y_t \qquad (16)$$

where $\bar{x}, \bar{y}$ are long-term means of x_t and y_t whilst x_t is the series with missing data and y_t a related series with no data gaps. The method assumes that due to the high correlation between the pair of points (variables), the ratio of the long-term averages will be reflected at any time scale. This may, however, not be true for locations with unique local regional climatic anomalies.

An advantage of this method is that the significance of the estimated data can be tested using standard statistical tests. A disadvantage of the method is that different locations may have unique characteristics that may not be easily accounted for by the simple mathematical function. Another disadvantage is that the calibration of those models based on spatial correlation requires a good base network, which is often lacking and each model may be applicable only for particular time scales. In this study, correlation methods were used for the estimation of minimum and maximum rainfall data. The data were quality - controlled before they were used in any analysis.

3.3 Homogeneity of Climatic Data

3.3.1 Mass Curves Method

Cumulative data or deviations from the mean are plotted against time for mass curves and residual mass curves respectively. A strictly homogeneous record would be represented by a straight line whilst heterogeneity would be represented by significant deviations of some of the plots from the straight line. This is then the method that was used in this study for analysis of homogeneity of the data set and is given by the following equation.

$$c_N = \sum_{t=1}^{N} x_t \quad \text{.....(17)}$$

where

C_N is the n^{th} cumulative value

X_t is the observation at time (t)

3.4 Onset and Cessation of Rains

3.4.1 The Cumulative Rainfall Method

A graphical model was used for the determination of the times of onset and cessation of the rains for the meteorological stations of Mbabane, Big-Bend and Malkerns that experience a single rainy season (Ilesanmi, 1972). The disadvantage of this method is that it is difficult to decide on a criterion for the data for the onset and cessation of the rains (Alusa and Mushi, 1974; Ilesanmi, 1972).

The mean five-day (pentad) rainfall totals were calculated for the desired period. The percentage of the mean annual rainfall that occurs at each 5 - day interval for the station were observed and accumulated percentages determined and plotted. The times of onset and cessation respectively were defined as the second (onset) and first (cessation) point maximum positive and negative curvatures (Figure 4).

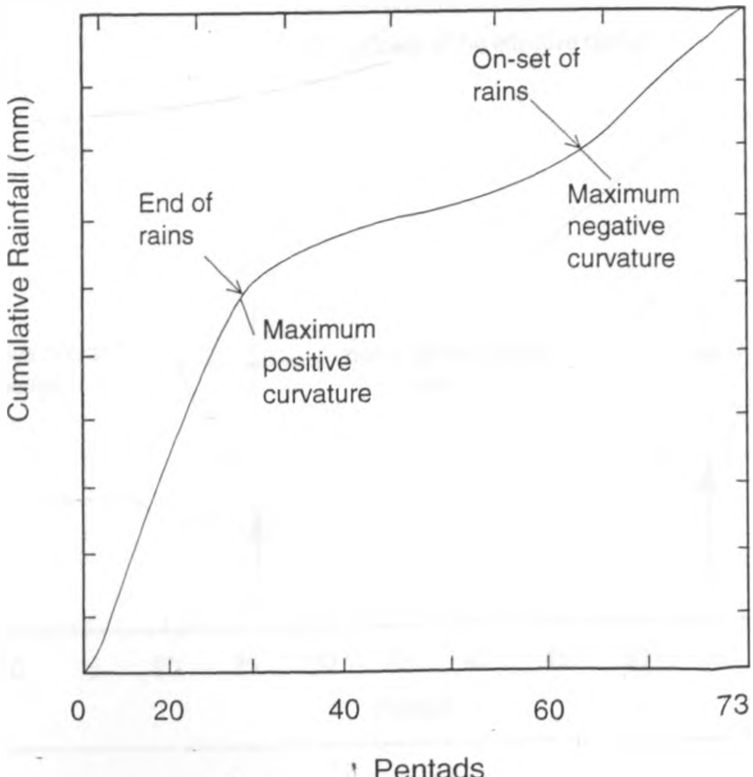

Figure 4 *Cumulative rainfall method of estimating onset and cessation of rains.*

3.4.2 The Effective Rainfall Method

Besides the cumulative rainfall method of determining the onset and cessation of the rains, the effective rainfall method was used in this study to denote the effective onset and cessation of the rains. It is based on the relationship between rainfall and potential evapotranspiration as shown in Figure 5. In coming up with the potential evapotranspiration values, the Pan Evaporation Method (FAO, 1988) was used. The advantage of this method over the cumulative method is that it uses a more agro-based approach, which uses the crop-soil parameters, rather than rainfall alone in determining the start and end of the rains (Appenxix 1-3).

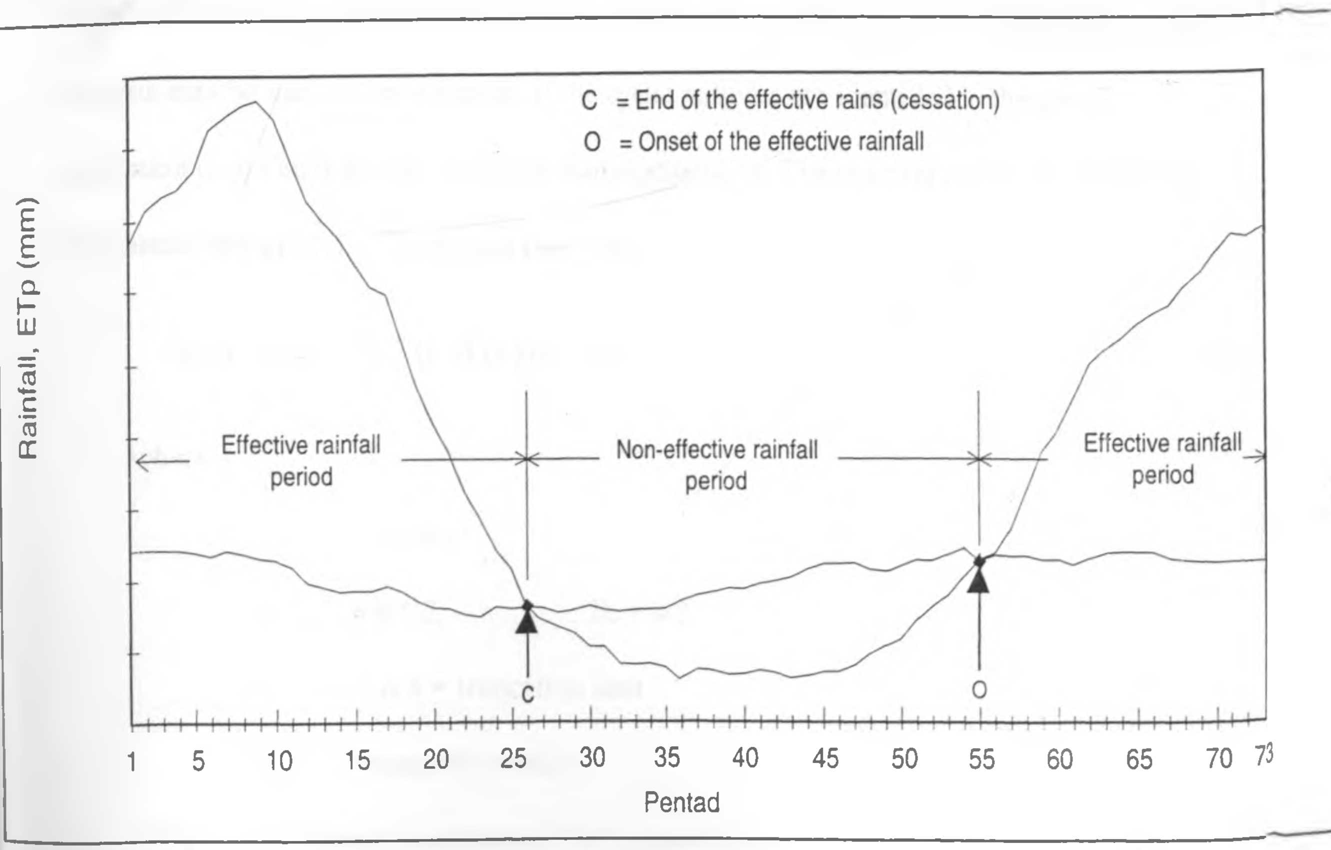

Figure 5 *Rainfall and potential evapotranspiration.*

3.5 Rainfall Reliability and Variability

This method uses the mean seasonal rainfall totals and the standard deviation for the growing season (Appendix 4). For example, if the rains normally start in September of any year and cease in April of any following year; then add up the monthly totals and find their reliability over time. The coefficient of variation is then given as:-

$$C_v = \frac{\sigma}{\bar{x}} \quad \text{.......... (18)}$$

where σ is the standard deviation and $\bar{x}$ is the mean seasonal rainfall The rainfall reliability, R, is given as:-

$$R = 1 - (C_v) \quad \text{.......... (19)}$$

3.6 Spectral Analysis

In this study, it was found necessary to use time series analysis for the prediction of rainfall (Appendix 5). If the time series consists of some cyclic or periodic functions, spectral analysis may be used to unveil them. If the cyclic patterns are identified in the series, prediction could be made about future rainfall situations. The spectral estimates at different frequencies are given by Chatfield, (1987) as:-

$$P(F) = 2\left\{1 - 2\sum_{k=1}^{L-1} R(k)W(k)\cos 2\pi kf\right\} \quad \text{.......... (20)}$$

where

f = 1/(4L)

k = 0,1,2, ... 2L = n/2

L = n/4 = truncation limit

W(k) = spectral window

The autocorrelation coefficient R(k) is given by -

$$R(k) = \frac{\sum_{t=1}^{n-k} (X_t - \overline{X})(X_{t+k} - \overline{X})}{\sum_{t=1}^{n} (X_t - \overline{X})^2} \quad \text{.......} \quad (21)$$

3.7 Water Requirement Satisfaction Index (WRSI)

The analysis of data for the development of a model for forecasting maize yields in Swaziland, was done using the Water Requirement Satisfaction Index (WRSI) which was purported by Frere and Popov (1979) and adopted (FAO) (Appendix 6).

The meteorological station that was found to have complete data to compute the Water Requirement Satisfaction Index (WRSI) was Mbabane. The model uses actual rainfall (R), climatological, crop and soil information.

The model is based on the cumulative water balance of the crop during its growing season in pentads until the crop reaches maturity. This model is primarily developed for areas where the standard limiting factor is soil water. The method does not directly take into account temperature, which is considered indirectly in the calculation of the crop water requirement. Temperature has been used in the calculation of the potential evapotranspiration.

Rainfall and climatological data were simultaneously used in the calculation of crop water requirements. The water balance is the difference between actual precipitation (R) received by the crop and the water lost by the crop through evapotranspiration and through percolation into the soil profile, taking into account the water retained in the soil layers.

This method produced an Index known as the "Water Requirement Satisfaction Index" that is shown in percentages at the end of the season. It reflects the cumulative stress endured by the crop due to the unavailability of soil water to the crop. The index was then compared to the final yield of the crop at the end of the season. The index was directly linked to the maize yield and this enabled yields to be estimated very early in the season as shown in chapter 4. The method assumes that the crop extracts available water from the soil at the same rate in all depths.

In computing the index, the initial stage is to get the Total Water Requirements (TWR) of the crop for the season using the equation below;

$$TWR = \sum_{i=n}^{n} E\,T_{p}x\,K_{c})_{i} \qquad (22)$$

where

TWR is the total water requirement for the crop in a growing season (mm/day)

ET_p is the potential evapotranspiration

K_c is the crop coefficient

i is the pentad

n is the pentad when the crop matures

$$WR = (ET_{p}\,x\,K_{c}) \qquad (23)$$

where i is the crop water requirement for pentad *i*.

Secondly, in the calculation was the computation of the deficit (D) or surplus (S) for a given pentad (i) using;

$$S_i = (R - WR)_i \qquad (24)$$

where R is the actual Rainfall for pentad i and WR the crop water requirement for pentad i. If $S_i > 0$, then it is a surplus. $Si < 0$ implies a deficit (Di)

The soil water reserve (W) was required in the calculation of the index. where W is the quantity of water that existed within the rooting zone of the crop at a given moment and which was readily utilised by the crop. The maximum quantity of water available to the crop corresponds to the difference between field capacity and the wilting point. The water holding capacity of the soil at Mbabane used in the study was 60 mm (Lukando, 1993).

This study assumed that the surplus water went to the soil moisture reserve or runoff depending on the soil water holding capacity (WHC). If there was a deficit, then the equivalent was extracted from the soil moisture reserve until the plant suffered due to deficit water supply. Soil water reserve (W) for a given pentad is computed using the following equation:

$$W_i = W_{i-1} + (R - WR)_i \qquad (25)$$

where W_i is the present soil water reserve of pentad i. W_{i-1} is the soil water reserve of the previous pentad. R and WR are as defined earlier. If $W_i < 0$, then $D_i = W_i$ and taken as $W_i = 0$ and $S_i = 0$. If $W_i > WHC$, then $S_i = W_i - WHC$ and $D_i = 0$. If $0 \leq W_i \leq WHC$, then $S_i = D_i = 0$, where WHC is the maximum water holding capacity of soil.

The index was calculated by first assuming that the water available in the soil before the sowing date was greater than the water requirements of the plant during the first pentad of its emergence. Therefore, the index was taken as equal to 100 at the time of emergence. This index remains 100 until a deficit occurres. Thus in computing the water requirement satisfaction index (I_i) for a given pentad i,

It was assumed that I = 100 at planting

On subsequent pentads, if there is a deficit e g. $D_i < 0$, then

$$I_i = I_{i-1}\left(\frac{|D_i|}{TWR} x100\right) \qquad (26)$$

where I_i is the index for pentad i

I_{i-1} is the previous index for pentad i

TWR is the total water requirement of the crop

This calculation continued pentad by pentad until the crop attained maturity. The index at the end of the growing season reflected the cumulative water stress endured by the crop pentad by pentad.

Correlation and regression analyses were carried out between yields and the indices. An equation was developed linking the indices and yield obtained at the end of the season. This was done for all seasons. The model used was of the form:-

$$Y = a + bx + \varepsilon \qquad (27)$$

Where

Y = total harvest in (kg/ha) in the season

a = constant, intercept of the line on the Y axis

b = coefficient of variable, x

x = Water Requirement Satisfaction Index or moisture surplus or moisture deficit at reproductive phase or at maturity stage

ε = unexplained random error term.

3.7.1 Climatological Data

In the computation of the WRSI, actual pentad rainfall was used. Potential evapotranspiration (ETp) was calculated using wind speed records, radiation/sunshine hours and mean daily temperatures. The ETp was calculated using the FAO Penman method as proposed by Doorenbos and Pruitt in FAO (1988).

3.7.2 Crop Data

3.7.2.1 Phenological and Yield Data

The maize growing cycle length varies with zone and variety. The 150-day variety was used in the current study for the period 1979 - 1992. For the periods 1983/84 - 1987/88, yield estimates from the National Early Warning Unit (NEWU) were used. According to Lukando (1993) available phenological data generalises the crop cycle lengths as 26, 28 and 30 pentads for maize grown respectively in the Lowveld, Middleveld and Lubombo Plateau, and Highveld.

3.7.2.2 Crop Coefficient (K_c)

These values have been calculated by FAO from their long experience in agriculture in Africa (FAO, 1986). K_c is the ratio between potential evapotranspiration (ETp) and the crop evapotranspiration (ET_{crop}) estimated by Penman (1988). The crop coefficients used in this study were obtained from FAO (1988).

3.7.3 Soils Data

Soil Water Holding Capacity (WHC) used in this study were obtained from Malkerns Research Station and the Land Use Planning Unit, Ministry of Agriculture and Co-operatives (Lukando, 1993).

3.8 Analysis of Land Management Options

This analysis of feasible land management options was based on the dominant soil types and their associated problems. The classification of soil types in Swaziland has been correlated with the standard classification by FAO-UNESCO-ISRIC (1988).

A seasonal land management calendar for maize production in Swaziland was developed i this study taking into account the widely used tillage operations in the county. The effects of tim of planting and fallowing on crop yields were also considered.

4. RESULTS AND DISCUSSION

The objective of this study forms guiding principles on the arrangement and presentation of the results. To achieve the objectives, various analyses were carried-out on the data. This included homogeneity tests, determination of onset and cessation of rains, as well as seasonal and cyclical analyses (spectral analysis). Finally, a model based on the Water Requirement Satisfaction Index (WRSI) was developed by this study for the forecasting of maize yields. The results obtained from the various analyses are presented in the following sections.

4.1 Missing Climatic Data

Data found to be missing were estimated using correlation and the arithmetic mean methods as discussed in section 3.2 All the records were subjected to quality-control tests before they were used for any analysis.

4.2 Climatic Data Quality Control

The mass curves method was used for the homogeneity test and some of the results obtained are shown in Figure 6. The mass curves obtained were linear, showing that the rainfall records were not heterogeneous. The rainfall records were therefore, declared homogeneous and hence suitable for climatological analysis.

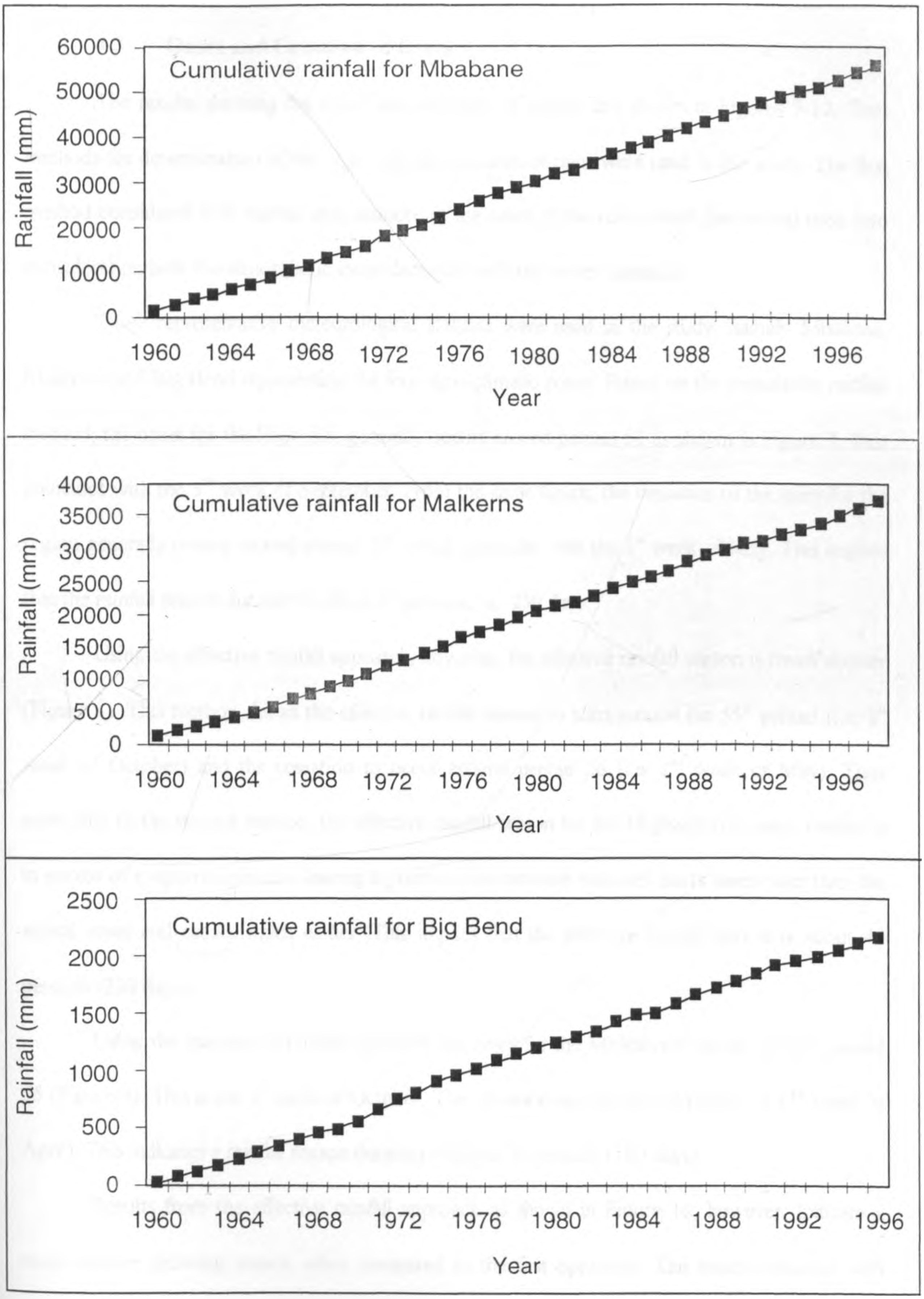

Figure 6 *Rainfall homogeneity tests for Mbabane, Malkerns and Big Bend meteorological stations in Swaziland.*

4.3 Onset and Cessation of Rains

The results showing the onset and cessation of rainfall are shown in Figures 7-12. Two methods for determination of the onset and the cessation of rains were used in this study. The first method considered only rainfall as a measure of the onset of the rains whilst the second took into consideration both the atmospheric evapodemands and crop water demands.

Three representative meteorological stations were used in the study, namely Mbabane, Malkerns and Big Bend representing the four agro-climatic zones. Based on the cumulative rainfall method, the onset for the Highveld, generally occurs around pentad 51 as shown in Figure 7. This coincides with the 3rd week of September. From the same figure, the cessation of the rains for the region generally occurs around pentad 25, which coincides with the 1st week of May. This implies that the rainfall season duration is about 47 pentads, i.e. 230 days.

Using the effective rainfall approach, however, the effective rainfall season is much shorter (Figure 8). This method shows the effective rainfall season to start around the 55th pentad (i.e. 1st week of October) and the cessation to occur around pentad 26 (i.e. 2nd week of May). Thus according to the second method, the effective rainfall season for the Highveld (i.e. when rainfall is in excess of evapotranspiration leaving a positive soil moisture balance) starts much later than the actual onset and ceases much earlier. This implies that the effective rainfall period is about 44 pentads (220 days).

Using the cumulative rainfall approach the onset for the Middleveld occurs around pentad 55 (Figure 9). This is the 1st week of October. The cessation occurs around pentad 19 (1st week of April). This indicates a rainfall season duration of about 36 pentads (180 days).

Results from the effective rainfall approach as shown in Figure 10, however, indicate a much shorter growing season when compared to the first approach. The onset coincides with pentad 65 (4th week of November), which is about a month later as compared with the previous method. The cessation takes place around the 16th pentad (4th week of April). This indicates that in the Middleveld, the effective rainfall season is shorter than that of the Highveld by three months. The effective rainfall season only lasts about 120 days.

It is evident from the results that there are about 30 days of transition between the time the rains start and the time of the effective rainfall onset to facilitate seedbed preparation and sowing for the agro-ecological zones investigated in this study. An average growing season in Swaziland is about 150 days. Furthermore, the results indicate that for the Highveld region, the growing season is between September and May whilst for the Middleveld and the Lowveld, it is between the months of October and April and November to March respectively. These results on average show that by the beginning of September, in Swaziland, final seedbed preparation should have taken place in readiness for sowing.

Since it is the difference between rainfall and evapotranspiration losses that determines crop development, it is the effective rainfall method that should be used for the planning of farming operations. Farmers should therefore be advised on planting dates based on the effective rainfall approach and not on the cumulative rainfall approach. The crop types should be those that will mature within the effective rainfall period when the net rainfall is positive. Since the actual onset based on the cumulative rainfall method occurs a few weeks ahead of the effective rainfall onset, the former can be used as an indicator of the time for final tillage operations to take place in readiness for sowing.

For the Lowveld, however, the rainfall onset occurs much later (pentad 50) and ceases much earlier (pentad 18) (Figure 11). This shows that the Lowveld zone has a season of 42 pentads (i.e. 210 days). The onset and cessation of rains periods for Big Bend are 2nd week of September and 4th week of March respectively. However, the rainfall received during this period is very low and hence inadequate. This zone experiences a rainfall deficit throughout the year as potential evapotranspiration rates are in excess of the rainfall (Figure 12). This implies that crop production can only be carried out effectively under irrigation.

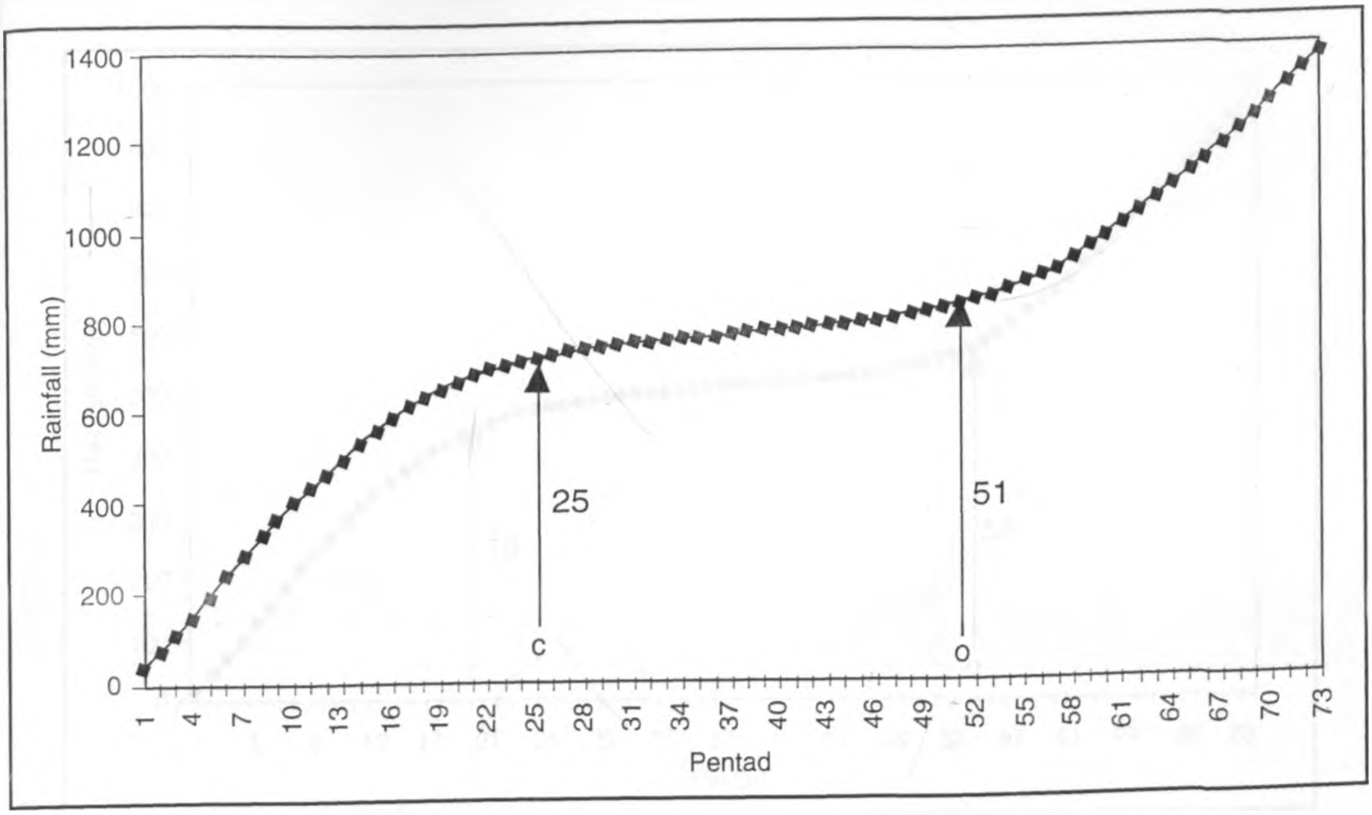

Figure 7 *Cumulative rainfall method for predicting onset (O) and cessation (C) of rains for Mbabane, Swaziland.*

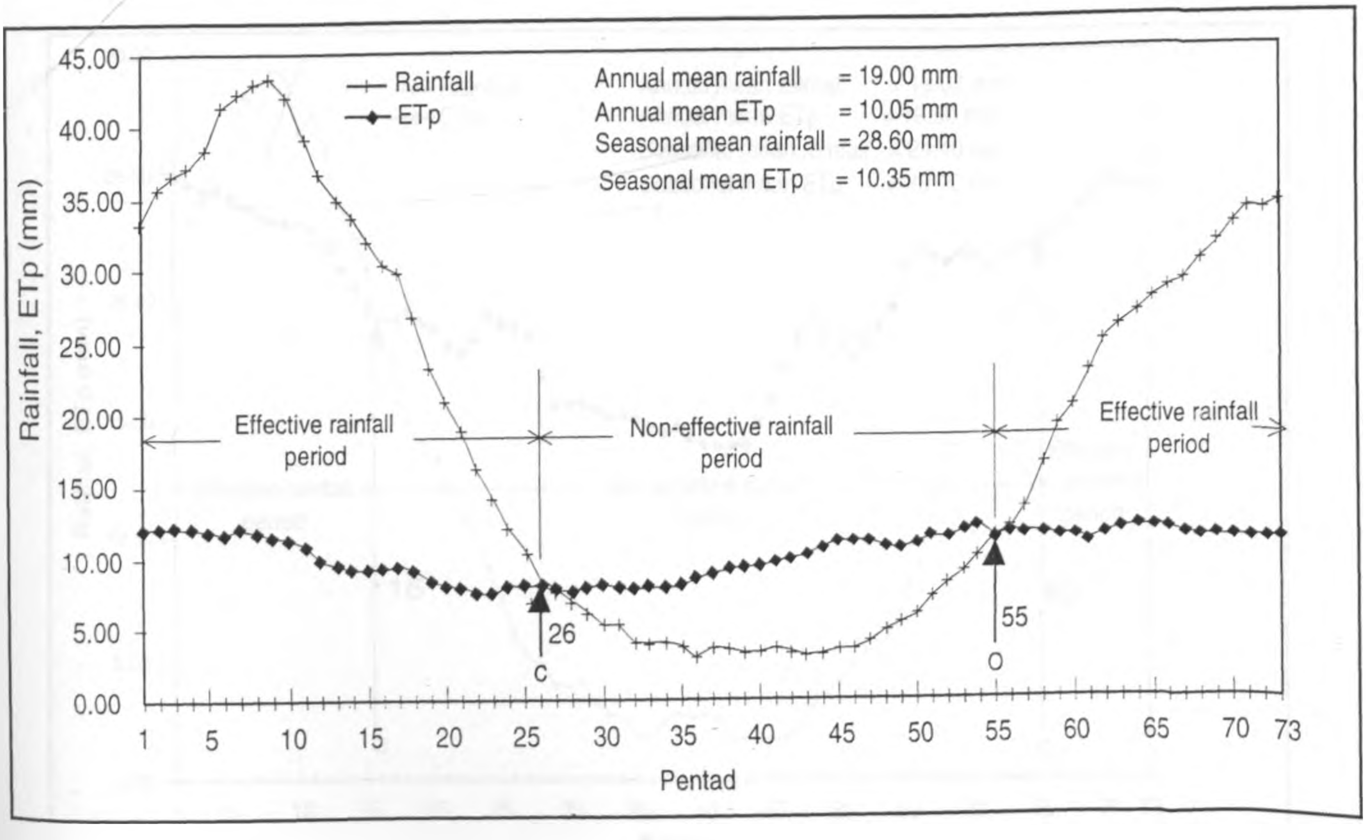

Figure 8 *Rainfall and Evapotranspiration for Mbabane showing effective rainfall season.*

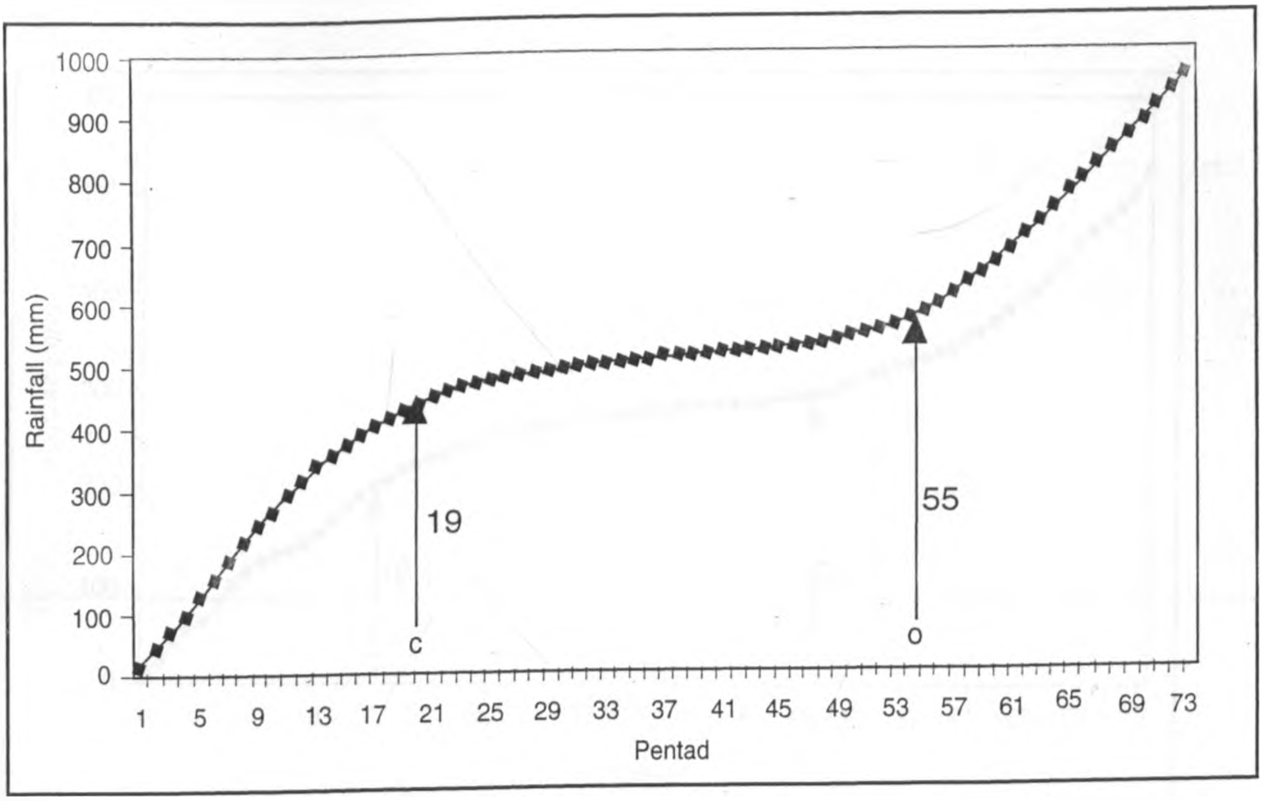

Figure 9 *Cumulative rainfall method for predicting onset (O) and cessation (C) of rains for Malkerns, Swaziland*

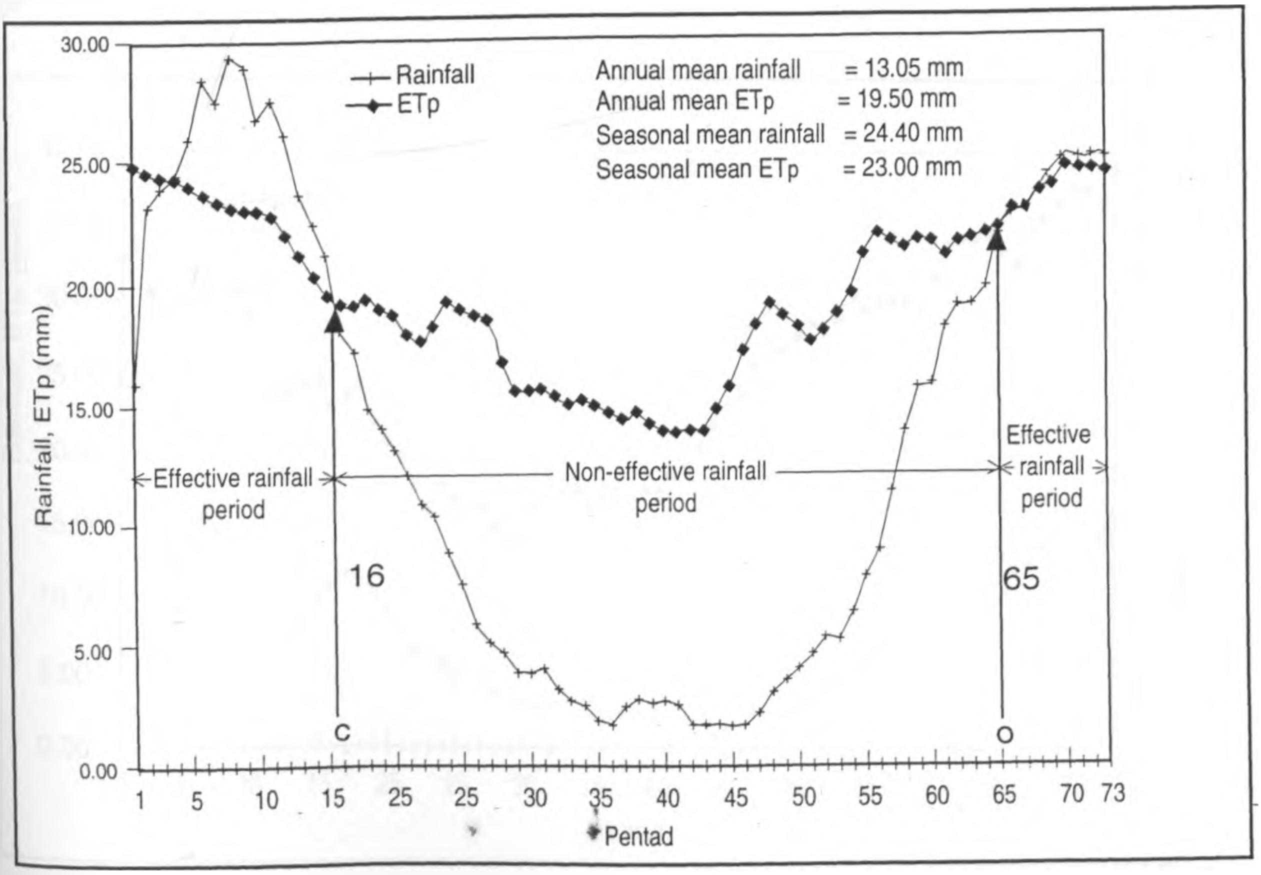

Figure 10 *Rainfall and Evapotranspiration for Malkerns showing effective rainfall season.*

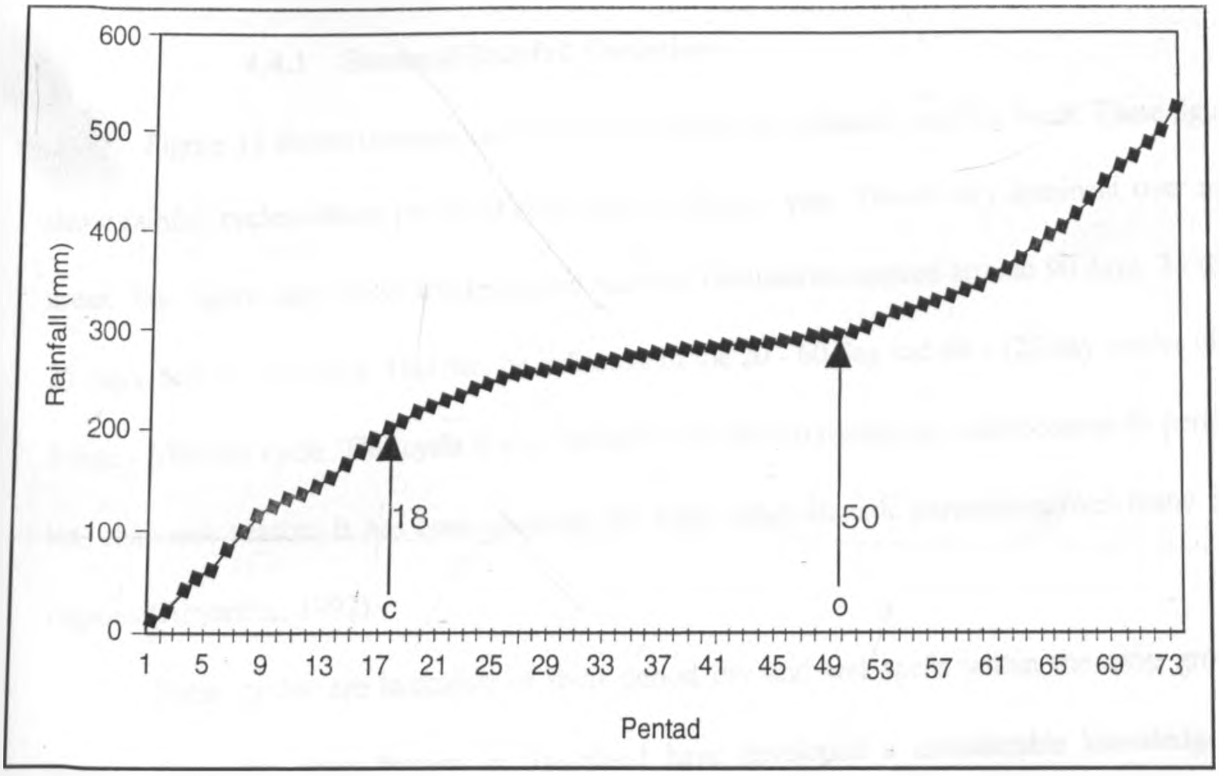

Figure 11 *Cumulative rainfall method for predicting onset (O) and cessation (C) of rains for Big Bend, Swaziland.*

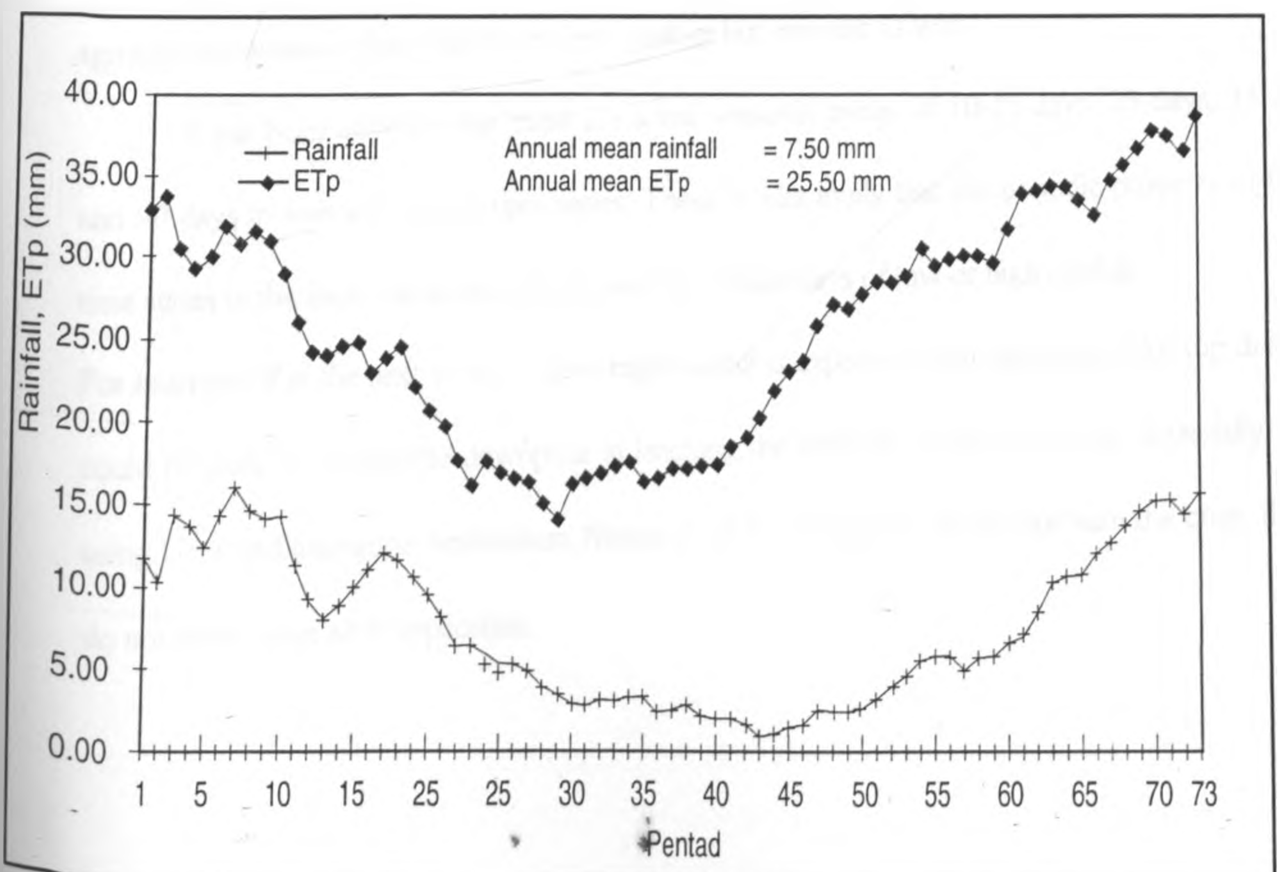

Figure 12 *Rainfall and Evapotranspiration for Big Bend showing effective rainfall season.*

4.4 Seasonal and Cyclical Rainfall Variations

4.4.1 Seasonal Rainfall Variations

Figure 13 shows the seasonal rainfall fluctuations for Mbabane and Big Bend. These figures show rainfall cycles whose period of recurrence is about 1 year. This is very dominant over most areas. The figure also shows shorter period seasonal fluctuations centred around 90 days, 35 days, 25 days, and 10 - 15 days. This may be indicative of the 20 - 60 day and 60 - 120 day modes of the Julian - Madden cycle. This cycle is also referred to as the intra-seasonal cycle because its period is less than one season. It has been observed for many other climatic parameters over many other regions (Anyamba, 1992).

These cycles are indicative of short period dry and wet spells within the crop growing season. Over the years farmers in Swaziland have developed a considerable knowledge and experience of their environment and through a variety of ameliorative measures they have survived harsh climatic conditions. Seasonal rainfall analysis assists in indicating rainfall fluctuations or variability within the growing season. This analysis has showed that not all seasonal rainfall in the agroclimatic zones of Swaziland is entirely random but periodic as well.

It has been unveiled that there are some seasonal cycles of 10-15 days, 25 days, 35 days and 90 days in seasonal rainfall time series. These results imply that the periodic property of these time series in the areas mentioned can be used to predict days of low or high rainfall.

For example, if in the next 10 to 15 days high rainfall is expected, then operations like top dressing could be done to exploit the downpour in leaching the fertilizer to the root zone, especially when using Urea and limestone Ammonium Nitrate (L.A.N.) fertilizers, which can burn the crop, if rains do not come soon after application.

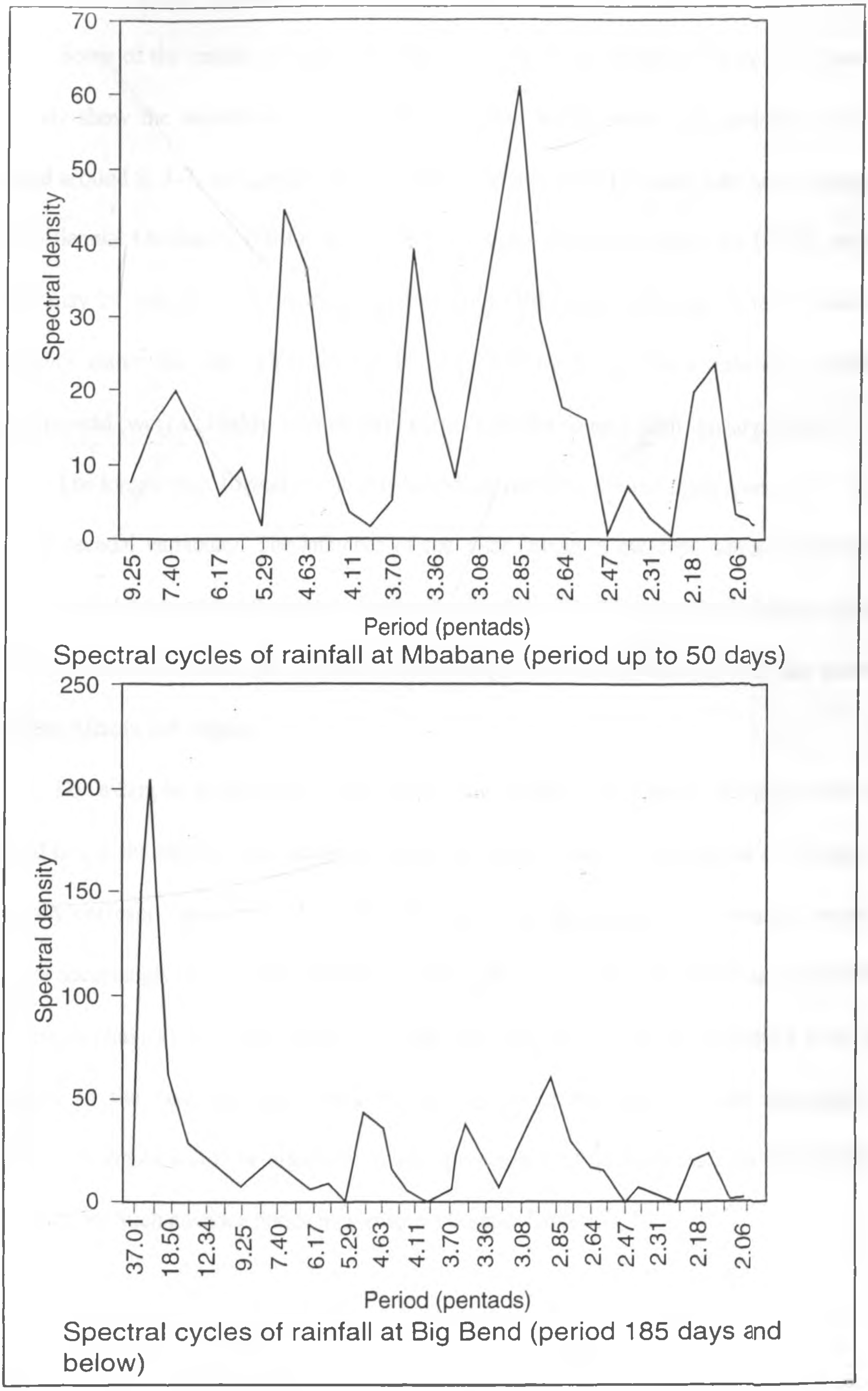

Figure 13 *Spectral cycles of seasonal rainfall variations for Mbabane and BigBend, Swaziland.*

4.4.2 Cyclical Rainfall Variations

Some of the results of cyclical rainfall variations are presented in Figure 14. These results generally show the recurrence of above/below normal rainfall events with periods of recurrence centred around 2, 3-7, and greater than 10 years. The first cycle (2 years) may be indicative of the Quasi-Biennial Oscillation (QBO) whilst the 3 - 7 years cycle falls within the ENSO periodicity. These may be indicative of the dominance of both QBO and ENSO in the interannual rainfall variability within the area. This can also be confirmed by the generally observed recurrence of above normal (wet) and below normal (dry) events over the country with similar patterns.

The longer than 10 years cycle may be indicative of the sunspot cycle (period 11 - 12 years) or inter-decadal variability. The influence of the solar (sunspot) cycle on climate parameters has been observed over many other areas. Generally the QBO, ENSO, and solar cycles are thought to be associated with some of the rainfall fluctuations that have been observed over the eastern and southern African sub-region.

For example, if in the next seven years low rainfall is anticipated, warning could be sent around to use the existing food resources carefully, in anticipation of low rainfall or drought which generally corresponds to low crop yields. Also adopt farming practices to lower the target yield, fertilize accordingly, lower plant population. Secondly, the government would have some time to mobilize or plan its resources to be able to meet shortages that may arise. Similarly, if a wet year is expected in the next say, five years, farmers would be mobilized to take advantage of it. Agricultural inputs would be organized in time, preparation of farms in readiness for planting done in good time. Such advance notice may ensure a bumper harvest.

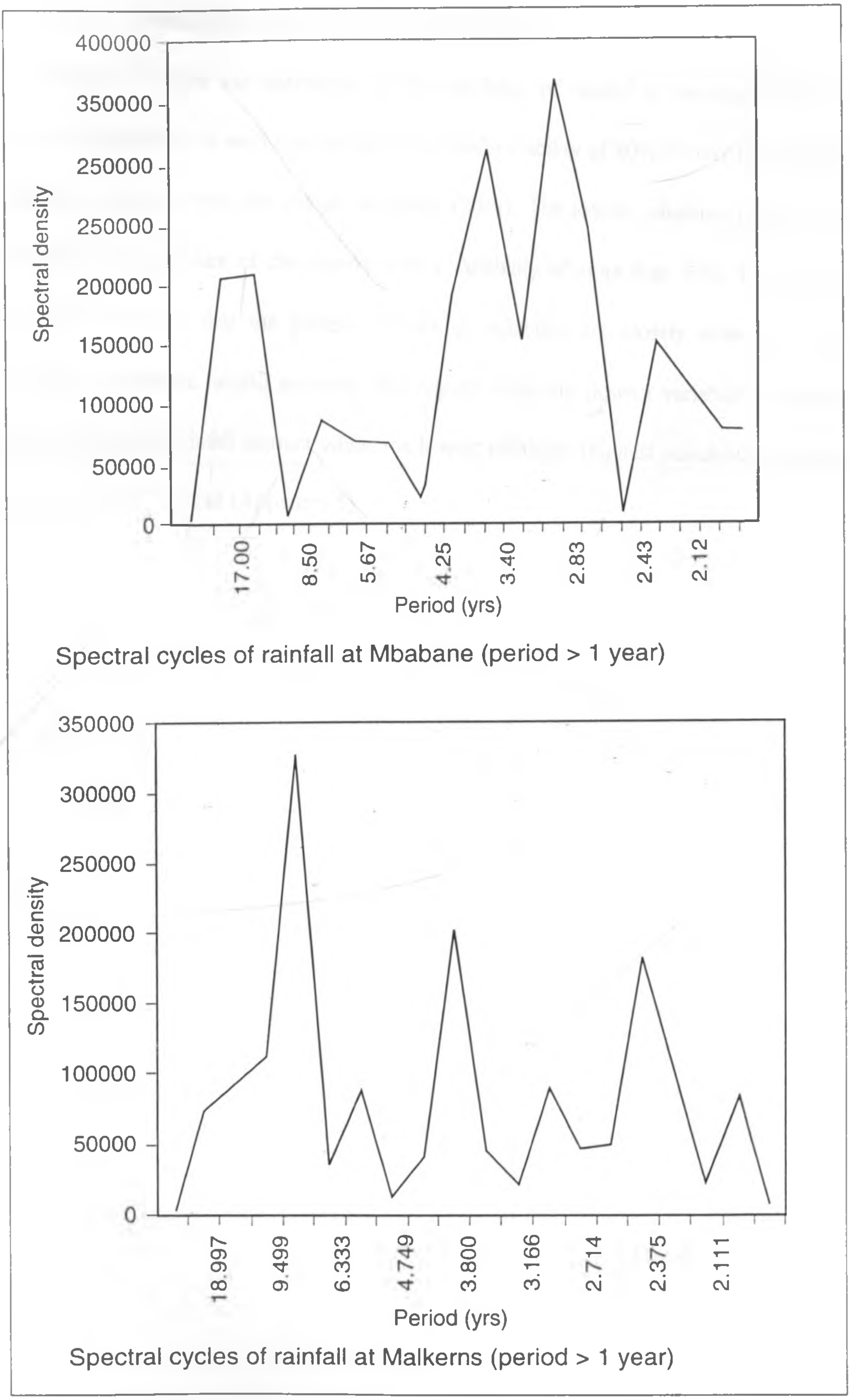

Figure 14 *Spectral cycles of seasonal rainfall variations for Mbabane and Malkerns, Swaziland.*

4.5 Reliability and Variability of Rainfall

Figure 15 show the distribution of the reliability of rainfall in Swaziland over time and space. The distribution is such that the highest rainfall reliability of 80% is over the Highveld. This is therefore, the area with the lowest variability (20%). The lowest reliability (70%) is over the North-east and South-east of the country with a variability of more than 30%. The results of this study therefore show that the patterns of rainfall reliability are closely related to the spatial distribution of seasonal rainfall amounts. The highest reliability (lowest variability) coincides with the highest seasonal rainfall amount whilst the lowest reliability (highest variability) coincides with the lowest seasonal rainfall (Appendix 5).

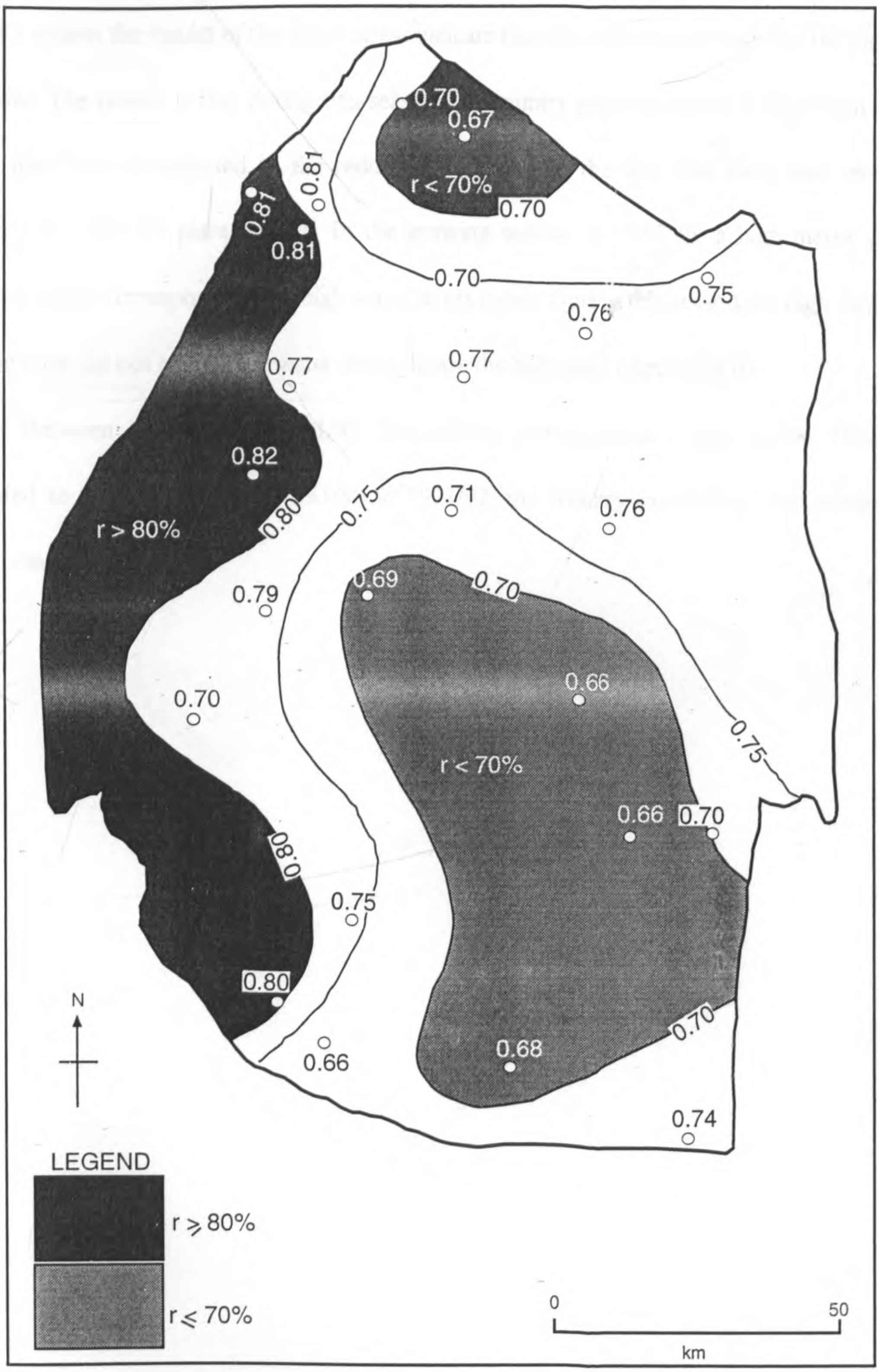

Figure 15 *Reliability of rainfall in Swaziland.*

4.6 The Water Requirement Satisfaction Index (WRSI)

Figure 16 shows that water stress indices and yields vary a lot from year to year. During the 1982/83 season the results of the water stress indicate that the indices were high but the yields were very low. The reason is that during this season, the country experienced an army worm invasion, which may have contributed to the reduced yields despite the fact that there was enough soil moisture to cater for plant growth. In the growing season of 1985/86, a high maize yield was obtained which corresponded to a high water stress index. During this season the high index shows that the crop did not experience water stress, hence the high yield (Appendix 6).

Between 1987/88 and 1991/92, low indices corresponded to low yields. This may be attributed to the fact that from 1987/88 to 1991/92, the country experienced the worst drought ever in many years.

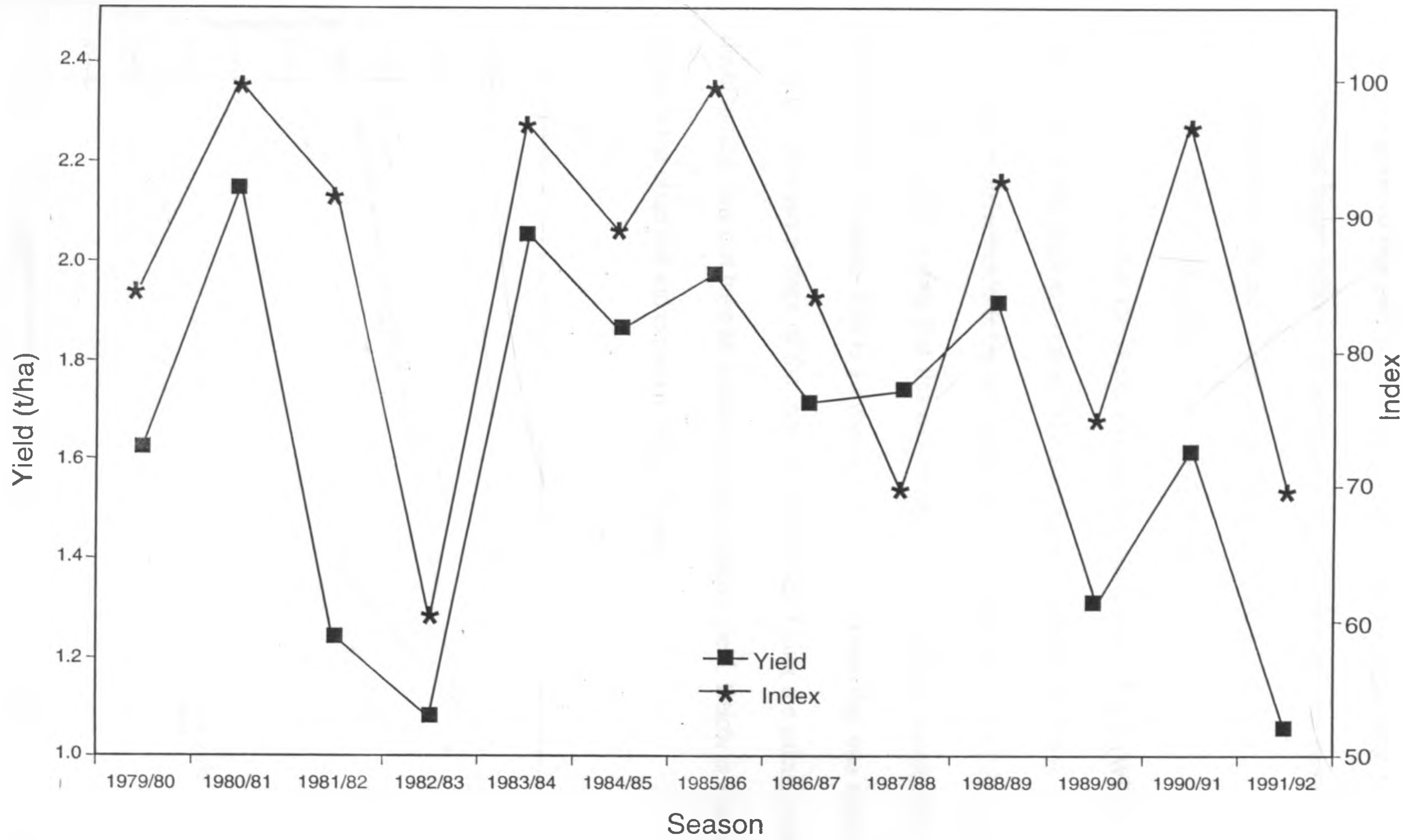

Figure 16 *Relationships of predicted maize yield and WRSI for Mbabane, Swaziland.*

4.7 Regression Analysis of Yield

Figure 16 is a plot of the indices against the corresponding yield over time. This graph indicates that higher indices corresponded to higher yields and vice versa. When regression analysis was done between the indices and yields, the model equation was:-

$$y = 0.02 + 0.02\ WRSI \qquad (r^2 = 0.54)$$

This shows that the Water Requirement Satisfaction Index (WRSI) explains 54% of yield variations in the Highveld region. The correlation coefficient between WRSI and yields is about 0.73. This is understandable because water stress in plants has a direct effect on the yield.

It is worth noting that this model can be used for crop monitoring in the early stages of development of maize. This is a dynamic model in the sense that one starts calculating the index from the emergence stage of the crop up to maturity. Using the calculated index at any stage of development, one can have an estimate of the expected yield. Below is a comparison of regression between the observed and expected yields of maize:-

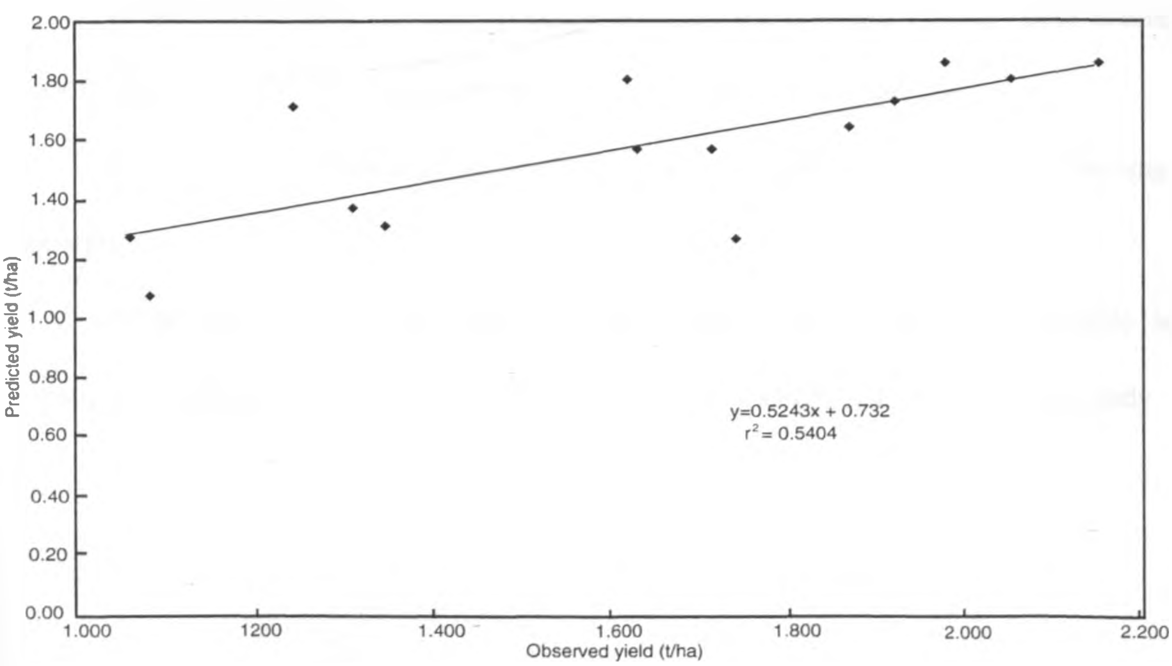

Figure 17 *Comparison of observed and predicted maize (WRSI) yield for Mbabane, Swaziland.*

4.8 Soil Types and Land Management Options

4.8.1 Soil Types and Associated Problems

The most representative soil types that are important to land management in Swaziland include:- Regosols and Gleysols (Highveld zone); Ferralsols, Phaezoms, Planosols and Solonetz (Middleveld zone); Vertisols and Lixisols (Lowveld zone); and Nitisols (Lubombo Plateau). These soils are important in terms of their wide distribution and significance to agricultural production. The soil problems affecting agricultural production in Swaziland include:- sodicity, poor drainage, moisture deficit, soil compaction, erosion and low fertility. The occurrence of these problems in Swaziland is influenced by slope and agroclimatic zones. In the Highveld zone (upland area), the most dominant soil problems are:- soil erosion (rill and interill erosion), poor drainage, low soil fertility and low soil moisture retention. In the Middleveld zone (upper midland area) the most dominant soil problems are:- poor drainage, soil compaction, low soil fertility, sodicity, stony subsoil layer and low soil moisture.

In the lowveld zone (lowland area), the dominant soil problems include:- poor drainage, poor workability, soil compaction, gully erosion, low soil moisture and sodicity.

In the Lubombo Plateau (lower midland area), the dominant soil problem is:- leaching of nutrients.

More information on soil type specific problems, their locations and suitable land management options is provided in the tables below (Tables 2 and 3); put together by this study.

Table 2 *Problems associated with Swaziland soils.*

Type of Soil	Location	Associated Problems
Vertisols	Big Bend (Lowveld zone)	Poor drainage, poor permeability, high clay content, poor workability, soil compaction, sodicity, and gully erosion.
Planosols	Kabhudla (Middleveld zone)	Poor drainage, soil compaction (subsurface hard pans), low soil fertility.
Gleysols	Motshane & other wetlands (Highveld zone)	Poor drainage, oxidation of peats.
Phaeozems	Kabhudla (Middleveld zone)	Stony subsoil layer low soil moisture, soil compaction.
Regosols	Motshane (Highveld zone)	High infiltration rates (low soil moisture), low soil fertility and soil surface sealing and crusting.
Solonetz	Kabhudla (Middleveld zone)	Sodicity (high exchangeable sodium percentage), poor soil structure.
Nitisols	Tikhuba (Lubombo plateau)	Leaching of nutrients (low soil fertility).
Ferralsols	Malkerns, Nhlangano and Ntfonjeni (Middleveld zone)	Low soil fertility (due to a very low CEC and BSP).
Lixisols	Maloma (Lowveld zone)	Soil erosion, low soil moisture, soil compaction.

Table 3 *Land Management Options for Problem Soils in Swaziland..*

Type of Soil	Suitable Land Management Options
Vertisols	Minimize waterlogging through seasonal drainage. Avoid deep tillage due to subsoil sodicity in some areas. Discourage structural conservation measures due to unstable soil structure.
Planosols	Minimize waterlogging through deep tillage and artificial drainage. Improve fertility through application of FYM and inorganic fertilizers. Ideal for shallow rooted crops and pastures for grazing.
Gleysols	Minimize waterlogging through controlled drainage. Avoid oxidation of peats. Use aquatic plants to reduce waterlogging.
Phaeozems	Minimum disturbance of topsoil layer. Ripping of subsoil hardpans for agroforestry.
Regosols	Improve the soil moisture retention capacity and soil fertility through application of FYM and inorganic fertilizers. Encourage shallow tillage operations.
Solonetz	Manage the sodicity problem through agroforestry.
Nitisols	Improve the organic matter content of the soil.
Ferralsols	Improve soil fertility through application of FYM and inorganic fertilizers.
Lixisols	Control soil erosion. Improve soil moisture retention capacity and permeability.

4.8.2 Land Management Options

The best management practices (Table 4) for Swaziland are chosen on the basis of the dominant soil types and associated problems. This calls for an objective assessment of soil properties influencing runoff and erosion. The effectiveness of land management practices in Swaziland could be objectively assessed in terms of:- enhanced infiltration of water; increased soil water storage capacity; adequacy of excess water drainage; improvement of effective use of stored water; minimization of evaporation from the soil; and minimization of soil loss, soil compaction and sodicity.

There are moisture saving techniques that have been developed through research and are now recommended for Swaziland. The land management options include:- early deep tillage operations to maximize on soil moisture conservation, shallow tillage operations to minimize soil water losses during the rainy period, application of farmyard manure (FYM) to enhance soil water storage, use of crop residue mulching to improve the availability of soil water to plants; use of drought resistant/high yielding crops to improve crop water use efficiency . In the Lowveld zone, irrigation is necessary during crop establishment and the critical flowering and fruit development stages of crops.

4.8.3 Tillage Operations and Seasonal Land Management Calendar

In Swaziland, soil-water and nutrients are optimized through timely tillage operations. Thus, immediately after crops are harvested in April, the tillage operations done include deep ploughing, immediately after harvest, followed by a fallow period of two to three (2-3) months, then shallow cultivation again after the first rains, which normally occur between August and September. This shallow cultivation is often done through disking and harrowing in readiness for the start of the rains, which then denotes the planting time. The above mentioned land management strategy makes it imperative to forecast the onset, cessation and distribution of the rains in any crop growing season as it was seen necessary in this study to create a land managent calendar for farmers as shown in Table 4.

Table 4. *Seasonal land management calendar for maize production in Swaziland*

Agroclimatic zone and representative areas	Effective rainfall period	Dominant soil types	TILLAGE OPERATIONS						Time of Planting		Effect on Crop Yield		Fallow Period	
			PLOUGHING		*HARROWING*		*CULTIVATION*		EARLY PLANTING	LATE PLANTING	HIGH YIELD	LOW YIELD	SHORT FALLOW	LONG FALLOW
			DEEP	SHALLOW	FIRST	SECOND	FIRST	SECOND						
Highveld *Motshane* *Mbabane*	October to April	Regosols	✓	—	✓	—	✓	✓	✓	✓	✓	—	✓	—
		Gleysols	—	✓	✓	—	✓	✓	✓	✓	✓	—	✓	—
Middleveld *Kabhudla* *Malkerns* *Nhlangano* *Ntfonjeni*	November to April	Planosols	✓	—	✓	—	✓	✓	✓	—	✓	—	—	✓
		Phaeosems	—	✓	✓	✓	✓	✓	✓	—	✓	—	—	✓
		Solonetz	—	✓	✓		✓	✓	✓	—	✓	—	—	✓
		Ferralsols	✓	—	✓	✓	✓	✓	✓	—	✓	—	—	✓
Lubombo - Plateau *Tikhuba*	November to March	Nitisols	✓	✓	✓	—	✓	✓	✓	—	✓	—	—	✓
Lowveld *Big Bend* *Maloma*	No effective rainfall period (irrigation done)	Regosols	✓	✓	✓	—	✓	✓	✓	✓	✓	—	N/A	N/A
		Gleysols	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	N/A	N/A

EXPLANATORY NOTES: Shallow tillage recommended where topsoils are shallow and subsoils are sodic
Harrowing necessary when weed growth is a problem.
Fallow periods not applicable in the lowveld zone

LEGEND

✓ To be applied

— Not applicable

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Reliability of Available Rainfall Data

The rainfall data used in this analysis were found to be homogenous as shown by the linear mass curves. The mass curve method was used to test homogeneity of collected rainfall data.

5.1.2 Onset and Cessation of Rains

This study has shown that there are significant variations with the onset and cessation of rains in the four agro-climatic zones of Swaziland.

In the highveld zone, the onset and cessation of rains occurs during the months of September and May respectively. For the middleveld and Lubombo Plateau, the onset and cessation of rains occurs during the months of October and April respectively. Within the lowveld zone, there is no clear period of onset and cessation of rains. However the zone receives small amounts of rainfall (< 1mm of rainfall every pentad) during the period September to March.

In the lowveld zone, evapotranspiration rates are in excess of rainfall amounts throughout the year. Thus in this zone, crop production is possible only under irrigation.

This analysis of onset and cessation of rains has shown that there are shortcomings with the methods used in estimating the dates of occurrence of the two rainfall events. Of the two methods used in this study, the effective rainfall method as opposed to the cumulative rainfall method is a better estimator of the onset and cessation of rains in Swaziland.

5.1.3 Seasonal and Cyclical Rainfall Variations

Spectral analysis was used to predict seasonal and cyclical rainfall fluctuations in Swaziland. The results obtained showed that there are rainfall events that recur in years and within a crop growing season. The latter include events that recur after 10-15 days, 30-50 days and 90 days within the season. These spectral cycles are indicative of short periods of dry and wet spells within the crop growing season. These cycles are reflective of the 20-60 days and 60-120 days mode of the Julian-Madden cycle.

The seasonal rainfall variations in Swaziland, show that there is a high probability of receiving adequate (surplus) rainfall in Mbabane and likewise there is a high probability of receiving inadequate (deficit) rainfall in Big Bend (Figure 13).

The cyclical (> 1 year) rainfall variations include cyclic periods of 2 years, 3-7 years and ≥10 years. These variations may be associated with the QBO, ENSO and solar variability cycles (Figure 14).

Again the cyclical rainfall variations in Swaziland show some trend. For instance, in Mbabane, above average rainfall is expected every 2 to 4 years. Where as in Malkerns, above average rainfall is expected every 7 to 10 years. This confirms the expected trend of unreliable and erratic rainfall patterns in the Middleveld as opposed to consistent and reliable rainfall in the Highveld zone.

5.1.4 Reliability and Variability of Rainfall

The distribution of rainfall in Swaziland varies with agro-climatic zones. Rainfall reliability ranges from 80% in the Highveld to 70% in the Lowveld. The highest reliability (lowest variability) corresponds with the highest mean annual rainfall and vice versa for the lowest reliability (highest variability).

5.1.5 Water Requirement Satisfaction Index (WRSI)

WRSI was used in this study to determine the effects of water stress on crop yields. Thus where the water stress index was very high (e.g. 1991/92 season) maize yields were very low. Likewise, where the index was low (e.g. 1983/84 season) due to high precipitation, maize yields were very high (Figure 16).

This study has come up with a model that could be used in forecasting crop yields early in the season. The WRSI model can be used to forecast crop yields holding other factors constant early in the season. The model does not account for the effects of pests and diseases on crop yields.

The forecast crop yields compared quite well with observed crop yields in Swaziland. It is anticipated that this model will be improved and adopted for use in planning crop production in Swaziland.

5.1.6 Best Land and Crop Management Practices

In Swaziland, land and crop management should be systematically adjusted in response to specific rainfall indicators in the early part of a crop growing season. An analysis of seasonal rainfall variations has showed that there is a recurrence of above and below normal rainfall events within a crop growing season. The chances of crop failure could be reduced significantly with moderate to high levels of land and crop management.

The timing of tillage, planting and cultivation operations should be done on the basis of the dominant soil types and associated problems. Alongside these, the date of onset of the rains which has a bearing on the season's crop performance. An early onset justifies high seed rates and high inorganic fertilizer application at planting. A late onset of rains calls for the planting of drought tolerant crops.

Rainfall is expected over a period of about 150 days after the date of onset of rains in any crop growing season in Swaziland. Thus farmers should be advised on the varieties of crops and best land management practices. The earlier the rains begin, the greater the moisture retention in the soil before planting. In Swaziland, there is a transition period of 30 days before the onset of the rains. During this period, tillage operations should be done in anticipation of an early planting immediately after the onset of the rains. Late planting (e.g. during the 1st pentad of October) should prompt the farmers to switch to early maturing maize crop varieties rather than late maturing (indigenous) maize varieties like SR52. These late maturing varieties take more than 150 days to mature. Thus they may not have enough soil moisture to last them through to maturity, especially when planted late.

5.2 Recommendations

Tillage operations must be done during the transitional period before the onset of the rains. However, where soil compaction is a problem, tillage could be delayed to the 1st-2nd pentad after the onset of the rains.

Timely planting of all seasonal crops is important so that the farmer can improve yields. Early planting will give better crop yield than late planting, but where late planting is inevitable, drought tolerant crop varieties should be recommended to farmers.

Shallow tillage is recommended where topsoils are shallow and subsoils are sodic. Deep tillage is necessary to break subsurface hardpans and only when such subsoils are structurally stable. Harrowing may be done only when weed growth is a menace.

The WRSI model should be used to forecast crop yields in Swaziland. This is an important tool for planning crop production in the country. However, the model still requires some improvement so as to account for more enviromental factors that influence crop performance.

The effectiveness of land management practices in Swaziland should be objectively assessed in terms of improved use of precipitation, crop water use under irrigation and fertilizer use efficiencies.

Irrigation is necessary during crop establishment and the critical flowering and fruit development stages of all crops in the lowveld zone of Swaziland.

New crop varieties should be bred to mature within the effective growing season as denoted by this study to avoid losses.

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APPENDICES

Appendix 1. *Climatic data for the effective rainfall method, Mbabane, Swaziland.*

Mbabane Altitude 1182 m Longit. 31.15E Latitude. 26.33S																			
pentad	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
drytbulb	19.44	19.04	19.19	19.49	19.13	18.86	19.17	18.89	18.62	18.58	18.71	18.39	18.47	18.50	17.62	17.64	18.04	17.23	17.02
wetbulb	18.27	17.24	17.32	17.64	17.40	17.36	17.54	17.35	17.03	17.15	17.11	16.97	16.86	16.70	16.27	16.28	16.53	15.80	15.29
depressio	1.16	1.81	1.87	1.86	1.73	1.50	1.63	1.54	1.59	1.43	1.60	1.41	1.61	1.80	1.35	1.36	1.51	1.43	1.72
Rainfall	33.39	37.65	38.55	38.55	44.02	46.81	42.04	41.47	41.43	37.82	33.52	27.76	34.98	35.29	28.42	25.46	24.72	18.59	19.36
Rainfall/d	6.68	7.53	7.71	7.71	8.80	9.36	8.41	8.29	8.29	7.56	6.70	5.55	7.00	7.06	5.68	5.09	4.94	3.72	3.87
cumrain	33.39	71.04	109.6	148.1	192.1	239.0	281.0	322.5	363.9	401.7	435.2	463.0	498.0	533.3	561.7	587.1	611.9	630.4	649.8
ea	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	12.3	14.00	14.00	14.00	14.00	14.00	13.1	13.1
ed	17.10	17.10	17.10	17.10	17.10	18.9	17.1	18.9	17.1	18.9	18.9	18.9	17.1	17.1	18.9	18.9	17.1	18.9	17.1
f(ed)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
ea-ed	-3.10	-3.10	-3.10	-3.10	-3.10	-4.90	-3.10	-4.90	-3.10	-4.90	-4.90	-6.60	-3.10	-3.10	-4.90	-4.90	-3.10	-5.80	-4.00
T	11.92	12.13	12.13	12.55	11.98	12.03	11.92	12.23	11.94	11.75	11.83	10.36	12.00	11.77	11.84	11.69	11.80	11.25	10.97
(1-W)	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.42	0.39	0.39	0.39	0.39	0.39	0.39	0.42
W	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.58	0.61	0.61	0.61	0.61	0.61	0.61	0.58
U	74.04	59.48	67.22	50.30	58.37	47.86	50.97	49.42	57.59	54.07	57.42	35.70	48.08	48.44	38.79	41.04	41.04	39.33	40.45
u	118.46	95.17	107.56	80.48	93.39	76.58	81.56	79.07	92.14	86.52	91.87	57.12	76.92	77.50	62.07	65.66	65.66	62.92	64.72
f(u)	0.59	0.54	0.57	0.49	0.51	0.49	0.49	0.49	0.51	0.49	0.51	0.43	0.49	0.49	0.43	0.46	0.46	0.43	0.43
n	5.58	5.07	5.08	5.15	4.16	5.45	8.56	5.48	5.96	5.42	5.03	5.33	5.07	6.18	5.99	5.72	5.98	5.82	5.45
N	13.50	13.50	13.50	13.50	13.50	13.50	13.20	13.20	13.20	13.20	13.20	13.20	12.30	12.30	12.30	12.30	12.30	12.30	11.60
n/N	0.41	0.38	0.38	0.38	0.31	0.40	0.65	0.41	0.45	0.41	0.38	0.40	0.41	0.50	0.49	0.46	0.49	0.47	0.47
f(n/N)	0.46	0.42	0.42	0.42	0.37	0.46	0.69	0.46	0.51	0.46	0.46	0.46	0.46	0.55	0.55	0.51	0.55	0.55	0.55
Ra (mm/d)	17.60	17.60	17.60	17.60	17.60	17.60	16.40	16.40	16.40	16.40	16.40	16.40	14.40	14.40	14.40	14.40	14.40	14.40	12.00
Rs	8.04	7.71	7.71	7.76	7.11	7.95	9.42	7.50	7.80	7.47	7.23	7.41	6.57	7.22	7.11	6.95	7.10	7.01	5.82
Rns	6.03	5.78	5.78	5.82	5.33	5.96	7.06	5.63	5.85	5.60	5.42	5.56	4.93	5.41	5.33	5.21	5.32	5.26	4.37
f(T)	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	12.70	13.10	13.10	13.10	13.10	13.10	13.10	12.70
Rnl	0.90	0.83	0.83	0.83	0.73	0.90	1.36	0.90	1.00	0.90	0.90	0.88	0.90	1.08	1.08	1.00	1.08	1.08	1.05
Rn	5.12	4.96	4.96	4.99	4.61	5.06	5.71	4.72	4.85	4.69	4.52	4.68	4.02	4.33	4.25	4.21	4.24	4.17	3.32
ETo	2.41	2.37	2.34	2.45	2.19	2.15	2.89	1.94	2.34	1.93	1.78	1.52	1.86	2.05	1.77	1.69	2.03	1.57	1.20

Mbabane																				
pentad	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
drytbulb	17.25	16.37	16.47	15.68	14.49	15.33	14.93	14.05	13.84	13.40	12.31	11.54	10.23	11.11	10.15	10.31	10.46	9.56	9.82	10.04
wetbulb	15.46	14.32	14.24	13.40	12.24	12.35	12.20	11.80	11.00	10.90	9.80	8.68	7.74	7.89	7.13	7.52	7.26	6.79	6.88	7.01
depressio	1.79	2.04	2.23	2.27	2.25	2.98	2.73	2.25	2.85	2.50	2.52	2.87	2.49	3.22	3.03	2.79	3.20	2.77	2.94	3.02
Rainfall	15.33	16.53	10.73	10.23	6.83	8.11	5.94	7.40	6.30	2.84	3.74	5.38	2.14	4.48	4.22	2.02	1.91	4.63	4.47	2.95
Rainfall/d	3.07	3.31	2.15	2.05	1.37	1.62	1.19	1.48	1.26	0.57	0.75	1.08	0.43	0.90	0.84	0.40	0.38	0.93	0.89	0.59
cumrain	665.1	681.7	692.4	702.6	709.5	717.6	723.5	730.9	737.2	740.1	743.8	749.2	751.3	755.8	760.0	762.0	763.9	768.6	773.0	776.0
ea	13.1	13.1	13.1	12.3	12.3	13.1	13.1	12.3	12.3	12.3	12.3	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
ed	17.1	14.9	14.9	14.9	12.9	14.9	12.9	12.9	11.5	9.8	11.2	11.2	9.6	9.8	8.3	8.3	8.3	8.3	8.3	8.3
f(ed)	0.15	0.18	0.18	0.18	0.19	0.18	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20	0.22	0.22	0.22	0.22	0.22	0.22
ea-ed	-4.00	-1.80	-1.80	-2.60	-0.60	-1.80	0.20	-0.60	0.80	2.50	1.10	0.30	1.90	1.70	3.20	3.20	3.20	3.20	3.20	3.20
T	11.45	11.12	10.60	10.17	10.42	11.10	10.70	10.31	10.53	10.06	9.92	9.28	9.03	9.20	9.06	8.93	8.70	8.99	9.30	9.46
(1-W)	0.39	0.39	0.42	0.42	0.42	0.39	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.45	0.45	0.45	0.42	0.42
W	0.61	0.61	0.58	0.58	0.58	0.61	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.55	0.55	0.55	0.58	0.58
U	46.13	44.40	50.00	43.49	41.92	39.44	52.44	55.08	64.13	62.29	55.89	51.38	52.77	53.22	58.32	60.98	62.17	49.98	62.40	58.27
u	73.81	71.04	80.01	69.59	67.07	63.11	83.91	88.13	102.60	99.66	89.43	82.21	84.44	85.16	93.31	97.57	99.47	79.97	99.84	93.23
f(u)	0.46	0.46	0.49	0.46	0.46	0.43	0.49	0.51	0.54	0.54	0.51	0.49	0.49	0.51	0.51	0.54	0.54	0.49	0.54	0.51
n	6.26	5.83	6.06	7.02	6.87	7.57	7.14	6.87	7.38	6.72	6.98	6.73	7.08	6.95	6.94	6.89	6.61	6.56	7.19	6.87
N	11.60	11.60	11.60	11.60	11.60	10.90	10.90	10.90	10.90	10.90	10.90	10.60	10.60	10.60	10.60	10.60	10.60	10.70	10.70	10.70
n/N	0.54	0.50	0.52	0.60	0.59	0.69	0.66	0.63	0.68	0.62	0.64	0.63	0.67	0.66	0.65	0.65	0.62	0.61	0.67	0.64
f(n/N)	0.60	0.55	0.60	0.64	0.64	0.73	0.69	0.69	0.73	0.69	0.69	0.69	0.73	0.69	0.69	0.69	0.69	0.69	0.73	0.69
Ra (mm/d)	12.00	12.00	12.00	12.00	12.00	9.70	9.70	9.70	9.70	9.70	9.70	8.70	8.70	8.70	8.70	8.70	8.70	9.10	9.10	9.10
Rs	6.24	6.02	6.13	6.63	6.56	5.79	5.60	5.48	5.71	5.41	5.53	4.94	5.08	5.03	5.02	5.00	4.89	5.06	5.33	5.19
Rns	4.68	4.51	4.60	4.97	4.92	4.35	4.20	4.11	4.28	4.06	4.15	3.70	3.81	3.77	3.77	3.75	3.66	3.80	4.00	3.90
f(T)	13.10	13.10	12.70	12.70	12.70	13.10	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.30	12.30	12.30	12.70	12.70
Rnl	1.18	1.30	1.37	1.46	1.54	1.72	1.66	1.66	1.85	1.75	1.75	1.75	1.85	1.75	1.93	1.87	1.87	1.87	2.04	1.93
Rn	3.50	3.22	3.23	3.51	3.37	2.62	2.54	2.45	2.43	2.31	2.40	1.95	1.96	2.02	1.84	1.88	1.80	1.93	1.96	1.97
ETo	1.42	1.64	1.50	1.53	1.84	1.30	1.51	1.29	1.59	1.91	1.63	1.19	1.53	1.53	1.75	1.81	1.77	1.77	1.86	1.83

Mbabane																				
pentad	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
drytbulb	10.29	10.71	10.83	12.03	12.09	12.33	12.54	12.54	13.66	14.09	14.27	15.54	15.72	16.43	16.45	16.09	16.36	16.34	16.43	16.31
wetbulb	7.19	7.62	7.92	8.59	8.74	8.99	9.43	9.43	10.26	11.71	10.68	11.79	12.31	13.13	13.25	13.09	13.40	13.61	14.08	13.59
depressio	3.10	3.09	2.91	3.43	3.36	3.34	3.11	3.11	3.40	2.39	3.59	3.75	3.41	3.30	3.20	3.00	2.96	2.73	2.35	2.73
Rainfall	2.63	3.26	3.03	2.93	3.78	3.93	2.58	6.21	6.43	6.69	6.31	9.49	11.16	9.12	12.40	13.53	14.89	16.81	22.72	25.50
Rainfall/d	0.53	0.65	0.61	0.59	0.76	0.79	0.52	1.24	1.29	1.34	1.26	1.90	2.23	1.82	2.48	2.71	2.98	3.36	4.54	5.10
cumrain	778.6	781.9	784.9	787.8	791.6	795.5	798.1	804.3	810.8	817.5	823.8	833.3	844.4	853.5	865.9	879.5	894.4	911.2	933.9	959.4
ea	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	13.1	13.1	13.1	13.1	11.5	13.1	13.1	13.1	13.1
ed	8.3	8.3	8.3	9.8	9.8	9.8	9.8	10.7	11.5	12.9	10.0	11.7	13.3	13.3	11.7	11.7	13.3	14.9	14.9	14.9
f(ed)	0.22	0.22	0.22	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.17	0.17	0.17
ea-ed	4.00	4.00	4.00	2.50	2.50	2.50	2.50	1.60	0.80	-0.60	2.30	1.40	-0.20	-0.20	1.40	-0.20	-0.20	-1.80	-1.80	-1.80
T	9.79	9.50	9.81	10.13	10.08	10.08	10.01	10.03	10.30	10.13	10.03	11.21	11.37	11.76	11.21	8.91	11.02	10.94	11.17	10.70
(1-W)	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.39	0.39	0.39	0.39	0.45	0.39	0.42	0.39	0.42
W	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.61	0.61	0.61	0.61	0.55	0.61	0.58	0.61	0.58
U	56.63	71.12	55.87	64.26	76.34	67.62	53.67	63.26	70.27	67.92	51.44	65.99	65.77	73.88	61.47	50.32	66.11	69.71	57.88	60.10
u	90.60	113.79	89.39	102.82	122.15	108.20	85.88	101.21	112.43	108.68	82.31	105.59	105.24	118.21	98.35	80.51	105.78	111.54	92.61	96.15
f(u)	0.51	0.57	0.51	0.54	0.59	0.57	0.51	0.54	0.57	0.57	0.49	0.54	0.54	0.59	0.54	0.49	0.57	0.57	0.51	0.54
n	6.88	6.91	7.25	7.32	7.05	7.04	6.94	6.74	7.00	6.42	6.20	6.98	6.08	6.24	5.94	4.77	5.53	4.90	5.28	5.28
N	10.70	10.70	10.70	11.30	11.30	11.30	11.30	11.30	11.30	12.00	12.00	12.00	12.00	12.00	12.00	12.70	12.70	12.70	12.70	12.70
n/N	0.64	0.65	0.68	0.65	0.62	0.62	0.61	0.60	0.62	0.54	0.52	0.58	0.51	0.52	0.50	0.38	0.44	0.39	0.42	0.42
f(n/N)	0.73	0.73	0.73	0.69	0.69	0.69	0.69	0.64	0.69	0.55	0.55	0.60	0.55	0.55	0.55	0.46	0.46	0.46	0.46	0.46
Ra (mm/d)	9.10	9.10	9.10	10.90	10.90	10.90	10.90	10.90	10.90	13.20	13.20	13.20	13.20	13.20	13.20	15.50	15.50	15.50	15.50	15.50
Rs	5.20	5.21	5.36	6.25	6.12	6.12	6.07	5.97	6.10	6.83	6.71	7.14	6.64	6.73	6.57	6.78	7.25	6.87	7.10	7.10
Rns	3.90	3.91	4.02	4.69	4.59	4.59	4.55	4.48	4.58	5.12	5.03	5.36	4.98	5.05	4.93	5.09	5.43	5.15	5.32	5.32
f(T)	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70	13.10	13.10	13.10	13.10	12.70	13.10	12.70	13.10	12.70
Rnl	2.04	2.04	2.04	1.75	1.75	1.75	1.75	1.63	1.66	1.33	1.40	1.49	1.37	1.37	1.37	1.11	1.14	0.99	1.02	0.99
Rn	1.86	1.87	1.98	2.94	2.84	2.84	2.80	2.86	2.91	3.80	3.63	3.86	3.61	3.68	3.56	3.98	4.29	4.16	4.30	4.33
ETo	1.94	2.04	2.00	2.27	2.27	2.24	2.16	2.02	1.88	2.06	2.58	2.65	2.16	2.20	2.46	2.14	2.57	1.98	2.26	2.10

Mbabane														
pentad	60	61	62	63	64	65	66	67	68	69	70	71	72	73
drytbulb	16.39	17.10	17.91	16.54	17.06	17.39	17.57	18.19	18.83	18.70	17.74	19.11	19.01	19.46
wetbulb	13.93	14.52	15.31	14.98	14.77	15.33	16.03	15.78	16.80	16.79	15.72	16.94	17.12	17.22
depressio	2.46	2.57	2.60	1.57	2.29	2.06	1.54	2.41	2.03	1.91	2.02	2.17	1.89	2.24
Rainfall	19.88	27.43	30.04	26.62	28.34	26.64	30.02	33.29	33.30	32.98	33.77	36.11	32.33	36.6
Rainfall/d	3.98	5.49	6.01	5.32	5.67	5.33	6.00	6.66	6.66	6.60	6.75	7.22	6.47	7.31
cumrain	979.3	1006.7	1036.7	1063.3	1091.7	1118.3	1148.3	1181.6	1214.9	1247.9	1281.7	1317.8	1350.1	1386.7
ea	13.1	13.1	14.0	13.1	13.1	13.1	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
ed	14.9	13.0	17.1	14.9	16.0	16.0	17.1	17.1	18.0	18.0	17.1	18.0	18.0	18.0
f(ed)	0.17	0.19	0.15	0.17	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
ea-ed	-1.80	0.10	-3.10	-1.80	-2.90	-2.90	-3.10	-3.10	-4.00	-4.00	-3.10	-4.00	-4.00	-4.00
T	10.88	10.75	11.85	11.39	10.79	11.09	11.88	11.52	12.18	11.56	11.81	11.62	11.96	11.92
(1-W)	0.42	0.42	0.39	0.39	0.42	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
W	0.58	0.58	0.61	0.61	0.58	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
U	64.43	66.99	66.53	67.27	63.85	65.45	64.15	69.46	58.33	60.00	66.00	58.68	63.67	63.61
u	103.09	107.19	106.44	107.63	102.15	104.72	102.64	111.14	93.33	96.00	105.60	93.88	101.87	101.78
f(u)	0.54	0.57	0.57	0.57	0.54	0.54	0.54	0.57	0.51	0.54	0.57	0.51	0.54	0.54
n	5.60	4.52	6.35	4.97	5.54	4.62	5.19	4.08	5.28	4.70	4.93	4.71	4.70	5.19
N	12.70	12.70	13.30	13.30	13.30	13.30	13.30	13.30	13.70	13.70	13.70	13.70	13.70	13.70
n/N	0.44	0.36	0.48	0.37	0.42	0.35	0.39	0.31	0.39	0.34	0.36	0.34	0.34	0.38
f(n/N)	0.46	0.42	0.51	0.42	0.46	0.37	0.46	0.37	0.42	0.37	0.42	0.37	0.37	0.42
Ra (mm/d)	15.50	15.50	17.20	17.20	17.20	17.20	17.20	17.20	17.80	17.80	17.80	17.80	17.80	17.80
Rs	7.29	6.63	8.41	7.52	7.89	7.28	7.66	6.94	7.88	7.50	7.65	7.51	7.51	7.82
Rns	5.47	4.97	6.31	5.64	5.91	5.46	5.74	5.20	5.91	5.63	5.74	5.63	5.63	5.86
f(T)	12.70	12.70	13.10	13.10	12.70	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10
Rnl	0.99	1.01	1.00	0.94	0.93	0.78	0.90	0.73	0.83	0.73	0.83	0.73	0.73	0.83
Rn	4.48	3.96	5.30	4.70	4.98	4.69	4.84	4.48	5.09	4.90	4.91	4.91	4.90	5.04
ETo	2.19	2.32	2.55	2.47	2.23	2.25	2.30	2.04	2.31	2.15	2.31	2.20	2.15	2.23

Appendix 2. *Climatic data for the effective rainfall method, Malkerns, Swaziland.*

Malkerns	Longitude 31.15E		Latitude 26.55S		Altitude 740m														
pentad	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
rainfall	15.91	30.63	25.12	25.31	31.96	29.02	26.04	34.06	23.62	21.36	32.15	19.53	21.51	17.66	14.96	16.67	15.32	8.99	14.08
r/d	3.18	6.13	5.02	5.06	6.39	5.80	5.21	6.81	4.72	4.27	6.43	3.91	4.30	3.53	2.99	3.33	3.06	1.80	2.82
Cum rain	15.91	46.55	71.67	96.98	128.94	157.96	184.01	218.07	241.68	263.05	295.20	314.73	336.24	353.90	368.86	385.53	400.85	409.84	423.92
T	22.66	22.66	22.74	23.25	22.79	22.71	22.96	22.78	22.44	22.57	22.44	19.69	22.27	22.03	21.41	21.55	21.64	20.87	20.40
W	0.72	0.72	0.72	0.74	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.70	0.72	0.72	0.72	0.72	0.72	0.70	0.70
1-W	0.28	0.28	0.28	0.26	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.30	0.28	0.28	0.28	0.28	0.28	0.30	0.30
Td	21.63	21.65	21.72	22.22	21.45	21.48	21.68	21.77	21.57	21.62	21.23	21.28	21.10	21.14	20.28	20.24	20.50	19.83	19.56
Tw	19.10	19.24	19.27	19.81	19.31	19.22	19.19	19.46	19.23	19.26	19.00	18.93	18.95	18.79	18.02	18.03	18.05	17.41	16.79
Td-Tw	2.54	2.41	2.46	2.41	2.14	2.26	2.49	2.30	2.33	2.36	2.24	2.35	2.16	2.35	2.25	2.21	2.46	2.42	2.77
ea	26.40	26.40	26.40	26.40	24.60	24.60	26.40	26.40	26.40	26.40	24.60	24.60	24.60	24.60	23.40	23.40	23.40	23.40	23.40
ed	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	19.30	19.30	19.30	19.30
ea-ed	4.40	4.40	4.40	4.40	2.60	2.60	4.40	4.40	4.40	4.40	2.60	2.60	2.60	2.60	1.40	4.10	4.10	4.10	4.10
U(km/d)	1356.05	1437.33	1171.63	1193.49	1161.81	1610.45	1137.07	1386.88	1145.92	1093.28	1122.08	946.00	1337.60	1208.00	980.80	1128.96	1131.52	976.96	1170.56
f(u)	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
n	6.81	6.35	6.18	6.44	5.48	6.17	7.34	6.24	7.03	6.73	6.21	6.08	5.83	7.02	6.59	6.67	6.05	6.79	6.62
N	13.50	13.50	13.50	13.50	13.50	13.50	13.20	13.20	13.20	13.20	13.20	13.20	12.30	12.30	12.30	12.30	12.30	12.30	11.60
n/N	0.50	0.47	0.46	0.48	0.41	0.46	0.56	0.47	0.53	0.51	0.47	0.46	0.47	0.57	0.54	0.54	0.49	0.55	0.57
Ra	17.60	17.60	17.60	17.60	17.60	17.60	16.40	16.40	16.40	16.40	16.40	16.40	14.40	14.40	14.40	14.40	14.40	14.40	12.00
f(n/N)	0.55	0.51	0.51	0.55	0.46	0.51	0.60	0.51	0.60	0.55	0.51	0.51	0.51	0.60	0.60	0.60	0.55	0.60	0.60
f(ed)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14
f(T)	15.00	15.00	15.00	15.40	15.00	15.00	15.00	15.00	15.00	15.00	15.00	14.60	15.00	15.00	15.00	15.00	15.00	14.60	14.60
Rs	13.20	13.20	13.20	13.20	13.20	13.20	12.30	12.30	12.30	12.30	12.30	12.30	10.80	10.80	10.80	10.80	10.80	10.80	9.00
Rns	9.90	9.90	9.90	9.90	9.90	9.90	9.23	9.23	9.23	9.23	9.23	9.23	8.10	8.10	8.10	8.10	8.10	8.10	6.75
Rnl	1.07	0.99	0.99	1.10	0.90	0.99	1.17	0.99	1.17	1.07	0.99	0.97	0.99	1.17	1.17	1.26	1.16	1.23	1.23
Rns-Rnl	8.83	8.91	8.91	8.80	9.00	8.91	8.06	8.23	8.06	8.15	8.23	8.26	7.11	6.93	6.93	6.84	6.95	6.87	5.52
ETo	9.68	9.74	9.74	9.60	8.45	8.38	9.13	9.25	9.13	9.20	7.89	7.89	7.08	6.96	6.05	8.02	8.10	8.13	7.19

Malkerns

pentad	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
rainfall	10.15	11.75	8.60	6.97	6.04	3.31	2.47	5.39	4.75	2.21	3.55	3.01	1.45	1.86	1.50	0.88	1.92	5.23
r/d	2.03	2.35	1.72	1.39	1.21	0.66	0.49	1.08	0.95	0.44	0.71	0.60	0.29	0.37	0.30	0.18	0.38	1.05
Cum_rain	434.07	445.81	454.41	461.38	467.42	470.73	473.21	478.60	483.35	485.56	489.12	492.12	493.57	495.43	496.92	497.81	499.73	504.96
T	20.33	19.79	19.78	19.01	18.29	18.83	18.42	17.52	17.53	17.34	16.70	16.07	15.35	15.63	14.84	15.25	15.17	15.09
W	0.70	0.70	0.70	0.70	0.67	0.67	0.67	0.67	0.67	0.67	0.65	0.65	0.65	0.65	0.62	0.65	0.65	0.65
1-W	0.30	0.30	0.30	0.30	0.33	0.33	0.33	0.33	0.33	0.33	0.35	0.35	0.35	0.35	0.38	0.35	0.35	0.35
Td	19.76	19.09	18.83	18.03	17.51	17.53	17.22	16.57	16.38	15.89	15.26	14.14	13.61	13.13	12.66	12.71	13.08	12.61
Tw	16.84	16.25	15.78	15.10	14.32	14.19	13.92	13.00	12.82	12.43	11.79	10.62	10.16	10.04	9.38	9.25	9.57	9.48
Td-Tw	2.93	2.84	3.05	2.93	3.19	3.34	3.31	3.57	3.57	3.46	3.47	3.52	3.45	3.09	3.28	3.46	3.51	3.13
ea	23.40	22.00	22.00	22.00	20.60	20.60	19.40	19.40	18.20	18.20	17.00	16.10	16.10	15.00	15.00	15.00	15.00	15.00
ed	19.30	19.30	16.80	16.80	16.80	13.30	13.30	11.40	11.40	11.40	11.40	9.60	9.60	9.60	8.10	8.10	9.60	9.60
ea-ed	4.10	2.70	5.20	5.20	3.80	7.30	6.10	8.00	6.80	6.80	5.60	6.50	6.50	5.40	6.90	6.90	5.40	5.40
U(km/d)	1409.44	1032.00	1244.16	1372.80	1177.92	1203.20	1143.20	1255.68	1229.20	1332.00	1915.20	1795.04	1607.68	1411.84	2149.92	1690.72	1822.40	1268.48
f(u)	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
n	7.11	6.75	6.79	7.35	7.54	7.72	7.90	7.53	8.32	7.67	8.44	7.75	8.08	8.09	7.90	8.27	8.11	7.88
N	11.60	11.60	11.60	11.60	11.60	10.90	10.90	10.90	10.90	10.90	10.90	10.60	10.60	10.60	10.60	10.60	10.60	10.70
n/N	0.61	0.58	0.59	0.63	0.65	0.71	0.72	0.69	0.76	0.70	0.77	0.73	0.76	0.76	0.75	0.78	0.77	0.74
Ra	12.00	12.00	12.00	12.00	12.00	9.70	9.70	9.70	9.70	9.70	9.70	8.70	8.70	8.70	8.70	8.70	8.70	9.10
f(n/N)	0.64	0.64	0.64	0.69	0.69	0.73	0.73	0.73	0.78	0.73	0.78	0.78	0.78	0.78	0.78	0.82	0.78	0.78
f(ed)	0.14	0.14	0.16			0.18	0.18	0.19	0.19	0.19	0.19	0.20	0.20	0.20	0.22	0.22	0.20	0.20
f(T)	14.60	14.60	14.60	14.60	14.20	14.20	14.20	14.20	14.20	14.20	13.80	13.80	13.80	13.80	13.50	13.80	13.80	13.80
Rs	9.00	9.00	9.00	9.00	9.00	7.28	7.28	7.28	7.28	7.28	7.28	6.53	6.53	6.53	6.53	6.53	6.53	6.83
Rns	6.75	6.75	6.75	6.75	6.75	5.46	5.46	5.46	5.46	5.46	5.46	4.89	4.89	4.89	4.89	4.89	4.89	5.12
Rnl	1.31	1.31	1.50	0.00	0.00	1.87	1.87	1.97	2.10	1.97	2.05	2.15	2.15	2.15	2.32	2.49	2.15	2.15
Rns-Rnl	5.44	5.44	5.25	6.75	6.75	3.59	3.59	3.49	3.35	3.49	3.41	2.74	2.74	2.74	2.58	2.40	2.74	2.97
ETo	7.13	6.00	7.89	8.94	7.91	8.91	7.84	9.46	8.30	8.39	7.51	7.92	7.92	6.88	8.68	8.08	6.88	7.03

Malkerns																		
Error!	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
rainfall	2.73	1.01	1.23	1.60	0.82	1.82	2.22	1.19	1.58	3.22	5.97	4.84	3.55	5.60	5.88	5.42	10.27	10.90
r/d	0.55	0.20	0.25	0.32	0.16	0.36	0.44	0.24	0.32	0.64	1.19	0.97	0.71	1.12	1.18	1.08	2.05	2.18
Cum rain	507.69	508.70	509.93	511.53	512.34	514.17	516.38	517.58	519.15	522.37	528.34	533.18	536.72	542.32	548.20	553.63	563.89	574.79
T	15.21	15.31	15.12	15.81	15.83	16.49	16.72	16.50	16.98	16.98	18.01	17.59	18.06	19.14	19.29	19.92	19.82	16.16
W	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.67	0.67	0.67	0.70	0.70	0.70	0.70	0.65
1-W	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.33	0.33	0.33	0.30	0.30	0.30	0.30	0.35
Td	12.97	13.24	13.06	13.37	13.29	13.87	14.37	14.44	14.80	14.68	15.85	15.89	16.05	16.96	17.59	17.99	17.75	18.30
Tw	9.26	9.88	9.76	10.01	10.51	11.05	11.24	11.50	11.84	11.80	12.72	13.44	13.44	14.06	14.54	14.93	14.96	15.00
Td-Tw	3.71	3.36	3.30	3.36	2.78	2.81	3.13	2.94	2.96	2.88	3.13	2.45	2.61	2.90	3.05	3.06	2.79	3.30
ea	15.00	15.00	15.00	15.00	15.00	16.10	16.10	16.10	17.00	17.00	18.20	18.20	18.20	19.40	20.60	20.60	20.60	20.60
ed	9.60	9.60	9.60	9.60	9.60	12.70	9.60	9.60	9.60	9.60	11.40	16.80	16.80	16.80	13.30	13.30	16.80	13.30
ea-ed	5.40	5.40	5.40	5.40	5.40	3.40	6.50	6.50	7.40	7.40	6.80	1.40	1.40	2.60	7.30	7.30	3.80	7.30
U(km/d)	1889.92	1700.16	1409.12	1522.08	1510.24	1374.72	1898.40	1746.56	2007.68	1804.00	2059.36	1720.16	1736.16	1938.08	2096.48	1980.48	2000.00	1738.24
f(u)	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
n	7.74	8.21	8.15	7.93	8.07	7.92	8.68	7.93	7.83	7.34	6.97	6.58	7.31	7.04	6.83	6.35	6.36	4.73
N	10.70	10.70	10.70	10.70	10.70	11.30	11.30	11.30	11.30	11.30	11.30	12.00	12.00	12.00	12.00	12.00	12.00	12.70
n/N	0.72	0.77	0.76	0.74	0.75	0.70	0.77	0.70	0.69	0.65	0.62	0.55	0.61	0.59	0.57	0.53	0.53	0.37
Ra	9.10	9.10	9.10	9.10	9.10	10.90	10.90	10.90	10.90	10.90	10.90	13.20	13.20	13.20	13.20	13.20	13.20	15.50
f(n/N)	0.73	0.78	0.78	0.78	0.78	0.73	0.78	0.73	0.73	0.69	0.64	0.60	0.64	0.64	0.60	0.60	0.60	0.42
f(ed)	0.20	0.20	0.20	0.20	0.20	0.19	0.20	0.20	0.20	0.20	0.19	0.16	0.16	0.16	0.18	0.18	0.16	0.18
f(T)	13.80	13.80	13.80	13.80	13.80	13.80	13.80	13.80	13.80	13.80	14.20	14.20	14.20	14.60	14.60	14.60	14.60	13.80
Rs	6.83	6.83	6.83	6.83	6.83	8.18	8.18	8.18	8.18	8.18	8.18	9.90	9.90	9.90	9.90	9.90	9.90	11.63
Rns	5.12	5.12	5.12	5.12	5.12	6.13	6.13	6.13	6.13	6.13	6.13	7.43	7.43	7.43	7.43	7.43	7.43	8.72
Rnl	2.01	2.15	2.15	2.15	2.15	1.91	2.15	2.01	2.01	1.90	1.73	1.36	1.45	1.50	1.58	1.58	1.40	1.04
Rns-Rnl	3.10	2.97	2.97	2.97	2.97	4.22	3.98	4.12	4.12	4.23	4.40	6.06	5.97	5.93	5.85	5.85	6.02	7.68
ETo	7.12	7.03	7.03	7.03	7.03	5.95	8.73	8.82	9.67	9.74	9.01	5.31	5.25	6.26	10.01	10.01	7.29	11.89

Malkerns																		
pentad	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73
rainfall	11.04	18.40	17.85	19.18	11.80	22.38	22.88	18.49	22.25	24.59	24.52	24.38	23.07	20.05	24.08	24.77	26.08	20.57
r/d	2.21	3.68	3.57	3.84	2.36	4.48	4.58	3.70	4.45	4.92	4.90	4.88	4.61	4.01	4.82	4.95	5.22	4.11
Cum rain	585.84	604.24	622.09	641.27	653.07	675.45	698.33	716.82	739.07	763.66	788.18	812.56	835.64	855.68	879.77	904.53	930.62	951.18
T	20.26	19.64	20.07	19.43	19.95	19.88	20.81	20.69	20.37	20.42	20.75	20.42	21.26	20.91	20.81	21.30	22.08	22.41
W	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.72	0.70	0.70	0.72	0.72	0.72
1-W	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.28	0.30	0.30	0.28	0.28	0.28
Td	18.32	18.15	18.52	17.76	18.59	19.08	20.18	19.43	19.09	19.45	20.57	19.99	20.33	20.13	20.01	20.87	21.04	21.49
Tw	15.45	15.69	15.56	15.22	15.94	16.79	17.61	17.25	16.83	17.52	18.26	17.80	18.46	18.70	18.54	18.44	18.86	18.93
Td-Tw	2.87	2.45	2.96	2.55	2.66	2.28	2.57	2.19	2.26	1.93	2.31	2.20	1.87	1.43	1.47	2.43	2.18	2.56
ea	20.60	20.60	20.60	20.60	22.00	22.00	23.40	22.00	22.00	22.00	24.90	23.40	23.40	23.40	23.40	24.60	24.60	24.60
ed	16.80	16.80	16.80	16.80	16.80	19.30	19.30	19.30	19.30	19.30	19.30	19.30	19.30	19.30	19.30	19.30	22.00	22.00
ea-ed	3.80	3.80	3.80	3.80	5.20	2.70	4.10	2.70	2.70	2.70	5.60	4.10	4.10	4.10	4.10	5.30	2.60	2.60
U(km/d)	2286.88	1671.84	1620.00	1806.24	1971.36	1823.36	1803.36	1897.92	1726.72	1551.52	2404.80	1323.84	1787.52	1441.28	1681.12	1660.32	1428.96	1672.13
f(u)	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
n	7.14	5.66	6.04	5.94	5.79	5.11	5.71	5.24	6.06	5.63	5.54	5.37	5.97	5.53	6.18	5.76	5.99	6.48
N	12.70	12.70	12.70	12.70	12.70	12.70	13.30	13.30	13.30	13.30	13.30	13.30	13.70	13.70	13.70	13.70	13.70	13.70
n/N	0.56	0.45	0.48	0.47	0.46	0.40	0.43	0.39	0.46	0.42	0.42	0.40	0.44	0.40	0.45	0.42	0.44	0.47
Ra	15.50	15.50	15.50	15.50	15.50	15.50	17.20	17.20	17.20	17.20	17.20	17.20	17.80	17.80	17.80	17.80	17.80	17.80
f(n/N)	0.60	0.51	0.55	0.51	0.51	0.46	0.51	0.46	0.51	0.46	0.46	0.46	0.51	0.60	0.51	0.46	0.51	0.51
f(ed)	0.16	0.16	0.16	0.16	0.16	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.13
f(T)	14.60	14.60	14.60	14.60	14.60	14.60	14.60	14.60	14.60	14.60	14.60	14.60	15.00	14.60	14.60	15.00	15.00	15.00
Rs	11.63	11.63	11.63	11.63	11.63	11.63	12.90	12.90	12.90	12.90	12.90	12.90	13.35	13.35	13.35	13.35	13.35	13.35
Rns	8.72	8.72	8.72	8.72	8.72	8.72	9.68	9.68	9.68	9.68	9.68	9.68	10.01	10.01	10.01	10.01	10.01	10.01
Rnl	1.40	1.19	1.28	1.19	1.19	0.94	1.04	0.94	1.04	0.94	0.94	0.94	1.07	1.23	1.04	0.97	0.99	0.99
Rns-Rnl	7.32	7.53	7.43	7.53	7.53	7.78	8.63	8.73	8.63	8.73	8.73	8.73	8.94	8.79	8.97	9.05	9.02	9.02
ETo	8.20	8.35	8.28	8.35	9.48	7.63	9.36	8.30	8.23	8.30	10.65	9.44	9.54	9.47	9.60	10.52	8.46	8.46

Appendix 3. *Climatic data for the effective rainfall method, Big Bend, Swaziland.*

Bigbend Longitude. 31.87E Latitude 26.85S Altitude. 098m																			
pentad	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Td	25.00	24.79	25.07	25.40	24.81	24.82	24.96	24.59	24.01	24.19	24.35	21.27	23.96	23.77	23.36	23.59	23.88	22.58	21.16
Tw	21.53	21.68	22.09	22.58	20.29	15.96	20.67	22.03	21.57	21.29	19.80	18.86	20.83	20.56	20.30	21.31	18.72	12.12	19.45
depression	3.47	3.11	2.98	2.82	4.51	8.86	4.29	2.56	2.44	2.90	4.54	2.40	3.13	3.21	3.06	2.28	5.16	10.46	1.71
T	25.58	25.75	25.40	25.67	25.45	22.86	23.59	25.04	24.15	23.32	22.84	21.10	23.26	22.63	22.05	22.07	21.29	19.94	20.04
f(T)	15.90	15.90	15.90	15.90	15.90	15.00	15.40	15.90	15.40	15.40	15.00	15.00	15.40	15.00	15.00	15.00	15.00	14.60	14.60
W	0.75	0.75	0.75	0.75	0.75	0.71	0.73	0.75	0.73	0.73	0.71	0.71	0.73	0.71	0.71	0.71	0.71	0.69	0.69
1-W	0.25	0.25	0.25	0.25	0.25	0.29	0.27	0.25	0.27	0.27	0.29	0.29	0.27	0.29	0.29	0.29	0.29	0.31	0.31
ea	33.60	33.60	31.70	33.60	31.70	28.10	29.80	31.70	29.80	28.10	28.10	24.90	28.10	28.10	26.40	26.40	24.90	23.40	23.40
ed	23.80	20.70	28.50	28.50	20.70	12.80	20.70	25.10	25.10	25.10	20.70	22.00	20.70	20.70	20.70	25.10	16.60	7.40	22.00
ea-ed	9.80	12.90	3.20	5.10	11.00	15.30	9.10	6.60	4.70	3.00	7.40	2.90	7.40	7.40	5.70	1.30	8.30	16.00	1.40
f(ed)	0.14	0.14	0.14	0.14	0.14	0.16	0.14	0.14	0.14	0.14	0.14	0.13	0.14	0.14	0.14	0.12	0.16	0.22	0.13
rainfall	11.63	8.89	21.91	12.07	6.79	21.31	17.09	14.72	9.20	8.31	5.90	6.68	9.42	12.06	13.93	12.27	11.58	6.41	8.50
r/d	2.33	1.78	4.38	2.41	1.36	4.26	3.42	2.94	1.84	1.66	1.18	1.34	1.88	2.41	2.79	2.45	2.32	1.28	1.70
cumrain	11.63	20.52	42.43	54.50	61.29	82.60	99.69	114.41	123.61	131.92	137.82	144.50	153.92	165.98	179.91	192.18	203.76	210.17	218.67
U	275.12	244.82	262.62	216.67	237.07	275.49	214.84	230.20	218.82	233.77	234.37	174.32	236.55	228.11	204.26	213.03	191.48	167.30	177.82
f(u)	1.03	0.92	0.97	0.86	0.92	1.03	0.84	0.89	0.86	0.89	0.89	0.73	0.92	0.89	0.84	0.84	0.78	0.73	0.76
n	6.76	6.32	7.00	6.41	6.14	7.57	7.38	7.49	6.35	6.84	7.21	6.48	7.16	6.97	7.35	7.49	7.57	4.11	6.09
N	13.50	13.50	13.50	13.50	13.50	13.50	13.20	13.20	13.20	13.20	13.20	13.20	12.30	12.30	12.30	12.30	12.30	12.30	11.60
n/N	0.50	0.47	0.52	0.47	0.45	0.56	0.56	0.57	0.48	0.52	0.55	0.49	0.58	0.57	0.60	0.61	0.62	0.33	0.52
f(n/N)	0.55	0.51	0.55	0.51	0.51	0.60	0.60	0.60	0.55	0.55	0.60	0.55	0.64	0.60	0.64	0.64	0.64	0.42	0.55
Ra	17.60	17.60	17.60	17.60	17.60	17.60	16.40	16.40	16.40	16.40	16.40	16.40	14.40	14.40	14.40	14.40	14.40	14.40	12.00
Rs	8.81	8.52	8.96	8.58	8.40	9.33	8.69	8.75	8.04	8.35	8.58	8.12	7.79	7.68	7.90	7.99	8.03	6.01	6.15
Rns	6.60	6.39	6.72	6.43	6.30	7.00	6.51	6.56	6.03	6.26	6.43	6.09	5.84	5.76	5.93	5.99	6.02	4.51	4.61
Rnl	1.22	1.14	1.22	1.14	1.14	1.44	1.29	1.34	1.19	1.19	1.26	1.07	1.38	1.26	1.34	1.15	1.54	1.35	1.04
Rn	5.38	5.25	5.50	5.30	5.16	5.56	5.22	5.23	4.85	5.08	5.17	5.02	4.47	4.50	4.58	4.84	4.49	3.16	3.57
ETo	6.56	6.91	4.90	5.07	6.40	8.52	5.87	5.39	4.63	4.43	5.58	4.18	5.10	5.11	4.64	3.75	5.06	5.80	2.79

Bigbend																				
pentad	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Td	21.21	19.62	19.44	18.52	17.79	17.80	16.46	16.00	15.55	14.69	14.19	12.63	11.56	10.43	10.21	10.07	10.88	10.45	10.61	10.83
Tw	19.58	18.19	17.16	14.26	11.34	16.39	15.32	14.88	14.17	11.86	8.51	10.97	10.42	9.37	8.97	7.69	8.90	8.89	9.62	9.85
depression	1.62	1.43	2.28	4.27	6.45	1.42	1.13	1.12	1.38	2.83	5.67	1.66	1.13	1.07	1.24	2.37	1.98	1.56	0.99	0.98
T	19.90	19.28	18.10	18.23	17.47	17.17	17.03	16.75	16.92	16.61	16.81	16.56	16.19	16.43	16.01	16.84	17.40	17.54	17.72	18.16
f(T)	14.60	14.60	14.20	14.20	14.20	14.20	14.20	13.80	13.80	13.80	13.80	13.80	13.80	13.80	13.80	13.80	14.20	14.20	14.20	14.20
W	0.69	0.69	0.66	0.66	0.66	0.66	0.66	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.66	0.66	0.66	0.66
1-W	0.31	0.31	0.34	0.34	0.34	0.34	0.34	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.34	0.34	0.34	0.34
ea	23.4	22	20.6	20.6	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2	19.4	19.4	20.6	20.6	20.6
ed	22	19.3	19.3	13.3	10	16.8	14.6	14.6	14.6	12.2	6.7	10.9	10.9	9.4	9.4	9.4	9.4	9.4	12.3	12.3
ea-ed	1.4	2.7	1.3	7.3	9.4	2.6	4.8	4.8	4.8	7.2	12.7	8.5	7.3	8.8	8.8	10	10	11.2	8.3	8.3
f(ed)	0.13	0.14	0.14	0.14	0.14	0.16	0.18	0.18	0.18	0.18	0.19	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.19	0.19
rainfall	7.89	4.68	3.41	6.42	5.16	4.59	5.21	1.75	1.62	2.89	1.39	4.90	2.59	1.45	4.22	1.59	0.55	2.47	3.78	0.41
r/d	1.58	0.94	0.68	1.28	1.03	0.92	1.04	0.35	0.32	0.58	0.28	0.98	0.52	0.29	0.84	0.32	0.11	0.49	0.76	0.08
cumrain	226.56	231.24	234.65	241.07	246.23	250.82	256.02	257.77	259.39	262.28	263.67	268.57	271.15	272.60	276.83	278.42	278.97	281.43	285.22	285.63
U	172.53	148.35	164.09	148.59	136.49	139.74	141.78	129.32	142.15	138.67	148.53	144.98	125.98	140.73	137.23	127.07	125.97	120.30	148.29	154.47
f(u)	0.73	0.67	0.70	0.67	0.65	0.65	0.65	0.62	0.65	0.65	0.67	0.65	0.62	0.65	0.65	0.62	0.62	0.59	0.67	0.67
n	7.06	7.64	7.24	6.76	6.37	6.64	7.31	7.37	7.21	6.75	6.21	6.78	6.97	7.19	7.58	7.63	7.42	7.11	7.30	7.72
N	11.60	11.60	11.60	11.60	11.60	10.90	10.90	10.90	10.90	10.90	10.90	10.60	10.60	10.60	10.60	10.60	10.60	10.70	10.70	10.70
n/N	0.61	0.66	0.62	0.58	0.55	0.61	0.67	0.68	0.66	0.62	0.57	0.64	0.66	0.68	0.71	0.72	0.70	0.66	0.68	0.72
f(n/N)	0.64	0.69	0.64	0.64	0.60	0.64	0.69	0.73	0.69	0.64	0.60	0.69	0.69	0.73	0.73	0.73	0.73	0.69	0.73	0.73
Ra	12.00	12.00	12.00	12.00	12.00	9.70	9.70	9.70	9.70	9.70	9.70	8.70	8.70	8.70	8.70	8.70	8.70	9.10	9.10	9.10
Rs	6.65	6.95	6.74	6.50	6.29	5.38	5.68	5.70	5.63	5.43	5.19	4.96	5.03	5.13	5.29	5.31	5.22	5.30	5.38	5.56
Rns	4.99	5.21	5.06	4.87	4.72	4.03	4.26	4.28	4.23	4.07	3.89	3.72	3.78	3.85	3.96	3.98	3.92	3.97	4.03	4.17
Rnl	1.21	1.41	1.27	1.27	1.19	1.45	1.76	1.81	1.71	1.59	1.57	1.90	1.90	2.01	2.01	2.01	2.07	1.96	1.97	1.97
Rn	3.77	3.80	3.79	3.60	3.53	2.58	2.49	2.46	2.51	2.48	2.32	1.81	1.87	1.83	1.95	1.97	1.84	2.01	2.06	2.20
ETo	2.92	3.18	2.81	4.04	4.41	2.28	2.71	2.65	2.73	3.27	4.55	3.15	2.83	3.23	3.31	3.49	3.32	3.58	3.25	3.34

Bighend																				
pentad	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Td	10.89	11.25	12.03	12.22	12.77	13.74	14.93	15.89	16.64	17.39	17.22	17.86	18.01	17.50	18.34	15.20	20.09	20.01	20.60	20.56
Tw	9.69	8.73	9.35	10.62	11.54	12.33	13.28	12.30	12.55	14.78	14.70	15.32	15.57	14.79	13.78	15.06	17.44	17.73	18.36	17.96
depression	1.20	2.51	2.68	1.59	1.23	1.41	1.65	3.58	4.09	2.62	2.52	2.54	2.44	2.71	4.56	0.14	2.64	2.27	2.24	2.59
T	18.72	18.72	19.25	19.78	20.30	20.41	21.12	21.74	22.08	20.36	21.60	22.53	22.74	22.53	22.74	19.93	24.28	23.98	23.94	23.70
f(T)	14.20	14.20	14.60	14.60	14.60	14.60	15.00	15.00	15.00	14.60	15.00	15.00	15.00	15.00	15.00	14.60	15.40	15.40	15.40	15.40
W	0.66	0.66	0.69	0.69	0.69	0.69	0.71	0.71	0.71	0.69	0.71	0.71	0.71	0.71	0.71	0.69	0.73	0.73	0.73	0.73
1-W	0.34	0.34	0.31	0.31	0.31	0.31	0.29	0.29	0.29	0.31	0.29	0.29	0.29	0.29	0.29	0.31	0.27	0.27	0.27	0.27
ea	22	22	22	23.4	23.4	23.4	24.9	26.4	26.4	23.4	26.4	28.1	28.1	28.1	28.1	23.4	29.8	29.8	29.8	29.8
ed	12.3	10.9	10.9	10.9	10.9	12.7	12.7	11.4	11.4	16.8	16.8	16.8	16.8	16.8	13.3	18.2	19.3	19.3	19.3	19.3
ea-ed	9.7	11.1	11.1	12.5	12.5	10.7	12.2	15	15	6.6	9.6	11.3	11.3	11.3	14.8	5.2	10.5	10.5	10.5	10.5
f(ed)	0.19	0.2	0.2	0.2	0.2	0.19	0.19	0.19	0.19	0.16	0.16	0.16	0.16	0.16	0.18	0.15	0.14	0.14	0.14	0.14
rainfall	0.71	0.78	1.30	0.21	0.78	2.37	1.52	5.44	0.53	0.49	2.41	4.54	9.50	4.03	4.49	3.61	5.76	4.10	7.79	5.44
r/d	0.14	0.16	0.26	0.04	0.16	0.47	0.30	1.09	0.11	0.10	0.48	0.91	1.90	0.81	0.90	0.72	1.15	0.82	1.56	1.09
cumrain	286.34	287.11	288.41	288.62	289.40	291.77	293.29	298.74	299.27	299.76	302.17	306.71	316.21	320.24	324.72	328.34	334.10	338.19	345.98	351.42
U	153.60	203.98	166.31	186.63	196.64	218.79	216.03	229.85	237.82	245.76	268.36	272.55	268.72	272.57	270.65	206.71	272.10	251.67	240.78	266.98
f(u)	0.67	0.81	0.73	0.78	0.81	0.86	0.86	0.89	0.92	0.94	1.00	1.00	1.00	1.00	1.00	0.84	1.00	0.94	0.92	1.00
n	7.53	7.33	7.22	5.48	7.40	7.14	7.58	8.13	7.72	8.08	7.06	6.17	6.51	6.79	6.30	6.57	5.66	7.36	6.55	6.33
N	10.70	10.70	10.70	11.30	11.30	11.30	11.30	11.30	11.30	12.00	12.00	12.00	12.00	12.00	12.00	12.70	12.70	12.70	12.70	12.70
n/N	0.70	0.68	0.68	0.48	0.66	0.63	0.67	0.72	0.68	0.67	0.59	0.51	0.54	0.57	0.53	0.52	0.45	0.58	0.52	0.50
f(n/N)	0.73	0.73	0.73	0.55	0.69	0.69	0.69	0.73	0.73	0.69	0.64	0.55	0.60	0.60	0.60	0.55	0.51	0.64	0.55	0.55
Ra	-9.10	9.10	9.10	10.90	10.90	10.90	10.90	10.90	10.90	13.20	13.20	13.20	13.20	13.20	13.20	15.50	15.50	15.50	15.50	15.50
Rs	5.48	5.39	5.35	5.37	6.30	6.17	6.38	6.65	6.45	7.74	7.18	6.69	6.88	7.03	6.77	7.89	7.33	8.36	7.87	7.74
Rns	4.11	4.04	4.01	4.02	4.72	4.63	4.79	4.99	4.84	5.81	5.39	5.02	5.16	5.28	5.07	5.91	5.50	6.27	5.90	5.80
Rnl	1.97	2.07	2.13	1.61	2.01	1.91	1.97	2.08	2.08	1.61	1.54	1.32	1.44	1.44	1.62	1.20	1.10	1.38	1.19	1.19
Rn	2.14	1.97	1.88	2.42	2.71	2.71	2.82	2.90	2.76	4.19	3.85	3.70	3.72	3.84	3.45	4.71	4.40	4.89	4.72	4.62
ETo	3.62	4.36	3.81	4.69	5.01	4.73	5.04	5.93	5.96	4.82	5.52	5.90	5.92	6.00	6.74	4.60	6.05	6.24	6.05	6.21

Bigbend														
pentad	60	61	62	63	64	65	66	67	68	69	70	71	72	73
Td	20.69	20.69	21.55	21.73	21.72	21.93	22.51	22.29	22.37	22.33	22.55	22.17	23.22	22.77
Tw	15.86	11.69	19.59	19.49	19.16	19.78	18.01	13.52	18.63	17.98	18.02	19.91	18.04	11.95
depression	4.83	9.00	1.96	2.25	2.57	2.15	4.51	8.77	3.74	4.35	4.52	2.26	5.18	10.82
T	24.39	23.45	24.82	24.84	24.90	24.75	24.91	23.75	25.36	25.80	25.22	25.74	25.80	24.87
f(T)	15.40	15.40	15.40	15.40	15.40	15.40	15.40	15.40	15.90	15.90	15.90	15.90	15.90	15.40
W	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.75	0.75	0.75	0.75	0.75	0.73
1-W	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.25	0.25	0.25	0.25	0.25	0.27
ea	29.8	28.1	31.7	31.7	31.7	31.7	31.7	29.8	31.7	33.6	31.7	33.6	33.6	31.7
ed	15.5	8.7	22	22	22	22	18	8.7	17.4	18	18	22	18	7.4
ea-ed	14.3	19.4	9.7	9.7	9.7	9.7	13.7	21.1	14.3	15.6	13.7	11.6	15.6	24.3
f(ed)	0.16	0.22	0.13	0.13	0.13	0.13	0.15	0.22	0.15	0.15	0.15	0.13	0.15	0.22
rainfall	7.79	7.01	10.74	16.93	7.92	8.13	12.79	15.27	20.68	12.80	10.71	13.55	10.77	26.46
r/d	1.56	1.40	2.15	3.39	1.58	1.63	2.56	3.05	4.14	2.56	2.14	2.71	2.15	5.29
cumrain	359.21	366.22	376.96	393.88	401.80	409.93	422.71	437.99	458.66	471.47	482.18	495.72	506.50	532.96
U	269.72	276.45	255.41	260.70	245.70	234.14	245.21	240.28	209.29	229.28	225.79	226.88	236.74	259.93
f(u)	1.00	1.03	0.97	0.97	0.94	0.89	0.94	0.92	0.84	0.89	0.89	0.89	0.92	0.97
n	5.05	4.08	6.39	6.22	6.14	5.54	6.37	6.33	7.06	6.20	6.73	7.18	5.93	5.23
N	12.70	12.70	13.30	13.30	13.30	13.30	13.30	13.30	13.70	13.70	13.70	13.70	13.70	13.70
n/N	0.40	0.32	0.48	0.47	0.46	0.42	0.48	0.48	0.52	0.45	0.49	0.52	0.43	0.38
f(n/N)	0.46	0.37	0.55	0.51	0.51	0.46	0.55	0.55	0.55	0.51	0.55	0.55	0.51	0.46
Ra	15.50	15.50	17.20	17.20	17.20	17.20	17.20	17.20	17.80	17.80	17.80	17.80	17.80	17.80
Rs	6.96	6.36	8.43	8.32	8.27	7.88	8.42	8.39	9.04	8.48	8.82	9.12	8.30	7.85
Rns	5.22	4.77	6.32	6.24	6.20	5.91	6.31	6.29	6.78	6.36	6.62	6.84	6.23	5.89
Rnl	1.13	1.25	1.10	1.02	1.02	0.92	1.27	1.86	1.31	1.22	1.31	1.14	1.22	1.56
Rn	4.08	3.52	5.22	5.22	5.18	4.99	5.04	4.43	5.47	5.14	5.31	5.70	5.01	4.33
ETo	6.84	7.96	6.35	6.35	6.24	5.98	7.16	8.48	7.10	7.33	7.03	6.86	7.34	9.52

Appendix 4. *Spectral analysis data for Mbabane, Malkerns and Big Bend, Swaziland.*

Mbabane			Malkerns			Bigbend		
Frequency/yr	period/years	Sp.density	Frequency/pentad	period/pentad	Sp.density	Frequency/pentad	period/pentad	Sp.density
0.00000		0.0	0.0000		0.00	0.0000		0.0
0.02941	34.00	204812.0	0.0135	74.02	6283.22	0.0139	72.0	588.1
0.05882	17.00	209227.0	0.0270	37.01	18.0066	0.0278	36.0	42.4
0.08824	11.33	7252.5	0.0405	24.67	205.29	0.0417	24.0	10.4
0.11765	8.50	87968.8	0.0540	18.50	61.6047	0.0556	18.0	20.9
0.14706	6.80	70691.6	0.0676	14.80	31.5394	0.0695	14.4	15.9
0.17647	5.67	68689.5	0.0811	12.34	22.99	0.0833	12.0	25.4
0.20588	4.86	22687.6	0.0946	10.57	16.7932	0.0972	10.3	14.0
0.23529	4.25	200326.0	0.1081	9.25	7.69924	0.1111	9.0	29.5
0.26471	3.78	312292.0	0.1216	8.22	15.3268	0.1250	8.0	11.9
0.29412	3.40	152263.0	0.1351	7.40	20.2291	0.1389	7.2	31.9
0.32353	3.09	370114.0	0.1486	6.73	14.5652	0.1528	6.5	22.9
0.35294	2.83	245872.0	0.1621	6.17	5.81376	0.1667	6.0	45.9
0.38235	2.62	10051.7	0.1756	5.69	9.48419	0.1806	5.5	67.1
0.41176	2.43	153770.0	0.1891	5.29	1.66615	0.1945	5.1	41.9
0.44118	2.27	119589.0	0.2027	4.93	44.2417	0.2084	4.8	10.7
0.47059	2.12	79430.0	0.2162	4.63	36.3978	0.2222	4.5	4.0
0.50000	2.00	79216.9	0.2297	4.35	11.8841	0.2361	4.2	6.7
			0.2432	4.11	3.81171	0.2500	4.0	22.1
			0.2567	3.90	1.60198	0.2639	3.8	6.4
			0.2702	3.70	5.32713	0.2778	3.6	3.0
			0.2837	3.52	39.4065	0.2917	3.4	13.1
			0.2972	3.36	19.0918	0.3056	3.3	10.3
			0.3107	3.22	7.7587	0.3195	3.1	26.2
			0.3242	3.08	26.5016	0.3334	3.0	3.0
			0.3378	2.96	45.7146	0.3473	2.9	13.4
			0.3513	2.85	61.9885	0.3611	2.8	14.2
			0.3648	2.74	28.8429	0.3750	2.7	26.8
			0.3783	2.64	17.6102	0.3889	2.6	63.9
			0.3918	2.55	16.366	0.4028	2.5	42.3
			0.4053	2.47	0.26351	0.4167	2.4	40.1
			0.4188	2.39	7.34422	0.4306	2.3	57.4
			0.4323	2.31	2.66987	0.4445	2.2	7.4
			0.4458	2.24	0.49801	0.4584	2.2	29.5
			0.4593	2.18	19.5289	0.4723	2.1	11.8
			0.4729	2.11	23.8016	0.4862	2.1	8.3
			0.4864	2.06	3.04764	0.5000	2.0	2.0
			0.5000	2.00	2.04089			

Appendix 5. *Rainfall reliability and variability data for Swaziland.*

Station	Bigbend	Vuvulane	Foyer	Dwaleni	Bulembu	Hluti	Lavumisa	Mananga	Mabunza	Malkerns	Mankayan	Matsapha	Mayiwane
Mean	594.41	786.40	795.11	827.79	1433.71	738.17	541.20	703.67	918.38	975.00	867.76	867.19	872.35
Sd	177.33	217.28	182.96	229.16	235.85	236.86	138.17	176.03	165.65	204.37	212.85	264.61	287.68
Cv	0.30	0.28	0.23	0.28	0.16	0.32	0.26	0.25	0.18	0.21	0.25	0.31	0.33
r	0.70	0.72	0.77	0.72	0.84	0.68	0.74	0.75	0.82	0.79	0.75	0.69	0.67

Station	Mbuluzi	Mpaka	Mpisi	Ngonini	Nhlangano	PiggsPeak	Siphofaneni	Sitobela	Mbabane	St-Philips	Tunzini	Swazi-plantation
Mean	1131.05	764.67	632.96	869.61	793.15	1256.15	626.27	631.07	1449.60	573.11	741.75	1188.73
Sd	255.43	182.80	186.18	263.83	155.22	300.24	212.84	165.12	266.32	195.29	186.79	225.05
Cv	0.23	0.24	0.29	0.30	0.20	0.24	0.34	0.26	0.18	0.34	0.25	0.19
r	0.77	0.76	0.71	0.70	0.80	0.76	0.66	0.74	0.82	0.66	0.75	0.81

Appendix 6 *Water Requirement Satisfaction Index (WRSI) and maize yield data for Swaziland*

Season	Actual Yield (Tonnes/ha)	Predicted Yield (Tonnes/ha)	Index
1979/80	1.624	1.58	100.00
1980/81	2.148	1.88	100.00
1981/82	1.240	1.72	100.00
1982/83	1.078	1.08	91.23
1983/84	2.052	1.82	96.27
1984/85	1.863	1.66	94.94
1985/86	1.973	1.88	100.00
1986/87	1.713	1.58	96.92
1987/88	1.740	1.28	96.76
1988/89	1.916	1.74	100.00
1989/90	1.308	1.38	94.00
1990/91	1.614	1.82	97.00
1991/92	1.056	1.28	70.00