THE RELATIONSHIP BETWEEN DAILY AND MONTHLY PAN EVAPORATION AND RAINFALL TOTALS IN SOUTHERN AFRICA

THESIS

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"An approximate answer to the right question is worth a great deal more than a precise answer to the wrong question" (First Golden Rule of Mathematics).

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ABSTRACT

Recent droughts in South Africa have highlighted the vulnerability of the economy to water restrictions. However, the degree of surface aridity in southern Africa is not only a function of precipitation, but also one of evaporation. The quantitative assessment of evaporative loss is important since it is a major component of the water budget. For example, in southern Africa, evaporation accounts for 79.5% of the hydrological water budget. As the cost of water resource development increases, so there has been an increasing demand for hydrological modelling to optimise project planning. Reliable estimates of evaporation are essential to significant improvements in the practice of hydrology and particularly in a country like South Africa which is prone to the adverse effects of drought.

It is difficult to adequately measure potential evaporation over an area as large and as sparsely populated as southern Africa. Despite the research that has been undertaken to estimate evaporation from related meteorological and physical variables, generally, the estimation of evaporation in southern Africa has been unsatisfactory. There are a number of methods for estimating potential evaporation. However, a major problem tends to be the incompatibility between the data requirements of some of the more physically-based models, and the actual data that is available and collected on a routine basis at a sufficient number of stations.

In existing water resources estimation models, evaporation is often incorporated as a time series input of pan evaporation, using daily or monthly values. The lack of a nearby record of pan evaporation often necessitates the use of published regionalised mean monthly pan values. This technique of using the mean monthly evaporation values in water resources estimation models tends to overestimate or underestimate the actual evaporation that is occurring, depending on the actual amount of rain occurring in a specific month. This is because no attempt has been made to correct these mean evaporation values for the amount of rainfall that occurs in a specific month, in a specific region. The regional rainfall/evaporation relationships (that vary spatially and temporally) are not taken into account.

A need was identified for an assessment of the value of grouping data by rainfall as a better tool for estimating evaporation. Here, the monthly evaporation and the mean monthly evaporation for a specific rainfall group category will be estimated using daily data. Due to data availability, the most appropriate time scale to use is one day. Therefore, in this study an attempt has been made to relate rainfall amounts to evaporation values and to develop rainfall/evaporation relationships, identifying variations by season and region. It is important to identify and quantify these relationships and assess the possibility of incorporating these variations into existing Water Resource Estimation Models.

The ability to derive and develop meaningful relationships between daily rainfall and daily evaporation for each season, and for a number of sites considered representative of the climatological zones for southern Africa was assessed. The first approach was to compare daily evaporation plotted against daily rainfall, and in the process develop a quantitative rainfall/evaporation relationship. Unfortunately, no direct linear relationships were identified.

The second approach was to test the performance of the water resource estimation model using the following possible choices, (i) a real daily input (COREVAP1) - here the estimated monthly evaporation is the sum of the product number of days within each month * mean daily evaporation for each specified raingroup category, (ii) a distributed mean monthly input (COREVAP2) - here evaporation is estimated using a random sampling procedure to draw samples from a restricted part of the daily evaporation distribution for each raingroup and is defined by the mean and standard deviation, and (iii) a distributed mean monthly input and correction (COREVAP3) - here samples are drawn from the full distribution of daily evaporation for each raingroup category. The performance of the COREVAP programs was analyzed in terms of the improvement effected by estimating evaporation using the mean monthly evaporation regardless of rain. COREVAP1 produced the best simulations of monthly evaporation. This was expected as the program uses the straight-forward mean evaporation value multiplied by the number of days to simulate the monthly evaporation values. However, the COREVAP programs did not perform well when using the monthly evaporation data based on daily infilled values using the transformed parameters.

Any regionalisation of parameter files would mean that a range of parameters in a region would now be represented by a single value. The need to assess the effect of this change from a regional range of values to a single representative value was identified. This was done by conducting a sensitivity analysis, in terms of what effect a percentage increase or decrease in the lambda, mean evaporation and mean rainfall values would have on the resultant simulated monthly evaporation and coefficient of efficiency values. A sensitivity analysis was conducted on COREVAP1 to determine which parameters of the model had the greatest influence on the simulations. This was done with reference to the percentage error of monthly evaporation and the monthly and accumulative coefficient of efficiency values. Generally, the percentage increase/decrease in mean evaporation values that are acceptable for the representative stations are low. In contrast, fairly high percentage changes in mean rainfall values are tolerated.

The objective of the regionalisation of parameters was to determine whether general characteristics can be applied to some stations that are significantly different compared to other stations, so that the stations may be combined to represent a separate region. The demarcation of regions was conducted on the basis of the regional relative mean evaporation values (per raingroup, per season), the daily mean evaporation values per month and the average number of days within each raingroup, per season. Intra-station and inter-region variability was analysed using the Kruskal-Wallis H test and the Friedman Fr test. The regional parameters were then used as input into the COREVAP programs and the simulation results were analysed in terms of whether the simulations still produce positive accumulative coefficient of efficiency values. The results obtained when substituting the regional parameters were not good. Based on these results, it has been concluded that the hypothesis that grouping data by rainfall may be a better tool for estimating evaporation compared to simply using the mean monthly evaporation, may be rejected.

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CHAPTER 1

1. INTRODUCTION

Water constitutes one of South Africa's most valuable natural resources. Recent droughts in South Africa have highlighted the vulnerability of the economy to water restrictions. South Africa is predominantly a semi-arid country. The average annual rainfall is 497mm which is well below the world average of 860mm. On average 91% of the mean annual rainfall is returned to the atmosphere by evapotranspiration, while globally the percentage is 65 - 70% (Whitmore, 1971; Schulze, 1984). The development of a country's water resources is important both as an input to the economic growth process and as an element of the basic needs package, which most countries aim to provide for their population. In 1983 the total surface water resources of South Africa, including the independent states was estimated at 54 000Mm^3 per annum, with a further estimated 15% contributed by groundwater resources (Du Plessis, 1984). However, not all of this water is economically exploitable. Projected water demand has increased from 10 000Mm^3 in 1980 to 15 000Mm^3 in 1990 (Weaver, et. al., 1986). It is evident that the water supply per capita is dwindling rapidly as a result of high population growth rates and the ever-increasing demands that are being made on finite and often unreliable water resources. This increasing level of utilization of South Africa's limited water resources has placed a greater emphasis on the need to efficiently plan for the optimum development, the maximum utilization and the improvement of our knowledge of the spatial and temporal distribution of present surface and groundwater resources.

It is recognized that the degree of surface aridity in southern Africa is not only a function of precipitation, but also one of evaporation. The conversion of water molecules from the liquid to the vapour state across an evaporating surface, and the vertical transport of this water vapour upward into the atmospheric boundary layer is known as evaporation. The quantitative assessment of evaporative loss is important since it is a major component of the earth's water budget. For example, in South Africa, approximately 470 000Mm^3 of water is evaporated into the atmosphere by this process each year. Evaporation is a crucial consideration in any water resources planning and management programme, in evaluating the potential for water resources development and also in various water supply studies. Yet in relation to its dominance as an output of the hydrological cycle, relatively little research and operational effort has generally been expended in southern Africa in obtaining realistic estimates of evaporation. Evaporation needs to be defined and an understanding of the processes involved is fundamental to its accurate estimation and measurement.

It is important to distinguish between potential and actual evaporation. Potential evaporation may be defined as an "atmospheric demand" given an unlimited supply of moisture, and determined by various climatic variables. Schulze et. al., (1992) use the term "reference evaporation". Actual evaporation is the evaporation that would occur from a non-continuously moist surface.

Evaporation is a composite phenomena and involves the continuous and simultaneous supply of water and energy to a particular surface, the transport process and the influence of environmental factors. Factors influencing evaporation rates are known but the accurate quantitative analysis of the relative effectiveness of each of these factors is difficult because of their interdependent effects. This point is reflected in later chapters. It is difficult to adequately measure potential evaporation over an area as large and as sparsely populated in parts as southern Africa.

There are a number of methods for estimating potential evaporation, each unique in terms of data requirements, as well as basis, accuracy and area of application. These techniques have focused on the relationship between evaporation and the related climatic elements which affect evaporation, factors such as windspeed, humidity, cloudiness, air temperature and daylength. However, a major problem tends to be the incompatibility between the data requirements of some of the more physically-based models and the actual data that is available and collected on a routine basis at a sufficient number of stations. Therefore, despite the research undertaken to estimate evaporation from related meteorological and physical variables, generally the estimation of evaporation in southern Africa has been unsatisfactory.

The climate of southern Africa is characterized by a high degree of intra- and inter-annual variability. 48% of South Africa has an average annual rainfall of less than 400mm, 32% between 400 - 800mm and 20% of the area has a rainfall exceeding 800mm, indicating regional variability. Only 3% of South Africa receives rainfall throughout the year, while 86% of the country receives summer rainfall and 11% winter rainfall, indicating seasonal variability (Department of Water Affairs, 1986; Weaver et. al., 1986). Superimposed on these variations will be a shorter time scale variation that is dependent on the radiation/humidity/rain condition during a single day. This variation can be expected to vary with the synoptic conditions prevailing on that day. During winter, solar radiation is at a minimum, temperatures are low, percentage cloud cover is at a maximum and saturation vapour pressure deficit is low ; conditions conducive to rainfall and low evaporation. Conversely, in summer, solar radiation is at a maximum, temperatures are high, percentage cloud cover is low and the saturation vapour pressure deficit is at a maximum, conditions conducive to high evaporation values and to the potential build-up of conditions culminating in convectional or convergent rainfall. Cyclonic or frontal precipitation which is generally of a low to moderate intensity, and long duration, is characteristic of the winter rainfall region and the southern Cape coastal belt area that receives rain throughout the year. The rest of South Africa is characterized by summer rainfall. Orographic rainfall is dominant in the eastern and southern escarpment and mountain ranges, and produces moderate intensity, fairly long duration rainfall. Convergent systems and thunderstorm activity are dominant over the interior and produce high intensity, short duration rainfall events.

The regional differences in the occurrence of rainfall during the year and the type of rain that occurs will inevitably lead to differences in the rainfall/evaporation relationship. The problem is to quantify this relationship at suitable scales, both spatially (regional) and temporally (seasonal). Due to data availability, the most appropriate time scale to use is one day.

The most common instrument used to measure potential evaporation is the evaporation pan. In existing water resource estimation model's, evaporation is often incorporated as a time series input of pan evaporation, using either daily or monthly values. However, the lack of a nearby record of pan evaporation often necessitates the use of published regionalized mean monthly pan values. There is often no attempt to correct these mean values of evaporation for the amount of rainfall that occurs in a specific month, in that specific region. However, it is important to identify that there are variations in the rainfall/evaporation relationship and these vary temporally and spatially.

In this study an attempt has been made to relate rainfall amounts to evaporation values and to develop rainfall/evaporation relationships, identifying variations by season and region. It is important to identify and quantify these relationships and assess the possibility of incorporating these variations into existing water resource estimation methods.

More specifically the initial aims and objectives of the study are stated in chapter 2. An important consideration in an attempt to identify and develop rainfall/evaporation relationships are the various meteorological characteristics of different weather systems, and the actual type of precipitation that occurs. These factors and the relationship between rainfall characteristics and the major macro-scale atmospheric circulation systems over southern Africa are discussed in chapter 3. A review of previous approaches to demarcating rainfall regions provides a background to the specific regional and seasonal divisions used in this study. Chapter 4 reviews the likely seasonal/regional variations in the occurrence of rainfall and highlights the problems associated with measuring rainfall and the availability of daily rainfall data. The evaporation concept is defined in chapter 5 and the factors influencing evaporation are identified. The relationship between evaporation and the influencing factors combine to make the in situ measurement of evaporation a difficult process. The section on evaporation estimation and measurement techniques highlights this problem. In chapter 6 the study area is defined, the data base is selected and the spatial distribution of stations and initial regional divisions are identified. Chapter 7 presents a graphical and quantitative discussion of the rainfall/evaporation trends, both spatially and temporally. The results of the coefficient of efficiency analysis based on daily data are presented in chapter 8. The performance of the COREVAP programs are analyzed in chapter 9 and the results of a sensitivity analysis are reported in the second section of the chapter. Chapter 10 deals with the regionalization of the rainfall/evaporation relationships, based on the parameter characteristics. The concluding results and summary remarks are presented in chapter 11.

CHAPTER 2

2. AIMS AND OBJECTIVES

The specific aims and objectives of this thesis are as follows :

i) Identify and select rainfall and evaporation stations to be used in the study.

ii) Quantify the relationships between rainfall and evaporation at appropriate time and space scales for southern Africa.

iii) Assess the usefulness of incorporating these relationships into simple water resource estimation models.

CHAPTER 3

3. SYNOPTIC WEATHER TYPES

3.1 INTRODUCTION

An important consideration in an attempt to identify and develop rainfall/evaporation relationships are the various meteorological characteristics of different weather systems, and the actual type of precipitation that occurs. This chapter discusses these factors, and the relationship between rainfall characteristics and the major macro-scale atmospheric circulation systems over southern Africa.

3.2 TYPES OF PRECIPITATION

Precipitation is classified according to its form, intensity and the type of lifting mechanism. Although there is always water vapour present in the air, rain is not always falling and something is needed in addition to moist air, to cause rain. The prerequisites for the production of rain include

i) a mechanism to produce cooling of the air,
ii) a mechanism to produce condensation,
iii) a mechanism to produce the accumulation of moisture, and
iv) a mechanism to produce clouds and rain droplets.

Precipitation duration and intensity depend on the rate at which the above processes are occurring. Forms of precipitation include drizzle, rain, snow, sleet and hail. Rainfall may further be classified as light, moderate or heavy depending on the raindrop size (Henderson-Sellers and Robinson, 1986). For drizzle, the droplet size is generally below 0.5mm in diameter, while the largest raindrops that can exist without breaking up are about 5mm in diameter. Besides being classified according to form and intensity precipitation is also classified according to the type of lifting mechanism (O'Hare and Sweeney, 1992). The three important types include orographic, convective and frontal rainfall.

Orographic rainfall results from the cooling of moisture-ladened air masses which have been forced to rise by contact with topographic highs. The moist air is forced to rise up the windward side of the mountain and the moisture is precipitated out. Once the air mass passes the peak of the mountain, no further orographic lifting occurs as no more moisture is available. Therefore, the windward sides of mountain ranges are generally more cloudy, have smaller temperature ranges and orographic rainfall is more pronounced. The southern and eastern escarpments of South Africa frequently receive light orographic rainfall.

Convective rainfall : Two factors are necessary to produce convective rainfall ; a heat supply (solar radiation) to expand and raise the lower layers of the atmosphere, and sufficient water vapour in the air to give a high relative humidity. Surface heating produces vertical instability of moist air masses and a convection current is set up. Convective rainfall results and is usually of short duration but high intensity. The Inter-Tropical Convergence Zone (inland summer rainfall region) is a region of pronounced convective activity.

Frontal rainfall : Fronts are associated with distinctive cloud and weather sequences, and are major determinants of weather variability. Frontal action may trigger off latent instability as the original air mass may be modified when moving over warmer, colder, drier or moister regions. For example, cold air becomes unstable when moved towards warmer air, and conversely, warm air becomes more stable as it moves away from a warmer to a cooler area. For warm fronts, the slope of the frontal surface is normally between 1:100 and 1:400 (Eagleson, 1970 : p 160). This is a relatively flat frontal surface gradient and lifting and cooling of the air is gradual, producing moderate rainfall rates of relatively long duration. Warm fronts rarely affect southern Africa, generally only reaching regions to the south of Africa, for example, Gough and Marion Islands. Cold fronts have frontal gradients between 1:25 and 1:100 (Eagleson, 1970 : p 161). These steeper gradients are conducive to rapid rising and cooling of the displaced warm air, and result in short duration, high intensity rains and high winds. Specific weather at the front depends on the properties of the air masses involved and their velocities. The greater the contrast between adjacent air masses, the steeper the frontal gradient and the greater the convergence, which ultimately results in heavier cloud formation and precipitation. The occluded front (a front formed by the merging of a cold and a warm front) gives a wide range of weather conditions, varying from light drizzle to heavy rain, depending on the nature of the air masses, their velocities and the maturity of the system. The south western and southern Cape regions receive most of their rainfall from frontal systems, generally being of relatively low intensity but long duration.

3.3 ATMOSPHERIC CIRCULATION AND WEATHER OVER SOUTHERN AFRICA

Atmospheric conditions that cause precipitation are complicated, irregular in space and time, and are highly variable. The weather-producing systems of southern Africa are distinguished by their different scales and circulation patterns which are caused by energy imbalances, and result in temperature and pressure variations. The three main categories of atmospheric circulation patterns include, fine-weather and mildly disturbed conditions, tropical disturbances associated with tropical easterly airflow, and temperate mid-latitude disturbances associated with westerly airflow. These synoptic systems are schematically presented in figure 3.1 (Preston-Whyte and Tyson, 1988).

3.3.1 Fine-weather and mildly disturbed conditions.

Fine weather and mildly disturbed conditions are associated with subtropical anticyclones, coastal lows and berg winds.

Subtropical anticyclones or high pressure systems are features associated with air subsidence, compression and adiabatic-warming of the local atmosphere. When situated over central South Africa, the anticyclone is responsible for fine, stable, dry conditions and berg winds usually occur along the southern and south-eastern coasts. Anticyclones have an important control over prevailing weather conditions over southern Africa because of their associated production of subsidence which is responsible for high atmospheric stability. These systems can produce severe heat waves and desiccation.

Subtropical anticyclones dominantly occur over the interior plateau in June and July (a frequency of 79%) in comparison to December where their frequency of occurrence decreases to only 11% (Preston-Whyte and Tyson, 1988 : p 218). For example, the weather pattern for the 17 - 20 of July 1991, was characterized by strong anticyclonic airflow over the land resulting in higher day temperatures, stable conditions, no rain and high potential evaporation rates over the interior (figure 3.2).

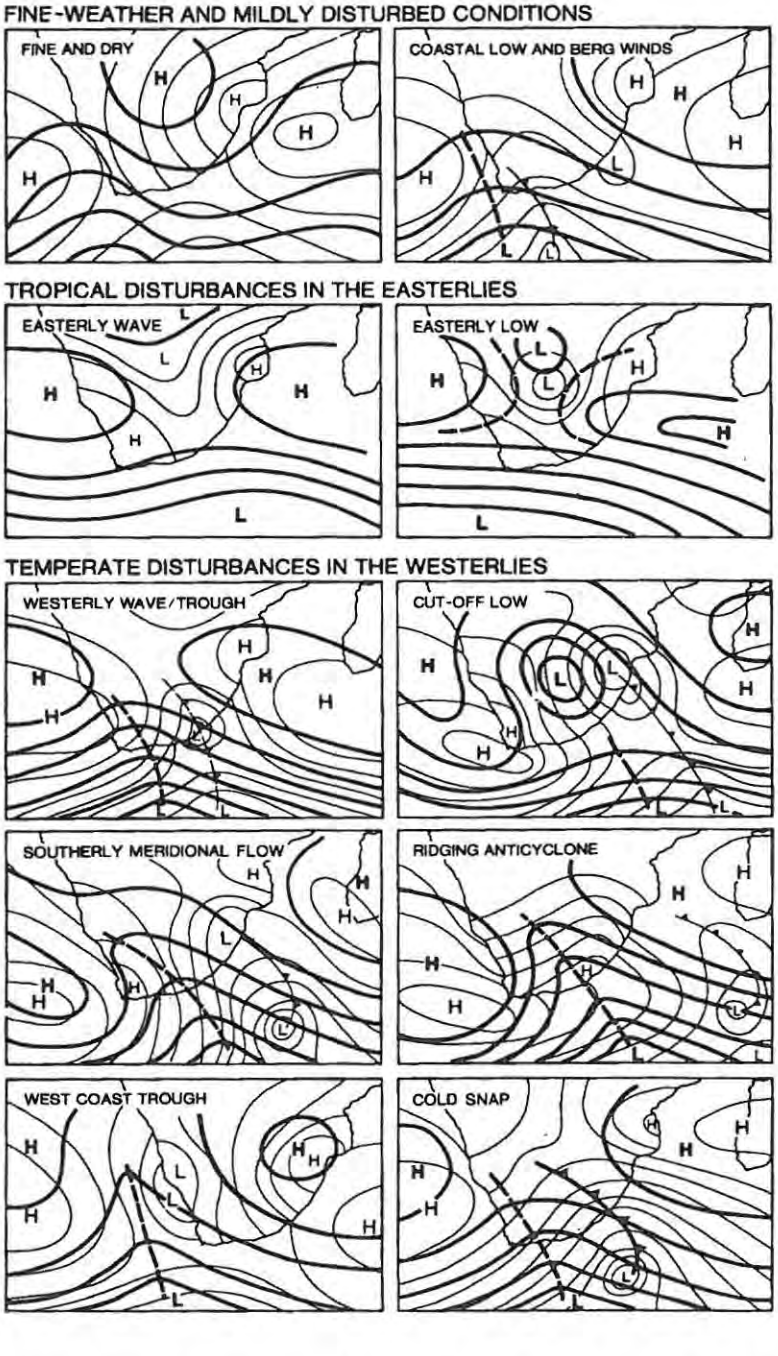


Figure 3.1 : A schematic classification of Southern African weather type (After, Preston-Whyte and Tyson, 1988 : p 216).

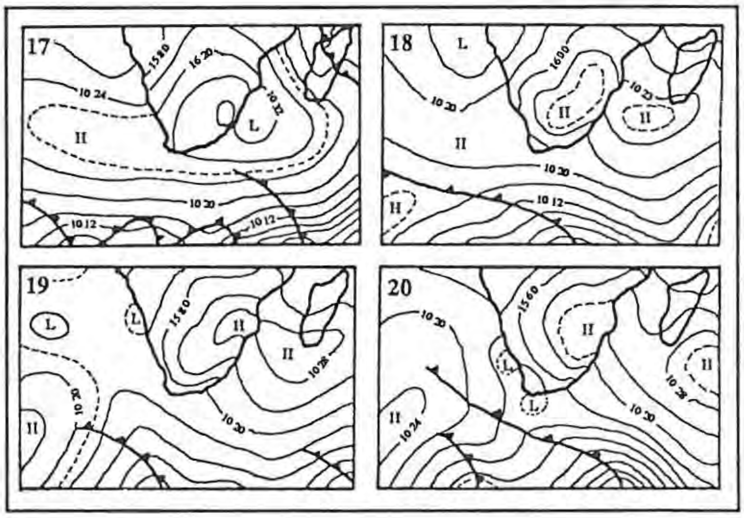


Figure 3.2 : Weather pattern for the 17 - 20 of July 1991 (From, Weather Bureau Newsletter, July 1991).

Coastal lows and berg winds : Coastal lows are initiated along the west coast, and tend to move in an easterly and north-easterly direction along the coast, producing warm off-shore airflow ahead of the system and cool onshore airflow behind the system. Coastal lows are confined to coastal areas and seldom extend further inland than the Cape mountains and Natal midlands. These systems produce localized low intensity precipitation. The occurrence of coastal lows may have a significant influence on evaporation rates in coastal regions. Berg winds are associated with large-scale, pre-frontal divergence, and warming of the subsiding air that is moving offshore. Berg winds are most common in the late winter and early spring, and are generally responsible for high temperatures and consequently higher rates of evaporation.

3.3.2 Tropical disturbances in the Easterlies.

These include features such as the easterly waves and easterly lows. The easterly low pressure system promotes strong uplift which favours the development of precipitation. Generally, the air is unstable, and moderate to high intensity rain falls, often lasting for a few days and occurring over a wide area, mainly to the east of the low pressure system. To the west of the low pressure system, subsidence occurs resulting in no rainfall, clear skies and hot conditions. The easterly wave disturbance produces scattered extensive rainfall over the north-eastern parts of South Africa (figure 3.3). These tropical disturbances are a summer phenomena, occurring more frequently in December to February, and exhibit an annual cycle. These systems produce the instability and consequent rainfall experienced in the summer-rainfall regions of the north-eastern parts of South Africa. The type of precipitation appears to be of low to moderate intensity rainfall lasting for a few days.

3.3.3 Temperate disturbances in the Westerlies.

Six classes of temperate disturbances are recognised, and include the westerly waves, the cut-off lows, the southerly meridional flow, ridging anticyclones, west coast troughs and cold fronts.

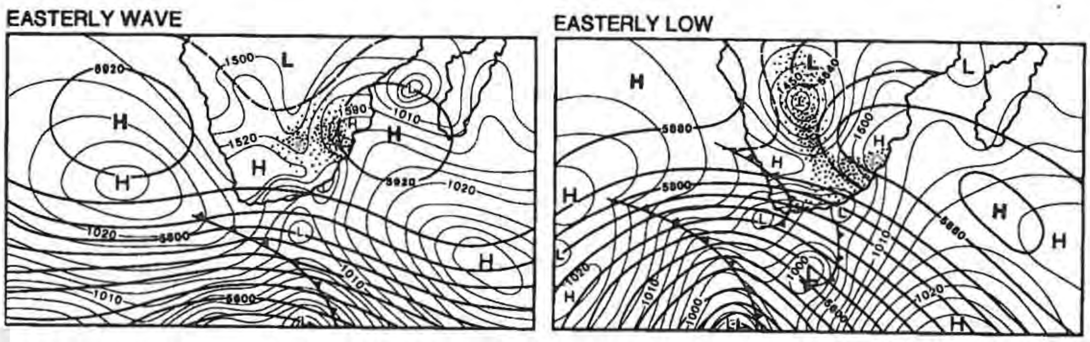


Figure 3.3 : A summer easterly wave and easterly low situation. Areas receiving precipitation are stippled (After, Preston-Whyte and Tyson, 1988 : p 224).

Westerly waves traverse the southern coast of South Africa. Ahead of the low pressure system, subsidence occurs producing stable conditions and fine weather. Behind the low pressure system, the air is unstable, and cloud formation occurs resulting in rainfall. An example of a westerly wave producing light coastal rainfall during early summer is illustrated in figure 3.4. Precipitation from these systems contribute to the all-year-round rainfall of the southern coastal region.

Cut-off lows are unstable systems, associated with strong convergence and widespread heavy rainfall. These cut-off lows have been responsible for many flood-producing rains particularly over eastern South Africa, for example, the Laingsburg floods of 1981, and the Natal floods of 1987. The cut-off low produces high intensity, and fairly long duration rainfalls. For example, during the Laingsburg floods, 180mm fell in one day, and in Port Elizabeth (1 September 1968), a maximum rate of 118mm/hour was recorded (Preston-Whyte and Tyson, 1988 : p 237).

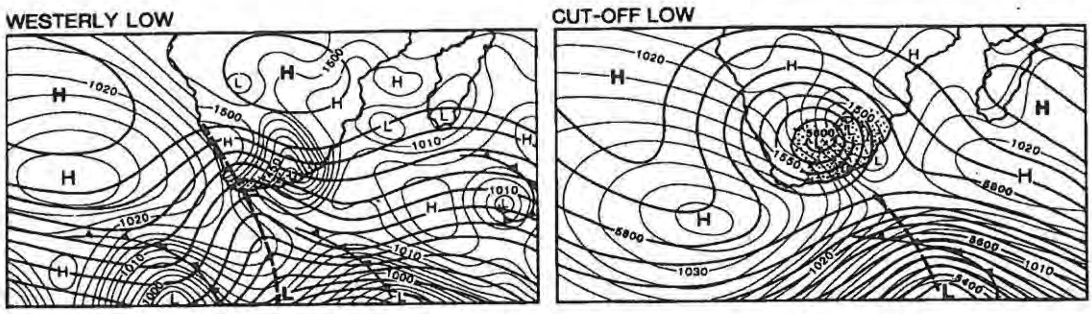


Figure 3.4 : An example of a westerly low and cut-off low system. Areas receiving precipitation are stippled (After, Preston-Whyte and Tyson, 1988 : p 226).

Southerly meridional flows : This synoptic situation causes temperatures to drop sharply, producing light rainfall over the southern coastal regions of South Africa (figure 3.5). In the lowveld of the eastern Transvaal, southerly meridional flows enhance convective activity.

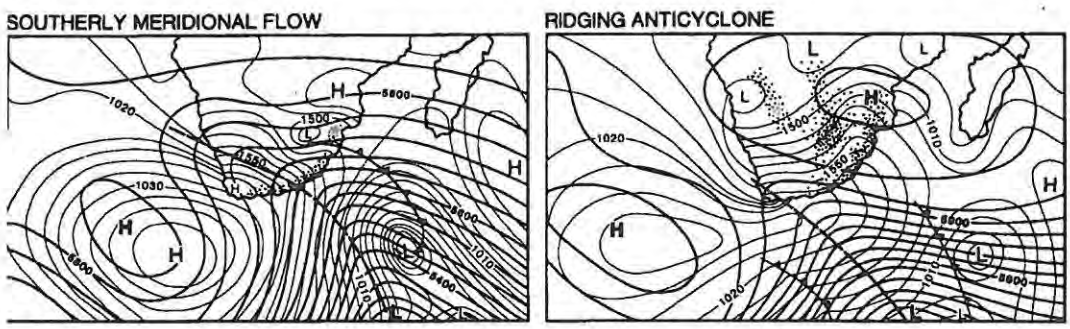


Figure 3.5 : An example of a spring southerly meridional flow system and a summer ridging anticyclone system (After, Preston-Whyte and Tyson, 1988 : p 230).

Ridging anticyclones promote strong advection of moist unstable air over the land and produce widespread uplift over the eastern regions of southern Africa. This leads to the development of extensive cloud cover formation, producing general rainfall and thunderstorm activity along the southern and eastern coastal and adjacent inland areas. Ridging anticyclones predominantly develop in the summer months with maximum frequencies of occurrence in October to February (Preston-Whyte and Tyson, 1988). Ridging anticyclones are a summer-rainfall feature, providing rainfall to Natal and the eastern and central areas of South Africa (figure 3.5).

West Coast Troughs : When a surface trough of low pressure develops over the west coast, it produces a situation conducive to widespread rains over the western and central parts of southern Africa. West coast troughs are usually an early-summer and early-autumn phenomena (figure 3.6).

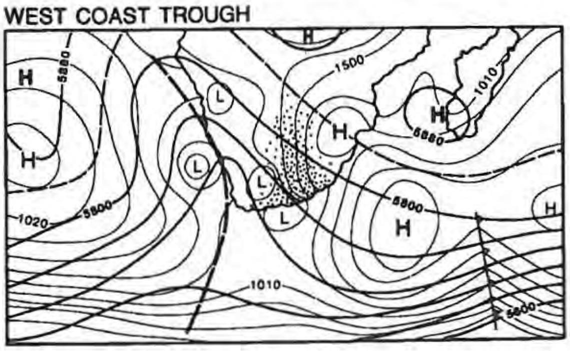


Figure 3.6 : An example of a strongly developed summer west coast trough system (After, Preston-Whyte and Tyson, 1988 : p 232).

Cold fronts are important determinants of weather and usually occur together with the westerly waves and cut-off lows. Cold fronts occur most frequently in winter and produce conditions favourable for convergent rainfall, mostly over the southern and south-western Cape. Ahead of a cold front, conditions are stable, with clear skies and gusty winds (which no doubt promote high evaporation rates). During the sequence of synoptic events on the 4 - 7 of June 1991 (figure 3.7) dry warm anti-cyclonic conditions prevailed over southern Africa on the 4th. On the 5th a cold front was situated close to the western coast and prefrontal rain fell over the south western Cape. By the 6th, the cold front was established over the western Cape, resulting in high rainfalls. Strong cold air advection behind the front lowered the freezing levels over the southern Cape and culminated in snow falling over the southern Cape mountains. By the 7th, the cold front had moved rapidly into the central interior and stagnated.

Figure 3.7 : Weather pattern for the 4 - 7 of June 1991 (From, Weather Bureau Newsletter, June, 1991).

3.3.4 Other important rain-producing systems.

Thunderstorms : Most of the rainfall received in the summer rainfall regions is convective, the degree of convectivity being influenced by diurnal heating and atmospheric instability. Convective rainfall over South Africa shows a clear diurnal variability. For example, over the inland areas, convective rainfall tends to fall most frequently during the afternoon and early evening (Tyson, 1986). The higher intensity convective storms generally follow this pattern while lower intensity storms show less diurnal variation, as illustrated over the south-western and southern Cape where precipitation tends to fall most frequently at night or early morning. Highest intensities of rainfall storms occur over the highveld and escarpment where rainfall exceeds 10mm/hour for more than 7% of the storms (Preston-Whyte and Tyson, 1988). Thunderstorms are a common phenomena in the interior and northern regions of southern Africa (especially the Transvaal, Eastern Transvaal and Orange Free State). During the summer months line storms are important sources of rainfall along the plateau regions of southern Africa. The distinctive difference between a storm and line storms is duration - the line storm lasts much longer. Line storms generally move over central South Africa in a westerly and south-westerly direction.

Composite synoptic types : The synoptic systems described above are model situations. In reality, the various circulation systems occur together to produce complex composite synoptic types. These systems then tend to produce widespread rainfall. Some examples include the following from Preston-Whyte and Tyson (1988). During September 1981, snow and rain fell over the Transvaal highveld in response to a combined cut-off low and ridging anticyclone to the south of the continent. In April 1983, the alignment of easterly and westerly waves produced general rains over the south-eastern parts of southern Africa. In December 1978, an easterly low occurred together with a cut-off low and produced widespread heavy rainfall. The combination of an easterly wave and easterly low, occurring together with a ridging anticyclone produced good rains over the eastern areas of South Africa (figure 3.8). The above examples illustrate the variability and complexity of synoptic conditions.

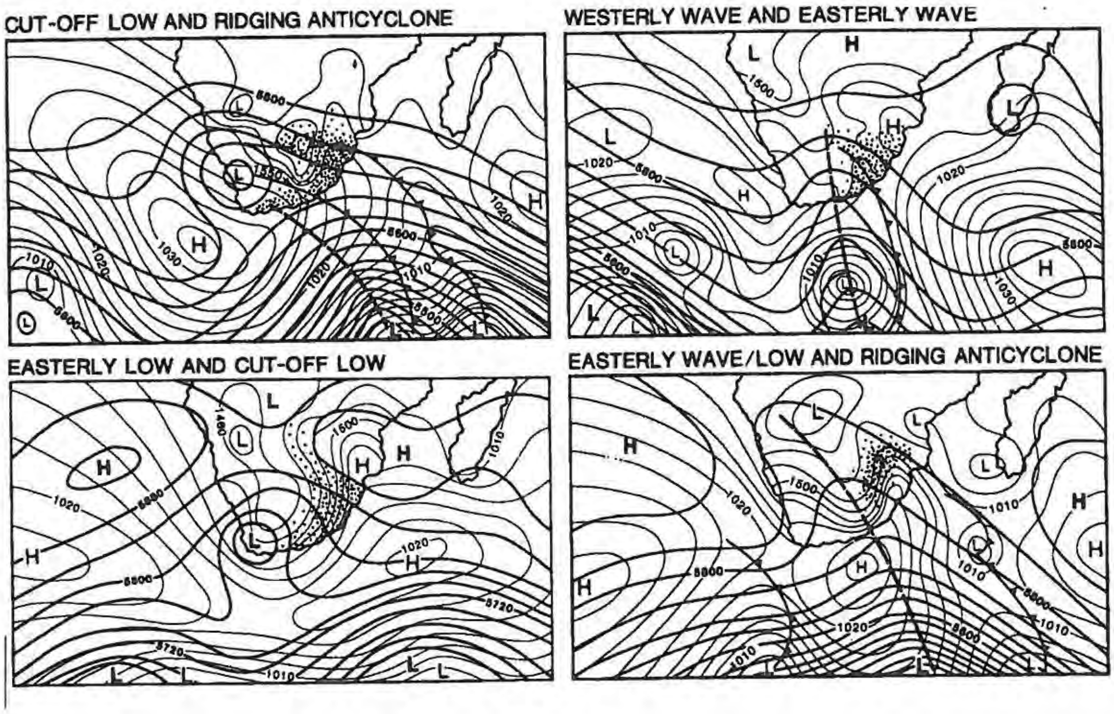


Figure 3.8 : Composite synoptic types. Areas receiving precipitation are stippled (After, Preston-Whyte and Tyson, 1988 : p 243).

In summary, not only is it difficult to pin-point the specific type of rainfall that is occurring in different regions of southern Africa, but also the intensity and duration of the rainfall.

These factors are important in determining rainfall/evaporation relationships within and between the different regions. This situation is further complicated by different synoptic systems occurring simultaneously to produce a different set of conditions, and by micro-scale conditions such as anabatic and katabatic winds, land and sea breezes, and local topography. Therefore, it is impossible to predict the daily conditions given the specific synoptic system that is prevailing on that day as no one set of conditions can be related to a specific synoptic system type. Therefore, the characterization of the weather systems is difficult as the combination of factors responsible for the development of specific weather systems are highly variable and complex.

3.4 THE RELATIONSHIP BETWEEN RAINFALL CHARACTERISTICS AND MAJOR MACRO-SCALE ATMOSPHERIC CIRCULATION SYSTEMS OVER SOUTHERN AFRICA

Many researchers (Lindesay, et. al., (1986); Lindesay, (1988); Van Heerden, et. al., (1988); and Walker, (1990)) have recognised the need to establish general relationships between South African rainfall and macro-scale atmospheric circulation over the southern African sub-continent. The inter-seasonal differences in South African rainfall have been identified and related to the phase changes of the Southern Oscillation.

In an attempt to characterize the association between the Southern Oscillation (SO) and South African rainfall in some detail, Lindesay, et. al., (1986) and Lindesay (1988) have found correlations between the Southern Oscillation Index (SOI), and the monthly and seasonal rainfall series. With reference to figure 3.9, the early summer season (October-December) rainfall correlations with the SOI are positive over most of South Africa, while for the later summer season (January-March) the correlation is strongest and positive over the central parts of South Africa, with lower negative correlations in the winter rainfall area of the south-western Cape (figure 3.9a,b). For the early winter season (April-June), the correlations over the summer and winter rainfall areas are very similar to those for January-March (figure 3.9c). However, this pattern of correlation reverses during the later half of the winter season (July-September) with weak negative correlations over the central and north-eastern areas and positive correlations in the south west (figure 3.9d). These seasonal correlations suggest that when the SOI is high, summer rainfall over South Africa is below normal. Secondly, for the winter rainfall areas, when the January-March correlations are negative, then the rainfall received during the high phase in summer is higher than the average. Therefore, over the summer rainfall regions, the high phase of the SO is responsible for increased rainfall totals, while the low phase of the SO is responsible for decreased rainfall totals. Over the winter rainfall regions this situation is reversed.

These macro-scale atmospheric systems have a direct effect on the synoptic systems that have been discussed earlier. Ultimately the various interactions between latitude, altitude, continentality and aspect, have a combined effect on rainfall, manifested in the differences in rainfall amounts, intensity, seasonality and local variability.

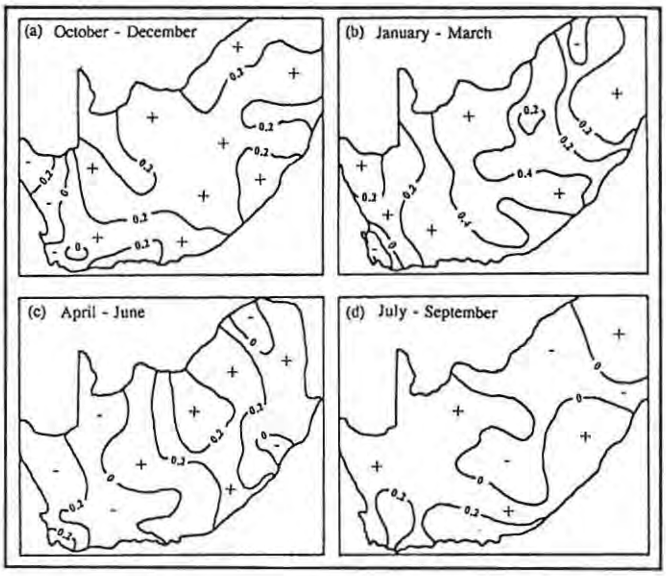


Figure 3.9 : Fields of correlation between seasonal rainfall series and the concurrent Southern Oscillation Index for a) early summer (October-December); b) late summer (January-March); c) early winter (April-June) and d) late winter (July-September) seasons. (After, Lindesay, 1988 : p 21).

CHAPTER 4

4. RAINFALL

4.1 INTRODUCTION

This chapter discusses the likely seasonal/regional variations in the occurrence of rainfall. A review of previous approaches to demarcating rainfall regions provides a background to the specific regional and seasonal divisions used in this study. The final section briefly discusses the problems associated with measuring rainfall and the availability of daily rainfall data in southern Africa.

4.2 SEASONAL/REGIONAL VARIATIONS IN THE OCCURRENCE OF RAINFALL

The climate of southern Africa is characterised by a high degree of intra- and inter-annual variability (Lindesay, 1984). The average annual rainfall for South Africa is 497mm which is well below the world average of 860mm (DWA, 1986). 48% of the total land surface has an average annual rainfall of less than 400mm, 32% between 400 - 800mm and 20% of the area has a rainfall exceeding 800mm (Kriel, 1983).

South Africa is situated within the high pressure belt of the mid-latitudes. The warm, dry descending air associated with these high pressure systems occur over a large area of the country, and produce conditions unfavourable for the development of rainfall. These synoptic systems are further influenced by the warm Agulhas current flowing south along the east coast, and the cold Benguela current flowing north along the west coast. The warmer east coast air masses are less stable than those along the west coast and are more likely to produce rainfall. Consequently rainfall is unevenly distributed over the country with more humid subtropical conditions being experienced along the east coast while dry, arid conditions prevail along the west coast. An example of the degree of variability in mean annual rainfall as a result of the above synoptic and sea current influences, is that the mean annual rainfall for Durban (on the east coast) is 1070mm in comparison to Port Nolloth's (on the west coast) 58mm, although both stations are at approximately the same altitude and latitude (Department of Water Affairs, 1986). Therefore, two extreme situations exist. On the east-facing Drakensberg escarpment in Natal, the air is often moisture-ladened and several different rainfall-producing mechanisms exist. In the arid area of the north-western Cape Province, the air is hot, dry and the topography is flat, culminating in fairly stable synoptic conditions with occasional convectional thunderstorms. Between these two extreme situations fall the complex climatology of the interior and southern regions of South Africa.

Southern Africa may be broadly categorized into winter, summer and all-seasons rainfall regions. The western and south-western Cape regions fall into the winter rainfall cycle, as more than 80% of annual rainfall occurs in winter. This is due to an annual cycle in anti-phase to that over the summer rainfall region. For example, the contribution of winter rainfall to the total annual precipitation increases from less than 10% in the far northern Transvaal to over 40% along the southern Cape coast (Tyson, 1986). Rainfall occurs mainly from frontal systems skirting the coast and this type of precipitation is generally of low to moderate intensity and of longer duration. Along the Cape mountains, orographic influences may result in heavier rainfall showers. Highest rainfall occurs in the mountain ranges of the south-western Cape and in the Drakensberg where the mean annual rainfall exceeds 3000mm in places.

The southern Cape coastal belt and immediate adjacent interior regions receive rain throughout the year. Precipitation is typically of low intensity and fairly long duration. The rest of southern Africa falls into the summer rainfall region. During the summer months low pressure troughs develop periodically over the interior. They have the effect of drawing in moist air from the north and north-east, which rises, cools and produces rainfall. The influence of these convergent systems diminishes over the western half of the interior, explaining why in the north-western Cape the air is hot, dry, stable and not favourable for producing rain. In the north-eastern and northern interior, 80% of the annual rainfall occurs between October and March in the form of high intensity, short duration convectional storms that are a result of atmospheric instability and diurnal heating (Tyson, 1986). These storms are generally associated with thunder, lightening and hail. Generally, rainfall tends to be more frequent and of a greater intensity in the summer rainfall regions as compared to lower intensity, longer duration rain events in the winter rainfall regions. Broader synoptic systems are responsible for long-term weather patterns such as droughts and floods. However, as this thesis is concerned with daily input data, these systems will not be discussed.

Superimposed on these variations will be a shorter time scale variation that is dependant on the radiation/humidity/rain condition during a single day. This variation can be expected to vary with the synoptic conditions prevailing on that day.

The regional differences in the occurrence of rainfall during the year, the prevailing synoptic conditions and the type of rain that occurs will inevitably lead to differences in the rainfall/evaporation relationships. The problem is to quantify these relationships at suitable scales, both spatially (regional) and temporally (seasonal). The actual daily rainfall and evaporation data input is important as this data forms the basis of the development of the regional rainfall/evaporation relationships. Therefore, a discussion on the measurement of rainfall and the particular problems associated with obtaining rainfall data is important as it is the primary input to all the rainfall/evaporation relationships that will be developed later.

4.3 DEMARCATION OF RAINFALL REGIONS

South Africa, with its considerable latitudinal extent displays a diversity of regional climatic characteristics. As stated earlier, the rainfall climatology is characterised by generally higher rainfall during summer in the eastern parts and by winter rainfall in the south western Cape. In the intermediate regions, the rainfall regimes merge. Although various researchers have differing ideas as to the method of dividing South Africa into rainfall regions and exactly where these divisions occur, they are all in agreement with the generalized classification made above.

The Schumann and Hofmeyr (1938) method of demarcating regions of similar seasonal rainfall for South Africa was to fit a sine curve to a plot of the normal monthly rainfalls of a given station. The phase (the number of days after 31 December at which the maximum of the sine curve falls) and the relative amplitude (the oscillation divided by the average monthly rainfall for the whole year) values for each station were plotted on a map, and lines of equal phase and relative amplitude were drawn, demarcating the seasonal rainfall regions (figure 4.1). McGee and Hastenrath (1966) felt that this method and other similar methods did not portray adequately the transition from one region to another. The authors applied harmonic analysis to the mean monthly precipitation of selected stations in South Africa. The gradual merging of the summer and winter rainfall regimes of the eastern Cape Province and the south western Cape were identified. In addition, the rapid transition from the southern Cape mountains to the coast and the abrupt change of the rainfall regime at the western edge of the plateau were identified.

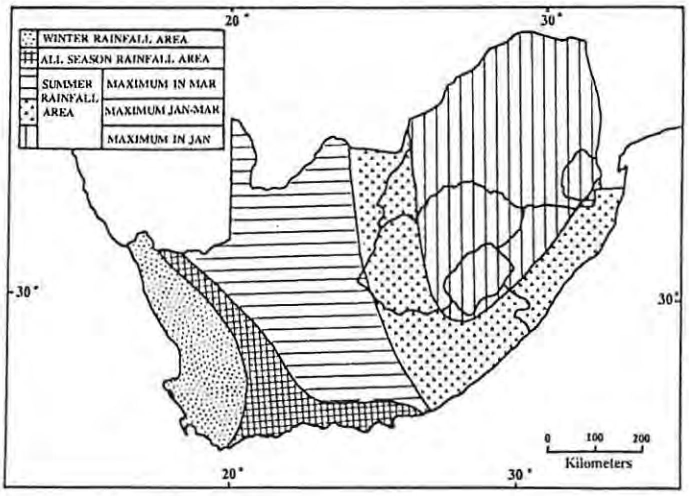


Figure 4.1 : The demarcation of seasonal rainfall zones in South Africa using the Schumann and Hofmeyr approach (After, McGee, 1977).

In a later study, McGee (1977) employed the Markham method to determine the seasonality of rainfall in South Africa. This method is based on the vector representation of the mean monthly rainfall totals. The seasonality index ranges from 100% (if all the precipitation occurred during a single month) to 0% (if precipitation was the same every month). McGee (1977) used monthly rainfall normals for 1921 - 1950, for 200 stations in South Africa, and found that the seasonality index had a latitudinal trend. Seasonality index values in the southern Cape were found to be low, generally less than 10%, indicating the non-seasonality of rainfall and the merging of the summer and winter rainfall regimes. Over the rest of the country, most values were in excess of 40% and the Transvaal stations had no index values less than 50%. Most of the northern Cape stations had the highest index values of 60%, indicating a very strong seasonality. Summer and winter regimes are clearly separated (figure 4.2).

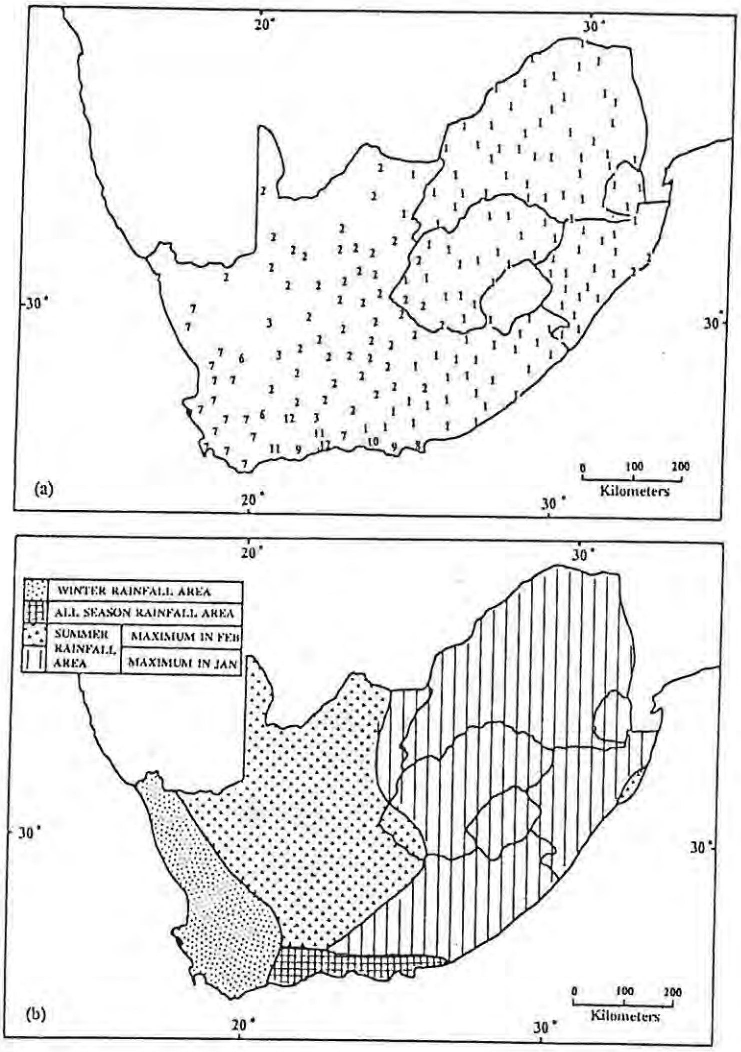


Figure 4.2 : (a) The concentration of precipitation in South Africa, by months (January = 1, February = 2, etc), and (b) The demarcation of seasonal rainfall zones in South Africa using the Markham method (After, McGee, 1977).

The summer regime is further separated into two halves, one half representing the concentration of rainfall in February, and the second half representing the maximum rainfall in January (for most of the eastern parts of South Africa). McGee's (1977) analysis also supports the existence of a narrow band of demarcation between the summer and winter regimes, along the western edge of the plateau. Comparing these three methods of demarcating rainfall seasonality, it was found that there were discrepancies between the rainfall seasonality maps (figures 4.1 and 4.2). The demarcation of the winter rainfall area is similar for both studies. However, in McGee's (1977) study the all-season rainfall area is restricted to the area where the seasonality index is less than 10%. In Schumann and Hofmeyr's (1938) study the all-season rainfall area extends up to the north-western Cape Province. McGee and Hastenrath's (1966) study supports McGee's (1977) demarcation, with respect to the sharper division between the winter and summer regimes.

Continuing on from these studies, Taljaard and Steyn (1991) recognised the need to divide southern Africa into homogeneous rainfall regions. This method depended on the seasons and months of highest rainfall. The winter (WMAX) and all-seasons rainfall (ASR) regions were clearly distinguished (figure 4.3). Next, the month of maximum summer rainfall was considered. Most of the Transvaal regions had a characteristic December or January maxima, except the south-western areas and the Transvaal was designated as a single region (TVL). The north-eastern regions of the Orange Free State experience a January maxima while the central and southern regions experience a February maxima. The northern areas of the northern Cape Province displayed an early February maxima, while in the southern areas the maxima occurred in late February. Consequently, the Orange Free State (except for the extreme north-eastern regions) and the northern Cape (except for the extreme south-western regions) were combined into one rainfall region with a February maxima (NCOFS).

The remaining area between the northern Cape and the winter and all-seasons rainfall regions, was designated as the Karoo, Cape Midlands and Border region (FEMAR), displaying a late February to March maxima. There are transitional zones along the western and southern borders of the Karoo where the March maxima transgresses into the winter and all-seasons regions. The remaining regions were added together to form a homogeneous region that included Natal, Transkei and Lesotho (NTL). The rest of southern Africa was divided according to state boundaries, and the regions are Zimbabwe (ZIM), Botswana (BOTS), northern Namibia (NNAM) and southern Namibia (SNAM).

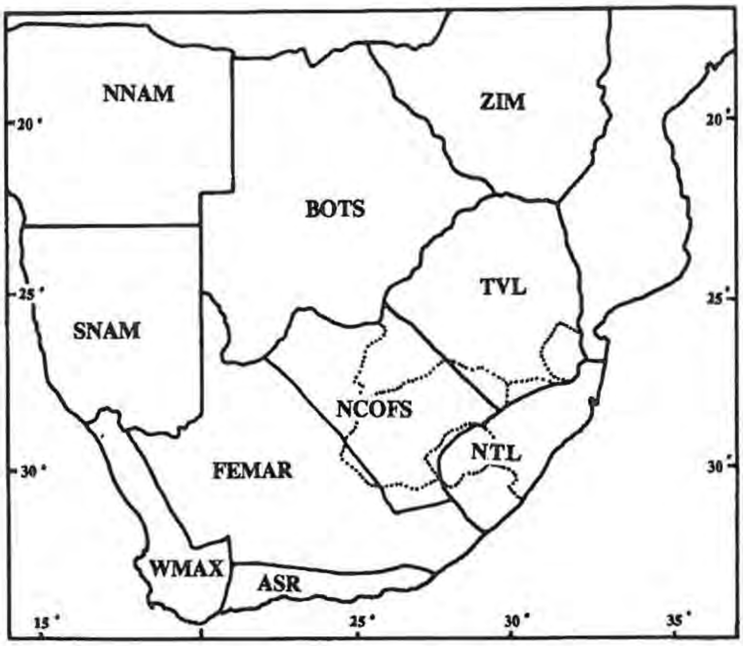


Figure 4.3 : The ten rainfall regions of southern Africa (After, Taljaard and Steyn, 1991 : p 14).

4.4 MEASUREMENT OF RAINFALL

Rainfall is normally measured directly using a raingauge. Several problems are inherent in this simple measurement technique. The major sources of error include the ability of a raingauge to accurately measure the amount of precipitation falling at a point, the data recording procedure, and the reduction of instrument failure time and consequent loss of data.

As emphasized by Schulze et. al., (1989, 1992) the quantity of rainfall reaching level ground is invariably greater than recorded by the gauge which leads to inherent errors in raingauge sampling. This has lead to a number of comparisons of different raingauge types and siting principles. The errors that occur in obtaining a representative sample at a gauge location have been termed 'local' errors, and may include splash in or splash out, evaporation losses, losses in wetting of the gauge surfaces, and inaccuracies due to the improper exposure of the gauge orifice (De Villiers, 1980).

The effect of wind and aspect is important. In windy conditions, turbulence in the air flow is created by the gauge itself, producing a turbulent eddying effect and resulting in a decrease in the catch of rainfall and unrepresentative measurements (Henderson-Sellers and Robinson, 1986). Some raingauges are equipped with wind shields - the effect being to divert the airflow down and around the gauge and minimize updrafts, downdrafts and turbulent eddies over the gauge. This only partially corrects the problem and generally is not that effective. A possible solution is to situate the gauge closer to the ground, as windspeed decreases rapidly as ground level is approached. However, the closer the raingauge is to the ground, the more likely it is for the raingauge to collect precipitation which has splashed in from the ground. This is important as many regions of southern Africa are characterized by convective high intensity rainfall promoting insplash, and the consequent exaggeration of the recorded rainfall amounts. Schulze (1975), showed that decreasing the gauge height from the standard orifice height of 1.22m to 0.3m resulted in the catch deficiency decreasing by 7.3%. However, a greater rainfall catch was recorded for summer, compared to an adjacent standard gauge, and this was largely due to insplash associated with large raindrops from convective storms.

A further detailed study by De Villiers (1980) showed that for different gauges at one meteorological site, the catch differences due to gauging techniques may be as high as 31.9%. It is evident that a sensible compromise is required with regards to raingauge heights.

The aspect element (the position of the rain receiving surface in relation to the paths of the falling rain drops) is important. Rain falls obliquely as a result of wind action. Therefore the windward facing slope will be more wetted than the leeward facing slope. De Villiers (1980) calculated the percentage difference in catch between the windward and leeward facing slopes for various inclinations of the ground and rain vectors, and found that these differences vary between 34% and 85%. On a macro-scale these differences may be cancelled out in the sense that what is lost on the one side of the slope is gained on the other side. However, in many instances this does not apply and so necessitates the use of inclined gauges. De Villiers (1980) experimented with different gauges to establish whether there was any meaningful difference between the values for different gauges on a sloping surface . He found that there were relatively large discrepancies, and the total catch for the inclined gauges was significantly higher than any of the other gauges.

A raingauge provides point measurements. Rainfall amounts, especially from a single storm event, can have a wide spatial variation. For example, in a thunderstorm system rainfall amount and intensity is not uniform throughout the system but may be concentrated in limited sectors. If there is no dense network of raingauges, then these spatial variations will not be identified (Henderson-Sellers and Robinson, 1986). This might explain differences in rainfall measurements from raingauges that are situated fairly close to each other.

Other problems include the data recording procedures and the reduction of instrument failure time and consequent loss of data. Hughes and Guthrie (1984) have emphasized that the ability of a gauge to measure point rainfall accurately and the extrapolation of this data to areal estimates, become redundant considerations if the recording device fails and no data is collected.

In conclusion, point rainfall values are only indices of the true rainfall due to the catch deficiencies caused by the aerodynamic interactions of rainfall, wind, the raingauge, altitude, slope steepness and orientation, and the barrier effects of the topography (Wiesner, 1970; Schulze, 1989). It is important to relate the amount of precipitation received by a given area to the nature of the surface and the associated wind field as well as the meteorological factors. All rainfall measurements are relative. The above problems are real and will remain potential sources of error in many hydrological analyses. Raingauge records need to be used with care and attention should be given to possible potential errors which could be accentuated in empirical studies. An awareness of the limitations of the data must be developed. As Neff (1977) emphasizes, "records, once collected and published, often gain an aura of respectability and precision that is beyond tolerances that can legitimately be assigned to them" (Neff, 1977 : p 218).

4.5 AVAILABILITY OF DAILY RAINFALL DATA IN SOUTHERN AFRICA

Daily rainfall data in South Africa may be obtained from the Computer Center for Water Research (CCWR), University of Pietermaritzburg, using the XDAYRAIN extraction program. The primary sources of this data are the South African Weather Bureau, the Department of Agriculture and Environmental Affairs, the Department of Water Affairs and Forestry, the South African Forestry Research Institute, the South African Sugar Association, Provincial parks boards and various private individuals.

Daily rainfall data is obtainable for over 9000 stations. This figure suggests a highly adequate network. However, several problems need to be recognised. Many rainfall stations are operated by volunteers which may lead to errors in reading and recording of data. Other errors may occur when the data is being transposed to computer records. Thirdly, data recorded during extreme events is often unreliable. For example, Dent, Lynch and Schulze (1988) found that of 3500 extreme events, data from only 1300 events could be accepted beyond doubt. Another serious problem is that of missing rainfall records. Dent, Schulze and Angus (1988) found that 95% of the rainfall stations had less than 14% data missing, but less than 2% of the missing data occurred in short sequences. 50% of the daily rainfall stations had at least 4% data missing, and mainly in long sequences. Therefore, care should be taken in checking the daily rainfall data for reliability and consistency.

CHAPTER 5

5. EVAPORATION : CONCEPTS AND MEASUREMENT

5.1 INTRODUCTION

"The degree of surface aridity in southern Africa is not only a function of precipitation, but also one of evaporation" (Tyson, 1986 : p 5). The basic water balance equation may be represented by the equation,

$$\Delta S = P - E - R$$

where,

ΔS = change in storage

P = rainfall

E = evaporation

R = runoff

Whitmore (1971) and others have illustrated the importance of the evaporation component in the context of southern Africa. Evaporation is a crucial consideration in water resources planning and management programmes, in evaluating the potential for water resources development and also in various water supply studies. The evaporation concept needs to be defined and an understanding of the processes involved is fundamental to the accurate measurement or estimation of evaporation at any spatial or temporal scale.

5.2 DEFINING EVAPORATION

The conversion of water molecules from the liquid to the vapour state across an evaporating surface and the vertical transport of this water vapour upward into the atmospheric boundary layer is known as evaporation (Ward, 1975; Schulze, 1989). For evaporation to occur, a source of energy and driving force are required for the phase transformation. The driving force is the vapour pressure difference between the surface and the overlying air and the main energy source is radiation. Because there is a continuous exchange of water molecules between an evaporating surface and the overlying atmosphere, it is common in hydrologic practice to define evaporation as the net rate of vapour transfer (Ward, 1975; Rodda et al, 1976). The four types of evaporation include potential evaporation, actual evaporation, potential evapotranspiration and actual evapotranspiration. It is important to identify and differentiate between these concepts as they will be useful in later discussions and explanations.

There are several definitions for potential evaporation, varying from a simple statement equating potential evaporation to the evaporation that would occur from a free-water surface, to more complex definitions (McIlroy, 1984; Granger and Gray, 1989). Morton (1971) defines potential evaporation as the evaporation that would occur from a continuously moist surface with regional characteristics, but with an area so small that the energy fluxes from the surface would have an insignificant effect on the evaporability of the overpassing air. Other researchers have identified the need to further specify the characteristic conditions under which potential evaporation would occur, placing more emphasis on the surface parameters and energy fluxes (Van Bavel, 1966; Priestley and Taylor, 1972).

It is evident that the concept of potential evaporation has yet to be adequately and clearly defined in a generally accepted manner. Granger's (1989) definitions of "equilibrium", "wet-surface" and "potential" evaporation are useful. The "equilibrium" evaporation rate is governed solely by the available energy and represents the lower limit to evaporation from a moist surface. The "wet-surface" evaporation is governed by the available energy and atmospheric conditions, and represents the evaporation that may be calculated using the Penman equation. The "potential" evaporation represents the upper limit to evaporation from a moist surface and is defined by the atmospheric conditions and the saturation vapour pressure at the actual surface temperature. For the purposes of this thesis, the potential evaporation may be defined as an "atmospheric demand" given an unlimited supply of moisture, and determined by various climatic variables. Schulze et. al., (1992) use the term "reference evaporation". Actual evaporation is the evaporation that would occur from a non-continuously moist surface. The linkage between potential evaporation and actual evaporation, and the factors influencing these two processes are schematically represented in figure 5.1.

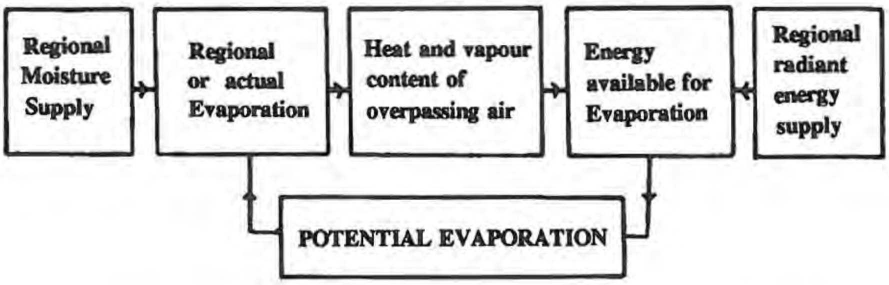


Figure 5.1 : Interactions between potential evaporation, actual evaporation and the influencing factors. (After, Morton, 1971 : p 82).

Having removed the restriction of adequate water supply for the concept of potential evaporation, it is necessary to make allowance for all factors relating to the soil and plant cover and the concepts of potential evapotranspiration and actual evapotranspiration are important. Water loss from plants, mainly leaves, is a complex process known as transpiration. Transpiration rates are difficult to measure and in practice it is difficult to separate water evaporated from the soil, intercepted moisture that remains on the vegetation after precipitation and is subsequently evaporated, and transpiration (Eagleson, 1970; Ward, 1971). For this reason, transpiration rates are dealt with in conjunction with evaporation rates and the composite term - evapotranspiration - is used for the combined processes of evaporation and transpiration.

The concept of potential evapotranspiration provides an upper limit to the combined losses due to both evaporation and transpiration and only occurs when the supply of water is unlimited , both to the plant stomata and to the soil surface. This implies that the potential evapotranspiration is restricted only by the energy fluxes available and not by a limited supply of moisture (Hansen, 1984). The actual evapotranspiration is the evaporation and transpiration that would occur from a surface with a limited supply of moisture. Various researchers have attempted to develop equations to express the relationship between potential evapotranspiration and actual evapotranspiration. The original research was done by Bouchet (1963) and later Morton (1976, 1978, 1980, 1983) developed the concept further, calling it the complementary relationship.

The **complementary relationship** takes into account the changes in the temperature and humidity of the air that is passing from a land to a lake environment. An increase in air temperature and a decrease in humidity would lead to an increase in the potential evapotranspiration. This is the result of the increase in heat flux and the decrease in vapour flux, associated with the reduction in the availability of water for the actual evapotranspiration (Morton, 1976, 1978). The above interactions tend to invalidate the generally accepted assumption that the potential evapotranspiration is the independent variable, while the actual evapotranspiration is the dependent variable. The complementary relationship introduces doubt about the commonly held ideas relating the actual and the potential evapotranspiration. Because the complementary relationship is based on the interaction between the evaporating surfaces and the overpassing air, the relationship avoids the complexities of the soil-plant system.

Bouchet (1963) hypothesized that, the decrease in the actual evapotranspiration was accompanied by an equal but opposite change in the potential evapotranspiration (Granger, 1989). Morton (1976, 1978) defined this concept further, by regression, by expressing the complementary relationship using two atmospheric boundary conditions ; under dry or arid conditions and under wet or humid conditions.

Morton (1983) established that the potential evapotranspiration for a wet environment (ET_w), is equal to half of the potential evapotranspiration for a dry environment, and thus ensures that the relationship is complementary (figure 5.2). Therefore,

$$ET=2ET_w-ET_p$$

where,

ET = actual evapotranspiration

ET_p = potential evapotranspiration

ET_w = wet environment actual evapotranspiration

(Morton, 1983 : p 15).

There is justification for scepticism about the complementary relationship because of the contrast between the simplicity of the concept, related to the complexity of the processes that this concept must reflect. Morton (1980) has cautioned that the complementary relationship is difficult to verify with currently available data and theoretical knowledge. However, there is sufficient evidence for its plausibility, as a working hypothesis, for example, the experimental research reported by Davenport and Hudson (1967), Solomon (1967), Morton (1978, 1983), Giusti (in Morton, 1983), Nash (1989) and Lemeur and Zhang (1990).

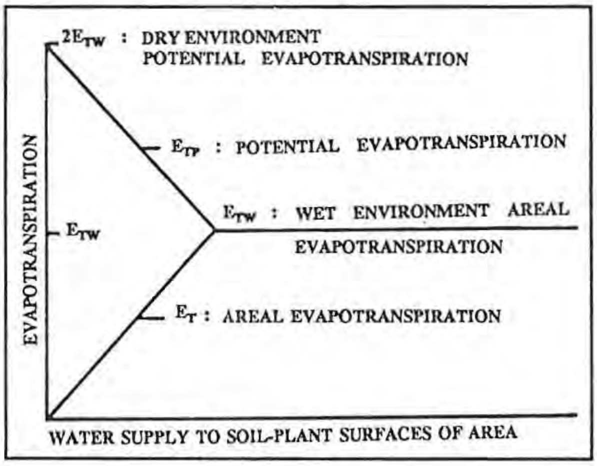


Figure 5.2 : Schematic representation of the complementary relationship potential evapotranspiration with a constant supply of radiant energy. (After, Morton, 1983 : p 16).

5.3 FACTORS INFLUENCING EVAPORATION RATES

Evaporation is the net result of the interaction of energy and aerodynamic factors. The mutual relationships and interdependency of the various climatic factors (such as radiation, temperature of the air, temperature of the evaporating surface, wind, vapour pressure deficits) are important.

The process of evaporation is most active under the direct radiation of the sun. Clouds which prevent the full spectrum of the sun's radiation from reaching the surface of the earth, will reduce the energy input and consequently reduce evaporation rates. The low frequency of cloud cover over much of South Africa and the high proportion of solar radiation reaching the surface contribute to potentially high evaporation rates, depending on the availability of moisture. The temperature of both the air and the evaporating surface are important as they govern the rate at which water molecules leave the surface and enter the overlying air. When a body absorbs energy its temperature increases. A simple relationship exists between the change in the energy of a body and its temperature change and may be expressed as,

$$\Delta E = pc \Delta T$$

where,

ΔE = change in energy
ΔT = change in temperature
p = density of a body
c = specific heat of a body
(Henderson-Sellers and Robinson, 1986)

The surface temperature increases as soon as the net radiation becomes positive. When the evaporating surface becomes warmer than the overlying air, a upward sensible heat flux is initiated. Since the rate of emission of molecules from water is a function of its temperature, the higher the temperature, the greater the energy of the molecules and so the higher the rate of emission. Similarly, as the capacity of the air to absorb water vapour increases as its temperature rises, so the more water vapour it can hold. For these reasons, evaporation tends to be higher in summer than in winter as heat is more readily available.

Air temperature has a diurnal variation which is related to radiation. Unless there are significant changes in the weather and cloud structures, the minimum air temperatures generally occur shortly after sunrise and the maximum temperatures in mid afternoon. This is important, as indicated earlier, the temperature of the air and the evaporating surface govern the rate of evaporation. However, as this thesis is concerned with daily evaporation rates, and not hourly evaporation rates, further discussion of this aspect is not essential.

Directly related to temperature is the water vapour capacity of the air. The rate of evaporation is proportional to the difference between the actual humidity and the saturated humidity at given temperatures. For example, as the relative humidity of the air immediately adjacent to the evaporating surface rises, so the capacity of the air to absorb more water vapour molecules decreases and leads to a reduction in the rate of evaporation (Ward, 1975; Shaw, 1983; Henderson-Sellers and Robinson, 1986). At a given temperature a maximum amount of water vapour can be held in the air and as the temperature rises, so more water vapour can be held. Generally evaporation may be higher in warm, dry conditions and lower in cold, calm conditions, because when the air is warm, the saturation vapour pressure of water is high, and when the air is dry, the actual vapour pressure of the water in the air is low. For South Africa, evaporation rates tend to be higher in the inland areas where the air tends to be drier than in the coastal regions that are affected by the influx of moist air from the oceans.

Advection is an important factor influencing evaporation. Advection results in the boundary layer of saturated air being removed and replaced by a drier air mass. Moderate windspeeds tend to maintain a steep humidity gradient, and in doing so, promote potentially high evaporation rates. When the wind velocity is high enough to remove all the water molecules escaping from the water surface, then a further increase in wind velocity will not increase evaporation appreciably. However, if the incoming air is preheated it will provide additional energy for evaporation. Conversely, the replacement of the boundary layer of saturated air by air of an equally high humidity, will not maintain the evaporation rate. These principle factors controlling evaporation rates, in turn, are affected by the nature of the evaporating surface and the prevailing weather pattern.

The nature of the evaporating surface affects evaporation by modifying the wind pattern. Over a rough, irregular surface, there is more turbulence and vertical mixing (Shaw, 1983). In contrast, over a smooth, even surface, there is little friction and turbulence and the process of evaporation is affected more by the horizontal velocity. For an open-water surface, (such as an evaporation pan) strong winds result in turbulence, causing waves to form, and this provides an increased surface for evaporation.

With respect to prevailing weather conditions, anticyclone or high pressure systems are dominated by subsidence. Dry air originates at high levels where there is little water vapour present. As the air sinks, it is warmed by compression. The air temperature increases with descent and the relative humidity decreases. The result is an increase in the stability of the atmosphere leading to fine, dry, settled conditions. High pressure systems are generally regions of clear sky conditions although strong surface heating can lead to cumulus cloud formation locally. These conditions are ideal for evaporation as long as there is air movement with the high pressure system. Conversely, low pressure systems or frontal depressions are usually associated with damp, unsettled weather and the air already contains a large amount of water vapour.

Evaporation is dependent on the availability of moisture. Once there is no moisture available then evaporation ceases. If there is a continuous supply of moisture, then evaporation is controlled by the meteorological factors already mentioned. Additional variables, influencing evaporation rates include soil and plant processes.

The rate of evaporation from a soil surface is governed by the same meteorological factors that govern evaporation loss from a free water surface, as soil evaporation is the evaporation of the films of water surrounding the soil grains and filling the voids between the soil particles. The amount of evaporation from a soil surface is dependant on the "evaporation opportunity". Therefore, the actual moisture content of the soil is important as it exerts the most direct influence on "evaporation opportunity". Capillarity movement of soil moisture is governed by the size and arrangement of the soil particles and will directly affect moisture availability for evaporation. Except for essentially physiological reactions, for example stomatal openings, the rate of transpiration is influenced by the same factors as those which control evaporation from a soil surface. Plants draw their supply of moisture from the soil and the rate of transpiration is limited to the rate at which soil moisture is supplied to the root system. The rate of transpiration is further governed by the stomata in the leaves, which act as valves to regulate the passage of water through the pores, according to the incidence of sunlight. Evaporation from the soil surface and transpiration, ultimately representing evapotranspiration, have been dealt with briefly. However, as potential evaporation will be used as a data input into this thesis, a detailed discussion on the physics and processes of evapotranspiration is unnecessary.

In conclusion, the relationship between evaporation and any of the above influencing factors combine to a greater or lesser degree, to make the in situ measurement of evaporation a difficult process. It may be an accepted fact that increased energy supply, higher temperatures of the evaporating surface and air, and advection will increase evaporation rates, while the humidity of the air has a damping influence. However, the exact role played by each of these factors and their quantitative contribution towards evaporation is not easy to identify and measure (Louw and Kruger, 1967; Sill, et. al., 1984). Given the complexity and variability of these processes, it is not surprising that there are difficulties in determining accurate estimation and measurement procedures.

5.4 EVAPORATION ESTIMATION AND MEASUREMENT TECHNIQUES

The importance of evaporation in the hydrological cycle is reflected in the long history of attempts to improve the accuracy of its estimation and measurement (Ward, 1975). Yet the estimation of evaporation still remains one of the most problematic components of the water balance equation. One of the major problems tends to be the incompatibility between the data requirements of some of the more physically-based models and the actual data that are available and collected on a routine basis at a sufficient number of stations (Viessman et. al., 1977; Ali and Mawdsley, 1987; Warnaka and Pochop, 1988). Another problem is applying essentially point process type approaches to larger areas and accounting for spatial variations. Two main approaches will be considered, the indirect approach or estimation techniques and the direct approach or measurement techniques.

5.4.1 Evaporation estimation techniques (Indirect Approach).

A number of methods exist for estimating evaporation and include the Water Budget, the Energy Budget, the Aerodynamic Approach and various Empirical methods.

The **Water Budget Approach** - Given the principle of continuity, the various components of the hydrological cycle may be expressed in the form of a water balance equation, which includes all the water components entering and leaving the catchment. Thus, the inflow or precipitation equals the outflow plus the change in the system. By evaluating or eliminating all but one of the factors in the equation, evaporation can be estimated. The water budget equation may be expressed as,

$$E=\Delta S+P-Q-D$$

where,

E = evaporation

ΔS = change in storage

P = precipitation

Q = discharge (surface runoff)

D = subsurface drainage

This approach appears simple but rarely produces reliable results. The main disadvantage is that the variables are difficult to measure accurately, especially changes in storage. Consequently, this technique is only really applicable over periods when changes in storage can be considered negligibly small and other errors are reduced by cancellation (Winter, 1981; Brutsaert, 1982; Sill et. al., 1984). This method is not generally practical over short time scales.

The **Energy Budget Equation** calculates the evaporation loss from a lake by computing the balance between the incoming energy and the expenditure of energy. The Energy Budget equation may be expressed as,

$$Qe=Qs-Qrs-Ql-Qc\pm Qg\pm Qv$$

where,

Qe = energy required for evapotranspiration

Qs = short-wave solar radiation

Qrs = reflected short-wave radiation

Ql = long-wave radiation from the water body

Qc = sensible heat transfer to the air

Qg = change in stored energy

Qv = energy transfer between water and bed

(Shaw, 1983)

This approach is based on temperature gradients and radiant energy and requires extensive and accurate measurements. While modern sensors and data recording equipment can provide the measurements, these are expensive and the method is impractical for routine use.

The **Aerodynamic Approach** is based on the assumption that evaporation is controlled by the windspeed and the vapour-pressure difference between the water surface and the atmosphere. Most empirical formulae in this approach use the Dalton equation,

$$E=a(1-b\mu)(es-ed)$$

where,

a and b = constants

μ = wind speed

es = saturation vapour pressure at the evaporating surface

ed = actual vapour pressure of the air

(Rodda, et. al.; 1976)

Much research has been undertaken by meteorologists on this approach but because of the very varied atmospheric conditions and the costly instrumentation and expertise required, this approach remains too complex for general application.

Empirical Methods include the Penman (1948) equation the Penman-Monteith model, the Thornthwaite (1948) equation, the Advection-Aridity model and the Linacre (1977) equation. Many of these empirical formula are based on Dalton's fundamental law, which states that if the vapour pressure of the adjacent air is less than the vapour pressure of the water surface then evaporation will occur. More recent methods have included principles of the aerodynamic and energy balance approaches. Although the various models differ among themselves, this does not imply that one or more of the approaches is incorrect - but that each may give a different weight to a given variable.

The **Penman (1948) equation** is one of the most widely used models and links the evaporation rate to the net flux of radiant energy at the surface with the ventilation of the surface by the air moving over it (Thom and Oliver, 1977). The model is based on two requirements ; there must be a supply of energy to provide latent heat of vaporisation, and there must be some method whereby the vapour is removed, if continuous evaporation is to occur. This is a combination method, combining both the energy budget and the aerodynamic approach, and in the process, eliminating the temperature of the evaporating surface parameter (Schulze, 1989). The Penman equation may be expressed as,

$$E=\frac{(\Delta/\gamma H+Ea)}{(\Delta/\gamma+1)}$$

where,

E = open water evaporation

Δ = slope of the saturation vapour pressure against temperature mm Hg/^{0}F

γ = psychrometer constant (0.27mm hg/^{0}F)

Ea = $0.35(1 + 9.8 * 10^{-3}\mu_2)$(ea - ed)

H = (1-r)Ra(0.18 + 0.55 n/N)

(Ward, 1967 : p 145)

Various researchers have cautioned that it is insufficient to use the wind speed function at a single height (2m) to measure turbulence (Ward, 1967). It has been suggested that for short periods of time, the accuracy of determining potential evaporation is unlikely to be better than 20% (Ward, 1967).

Makkink (1957) found that the Penman formula for potential evapotranspiration under-estimated measured values by 13%, but the Penman formula for evaporation overestimated measured free-water evaporation by 20%. Smith (1964) and Thom and Oliver (1977) found that the formula had a tendency to over-estimate potential evaporation during the spring months and under-estimate during the autumn months. In fact, Smith (1964) suggested that open-water pan evaporation provides a better measure of monthly and seasonal evaporation than the Penman and Thornthwaite formulae.

Obtaining an accurate value for net radiation is complicated. If the net radiation is measured, then the other parameters that need to be measured to estimate potential evaporation include air temperature, vapour pressure and windspeed. If the net radiation is calculated, the additional data requirements include latitude, time of year, sunlight duration, mean air temperature and mean daily windspeed. These extended meteorological data requirements mean that this equation is often impractical to use, as these data inputs are not generally available in southern Africa. Many of the constants in Penman's equation are empirical, and so must vary spatially. As the equation was developed in England, it must be adjusted when applied to areas with a different climate.

In the **Penman-Monteith Model,** the actual evapotranspiration is given by the formula,

$$E=\frac{\Delta Rn+\frac{Pcp}{ra}(es-e)}{\Delta+\gamma(1+\frac{rc}{ra})}$$

where,

E = actual evapotranspiration (Wm^{-2})
Δ = slope of the saturation vapour pressure curve at air temperature, t
Rn = net radiation (Wm^{-2})
γ = psychrometric constant
P = density of the air (kgm^{-3})
cp = heat of air at constant pressure ($Jkg^{-1}K^{-1}$)
ra = aerodynamic resistance (sm^{-1})
rc = canopy resistance (sm^{-1})
es = saturation vapour pressure (hPa)
e = actual vapour pressure (hPa)
(Lemeur and Zhang, 1990)

Lemeur and Zhang (1990) evaluated the Penman-Monteith model in terms of the consistency and reliability of the model applied in arid regions. They found that the model was sensitive to canopy resistance (rc), but not sensitive to the albedo (Lemeur and Zhang, 1990 : p 410). Stewart (1984) cautioned using the Penman-Monteith equation, as the model treats the evaporating area as if it were a 'single surface,' this being a considerable over-simplification of reality. Stewart (1984) concludes that the equation is not a valid method for estimating evaporation from areas of mixed vegetation.

The **Thornthwaite method** is used to estimate potential evapotranspiration and is based on the equation,

$$PE = 16\frac{(10t)}{(I)}a$$

where,

PE = potential evapotranspiration

t = mean temperature (^{o}C)

a = cubic function of I

I = annual heat index

(Wilson, 1974 : p 45)

The equation shows that the factors taken into account include mean air temperature and the hours of sunlight. Thornthwaite's justification for the use of only mean air temperature are that the need to calculate a parameter representing the vegetation cover effect is avoided, and that there is a fixed relationship between that part of the net radiation used for heating and that used for evaporation (provided that the soil is continually moist) (Ward, 1967). Thornthwaite maintained that the air temperature parameter would integrate the other meteorological factors affecting potential evaporation such as radiation, windspeed and humidity.

Many researchers have claimed that the model is empirical and complex. Thornthwaite has conceded that without nomograms and tables this formula is highly complicated. The formula is site-specific and although it gives satisfactory results for most regions of the United States and Canada, considerable discrepancies have been reported in the tropics and monsoon Asia (Chang, 1959). Generally, it has been shown that formulae which rely on temperature alone, neglecting the influence of wind, cloudiness and humidity are prone to estimation errors (Van der Bijl, in Chang, 1959; Smith, 1964).

It appears that the advantage and weakness of the Thornthwaite formula is that it's only input is mean air temperature. An advantage is that it may be applied in areas where there are few climatic data records. However, the limitations need to be recognised.

The **Advection-Aridity Model**, developed by Brutsaert and Stricker (1979); Brutsaert, (1982) calculates the actual evapotranspiration, using meteorological data, and is an implementation of the complementary relationship. In their approach, Brutsaert and Stricker (1979) have stated that the excess in the potential evaporation is equal to the deficit in the actual evapotranspiration, and that this excess and deficit provide an index of the aridity of the atmosphere, which in turn is related to the regional advection - and so the name Advection-Aridity model. The potential evaporation is given by the equation,

$$E=(2\alpha-1)\frac{\Delta}{\Delta+\gamma}(Rn-G)-\frac{\gamma}{\Delta+\gamma}Ea$$

where,

E = potential evaporation

α = saturated land surface, estimated as α = 1.26 for an 'advection-free' water surface

Δ = slope of saturation vapour pressure curve

γ = psychrometric constant

G = heat flux term

Rn = net radiation near the surface - the equivalent vapour pressure rate

Ea = drying power of the air, expressed as Ea = f(μr)(ea - ed), where,

f(μr) = function of mean windspeed (μr) at a level $z = z_r$ above ground

ea = vapour pressure of the air

ed = saturation vapour pressure at air temperature

(Brutsaert and Stricker, 1979 : p 443)

Lemeur and Zhang (1990) and Ali and Mawdsley (1987) have found that the Advection-Aridity model is sensitive to the albedo and surface roughness length. The reason for this seems to be the result of the use of Penman's wind function in the equation. Lemeur and Zhang (1990) claim that the use of a gross average of roughness length is inappropriate as the effects of short grass and bare soil will be neglected (because of the dominating effects of tall grass and trees). This is the result of the model having a regional approach. Ali and Mawdsley (1987) found that the model tended to overestimate evapotranspiration in dry conditions and underestimate when the water supply was unlimited. They attributed these errors to certain deficiencies within the model itself, such as the wind function and surface roughness parameters (Ali and Mawdsley, 1987 : p 275).

It is evident that the input requirements for this model need to be accurate and require a high degree of sophisticated monitoring and instrumentation, such as lysimeters. Even then, there do seem to be inherent deficiencies within the model itself such as the gross averaging of surface roughness, and the wind function, which suggests that there is room for improvement.

The **Linacre Equation** (1977, 1984) is based on the Penman equation, but relates its parameters to temperature variables, and uses temperature, altitude and latitude as the data base. The potential evaporation rate is expressed as,

$$Ep = \frac{\frac{650.Tm}{(85-\theta)} - 56 + (5 + 4.Ums)(Ta - Td)}{(80 - Ta)}$$

where,

Ep = potential evaporation (mm/day)

Tm = T + 0.006h

T = temperature

h = elevation in meters

Ta = mean air temperature in °C (Tmax + Tmin)/2

Td = mean dew point temperature in °C

(Ta - Td) = difference between air and dew point temperature, which equals (0.0023h + 0.37Ta + 0.53R + 0.35Rann - 10.9) °C

R = mean daily or monthly range of temperature (°C)

Rann = difference between the mean temperature of the hottest and coldest months of the year (°C)

Ums = average daily windspeed (ms^{-1}), which defaults to $1.5ms^{-1}$.

(Schulze, 1989 : p AT4-7)

Clemence and Schulze (1982) found that the Linacre equation (1977) gave better estimates of potential evaporation than other temperature-based equations and attributed this to the inclusion of the physical factors of elevation and latitude together with the temperature data. Clemence, Dent and Schulze (1985) added a maximum daily air temperature and daylength factor and altitude (m) to the Linacre equation in order to "integrate the effect of the maximum temperature in summer" (Clemence, Dent and Schulze, 1985 : p 177). However, although the Linacre equation performed better than other temperature-based equations, the estimates were not sufficiently accurate for general usage in southern Africa (Schulze, 1989). The need for local calibration was identified and Dent, Schulze and Angus (1988) further modified the Linacre equation by incorporating two physically-based variables, daylength and windspeed, expressing the radiation term as,

$$\frac{D_1(700Tm)}{(100-A)}$$

where,

D_1 = daylight hours (12)

Tm = T + 0.006h

T = mean temperature (°C)

h = elevation (m)

A = latitude (degrees)

This correction resulted in a marked improvement in the seasonal distribution of mean daily A-Pan evaporation values.

In general terms, there tends to be no one equation that can be readily used with a high degree of confidence and at the same time having input data requirements that can be readily met from available data. The main problem associated with these approaches is the need for extensive meteorological data inputs. This requires a high precision instrumentation network, a high degree of sophisticated monitoring (modern sensors) and recording equipment, continued maintenance and expertise, all being obtained at very high costs. Besides these problems, some of the equations are simply too empirical and complex, or there may be certain inherent deficiencies within the specific equations themselves.

5.4.2 Evaporation measurement techniques (Direct Approach).

Techniques used to directly measure the amount of evaporation occurring at a point include atmometers, evaporimeters, lysimeters and evaporation pans.

Atmometer and Piche evaporimeter : It is not obvious how their energy budget and aerodynamic properties relate to the energy budget and aerodynamic properties of evaporation from an open-water surface. Evaporimeters are housed in a Stevenson screen and one may presume that the amount of evaporation measured is analogous to a simple leaf placed in the shade, rather than from an open-water surface. Consequently, very little consistency has been found in correlating Piche evaporimeter and atmometer readings with open-water surfaces (Ward, 1971; Brutsaert, 1982).

Lysimeters operate on the principle that the evapotranspiration can be determined if the amount of rainfall, runoff and percolation in a plant-soil system are known. A major problem in measuring soil evaporation is to ensure that the soil conditions in the gauge are truly representative of the natural undisturbed conditions, otherwise the amount of moisture moving through the soil profile to the evaporating surface may be either overestimated or underestimated. Another problem is the generally unaccountable border effect caused by differences in exposure and different cultivation methods inside and outside the lysimeter (Chang, 1965). High installation and maintenance costs preclude the lysimeter from being used as a routine meteorological instrument.

The **Evaporation Pan** is the most common low technology measure of the amount of water lost from a unit surface of open water. The basis of evaporation determination by pan is the establishment of a water balance, which assumes the form,

$$E_0 = P - \Delta W$$

where,

E_0 = pan evaporation or potential evaporation

P = precipitation

ΔW = change in water levels
(Rodda et. al., 1976)

There are many different types of evaporation pans, each designed to suit particular research needs (Linsley et. al., 1958; Bloemen, 1978; Winter, 1981; Shaw, 1983). The three main types include the Colorado Sunken Pan or Symons Pan, the Geological Survey Floating Pan and the US Weather Bureau Class-A Pan. As A-Pan evaporation is a data input in this thesis, it is unnecessary to discuss the other types of evaporation pans, as extensive literature is readily available. The A-Pan is circular in shape with a diameter of 1.21m and is made of unpainted galvanized iron. The pan is 25.5 cm deep and is set on a base 15cm above the ground surface. The water level is maintained at a level 0.5cm below the rim. Daily evaporation is computed as the difference between the observed water levels, corrected for any precipitation that has occurred.

Research by Bosman (1987) has highlighted the need for proper pan installation and micro-site conditions, and have emphasized the influence of local climates on pan evaporation readings. Pan measurement errors may also arise because of the accumulation of dirt and algae in the pan itself. For this reason, and to prevent animals drinking from the pans, it is important that evaporation pans are screened. Bosman (1988) has found that screening suppresses losses from evaporation pans by 5 - 15% depending on the mesh size of the screen. Another problem is standardization. Today, most evaporation data is obtained from Class A-Pans, whereas earlier data may have been derived from a pan with different physical properties such as the Symons pan. Here, regional and seasonal dependent conversions to A-Pan equivalents are essential.

Evaporation pans give point measurement values. The extension of this information to other surfaces is not so obvious and is fraught with difficulties and inconsistencies. For example, how does pan evaporation relate to evaporation from a dam at that site, as the wind and temperature regimes of evaporation pans versus dams are very different? Many attempts have been made to relate pan evaporation to lake evaporation. The simplest approach is the development of an annual pan to lake coefficient, which is 0.7 for the A-pan (Brutsaert, 1982).

Another concern is the measurement of evaporation on days with rainfall. When it rains, rain falls into the evaporation pan and is accounted for by subtracting the amount of rainfall that was recorded by a raingauge. However, the dynamics and dimensions of the evaporation pan are obviously very different to those of a raingauge. Therefore, the method by which evaporation is measured and calculated on rainy days tends to be inadequate and prone to error and there is a general tendency to underestimate evaporation during rainfall events.

A-Pan evaporation has been selected as the reference for potential daily evaporation. The A-Pan is the most common evaporation pan in usage and the pan network, worldwide, is considerably denser and more representative than any other type of evaporimeter. (This is important in terms of comparing model performance in southern Africa with other regions that might have the same characteristics). For southern Africa, Clemence and Schulze (1982), Dent et. al., (1988), Schulze (1989) and Schulze et. al., (1992) have found that the A-Pan values give reasonably reliable estimates of potential evaporation and have been used extensively in ACRU. Although the use of A-Pan evaporation values to estimate potential evaporation is not without its problems, experimental evidence does indicate that these theoretical shortcomings are of lesser consequence than the problems of satisfying the data requirements of most of the estimation equations.

5.5 AVAILABILITY OF DAILY PAN EVAPORATION DATA IN SOUTHERN AFRICA

Daily pan evaporation may be obtained from the Computer Center for Water Research (CCWR), Pietermaritzburg, using the XTEMPEVAP extraction program. The primary sources of this data are the Department of Water Affairs and Forestry, the South African Weather Bureau and the Department of Agriculture and Environmental Affairs.

Daily pan evaporation is measured at over 750 stations in southern Africa, using the standard Class A-Pan (Schulze, et. al., 1992). This figure suggests a fairly large network.

Unfortunately, most of the daily pan evaporation data for stations does not exceed 10 years. The daily evaporation may contain gaps in the records, mainly over weekends and vacations, but often extending over several months. In some cases daily pan evaporation recording has been discontinued for several years. Care should be taken in checking the A-Pan data for reliability, as the problem of missing data cannot be overlooked. Perhaps one of the most serious problems of pan evaporation data, with respect to the objectives of this thesis, is the largely unknown errors associated with obtaining accurate pan losses during days with rainfall.

CHAPTER 6

6. METHODS AND MATERIALS

6.1 STUDY AREA

The study area has been taken as the whole of South Africa, including the independent states of Transkei, Ciskei, Bophuthatswana, and Venda. This is an area bounded approximately by latitudes 20 - 25°S and longitudes 16 - 33°E. The extent to which each part of this region is covered by the analyses carried out is determined by the number of available stations and is dealt with in the next section.

6.2 DATA BASE

Data Base : The data required for the study included both daily rainfall and daily evaporation. The Computer Centre for Water Research (CCWR), University of Natal, Pietermaritzburg, was the sole source of information because of easy data availability and accessibility. However, contributors of daily rainfall and daily evaporation to the CCWR include the South African Weather Bureau, the Department of Water Affairs and Forestry, the Department of Agriculture and Environmental Affairs, the South African Sugar Association, National Parks Boards and various private individuals. Data was extracted by running the CCWR programs XDAYRAIN and XTEMPEVAP, extracting daily rainfall and daily evaporation respectively. The data were then transferred to the PC local area network at the Institute for Water Research, Rhodes University. Some of the preliminary analyses were carried out on the CCWR computer but most were performed on PC's at Rhodes.

For southern Africa, those stations that record both daily rainfall and daily evaporation were selected as the data base for the study. Data from a total of 4757 rainfall stations are available compared to approximately 200 stations recording daily evaporation. However, only 186 stations are available where both daily rainfall and daily evaporation have been recorded.

Basis of data selection : The 186 stations were subjected to the following requirements ; (i) the records of daily rainfall and daily evaporation must correspond to the same time period, and (ii) the coincident rainfall and evaporation records must exceed ten years. The final number of data stations selected for the study totalled 117 and the spatial distribution of these stations is indicated in figure 6.1. The original station names have been used in the study. Details of the data record lengths of daily rainfall, daily evaporation, and concurrent daily rainfall and daily evaporation are presented in appendix A. The data stations were selected to represent the varying regional daily rainfall and daily evaporation characteristics of southern Africa wherever possible.

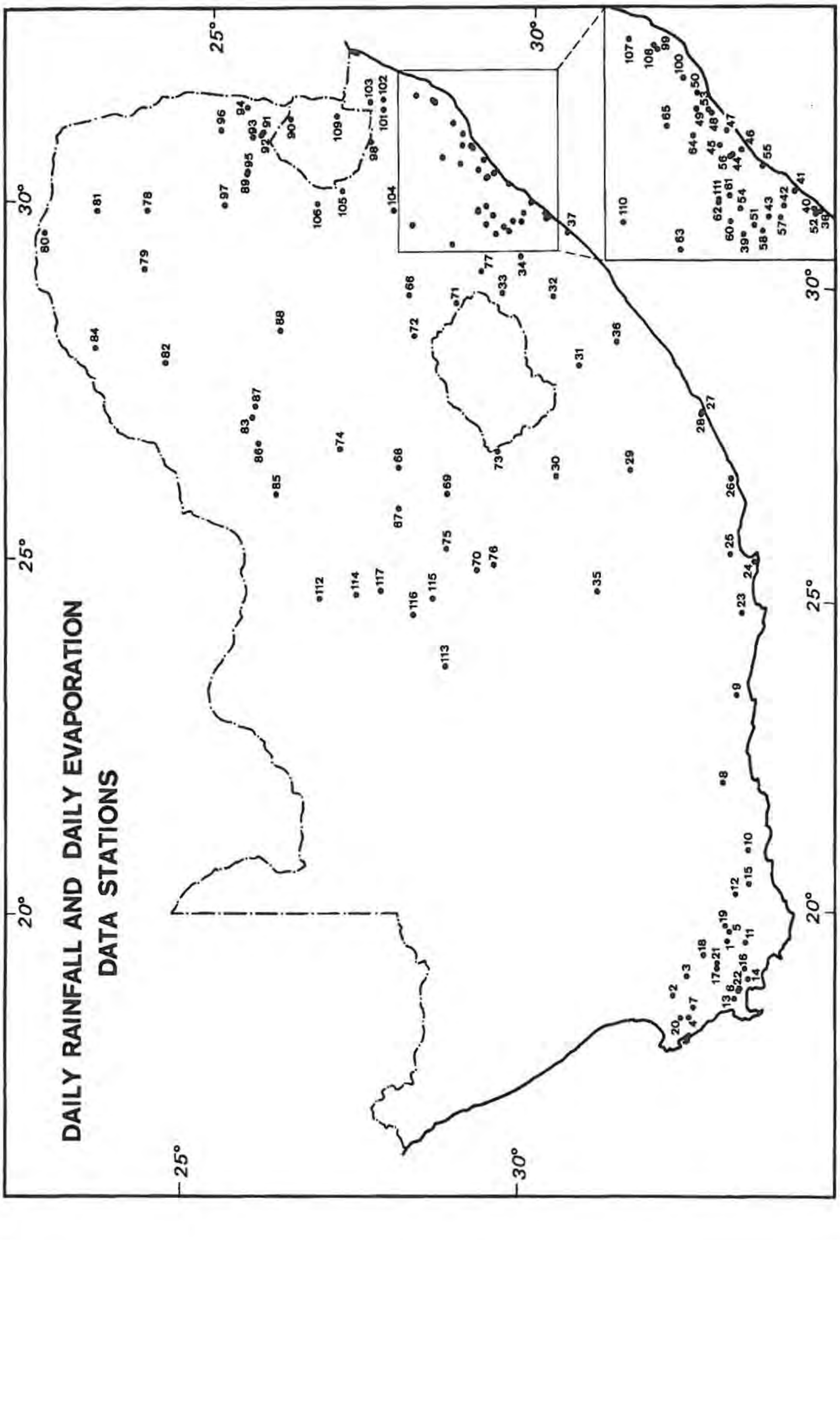
Spatial distribution and regionalization of data stations : The study area represents a very large area and not all regions will receive the same amounts of rainfall and exhibit the same rates of evaporation. In order to incorporate these differences into the rainfall/evaporation relationships the study area was divided spatially into ten specific regions, the south-western Cape, the eastern Cape coastal, the eastern Cape inland, the Natal coastal, the Natal inland, the Orange Free State, the Transvaal, the far eastern Transvaal, the northern Natal/Transvaal Border regions and the northern Cape region. Stations representing each region are tabulated in appendix A. This cursory initial subdivision of regions was based on the following findings.

Many researchers (Schumann and Hofmeyr (1938), McGee and Hastenrath (1966), McGee (1977), Taljaard and Steyn (1991)) have demarcated climatic regions of similar seasonal rainfall, and have established winter, all-year-round and summer rainfall regions. Other maps that were considered included the Schulze and Maharaj (1991) map on evaporation regions over southern Africa, the Dent, Schulze and Angus (1988) map on the delimitation of major wind regions in southern Africa, and, as vegetation type and growth is generally dependent on rainfall, the regional vegetation map produced by Acocks (1975), (Appendix B). Some of the regional divisions tended to be too general while others were too detailed and complicated. Finally, it was decided that the Taljaard and Steyn (1991) divisions would be used as a general basis for this initial regionalization of rainfall and evaporation, as the divisions tended to be reasonably detailed yet not too involved and were based on the months of maxima summer rainfall. However, the rainfall regions as demarcated by Taljaard and Steyn (1991) differ in some ways to the rainfall regions demarcated in this study and will be discussed further.

With reference to the Taljaard and Steyn map (Appendix B), WMAX represents the south-western Cape, the region with a winter rainfall maxima, while ASR represents the region with all-year-round rainfall. The north-eastern OFS has a January maxima while the central and southern regions have a February maxima. The northern Cape receives its highest rainfall in early February for the northern regions and late February for the southern regions. To account for these trends, Taljaard and Steyn (1991) combined the OFS (except the north-eastern regions) and the northern Cape (except the south-western regions) into a single rainfall region (NCOFS) with a February maxima. Most of the Transvaal experiences a December or January summer rainfall maxima and was designated as a separate region (TVL), including the north-eastern OFS but excluding the extreme south-western districts. The NTL region represents a combined Natal, Transkei and eastern Lesotho with a transitional rainfall maxima during December in the north, to February in the south. The FEMAR region includes the transitional regions of the Karoo, Cape Midlands and Border regions that have a late February to March rainfall maxima. The remaining regions include Zimbabwe (ZIM), Botswana (BOTS), northern Namibia (NNAM) and southern Namibia (SNAM), and were selected on the basis of them representing international states.

In this study, the first region demarcated was the winter and all-year-round rainfall regions. It was difficult to determine exactly where the borders between the two regions should be placed as some of the meteorological stations exhibited rainfall concentrated within the winter months, while other stations had a greater summer influence and tended towards an all-year-round rainfall situation. Consequently, the south-western Cape and all-year-round rainfall region of the southern Cape were grouped together as these stations are generally influenced by similar weather systems. The rest of South Africa falls into the summer rainfall or transitional to summer rainfall region.

Figure 6.1 : Spatial distribution of data stations.

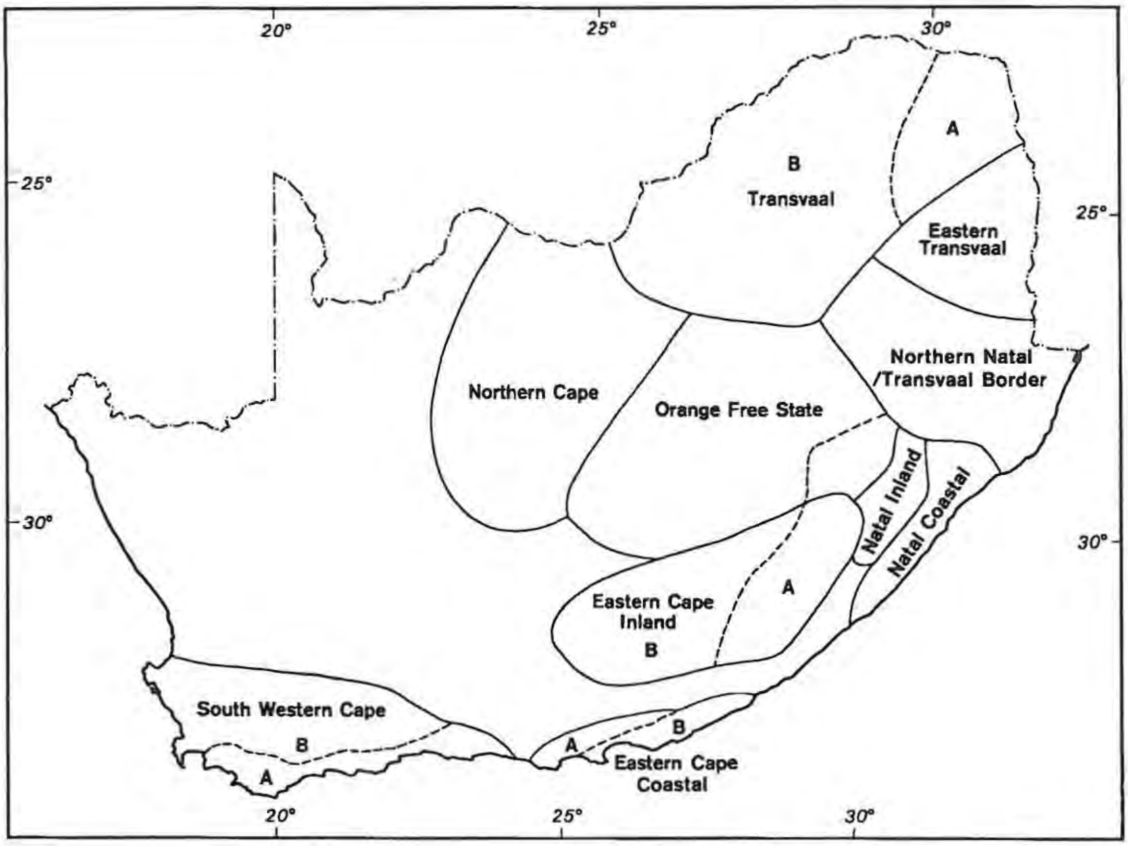


The eastern Cape region was further subdivided into the eastern Cape coastal and the eastern Cape inland regions to indicate possible regional differences as it is generally known that conditions along the coast differ from those experienced further inland. Natal, too, was subdivided into the Natal coastal and Natal inland regions, although the exact boundary line between these two subdivisions was arbitrarily decided apon.

The Orange Free State, was selected as a separate region on the basis of not really displaying any major differences in seasonal rainfall (Taljaard and Steyn, 1991). Similarly, the Transvaal was selected as another region, although the far eastern Transvaal bordering Mozambique, (because of its latitudinal position further north), may possibly display sufficiently different rainfall/evaporation characteristics to represent another region. The transitional region between the Transvaal and Natal, and the area along the Mozambique border, was designated as the northern Natal/Transvaal border region. Finally, the northern Cape was designated to include the northern and central interior and Namibia. It is hypothesized that the different regionalized zones are influenced by different climatic and meteorological systems and will exhibit different rainfall/evaporation characteristics, and these spatial differences will need to be incorporated into the rainfall/evaporation relationships to be established. The demarcation of the initial research regions are presented in figure 6.2.

The extent to which each region is adequately represented by the data stations is important. The south-western Cape region has 22 representative stations recording both daily rainfall and daily evaporation, with data record lengths exceeding 10 years. 63% of the stations have record lengths exceeding 15 years. The spatial distribution of these stations is representative of this region. Fewer stations are representative of the all-year-round rainfall region, and these stations have been included into the south-western Cape region. The eastern Cape coastal and inland regions are sparsely represented with only 6 and 8 stations representing these regions respectively. Data record lengths for both the eastern Cape coastal and inland regions are low compared to the south-western Cape with only one station with a data record exceeding 20 years, for each region.

Figure 6.2 : Demarcation of initial research regions.



In contrast the Natal coastal region has a higher number of stations (20) with concurrent daily rainfall and daily evaporation data exceeding 10 years and of these stations, 80% have data record lengths exceeding 20 years. The spatial distribution of these stations is representative of this region. The Natal inland region has fewer representative stations, but, some of these stations may have been included into the Natal coastal region. 33.3% of the stations have record lengths exceeding 20 years. The Orange Free State, Transvaal, eastern Transvaal and northern Natal/Transvaal border regions, have a wider 'spread' of stations representing each region. In terms of record length, only 33% of the stations representing the OFS have record lengths exceeding 20 years, while this percentage is even lower for the Transvaal (18%) and the eastern Transvaal (22%) respectively. Unfortunately, only 6 stations represent the large area designated as the northern Cape region, and of these stations, only 1 station has a record length exceeding 20 years. This is not adequate to establish exact locations of regional boundaries. The west Cape coastal and inland regions, extending up to the

Namibian border, are not represented by any stations with concurrent daily rainfall and daily evaporation data lengths exceeding 10 years. It is therefore impossible to develop any rainfall/evaporation relationships for this area.

In summary, the study relies on 117 data stations to develop generalized regional rainfall/evaporation relationships for southern Africa. The spatial distribution of these stations is not adequate for some of the regions. The data record lengths mentioned above are not continuous as they do not take into account missing daily data.

6.3 INITIAL INVESTIGATION OF DATA

The procedures followed, starting from the initial data extraction to the development of the parameter files required as input into the main analysis programs, are examined in this section. All the computer programs were written by Professor Denis Hughes, of the Institute for Water Research, Rhodes University.

Grouping of data : The data were grouped according to season, rainfall group and evaporation group. Initially, the analysis was based on four seasonal groupings, but because seasonal boundaries seemed to vary between regions it was decided to do the analysis on a monthly basis. The five rainfall groupings and six evaporation groupings are presented in table 6.1. The resolution of the data is 0.1mm, so that the 0 - 0.1mm rainfall category represents no rainfall. The daily evaporation data extracted from the CCWR was grouped according to the specified rainfall and evaporation groups. The frequency distribution graphs were compiled using the sorting procedures in a spreadsheet program on all available daily evaporation and rainfall data. These data were used to construct the evaporation frequency distribution graphs presented in chapter 7.

The daily rainfall data (extracted from the CCWR) were grouped according to the mean number of days on which rain occurred, within each rainfall group, for each month. Program A was designed to calculate the mean rain and number of raindays for each month and raingroup and the results used to construct the rainfall seasonality graphs are presented in chapter 7. The evaporation frequency distribution and rainfall seasonality graphs were the basis of a qualitative or graphical analysis, summarizing the regional rainfall/evaporation trends, presented in chapter 7.

Table 6.1 : Daily Rainfall and Daily Evaporation Groups

Rainfall Groups	Evaporation Groups
0mm - 0.1mm	0mm - 2.0mm
>0.1mm - 1.0mm	>2.0mm - 4.0mm
>1.0mm - 5.0mm	>4.0mm - 6.0mm
>5.0mm - 10.0mm	>6.0mm - 8.0mm
>10.0mm	>8.0mm - 10.0mm
	>10.0mm

Error checking of data : The main problems encountered were the presence of missing observations and outliers (mainly in the form of incorrect readings, that is, outside the admissible range of values). Data records collected over a long period of time will contain gaps, and usually, the number of gaps increases in proportion to the size of the data set. Gaps occur because a proportion of the observations are missing and some of the readings are incorrect or incorrectly recorded. An error check was conducted on the daily rainfall and daily evaporation data taking into account days with missing data. The main credibility check was a range test on each variable, in terms of what values looked 'odd' in comparison to the data set for that station. Outliers in the daily evaporation data values were identified. Outliers are observations that fall outside the admissible range of values. An outlier may be a case with an extremely high or low value on one variable. However, the outlier may not necessarily be influential. The outlier observation can only be called influential when its deletion from the analysis causes a pronounced change in one or more of the estimated parameters. Therefore, whether an observation is an outlier or not depends on the context of the analysis. Also, an observation that is an outlier in one sample may no longer be an outlier after the sample has been altered. For example, a change in form through the transformation process may change an observation so that it is no longer considered an outlier.

It is evident that identifying outliers can be a complex process, such as the use of regression plots and residuals. However, in this study, no complex statistical procedure was used to identify outliers in the data set. Possible outliers were identified by simply comparing the daily rainfall and daily evaporation data files obtained from the CCWR. Using this preliminary data check, it was difficult to determine whether the outlier would be influential or not. Consequently, values that were obvious errors, such as very high rainfall values coinciding with very high evaporation values were deleted. In some cases, the rainfall values may have been accumulated into a single value. For example, although rainfall may have occurred on a number of days, the accumulated amount may have been measured on the last day. While the rainfall database contains codes to indicate where this occurs, these values have to be removed in any analysis of rainfall/evaporation relationships.

When deleting 'suspicious-looking' values, the context of the situation was taken into account. For example, high rainfall values do not necessarily indicate erroneous data. Therefore, if there was any doubt as to whether the value could possibly be correct, then it remained in the data set. The outliers identified were probably due to errors including misreading, incorrect data processing, and errors due to the failure of raingauge equipment and interference with the evaporation pan.

Descriptive statistics : Descriptive statistics were required to indicate the characteristics of the daily evaporation data. Measures of central location and dispersion were obtained and included the mean (indicating central tendency), the standard deviation and skewness (dispersion measures) of evaporation values, within each month and raingroup. Program B was designed to estimate the summary distribution statistics, and create the parameter files used as input into the main analysis programs. Program B reads the daily rainfall and evaporation files, checks for missing data and determines the rainfall group. The program calculates the number of days with rainfall according to the raingroup categories for each month, the mean, standard deviation and skewness of evaporation values for each raingroup and month, and the mean daily rainfall for each month.

The range of values of skewness indicated that the shapes of the distribution of evaporation values within different raingroups/month/station were highly variable, and frequently very different from a Normal distribution. As a later part of the analysis (sampling from a distribution to obtain estimates of evaporation given rainfall) assumes Normality, it was necessary to determine a transformation approach. The Box-Cox family of transformations can be used to effect an approximation to a Normal distribution regardless of the original skewness and the specific equation of transformation is controlled by the lambda parameter. The transformation is represented by the equation,

$$T_E=\frac{E^{\lambda}-1}{\lambda}$$

for $\lambda \neq 0$

$$T_E=\ln(E)$$

for $\lambda = 0$

where,

T_E = transformed evaporation values

E = evaporation values

λ = lambda values

The best fit lambda value was calculated according to fixed criteria. The Johnson and Wichern (1982) algorithm can be used to optimise the lambda value. The expression

$$(\lambda-1)\sum lnE-\frac{n}{2}\ln[\frac{1}{n}\sum(T_E-\overline{T_E})^2]$$

is maximized to produce the best fit lambda value which represents the degree of deviation (positive or negative) from a non-skewed Normal distribution. Program B was also used to calculate the statistics of the transformed evaporation data for each raingroup and month and the combined parameter data sets formed the basis of the quantitative or numerical analysis presented in the second part of each sub-section of chapter 7. An annotated copy of one of the input parameter files is presented in table 6.2

Coefficient of efficiency analysis based on daily data : The coefficient of efficiency represents a statistical relationship which measures the "goodness-of-fit" between the observed and simulated evaporation values compared to using the observed mean as an estimation of the actual observed evaporation value. The mean daily evaporation is calculated for each raingroup and each month to produce the simulated daily evaporation values (the raingroup evaporation weights, REW's). The coefficient of efficiency may be expressed as,

$$CE = 1 - \frac{\sum (ObsE_i - SimE_i)^2}{\sum (ObsE_i - MeanE)^2}$$

where,

CE = coefficient of efficiency

$ObsE_i$ = observed daily evaporation

$SimE_i$ = simulated daily evaporation equivalent to the mean daily evaporation for the relevant rainfall group

MeanE = mean daily evaporation

Clearly, if the sum of squares difference between the observed and simulated values is lower than the sum of squares difference between the observed and observed mean then the coefficient of efficiency value will be positive. Otherwise the coefficient of efficiency value will be negative.

Program C calculates the coefficient of efficiency for daily data. Input into program C includes the ordinary and transformed parameter files, and the daily rainfall and daily evaporation data files. The results from the coefficient of efficiency analysis based on daily data were encouraging. The coefficient of efficiency values were positive for all 14 representative stations indicating that the simulations of daily evaporation (on the basis of the raingroup evaporation weights (REW's)), were better than when the mean overall evaporation values (not corrected for rain) were used.

Table 6.2 : Annotated copy of the input parameter file for Vryburg;Armoedsvlakt

Station number		Month	Daily mean evap	Ordinary or transformed data				
432237		1	9.05	ORDINARY				
Rainfall groups		No. data points	Lambda values	No. of days	Mean evap	Standard deviation	Skewness	Mean Rain
1	0.1	687	0.80	21.60	1.04	0.34	0.12	0.00
2	1.00	66	0.70	2.08	0.97	0.36	0.28	0.40
3	5.00	110	0.70	3.46	0.79	0.37	0.33	2.60
4	10.00	54	1.00	1.70	0.90	0.28	0.01	6.80
5	1000.00	69	0.80	2.17	1.04	0.48	0.17	19.09
432237		2	7.43	ORDINARY				
1	0.1	614	0.70	20.94	1.06	0.36	0.42	0.00
2	1.00	71	1.20	2.42	0.90	0.32	-0.40	0.43
3	5.00	103	0.50	3.51	0.80	0.36	0.67	2.33
4	10.00	52	0.90	1.77	0.81	0.37	0.01	7.04
5	1000.00	69	0.60	2.35	0.99	0.53	0.31	17.56
432237		3	6.21	ORDINARY				
1	0.10	703	0.50	22.12	1.05	0.35	0.59	0.00
2	1.00	58	0.50	1.83	0.82	0.39	0.58	0.43
3	5.00	115	0.70	3.62	0.85	0.38	0.28	2.44
4	10.00	43	0.80	1.35	0.78	0.39	0.07	6.95
5	1000.00	66	0.80	2.08	1.07	0.56	0.04	16.86
432237		4	4.92	ORDINARY				
1	0.10	790	0.50	25.46	1.01	0.37	0.80	0.00
2	1.00	43	0.20	1.39	0.89	0.43	0.92	0.45
3	5.00	58	0.80	1.87	0.85	0.38	0.08	2.37
4	10.00	33	0.60	1.06	1.05	0.50	0.51	6.57
5	1000.00	38	0.50	1.22	1.07	0.51	0.42	16.41
432237		5	4.05	ORDINARY				
1	0.10	934	0.40	28.81	1.00	0.37	0.63	0.00
2	1.00	18	0.20	0.56	1.01	0.47	0.54	0.49
3	5.00	32	1.00	0.99	0.81	0.37	-0.20	2.00
4	10.00	10	0.70	0.31	0.84	0.53	0.27	7.28
5	1000.00	11	1.00	0.34	1.30	0.68	-0.55	15.53
432237		6	3.55	ORDINARY				
1	0.10	871	0.50	29.51	1.00	0.39	0.68	0.00
2	1.00	12	0.50	0.41	0.97	0.40	0.72	0.30
3	5.00	15	0.30	0.51	0.84	0.49	0.58	2.34
4	10.00	6	0.50	0.20	0.82	0.69	0.53	6.07
5	1000.00	11	0.20	0.37	1.15	0.72	0.61	15.41

432237		7	3.86	ORDINARY				
1	0.10	916	0.50	30.21	1.00	0.36	0.82	0.00
2	1.00	5	0.30	0.16	0.80	0.55	0.88	0.38
3	5.00	10	0.70	0.33	0.92	0.38	0.23	1.63
4	10.00	2	0.00	0.07	0.56	0.42	0.00	5.65
5	1000.00	7	0.00	0.23	1.12	0.64	0.79	13.85
432237		8	5.41	ORDINARY				
1	0.10	914	0.30	29.76	1.00	0.35	0.65	0.00
2	1.00	9	1.30	0.29	1.05	0.48	-0.75	0.40
3	5.00	16	0.70	0.52	0.84	0.37	0.50	2.00
4	10.00	4	0.00	0.13	1.00	0.23	0.44	7.53
5	1000.00	9	0.30	0.29	1.10	0.58	0.33	16.46
432237		9	7.61	ORDINARY				
1	0.10	872	0.60	29.45	1.01	0.36	0.48	0.00
2	1.00	7	0.20	0.24	0.87	0.65	0.54	0.33
3	5.00	19	0.10	0.64	0.70	0.46	0.69	2.68
4	10.00	10	1.50	0.34	0.78	0.30	-0.69	6.95
5	1000.00	10	0.00	0.34	0.84	0.45	1.30	14.93
432237		10	9.06	ORDINARY				
1	0.10	807	0.50	26.28	1.02	0.33	0.43	0.00
2	1.00	36	0.80	1.17	0.88	0.32	-0.01	0.38
3	5.00	53	0.80	1.73	0.82	0.35	0.09	2.45
4	10.00	25	0.70	0.81	0.89	0.30	0.56	6.73
5	1000.00	31	1.20	1.01	0.95	0.39	-0.42	14.61
432237		11	9.61	ORDINARY				
1	0.10	677	0.90	23.04	1.05	0.31	0.14	0.00
2	1.00	50	1.10	1.70	0.86	0.31	-0.15	0.42
3	5.00	91	1.00	3.10	0.85	0.36	-0.27	2.56
4	10.00	47	1.30	1.60	0.83	0.28	-0.41	6.81
5	1000.00	46	0.90	1.57	0.92	0.37	0.12	17.41
432237		12	9.79	ORDINARY				
1	0.10	680	0.90	22.76	1.03	0.29	0.14	0.00
2	1.00	45	1.10	1.51	0.94	0.29	-0.19	0.47
3	5.00	93	0.20	3.11	0.89	0.31	0.58	2.40
4	10.00	54	1.10	1.81	0.90	0.27	-0.18	6.87
5	1000.00	54	1.00	1.81	0.91	0.35	-0.14	16.69
432237		1	9.05	TRANSFORMED				
1	0.10	687	0.80	21.60	0.03	0.34	-0.07	0.00
2	1.00	66	0.70	2.08	-0.05	0.37	-0.01	0.40
3	5.00	110	0.70	3.46	-0.25	0.40	-0.05	2.60
4	10.00	54	1.00	1.70	-0.10	0.28	0.01	6.80
5	1000.00	69	0.80	2.17	0.02	0.49	-0.10	19.09

432237		2	7.43	TRANSFORMED				
1	0.10	614	0.70	20.94	0.04	0.35	0.07	0.00
2	1.00	71	1.20	2.42	-0.08	0.30	-0.17	0.43
3	5.00	103	0.50	3.51	-0.26	0.41	0.00	2.33
4	10.00	52	0.90	1.77	-0.21	0.39	-0.14	7.04
5	1000.00	69	0.60	2.35	-0.07	0.56	-0.19	17.56
432237		3	6.21	TRANSFORMED				
1	0.10	703	0.50	22.12	0.02	0.34	0.03	0.00
2	1.00	58	0.50	1.83	-0.25	0.44	0.00	0.43
3	5.00	115	0.70	3.62	-0.19	0.41	-0.06	2.44
4	10.00	43	0.80	1.35	-0.25	0.42	-0.15	6.95
5	1000.00	66	0.80	2.08	0.03	0.57	-0.18	16.86
432237		4	4.92	TRANSFORMED				
1	0.10	790	0.50	25.46	-0.02	0.37	0.04	0.00
2	1.00	43	0.20	1.39	-0.20	0.47	-0.02	0.45
3	5.00	58	0.80	1.87	-0.17	0.40	-0.14	2.37
4	10.00	33	0.60	1.06	0.00	0.50	-0.03	6.57
5	1000.00	38	0.50	1.22	0.01	0.51	-0.12	16.41
432237		5	4.05	TRANSFORMED				
1	0.10	934	0.40	28.81	-0.04	0.37	-0.04	0.00
2	1.00	18	0.20	0.56	-0.08	0.48	0.00	0.49
3	5.00	32	1.00	0.99	-0.19	0.37	-0.20	2.00
4	10.00	10	0.70	0.31	-0.23	0.59	-0.18	7.28
5	1000.00	11	1.00	0.34	0.30	0.68	-0.55	15.53
432237		6	3.55	TRANSFORMED				
1	0.10	871	0.50	29.51	-0.04	0.39	0.02	0.00
2	1.00	12	0.50	0.41	-0.07	0.41	0.00	0.30
3	5.00	15	0.30	0.51	-0.29	0.59	-0.17	2.34
4	10.00	6	0.50	0.20	-0.41	0.94	-0.62	6.07
5	1000.00	11	0.20	0.37	-0.02	0.68	-0.07	15.41
432237		7	3.86	TRANSFORMED				
1	0.10	916	0.50	30.21	-0.03	0.36	0.09	0.00
2	1.00	5	0.30	0.16	-0.37	0.72	-0.49	0.38
3	5.00	10	0.70	0.33	-0.11	0.40	-0.06	1.63
4	10.00	2	0.00	0.07	-0.75	0.84	0.00	5.65
5	1000.00	7	0.00	0.23	-0.03	0.58	0.13	13.83
432237		8	5.41	TRANSFORMED				
1	0.10	9.14	0.30	29.76	-0.04	0.35	-0.05	0.00
2	1.00	9	1.30	0.29	0.08	0.46	-0.59	0.40
3	5.00	16	0.70	0.52	-0.19	0.40	-0.06	2.00
4	10.00	4	0.00	0.13	-0.02	0.23	0.00	7.53
5	1000.00	9	0.30	0.29	0.00	0.57	-0.08	16.46

432237		9	7.61	TRANSFORMED				
1	0.10	872	0.60	29.45	-0.01	0.36	0.03	0.00
2	1.00	7	0.20	0.24	-0.37	0.83	-0.31	0.33
3	5.00	19	0.10	0.64	-0.54	0.67	-0.10	2.68
4	10.00	10	1.50	0.34	-0.18	0.25	-0.29	6.95
5	1000.00	10	0.00	0.34	-0.30	0.52	0.04	14.93
432237		10	9.06	TRANSFORMED				
1	0.10	8.07	0.50	26.28	0.00	0.32	-0.04	0.00
2	1.00	36	0.80	1.17	-0.13	0.34	-0.12	0.38
3	5.00	53	0.80	1.73	-0.21	0.37	-0.17	2.45
4	10.00	25	0.70	0.81	-0.13	0.31	0.09	6.73
5	1000.00	31	1.20	1.01	-0.03	0.38	-0.22	14.61
432237		11	9.61	TRANSFORMED				
1	0.10	677	0.90	23.04	0.04	0.31	0.05	0.00
2	1.00	50	1.10	1.70	-0.13	0.30	-0.03	0.42
3	5.00	91	1.00	3.10	-0.15	0.36	-0.27	2.56
4	10.00	47	1.30	1.60	-0.15	0.26	-0.10	6.81
5	1000.00	46	0.90	1.57	-0.09	0.38	-0.04	17.41
432237		12	9.79	TRANSFORMED				
1	0.10	680	0.90	22.76	0.03	0.29	0.05	0.00
2	1.00	45	1.10	1.51	-0.05	0.29	-0.10	0.47
3	5.00	93	0.20	3.11	-0.16	0.34	-0.01	2.40
4	10.00	54	1.10	1.81	-0.10	0.27	-0.06	6.87
5	1000.00	54	1.00	1.81	-0.09	0.35	-0.14	16.69

COREVAP programs and coefficient of efficiency analysis based on monthly data : The COREVAP programs were run on a PC and developed to simulate monthly evaporation from monthly rainfall records. The results of the monthly analysis will depend on the accuracy of the observed monthly evaporation values.

When using the monthly rainfall and evaporation data files (obtained from the CCWR) as input into the COREVAP programs, the coefficient of efficiency values were highly negative. A data check was used to identify and eliminate possible problems and revealed that the observed and simulated monthly evaporation values were very different. The sum of the actual daily evaporation values were compared with the monthly evaporation totals obtained from the CCWR. A discrepancy between the daily evaporation totals and the generated

CCWR monthly evaporation totals was identified. The method of calculating the monthly evaporation totals from the daily data, on the CCWR, did not account for days with missing data. An additional problem was that in some cases the monthly evaporation totals did not correspond to the sum of the actual daily added totals, whether there was missing data or no missing data. Consequently, a routine was added to Program C (above) to infill missing daily evaporation values, using the mean for the relevant rainfall group, and calculate improved monthly evaporation totals.

In order to use the parameters generated from the daily analysis in a monthly analysis it was necessary to develop a procedure to estimate how many days of the month lie within each of the rainfall groups. The procedure uses the mean monthly rainfall and the mean number of days in each raingroup.

This procedure assumes that the actual number of days in each raingroup is increased or decreased (from the mean number of days) in proportion to the actual monthly rain, divided by the mean monthly rain. Therefore,

$$Ndays_{ij}=\frac{P_j}{\overline{P_j}}\times\overline{Ndays_{ij}}$$

for rain groups 2 to 5, where,

$Ndays_{ij}$ = the actual number of days in group i, for month j

$\overline{Ndays_{ij}}$ = the mean number of days in group i, for month j, for complete record

P_j = actual monthly rainfall (for month j)

P_j = mean monthly rainfall (for month j), for complete record

In effect, what this means is that as more rain occurs relative to the mean monthly rain, the number of days in each of the four raingroups will increase. The balance of the days will then fall into the no rain days category (raingroup 1). However, there is a need to check that $Ndays_{ij}$ does not exceed the total number of days in that month and adjust the four raingroup number of days as necessary.

The monthly rainfall and evaporation data (obtained from the infilling procedure) together with the parameter files (transformed and untransformed) are input into the COREVAP programs, and are used to compare across different groups (station/ season/ rainfall) and to estimate evaporation based on the amount of rainfall.

For COREVAP1, the estimated monthly evaporation is the sum of the product $Ndays_i$ * mean daily evaporation for raingroup i, for raingroups 1 to 5. COREVAP2 uses a random sampling procedure to draw $Ndays_i$ samples from a restricted part of the daily evaporation distribution for raingroup i (defined by the mean and standard deviation). The samples are restricted to be drawn from between plus and minus one standard deviation either side of the mean. The estimated monthly evaporation is the sum of the samples. COREVAP3 is similar to COREVAP2 but samples from the full distribution of the daily evaporation distribution for each raingroup. Thus, using COREVAP1,

$$Evap_{est}=\sum^{5}{}_{(i=1)}\bar{E}vap_i \times Ndays_i$$

or, for COREVAP2,

$$Evap_{est}=\sum^{5}{}_{(i=1)}\sum^{Ndays_i}{}_{(j=1)}(Sample_{SD})$$

or, for COREVAP3,

$$Evap_{est}=\sum^{5}{}_{(i=1)}\sum^{Ndays_i}{}_{(j=1)}(Sample_{FD})$$

where,

$Evap_{est}$ = estimated evaporation

$\bar{E}vap_i$ = mean evaporation for raingroup i

$Ndays_i$ = number of rain days in raingroup i

SD = standard deviation

FD = full distribution

All three programs allow the user to select whether the transformed or untransformed evaporation parameters (mean and standard deviation) are to be used.

Output from the COREVAP programs include the actual mean monthly rainfall, the observed or actual mean monthly evaporation, the file mean monthly evaporation, the simulated mean monthly evaporation and the monthly and accumulative coefficient of efficiency values. The file mean monthly evaporation is the mean daily evaporation for that month, multiplied by the number of days in that month. The accumulative coefficient of efficiency values are the sum of all the monthly coefficient of efficiency values. The performance of the COREVAP programs was analyzed in terms of the improvement effected by estimating evaporation using the three procedures described, relative to estimating evaporation using the mean monthly evaporation regardless of rain. This was done with reference to the percentage error of monthly mean evaporation and the monthly and accumulative coefficient of efficiency values. The performance of the COREVAP programs and the coefficient of efficiency analysis are presented in chapter 9.

Sensitivity analysis on COREVAP 1 : When comparing the results from the COREVAP programs, it was evident that COREVAP1 gave the best simulations of monthly mean evaporation and coefficient of efficiency values (chapter 9). However, any regionalisation of parameter files would mean that a range of parameters in a region would now be represented by a single value. The need to assess the effect of this change, from a regional range of values to a single representative value was identified. This was done by conducting a sensitivity analysis, in terms of what effect a percentage increase or decrease in the lambda, mean evaporation and mean rainfall values would have on the resultant simulated mean monthly evaporation and coefficient of efficiency values. The results are presented in the latter section of chapter 9.

Regionalisation of parameters : The objective of this part of the analysis is to determine whether general characteristics may be applied to some stations that are significantly different when compared to other stations, so that stations may be combined to represent separate regions. There is a need to determine whether the results obtained when using the model compared to simply using the monthly mean evaporation values not corrected for rain were still acceptable. The regionalisation of parameters was conducted using all 117 stations, and the results are presented in chapter 10.

Conclusions and recommendations : The conclusions and recommendations for further research are presented in chapter 11.

CHAPTER 7

7. REGIONAL RAINFALL/EVAPORATION TRENDS

7.1 INTRODUCTION

Regional differences in the occurrence of rainfall during the year and the type of rain that occurs will inevitably lead to differences in the rainfall/evaporation relationship. It is important to know whether or not high values of one variable are associated with high or low values of another variable, or whether or not there is any relationship or correlation at all. The linear relationship between daily rainfall and daily evaporation was investigated, for all 14 representative stations, on a seasonal basis, and the XY graphs are presented in figures 7.1 to 7.7. The relationship is positive when the value of the one variable increases as the other variable increases, and negative when one variable increases as the other variable decreases. Initially, it was assumed that the relationship between daily rainfall and daily evaporation values would be negative, in that with increasing rainfall values, the evaporation values would decrease. However, the XY graphs did not display any distinctive relationship between daily rainfall and daily evaporation, generally indicating a high scatter of evaporation values for the various rainfall values. The only trend that can be observed is a negatively sloped envelope curve, implying a decreasing upper limit to evaporation with increasing rainfall. However, even this is only weakly evident for some of the stations.

For statistical purposes, the data set needed to be presented in a form that gave a more precise indication of the relationship between daily rainfall and daily evaporation. The large masses of data needed to be summarized without producing a loss of or distortion in the essential characteristics of the data set, and simultaneously presenting the data in such a way as to make it more easily interpretable. Consequently, the data were arranged in frequency distributions.

In the first part of each sub-section of this chapter, the prevailing regional synoptic weather types are related to the prevailing evaporation trends in a graphical or qualitative analysis.

Two sets of graphs are used to achieve this aim, the rainfall seasonality graphs and the seasonal evaporation frequency graphs (figures 7.8 to 7.21).

The rainfall seasonality graphs indicate the distribution of the mean monthly number of days falling within each rainfall group category. These provide an impression of the type of rainfall events that occur in each region given the constraint that they are based on daily data. This information may then be related to the evaporation trends.

The second set of graphs are the evaporation frequency graphs for summer, autumn, winter and spring. These graphs show the percentage frequency of days on which evaporation falls within six evaporation categories for the five rainfall categories. (Rainfall and evaporation categories are presented in table 6.1). Taking Prospect as an example (figure 7.8c), with a rainfall event of 0 - 0.1mm, the percentage frequency of evaporation values falling into the 0 - 2mm evaporation group is very low. With a rainfall event exceeding 10mm, this percentage evaporation frequency value increases to approximately 45%. In contrast, the percentage frequency of evaporation values falling into the 8 - 10mm evaporation category, with a rainfall event of 0 - 0.1mm is approximately 43% compared to 12% for a rainfall event exceeding 10mm. This indicates that, during summer, evaporation values are generally high when there is no or very little rainfall, while low evaporation values coincide with high rainfall events.

Monthly mean rainfall and evaporation values based on over 15 years of concurrent daily data are shown in table 7.1 and 7.2 respectively. The second part of each sub-section of this chapter presents a numerical or quantitative analysis of the parameter statistics for each representative station. The mean, standard deviation and skewness of evaporation values are compared within the five rainfall groups, for each season.

TABLE 7.1 : MEAN MONTHLY RAINFALL VALUES FOR REPRESENTATIVE STATIONS
(Based on over 15 years of daily data)

Mean Monthly Rainfall (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Annual
Prospect	13.3	15.5	15.2	17.0	42.1	32.1	26.1	27.7	38.4	20.6	16.9	12.0	276.9
Longdown	23.9	18.6	20.7	27.1	44.8	97.2	101.9	113.6	130.8	57.4	36.0	26.0	698.0
Addo Sitrus NS	28.1	27.4	44.1	33.9	28.9	30.9	22.8	39.1	30.1	25.3	52.7	35.8	399.1
Oos-London W/K	66.3	72.4	82.2	116.8	98.0	68.9	38.5	54.2	71.7	68.7	85.4	83.9	907.0
Queenstown	66.1	60.0	87.2	53.3	31.8	17.3	20.1	16.7	15.1	35.7	67.6	74.9	545.8
Experiment station	103.4	141.1	126.6	99.2	55.9	58.6	26.0	24.2	52.3	90.3	97.8	109.9	985.3
Glendale	106.5	132.8	116.7	99.9	42.2	40.6	16.5	19.9	39.7	99.4	97.3	90.6	902.1
Cedara Agr Res	121.2	142.9	104.6	114.3	53.8	24.3	13.7	16.0	28.2	64.1	80.3	104.2	867.6
Glen Agr Coll, Bfn	65.5	87.2	101.9	82.3	59.5	21.6	11.4	9.0	14.5	24.6	47.4	65.6	590.5
Nelspruit	128.4	108.2	101.9	89.6	50.8	11.3	7.3	14.2	10.9	29.5	81.7	112.3	746.1
Letaba	132.6	136.1	162.2	113.4	45.9	20.7	5.3	7.7	13.4	29.9	51.5	88.9	807.6
Pietersburg	90.9	81.6	47.3	42.2	29.6	6.0	7.6	1.5	0.8	14.4	44.4	83.1	449.4
Pongola Expt Stn	75.5	123.2	86.0	71.1	43.0	20.1	8.0	7.3	15.7	38.7	63.1	98.3	650.0
Vryburg;Armoedsvlakt	61.8	76.9	49.8	65.8	18.3	10.4	7.3	1.8	5.8	26.6	43.1	50.3	418.5

TABLE 7.2 : MEAN MONTHLY EVAPORATION VALUES FOR REPRESENTATIVE STATIONS (Based on over 15 years of daily data)

Mean Monthly Pan Evaporation (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Annual
Prospect	280.3	287.1	227.5	189.4	121.4	78.4	59.7	67.0	87.3	124.5	194.5	233.1	1950.2
Longdown	244.2	259.9	215.3	182.3	118.1	83.2	71.3	67.9	82.5	107.9	153.8	202.2	1788.6
Addo Sitrus NS	218.3	224.1	174.8	147.0	107.0	82.1	63.2	67.3	88.6	111.7	148.8	179.5	1612.4
Oos-London W/K	207.4	201.6	173.4	150.3	116.0	97.3	87.3	97.9	116.8	129.3	158.6	173.8	1709.7
Queenstown	256.7	252.8	200.2	174.5	143.7	137.6	115.3	129.3	162.7	177.1	189.1	212.5	2151.5
Experiment station	184.2	182.8	160.8	151.5	115.6	95.5	79.7	86.1	101.3	118.5	148.0	156.0	1580.0
Glendale	199.6	191.2	173.5	168.5	131.3	114.1	94.1	105.1	128.5	140.5	164.8	167.5	1778.7
Cedara Agr Res	167.7	162.8	142.6	141.4	107.4	96.1	82.7	95.8	123.3	135.6	148.7	145.6	1549.7
Glen Agr Coll, Bfn	304.7	295.6	213.9	185.9	127.8	101.3	78.6	95.3	142.4	208.7	250.6	269.5	2274.3
Nelspruit	182.4	195.7	167.9	160.1	124.5	115.4	95.7	110.8	139.2	166.5	175.3	162.5	1796.0
Letaba	179.5	187.0	163.7	163.5	134.7	118.0	101.5	108.2	130.9	141.9	159.8	166.2	1754.9
Pietersburg	252.8	258.1	213.6	210.6	161.5	144.0	123.8	137.1	182.1	241.2	277.3	252.4	2454.5
Pongola Expt Stn	210.6	211.7	183.6	172.4	130.8	112.3	93.2	103.7	134.1	153.9	180.7	181.3	1868.3
Vryburg;Armoedsvlakt	277.7	271.2	214.6	196.2	169.3	141.8	113.7	118.1	162.2	197.8	242.7	261.1	2366.4

PROSPECT **LONGDOWN**

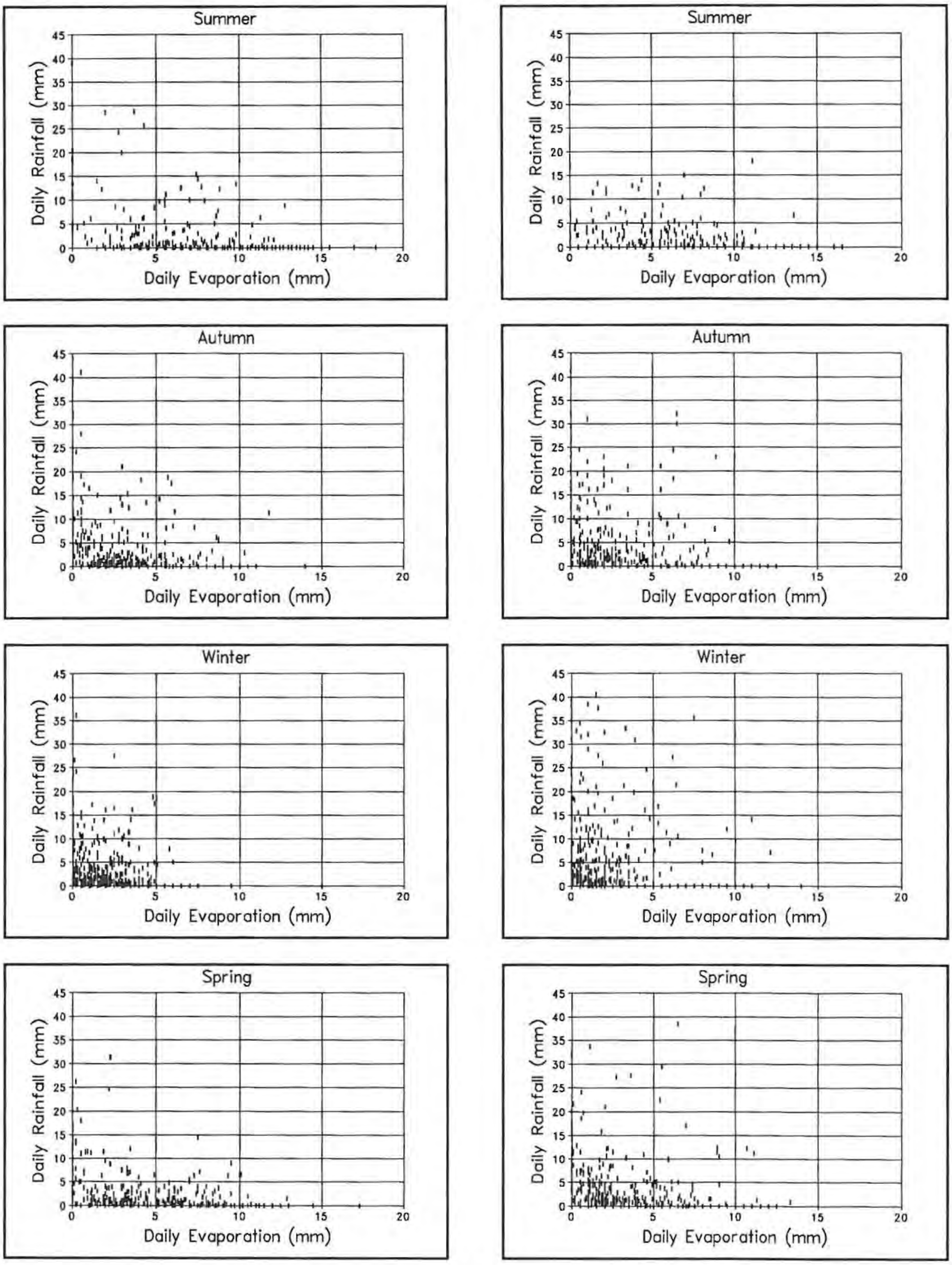


Figure 7.1 : **PROSPECT** and **LONGDOWN** : Linear relationship between daily rainfall and daily evaporation.

ADDO SITRUS NS | OOS-LONDON W/K

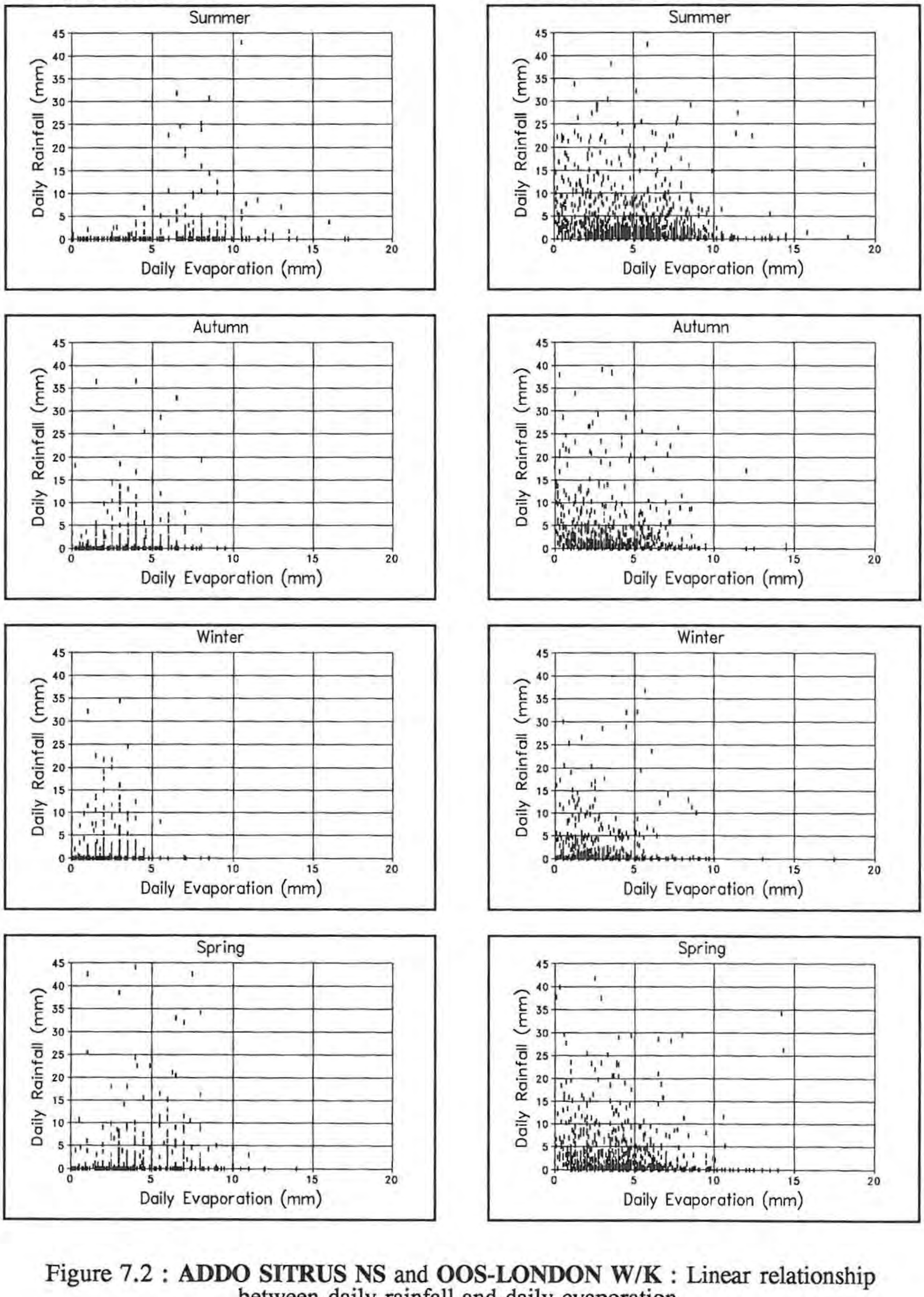


Figure 7.2 : **ADDO SITRUS NS** and **OOS-LONDON W/K** : Linear relationship between daily rainfall and daily evaporation.

QUEENSTOWN **EXPERIMENT STATION**

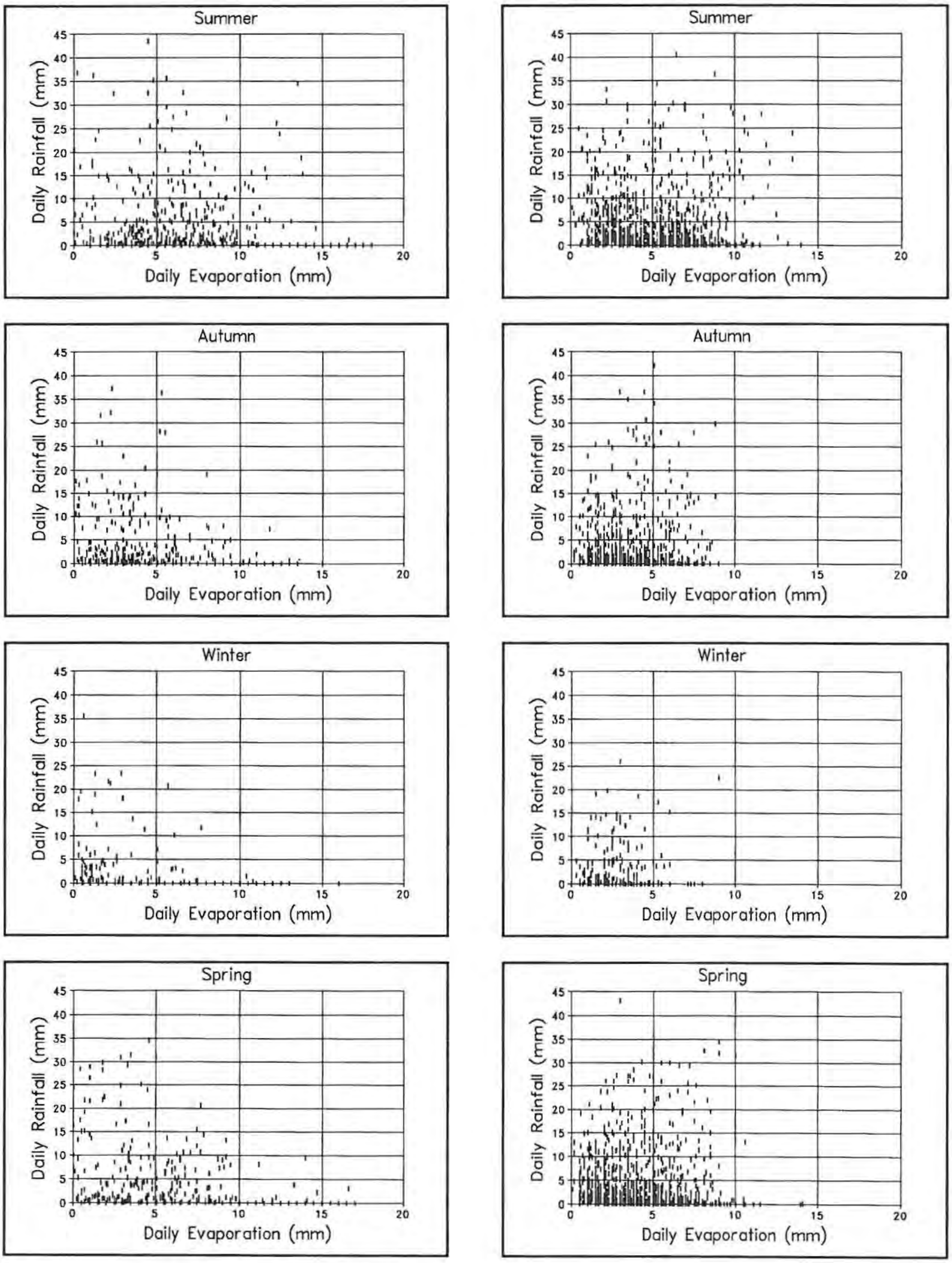


Figure 7.3 : **QUEENSTOWN** and **EXPERIMENT STATION** : Linear relationship between daily rainfall and daily evaporation.

GLENDALE **CEDARA AGR RES**

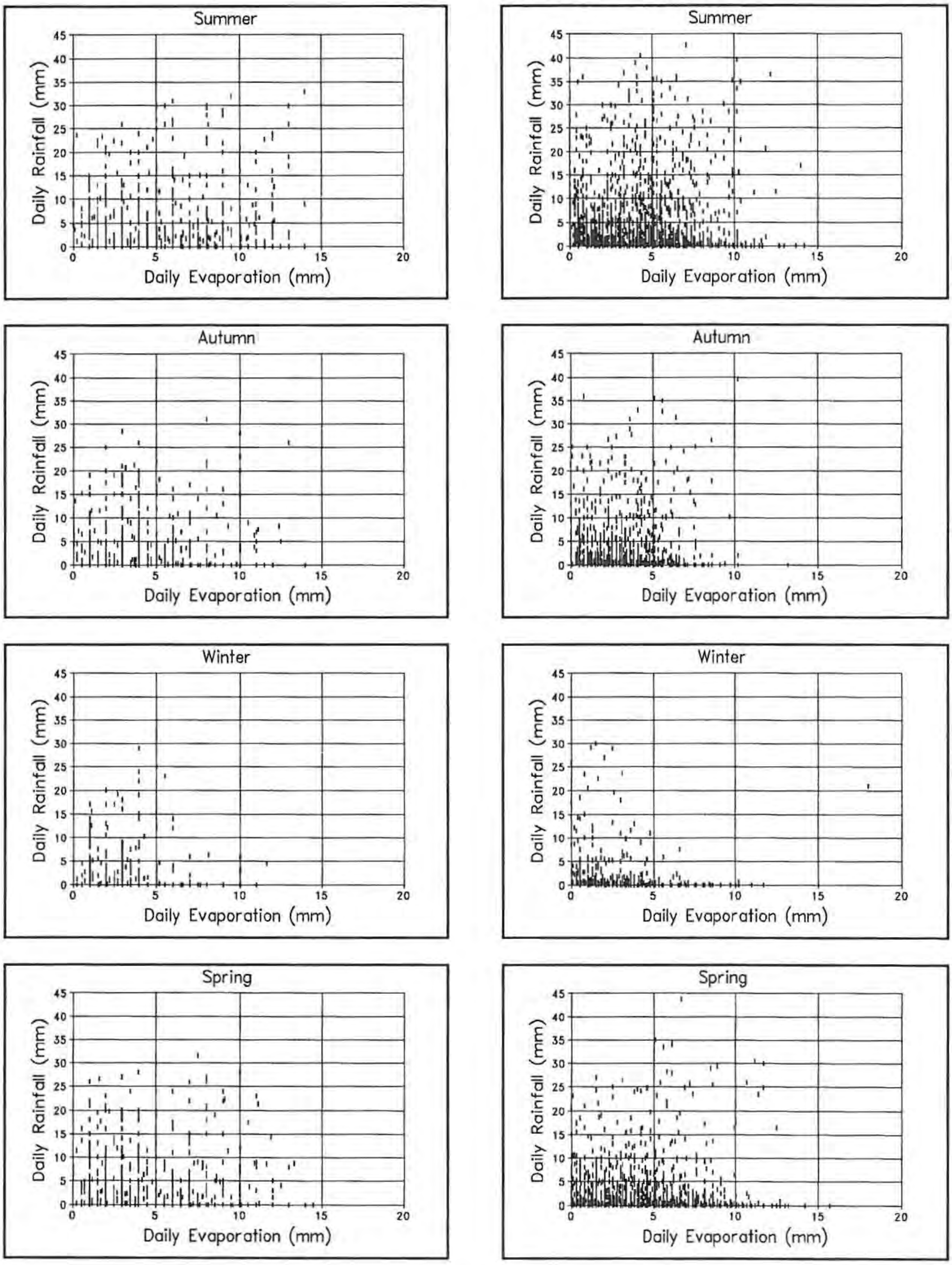


Figure 7.4 : **GLENDALE** and **CEDARA AGR RES** : Linear relationship between daily rainfall and daily evaporation.

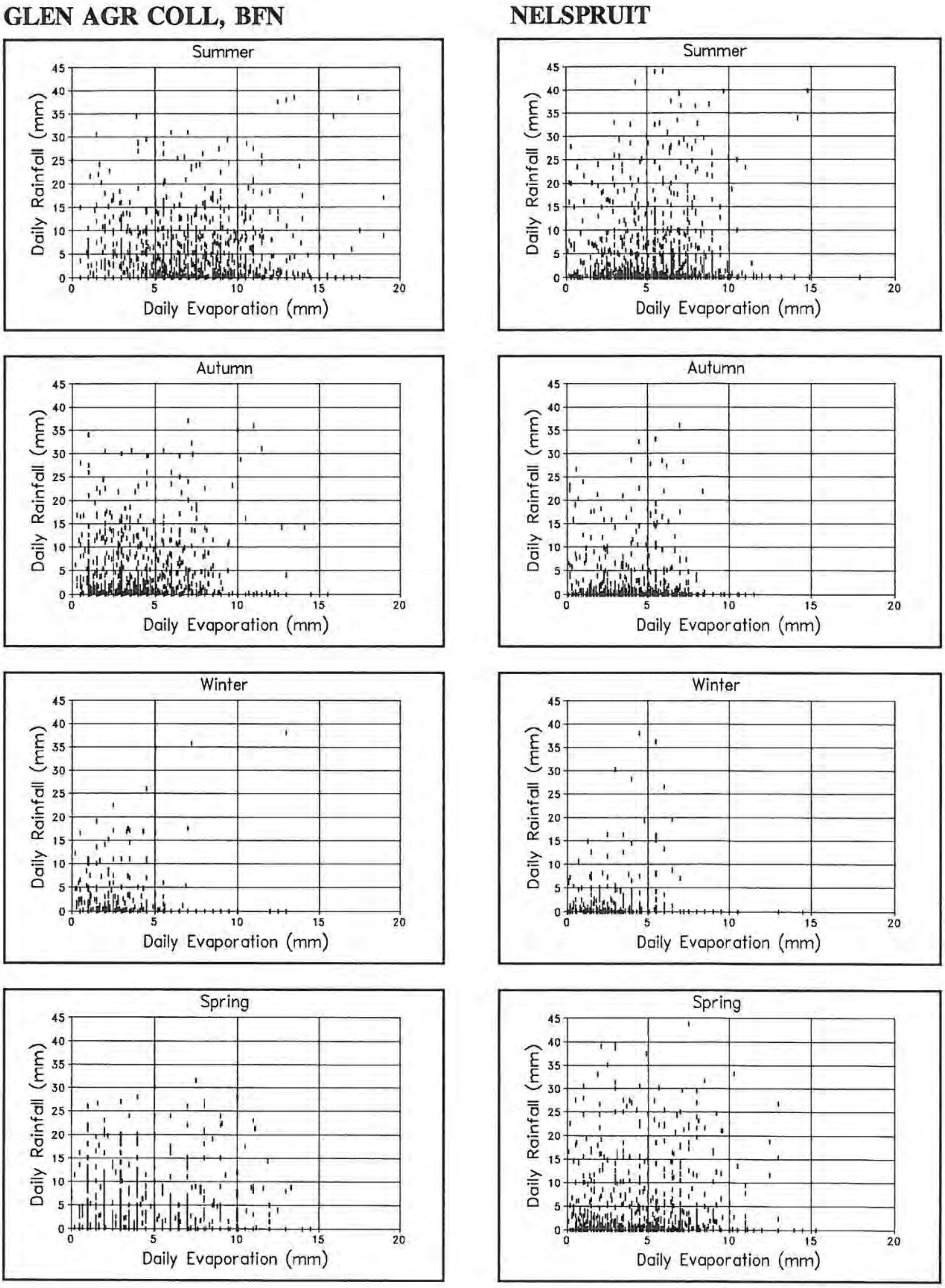


Figure 7.5 : **GLEN AGR COLL, BFN** and **NELSPRUIT** : Linear relationship between daily rainfall and daily evaporation.

LETABA **PIETERSBURG**

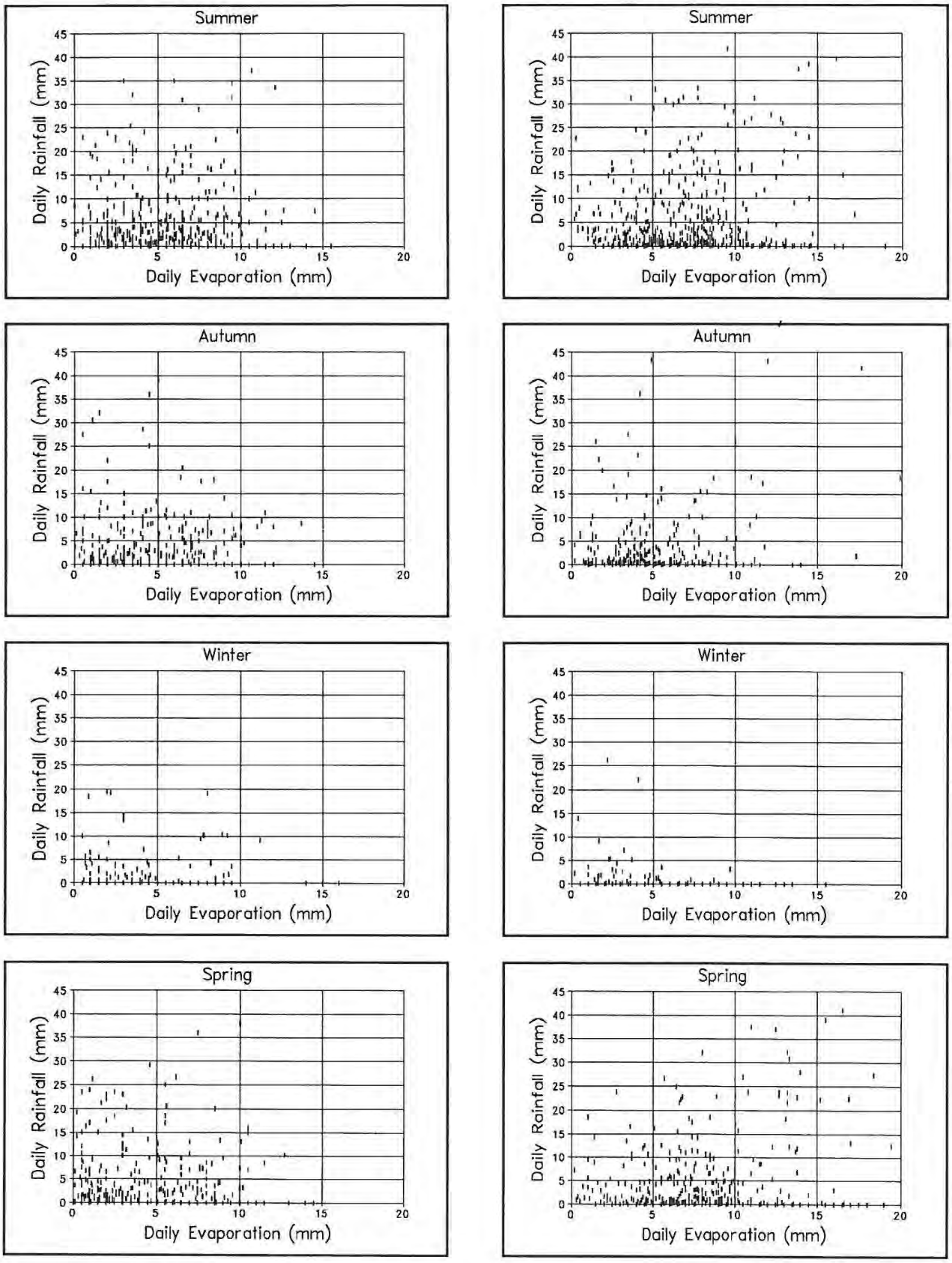


Figure 7.6 : **LETABA** and **PIETERSBURG** : Linear relationship between daily rainfall and daily evaporation.

PONGOLA EXPT STN | VRYBURG;ARMOEDSVLAKT

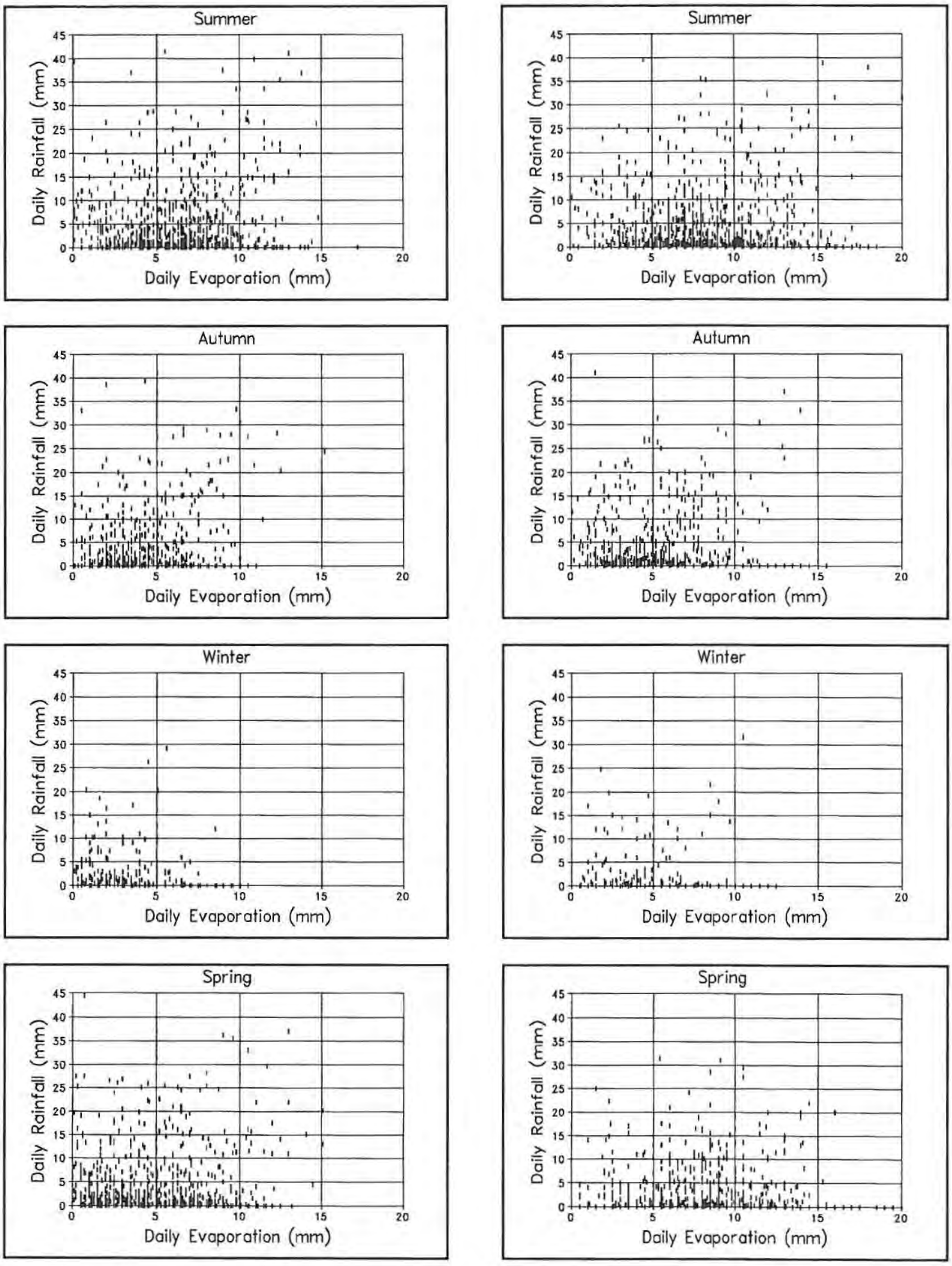


Figure 7.7 : **PONGOLA EXPT STN** and **VRYBURG;ARMOEDSVLAKT** : Linear relationship between daily rainfall and daily evaporation.

7.2 QUALITATIVE AND QUANTITATIVE ANALYSIS

For each regional representative station, the prevailing synoptic weather types are related to the prevailing evaporation trends, with reference to the rainfall seasonality and seasonal evaporation frequency graphs presented in figures 7.8 to 7.21. Descriptive statistics support the qualitative description and facilitate making comparisons between distributions. The most common descriptive measures summarizing the data in some quantitative form are the central location (mean) and dispersion or variability (standard deviation) of the data. The mean and standard deviation values can be misleading in skewed distributions. For example, in highly skewed data, a few very high or very low values can exert a considerable impact on the mean. Therefore, skewness is another dispersion measure that was considered. In the second part of each sub-section, the three measures mean, standard deviation and skewness values will be discussed for the regional representative stations, with reference to the rainfall/evaporation trends already identified in the first part of each sub-section. All the mean, standard deviation and skewness values are based on data values which are relative to the overall daily mean for each month. The discussion will concentrate on identifying specific regional or seasonal features which are particularly noteworthy or relevant to the likely success of the estimation procedures to be used.

7.2.1 SOUTH-WESTERN CAPE REGION : Prospect and Longdown.

Both stations show similar seasonal trends and are representative of the south-western Cape. There is a distinct relationship between rainfall and evaporation in this region - lower evaporation rates with higher rainfalls. The number of days with no rainfall is highest in spring and summer indicating that the stations fall into the winter rainfall region. 66% (183.4mm) and 73.8% (515.4mm) of the annual rainfall for Prospect and Longdown respectively, occur in the autumn and winter months, for example when cloudiness is at a maximum and radiation at a minimum. Temperatures are low, saturation deficit is at a minimum and frontal systems skirt the coast - synoptic conditions resulting in low to moderate intensity, long duration rainfall and low evaporation rates. For example, 69% (Prospect) and 52% (Longdown) of all rainfall events fall into the 0.1 - 5mm categories indicating that low intensity rainfall events predominate (figures 7.8a, 7.9a). Figures 7.8e and 7.9e illustrate the narrow range of evaporation rates experienced. Mean evaporation values in the first rainfall group are slightly higher than those for the spring/summer months with an average value of 1.07 and 1.12 for Prospect and Longdown respectively. With the higher magnitude rainfall events, evaporation values remain low and the evaporation data is positively skewed for the winter months, for all raingroups. During the autumn and spring months, conditions are transitional between summer and winter but generally closer to the winter conditions (figures 7.8d,f; 7.9d,f).

During summer, the south-western Cape experiences infrequent cyclonic rainfall. Ahead of a cold front, conditions are stable with clear skies and gusty winds which no doubt promote higher evaporation rates. Berg winds blowing as dry air flow from the interior will have a similar effect. There is an increase in evaporation values when no rainfall occurs, and the evaporation data is negatively skewed indicating that with a low magnitude rainfall event, the corresponding evaporation values are high (figures 7.8c; 7.9c), with an average of 1.04 and 1.07 for Prospect and Longdown respectively. Generally, mean evaporation values decrease in the highest rainfall groups. The range of standard deviation values are 0.2 to 0.6 with the higher values coinciding with higher skewness values, and occurring for the 4th and 5th rainfall groups. Therefore, Longdown does record higher evaporation rates during some of the rainfall events, but generally Prospect displays higher evaporation values compared to Longdown with a spring/summer difference of 165mm. The main influencing factor may be location as Prospect is situated further inland at an altitude of 160m while Longdown is nearer the coast at 335m. Longdown records a mean annual rainfall of 689.0mm compared to 276.9mm at Prospect, and almost double the number of days in the year when rainfall events exceed 10mm, 15.1 days compared to 7.7 days for Prospect. It is possible that Longdown station is influenced by frequent cold fronts skirting the coast that do not influence the weather as far inland as Prospect, so Longdown evaporation values tend to be lower. However, it is important to note that in the western Cape, in summer, a few summer raindays allows one or two anomalous data points to influence rainfall/evaporation patterns. Therefore, although there are differences between Longdown and Prospect stations, the general rainfall/evaporation characteristics for the south-western Cape are as might be expected for a winter rainfall region. This region is dominated by cool cloudy conditions, and with or without rain, there is little opportunity for evaporation during winter.

7.2.2 EASTERN CAPE COASTAL REGION : Addo Sitrus NS and Oos-London W/K.

Of the two stations representing this region, Addo Sitrus NS is an inland coastal station while Oos-London W/K is a true coastal station. There are slight differences in the rainfall/ evaporation characteristics between these two sites. **Addo Sitrus NS** station displays complex rainfall characteristics. There is a two-cycle event where there are slightly more days with no rain in December and January, and then again in the winter months (Figure 7.10a). This pattern is transitional towards a late summer and early winter rainfall regime. The amount of rainfall recorded during the spring/summer months is 53.5% (213.4mm) of the annual rainfall. Therefore, Addo station is situated in the transitional zone between the summer and winter rainfall regions.

Subtropical anticyclones or high pressure systems are situated over South Africa during summer producing stable, dry conditions and bergwinds along the east coast and adjacent inland areas. Berg winds are responsible for high increases in temperature, resulting in high evaporation values (figure 7.10c). Stable conditions are indicated by the fact that only 18% of the rainfall events exceed 10mm in the spring/summer months. Occasionally, high evaporation rates occur simultaneously with high rainfalls. This is because hot weather is sometimes stable, while other times not, producing rain.

During early spring and autumn, Addo experiences convectional thunderstorms resulting in high rainfalls, that coincide with high evaporation values. This accounts for the negatively skewed mean evaporation data for the 5th raingroup in the spring months, while the evaporation data is slightly positively or close to normally distributed for the remaining four raingroup categories (figure 7.10d,f). Standard deviation values are low (0.3 - 0.5). During the autumn/winter months, the mean evaporation data is negatively skewed with most of the evaporation values falling within the first two raingroup categories no matter what the magnitude of the rainfall event.

Oos-London W/K station exhibits a definite summer rainfall trend (figure 7.11a). Most rainfall events fall into the 0.1 - 5mm range, with a lower percentage (13%) exceeding 10mm (compared to 18% for Addo). The reason why Addo records slightly higher rainfall events may be associated with convectional thunderstorm activity which is common in that region during early spring and autumn. Both stations are positioned at similar altitudes (Addo at 150m and Oos-London W/K at 120m) yet Addo receives 399mm compared to 907mm per annum recorded at Oos-London W/K. Rainfall events exceeding 10mm are recorded on 11.6 days of the year for Addo compared to 15.4 days for Oos-London W/K. This may be due to a coastal influence. Therefore, for Oos-London W/K, the data is positively skewed, for the spring/summer months, with high evaporation values being associated with lower rainfall and visa versa. Mean evaporation for all raingroups are higher than those displayed by the representative stations already discussed. The range of standard deviation values is low (0.3 - 0.6) with only a few values in the top half of this range (figures 7.11c,f).

During the winter months, evaporation rates are more variable and are more evenly distributed throughout the rainfall groups. Standard deviation and skewness (positive) values are higher, representing the wider range of evaporation values (figure 7.11d). Therefore, the coastal station experiences a milder, warmer winter climate in comparison to the inland station (Addo) where there are higher diurnal fluctuations. The rainfall/evaporation characteristics tend to make reasonable sense, with Addo exhibiting weather characteristics typical of the eastern Cape and the Oos-London W/K station tending away from this typical eastern Cape situation indicating a coastal influence.

7.2.3 EASTERN CAPE INLAND REGION : Queenstown.

Queenstown falls into the summer rainfall region (figure 7.12a) with 71.7% (391.5mm) of the annual rainfall occurring in the spring/summer months. 59% of these rainfall events fall into the 0.1 - 5mm rainfall categories. However, Queenstown experiences a higher number of rain days during the year (19.5 days) when rainfall exceeds 10mm in comparison to Addo (11.6 days) and Oos-London W/K (15.5 days). Ridging anticyclones produce general rainfall and thunderstorm activity at this time of the year. Consequently, a higher percentage of high-intensity, short duration rainfall events prevail as a result of convective activity (which is characteristic of an inland region). Altitude may be an influencing factor as Queenstown is situated at 1067m. The mean evaporation values are closer to Normal distribution for the summer months, and are transitional to a positively skewed distribution for the spring months. The mean evaporation values are highest for the first raingroup and then lower and fairly uniform for the remaining four raingroups. Before thunderstorms, temperatures tend to be high giving rise to high evaporation values in the first raingroup. Standard deviations are low, ranging from 0.3 to 0.6 and skewness values tend to be fairly variable.

The autumn and spring months display the influence of the two season east Cape rain period, with the spring months indicating a transition to the summer pattern, and rainfall increases from a winter mean of 51.9mm (9.5% of the annual rainfall) to a spring mean of 178.2mm (32.6%). During winter, the air over the inland areas is dry, promoting higher rates of evaporation, with mean evaporation values being slightly lower in the first raingroup category, but higher in the 2nd and 3rd raingroup categories. Skewness values are positive (figure 7.12d,e), indicating that no matter what the magnitude of the rainfall event, evaporation values remain low, and are more positively skewed than those stations representing the eastern Cape coastal region.

Generally, this region is exhibiting rainfall/evaporation characteristics similar to those for Oos-London W/K.

7.2.4 NATAL COASTAL REGION : Experiment station and Glendale.

The Natal coastal region is influenced by a wide range of weather patterns, producing a wide range of evaporation values during different rainfall events. The Natal coastal stations fall into the summer rainfall region, with summer rainfall contributing 37.7% and 39.5% of the annual rainfall total for Experiment station and Glendale respectively. These stations are not situated at high altitudes (Experiment station at 96m and Glendale at 129m) and are probably not influenced by orographic rainfall. Of all the rainfall in the spring/summer, 64% (Experiment station) and 52% (Glendale) of the rainfall events fall into the 0.1 - 5mm raingroups, indicating that Experiment station receives predominantly smaller rainfall events. Therefore, it is reasonable that Glendale displays more number of days when rainfall exceeds 10mm (20.8 days) compared to Experiment station (16.2 days) and consequently Experiment station displays higher evaporation values in the first raingroup category (figures 7.13a; 7.14a). The average value is 1.12 and 1.07 for Experiment station and Glendale respectively.

There are a wide range of weather patterns in summer producing a wide range of evaporation values during rainfall events. Ridging anticyclones promote strong advection of moist unstable air which leads to the development of extensive cloud cover formation along the east coast and adjacent inland areas. Consequently, the humid warm summers are characterized by frequent storms and this may account for the high evaporation values after a thunderstorm (especially in the 4th and 5th raingroup). Cut-off lows are unstable and associated with strong convergence, producing widespread high intensity rainfall, lasting a few days. Coastal lows bring low intensity precipitation which may contribute to high evaporation on days with very little or no rainfall. The range of standard deviation values are low (0.2 - 0.6) and are lower for dry days than for wet days. The evaporation data is close to Normally distributed for the summer months but more positively skewed for the spring months, in the higher raingroups (figures 7.13c,f; 7.14c,f). Berg winds are common in the early spring months and result in high temperatures conducive to high evaporation values, and may be responsible for the higher variability within evaporation values.

Winter rainfall comprises only 10.4% (Experiment station) and 8.4% (Glendale) of the annual rainfall. Mean evaporation values for rainfall events not exceeding 4mm remain high, but decrease for higher magnitude rainfall events. Therefore, during winter, a smaller range of evaporation values are recorded (standard deviation range of 0.3 - 0.7) and there tends to be little difference between wet and dry conditions, with evaporation values remaining low in the higher raingroup categories and are positively skewed (figures 7.13d,e; 7.14d,e).

Therefore, the Natal coastal region is influenced by a wide range of weather patterns and consequently the estimation of evaporation is difficult unless the particular synoptic type is known, as a different set of conditions will produce markedly different rainfall/evaporation characteristics.

7.2.5 NATAL INLAND REGION : Cedara Agr Res.

Weather patterns influencing the Natal inland region are similar to those that influence the Natal coastal region, except that orographic rainfall may have an impact, as Cedara is situated at an altitude of 1067m. Cedara station falls into the summer rainfall region with summer rainfall comprising 42.5% (368.7mm) of the annual rainfall and fewer number of days with no rain (figure 7.15a). 74% of these rainfall events recorded are less than or equal to 5mm, with 13% exceeding 5mm, and 13% exceeding 10mm. Therefore, generally, either low intensity rainfall events predominate with fewer occasional larger rainfall showers, or, a lot of these rainfall events will be short duration high intensity storms and this accounts for the variability of evaporation values within each raingroup category.

During the summer months Cedara station records higher evaporation values in the no rainfall category when compared to the Natal coastal stations (figure 7.15c), with an average value of 1.25. The mean evaporation values for the remaining four rainfall groups are similar to those displayed by Experiment station. Standard deviation and skewness values are low (figures 7.15c,f). During winter, lower evaporation values occur during high rainfall events but with a wider range of evaporation values within the first two raingroups (figure 7.15e). Standard deviation values remain low. Skewness values are high for the 5th rainfall group indicating that in winter, the evaporation data is more positively skewed in the highest rainfall groups (figure 7.15d,e). With a widely variable situation as this it is difficult to produce any specific rainfall/evaporation relationships or to establish a predictive model.

7.2.6 ORANGE FREE STATE REGION : Glen Agr Coll, Bfn.

The weather patterns of the OFS region and consequently the rainfall/evaporation relationships are affected by the following synoptic systems. Easterly low pressure systems occur in the December to February months, promoting strong uplift which result in low to moderate intensity, fairly long duration rainfall. Ridging anticyclones bring general rainfalls over the eastern and central areas of South Africa, and occur most frequently between October-February. Convective thunderstorms produce high intensity, short duration rainfall events.

Glen Agr station falls into the summer rainfall region with the summer mean rainfall contributing 43.1% (254.6mm) of the annual rainfall. Of these rainfall events 36% fall into the 1 - 5mm rainfall group, and there is an even spread in the 0.1 - 1mm (21%), 5 - 10mm (20%) and >10mm (23%) rainfall groups (figure 7.16a). Rainfall events exceed 10mm on 16.29 days per annum, indicating the influence of thunderstorm activity. Therefore, Glen Agr station receives highly variable size rainfall events, influenced by a combination of weather patterns with differing rainfall magnitudes, duration and seasonality. Consequently, evaporation rates are high in summer for the first raingroup, with a wide range of variability (figure 7.16c), and an average value of 1.06. Evaporation values are higher in the 2 - 5 rainfall groups, displaying similar trends as those for Glendale. However, for the 4th and 5th rainfall groups, evaporation is not as high as for the Natal coastal and inland stations, but higher than those values obtained for the eastern Cape and south-western Cape stations. The range of standard deviation values are low (0.2 - 0.4) and skewness values are low and positive.

During winter, subtropical anticyclones predominate over the interior plateau, producing hot dry stable conditions and heat waves are common. Consequently, winter rainfall contributes only 5.9% (34.9mm) to the annual rainfall. Mean evaporation values are lower than those values obtained in the spring/summer months, with higher standard deviations coinciding with higher positive skewness values (figure 7.16d,e). A high number of no rain days are recorded in the winter months and this may account for the high positive skewness. Therefore, during winter evaporation values remain low, within the higher raingroup categories.

7.2.7 FAR EASTERN TRANSVAAL REGION : Nelspruit.

During summer, easterly lows dominate during the December - February months producing unstable conditions resulting in moderate to high intensity long duration rainfall. In addition, ridging anticyclones produce strong advection and widespread general rainfall during the October - February months. Southerly meridional flows cause temperatures to drop sharply enhancing convective thunderstorm activity, to produce low to high intensity short duration rainfall.

The far eastern Transvaal region falls into the summer rainfall region with 75% of the annual rainfall occurring in the spring/summer months. 64% of these rainfall events fall into the >0.1 - 5mm rainfall group, and rainfall exceeds 10mm on 18.2 days per annum. Mean evaporation values are higher for the first raingroup (average value of 1.12) when compared with the other representative stations but tend to be closer to the evaporation values obtained for Glen Agr Coll in the remaining four rainfall groups. Generally, the higher mean evaporation values are high in all raingroups (figure 7.17c,f). However, there is a marginal tendency for higher evaporation values to occur on drier days. Therefore, the variety and combination of weather systems responsible for producing rainfall (as described above) have the effect of producing a wide spread of evaporation values across all the raingroups, making it difficult to develop any general rainfall/evaporation relationships.

During winter, rainfall contributes only 4.3% to the annual rainfall values, and there are a high number of days with no rainfall (figure 7.17a). Evaporation values are higher on wettest days (figure 7.17d,e). This is difficult to explain and perhaps there are simply a small number of events dominating to produce these rainfall/evaporation patterns.

7.2.8 TRANSVAAL REGION : Pietersburg and Letaba.

The weather systems influencing the eastern Transvaal also influence the Transvaal region and will not be repeated here. Low rainfalls occur in the winter and early spring months, and this region records the highest number of days with no rainfall of all the regions mentioned earlier (figures 7.18a, 7.19a). The mean evaporation values for the first raingroup category are lower with an average of 1.02 and 1.00 for Pietersburg and Letaba respectively. For Pietersburg, the mean evaporation values in the 2 - 5 raingroups are lower than those obtained for the spring/summer months and the range of standard deviation values are 0.2 - 0.5 with positive skewnesses (figure 7.18d,e). Winter rainfall contributes only 2.2% to the annual rainfall total, and of this amount, rainfall intensities exceeding 10mm occur on only 0.2 days of the year (figure 7.18c,f). For Letaba, generally with increasing rainfall, mean evaporation values tend to decrease, although evaporation values in the 2 - 5 raingroups are highly variable and skewness values, too, are widely variable (figure 7.19d,e). Winter rainfall contributes only 3.3% to the annual rainfall total.

For the spring/summer months, the mean evaporation values for Pietersburg are similar to those displayed by Glen Agr Coll, with an average of 1.05. The range of standard deviation values are low (0.3 - 0.5) and evaporation values are negatively skewed in the 3rd, 4th and 5th raingroups with very high mean evaporation values coinciding with both high and low rainfall events (figure 7.18c,f). This is especially apparent for spring/summer and the influence of convective activity (Pietersburg is situated at 1234m) may be resulting in high evaporation values coinciding with high rainfall values. For Letaba, mean evaporation values are higher in the 2 - 5 raingroups indicating that high mean evaporation values coincide with high rainfall values (figure 7.19c). In contrast, for the spring months, the mean evaporation values are lower for the 2 - 5 raingroups and standard deviation values are low (0.3 - 0.6).

7.2.9 NORTHERN NATAL/TRANSVAAL BORDER REGION : Pongola Expt Station.

The weather systems producing rainfall in this region are similar to those for the eastern Transvaal and Transvaal regions (including easterly lows, ridging anticyclones and convective showers) and will not be repeated here. Pongola Expt station falls into the summer rainfall region with 74.6% of the annual rainfall occurring in the spring/summer months. 37% and 25% of the rainfall events fall into the 1 - 5mm and 0.1 - 1mm rainfall categories respectively, culminating in 62% of the rainfall events being equal to or less than 5mm (figure 7.20a). Mean evaporation values are highest for the first rainfall group (average value of 1.08) and are similar to those displayed by Letaba, Pietersburg and Experiment stations in the remaining four raingroups with values generally falling between the Natal and Transvaal stations. The range of standard deviation values are low (0.2 - 0.6) and distributions, although slightly positively skewed, tend to be closer to Normal (figure 7.20c,f).

In contrast, the winter months contribute only 4.8% to the annual rainfall total and the number of days with no rainfall are at a maximum (figure 7.20a). The mean evaporation values in the first rainfall group are lower (average of 1.02) in comparison to those values obtained for the spring/summer months and in the remaining rainfall groups, are comparable to the values obtained for Letaba and Pietersburg. Standard deviation values are low (0.2 - 0.6) and skewness values are positive. Further rainfall/evaporation characteristics are similar to those trends displayed by Nelspruit station, and will not be repeated here.

Therefore, the weather systems prevailing over this region are producing summer maximum rainfall and the magnitude of the rainfall events are dependant on the specific prevailing synoptic type.

7.2.10 NORTHERN CAPE REGION : Vryburg;Armoedsvlakt.

For Vryburg;Armoedsvlakt, 73.8% of the annual rainfall occurs in the spring/summer months (figure 7.21a). The maximum number of days with no rainfall are recorded in the late autumn and winter months, and are the highest of all the regions discussed. The winter months contribute only 3.6% to the annual rainfall total. The rainfall/evaporation trends indicate large differences between the spring/summer and autumn/winter months.

In summer/spring, evaporation rates are very high and follow the trend of increasing evaporation rates with increasing rainfall (figure 7.21c,f). This is to be expected as the dominant rainfall producing system is convective thunderstorm activity - a consequence of diurnal heating and atmospheric instability. Temperatures are high, conditions build up and become unstable, producing high intensity short duration rainfall, preceded by high evaporation rates. Mean evaporation values in the first raingroup are similar to those values obtained for the Transvaal stations (average value of 1.03), and are slightly higher in the 2 - 5 raingroups. However, the differences between mean evaporation values for the 2 - 5 raingroups are low, indicating that no matter what the size of the rainfall event, evaporation remains high (figure 7.21c,f). The range of standard deviation values are low (0.2 - 0.5).

During the autumn/winter months, evaporation values are lower in comparison to the spring/summer months, but still fairly high when compared to the other regional stations (figure 7.21d,e). Anticyclonic high pressure systems prevail over the northern and interior regions of South Africa, and are responsible for the dry stable conditions that are not conducive to rainfall, but do promote high evaporation rates. In the first raingroup, mean evaporation values are slightly lower than those obtained for the spring/summer months (average value of 1.00), but increase in the 2 - 5 raingroups where they are comparable to those values obtained for Pongola Expt station. A characteristic of this station is that the mean evaporation values for the 5th rainfall group are higher than those recorded for the first rainfall group (average of 1.13 compared to 1.00) indicating that high evaporation values coincide with high rainfall values (figure 7.21d,e). There is a distinct difference in skewness between the spring/summer and autumn/winter months. For the autumn/winter months, the evaporation data are positively skewed with more values concentrated at the lower end of the scale. Conversely, the data is negatively skewed in the spring/summer months. This trend represents the impact the synoptic systems (described above) have on the rainfall/evaporation relationships.

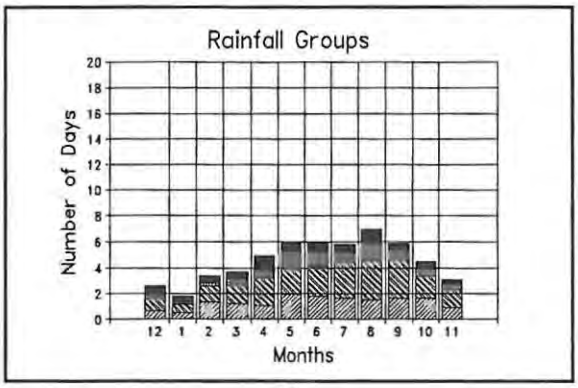
7.3 SUMMARY

Although regional differences in the rainfall/evaporation relationship have been identified, and related to the prevailing synoptic conditions, these are not always distinct. The variability in the rainfall/evaporation relationships for the winter versus the summer rainfall regions and the transitional zone between the winter and summer rainfall regions are clearly discernable. However, it is more difficult to pin-point or account for differences between regions that fall into the summer rainfall region. For example, differences in the rainfall/evaporation trends between the Natal coastal and inland areas and the north-eastern and northern regions of South Africa can be identified. However, particular differences between the Orange Free State, Transvaal, eastern Transvaal and northern Natal/Transvaal border regions are far more difficult to distinguish or account for, as these regions are affected by similar synoptic systems.

It is important to identify the type, magnitude and duration of the rainfall events that occur in different regions of southern Africa, as these factors determine the rainfall/evaporation relationships within different regions. Processes such as rainfall and evaporation are influenced by a number of factors (as indicated in chapters 3, 4 and 5) and are irregular in space and time. Attempting to clarify the relationship between these two processes is difficult as a combination of factors are responsible for the development of specific weather systems which are inherently highly variable and complex. This is further complicated by the fact that in many cases, as indicated above, different synoptic systems occur simultaneously to produce a different set of conditions. Consequently, no one set of conditions can be related to produce a specific rainfall/evaporation relationship. The point is that rainfall is occurring in association with a wide range of other conditions (temperature, humidity, wind, etc) that affect evaporation rates. Consequently, perhaps a more extensive study of the synoptic conditions, related to evaporation on a daily scale is required. However, such detailed analysis of weather parameters is beyond the original aims and objectives of this thesis.

Inconsistencies within the data set itself also complicate matters. Therefore, given the complexity and variability of these two processes, it is not surprising that difficulties have been encountered when attempting to develop rainfall/evaporation relationships, on a seasonal basis. This may influence the ability to successfully relate these rainfall/evaporation relationships to a large number of stations, and to develop specific regional divisions for southern Africa on the basis of the identified rainfall/evaporation trends.

A coefficient of efficiency analysis was conducted using the daily data to determine the effect of incorporating these rainfall/evaporation relationships into simple Water Resource Estimation Models. The results are presented in chapter 8.



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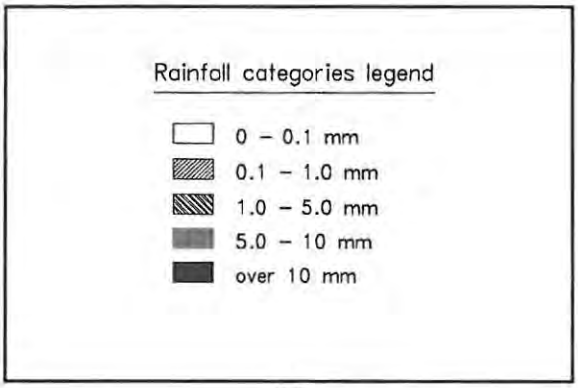

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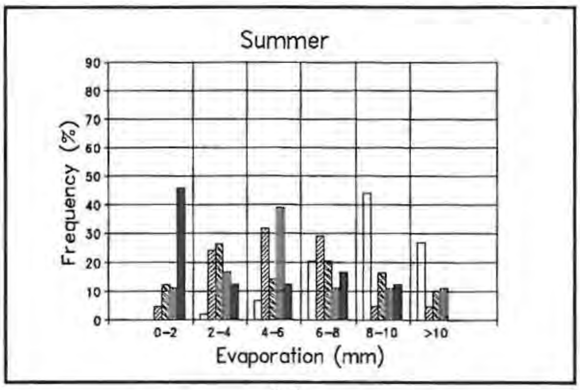
Figure 7.8 : **PROSPECT**
(South-western Cape region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall caregories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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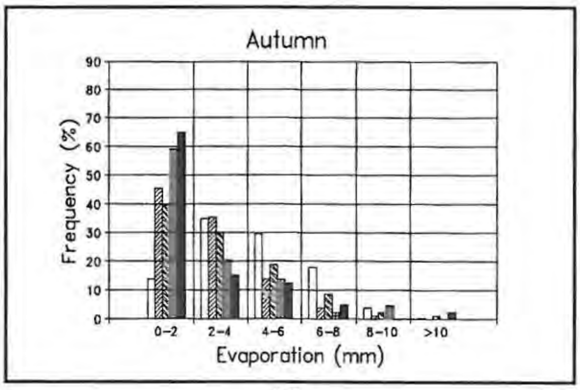

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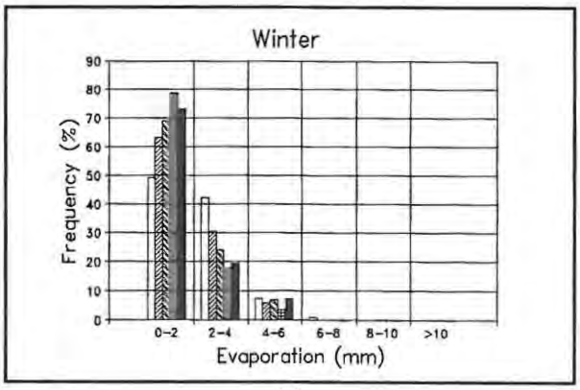

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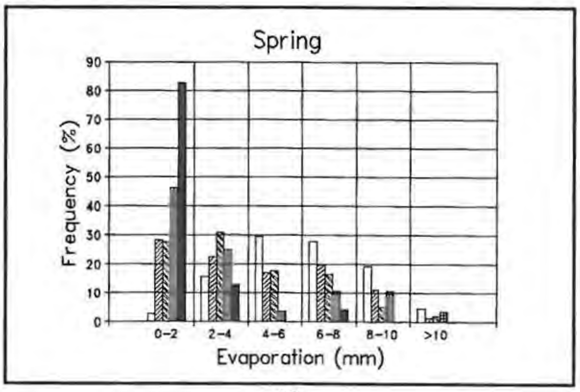

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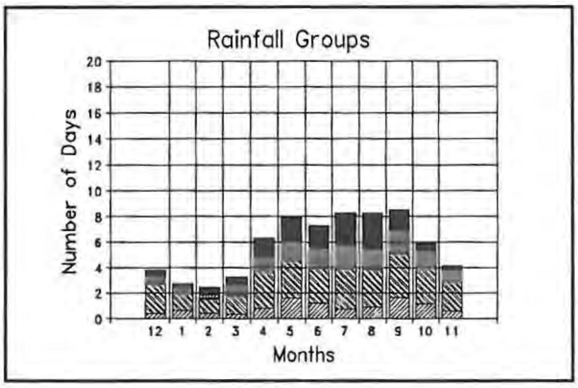

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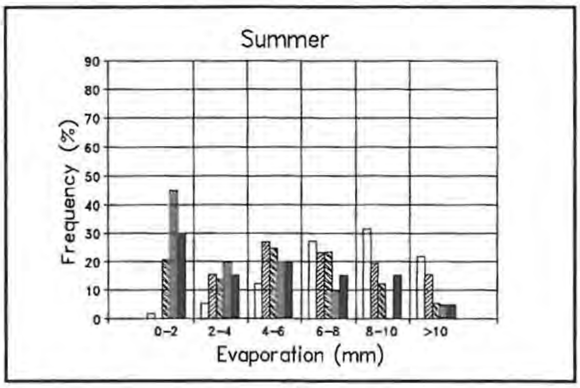

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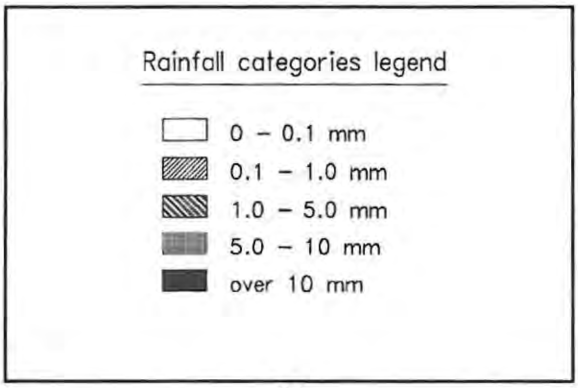

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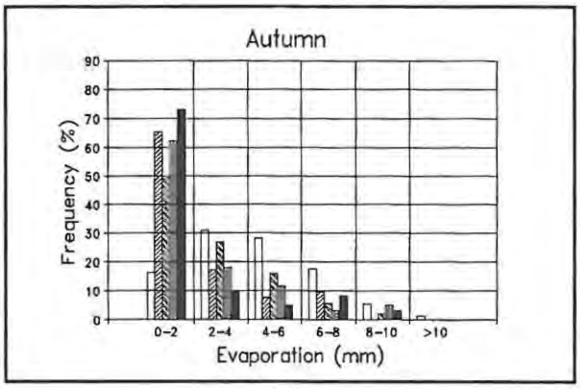

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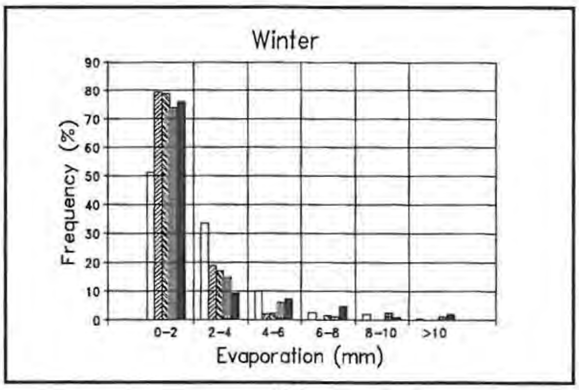

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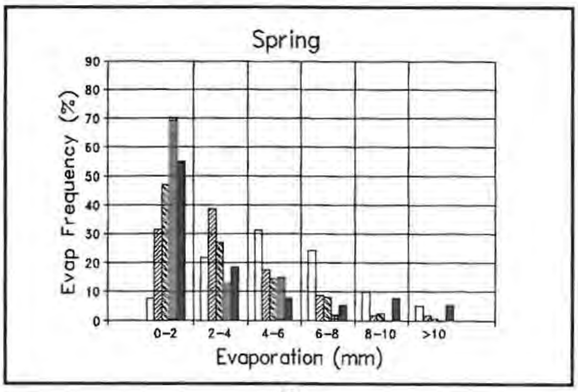

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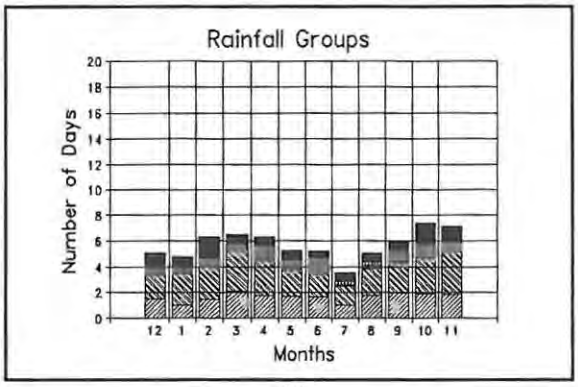
Figure 7.9 : **LONGDOWN**
(South-western Cape region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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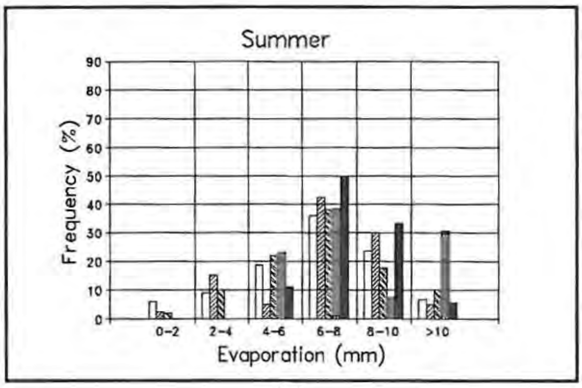

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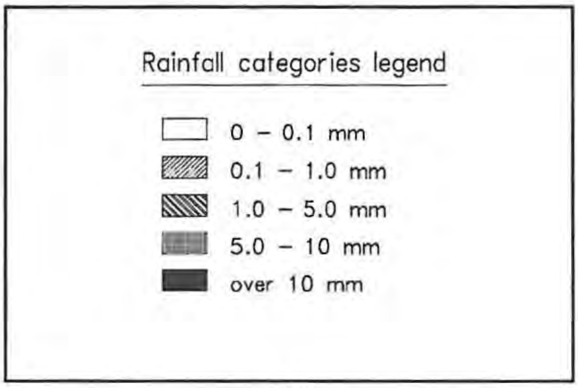

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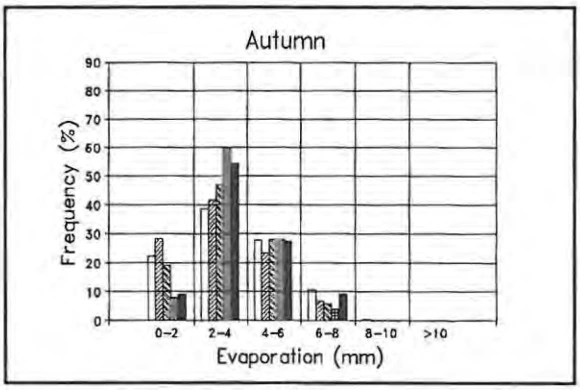

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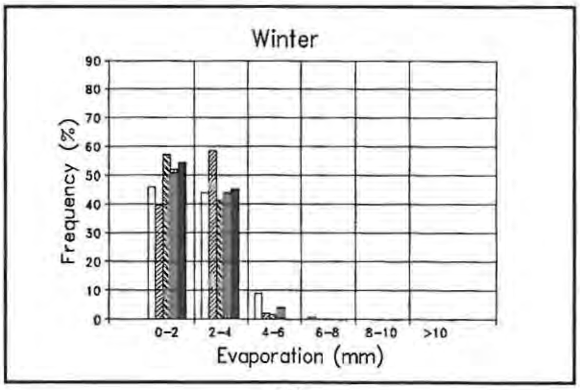
Figure 7.10 : **ADDO SITRUS NS**
(Eastern Cape Coastal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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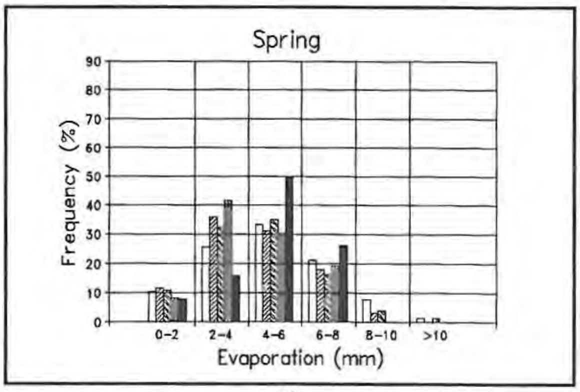

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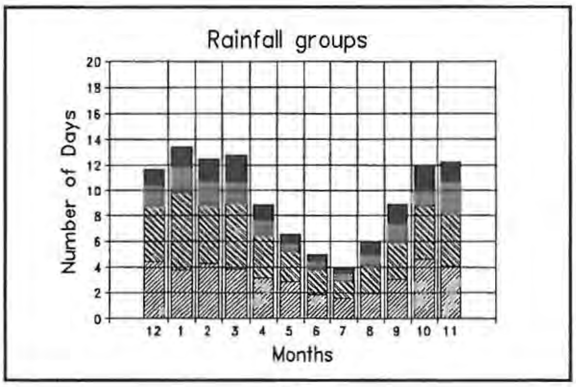

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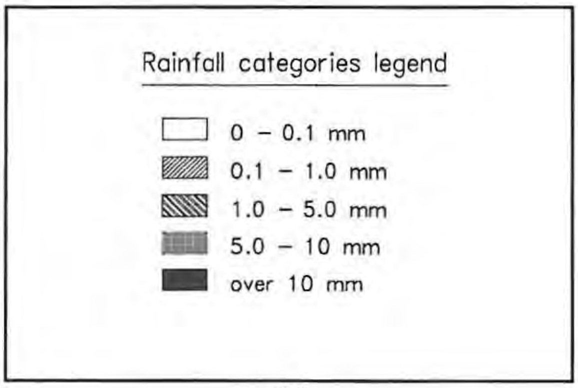

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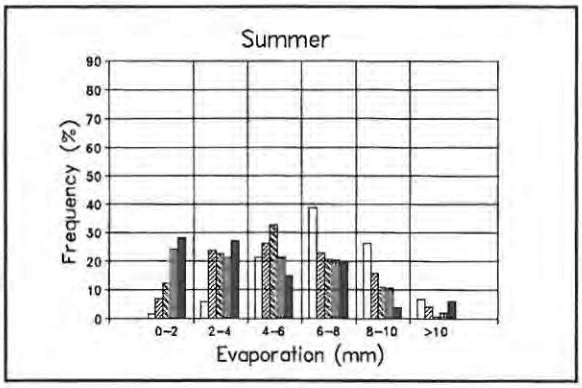

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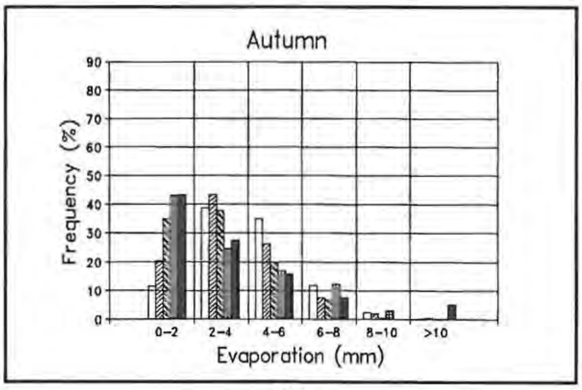

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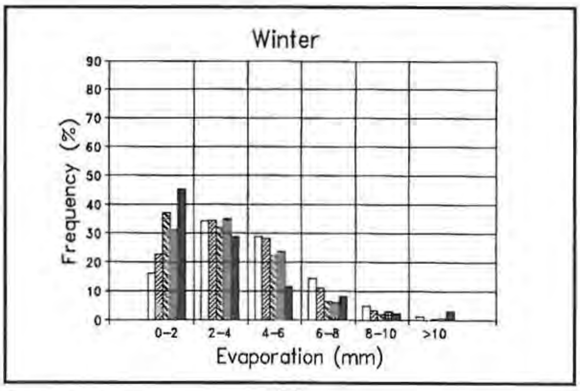

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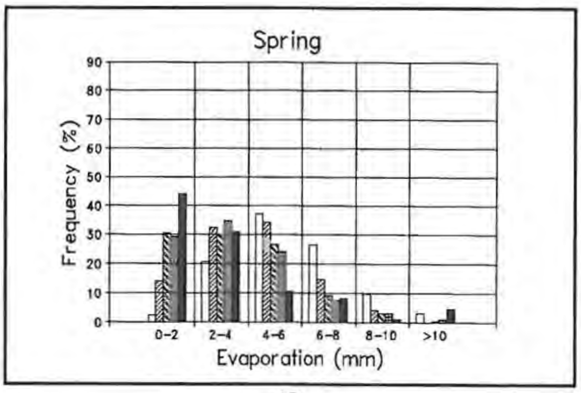

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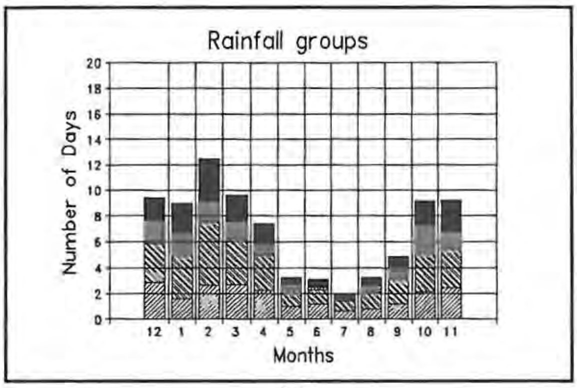
Figure 7.11 : **OOS-LONDON W/K**
(Eastern Cape Coastal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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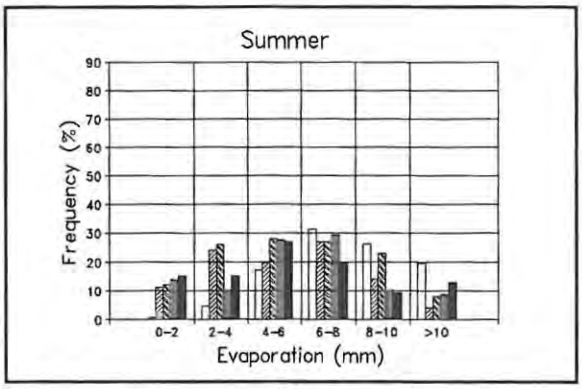

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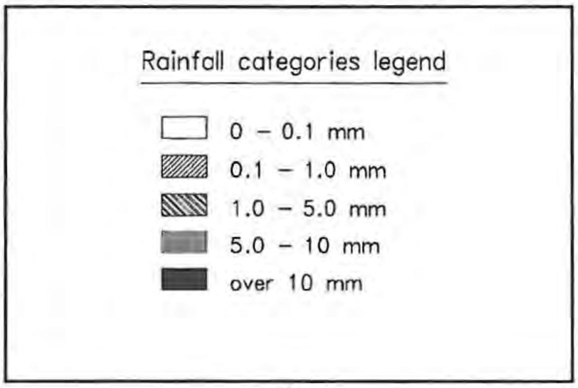

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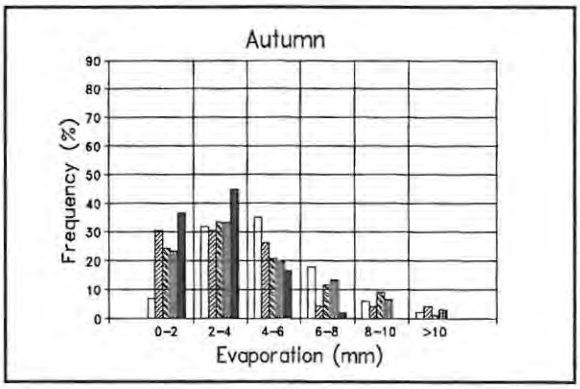

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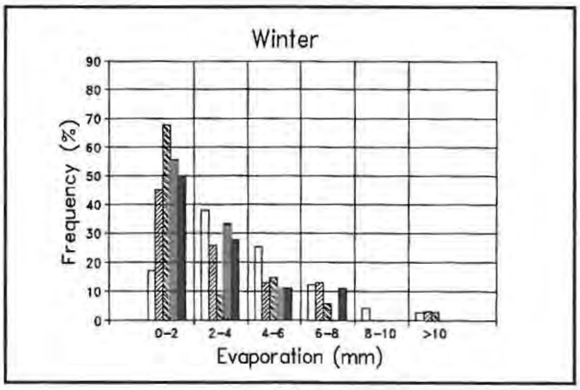
Figure 7.12 : **QUEENSTOWN**
(Eastern Cape Inland region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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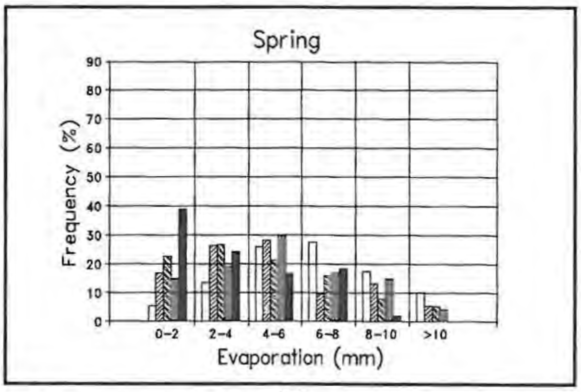

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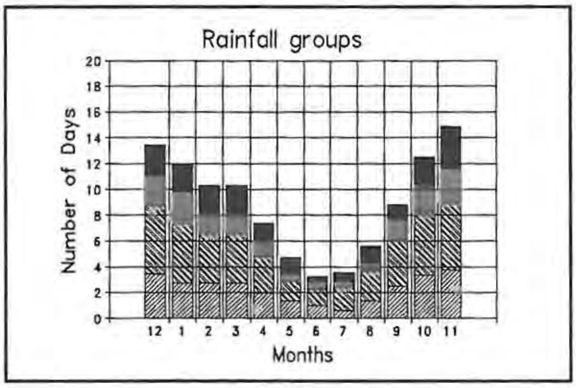

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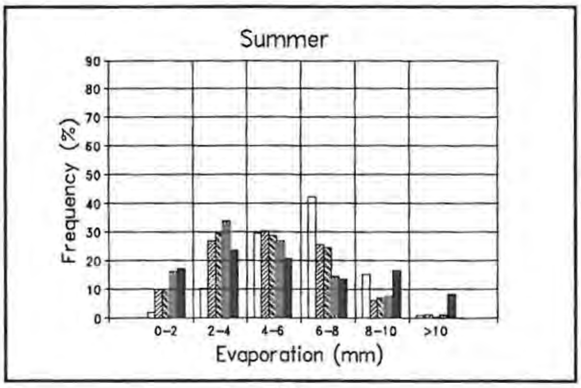

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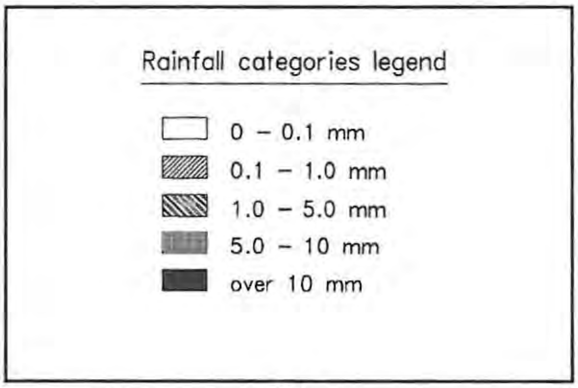

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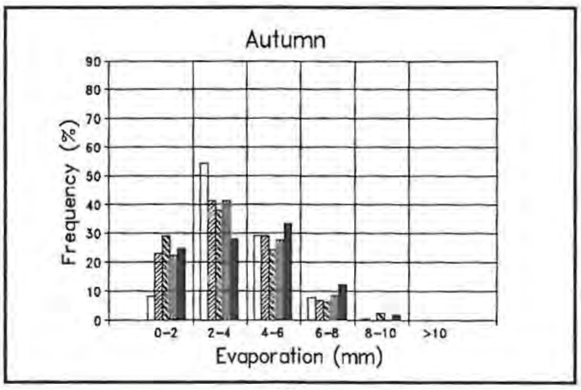

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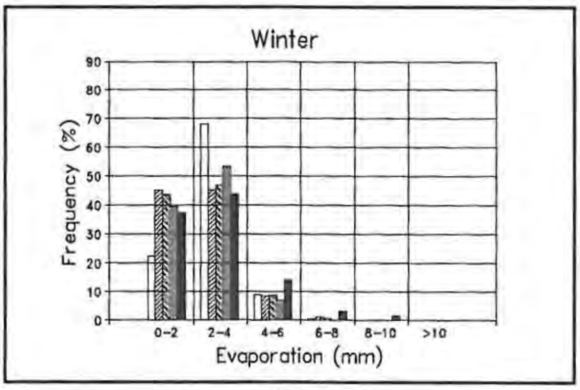

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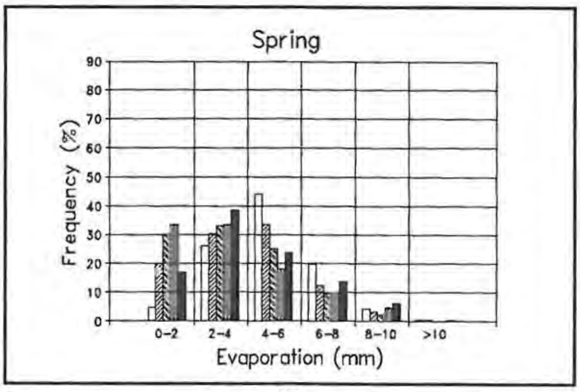

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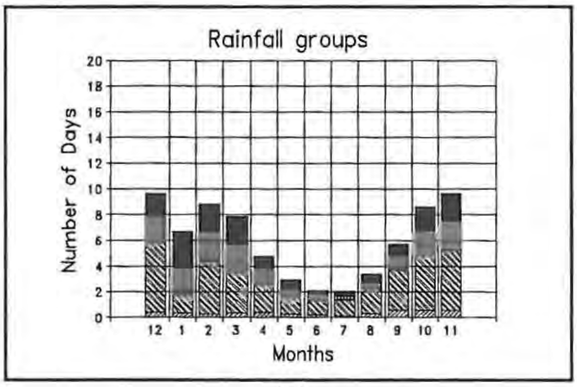
Figure 7.13 : **EXPERIMENT STATION** (Natal Coastal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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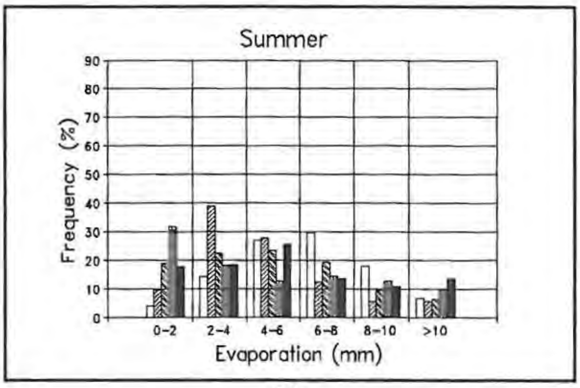

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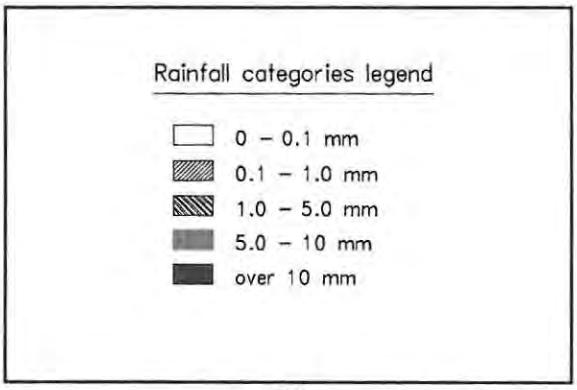

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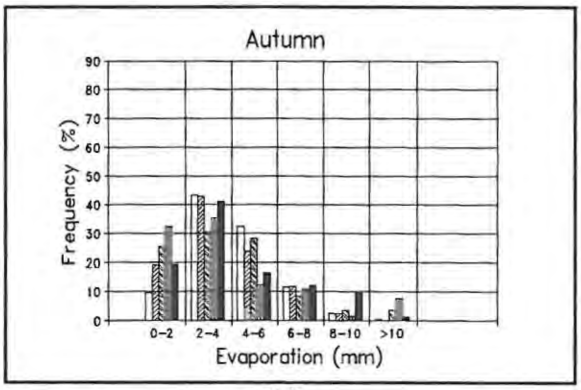

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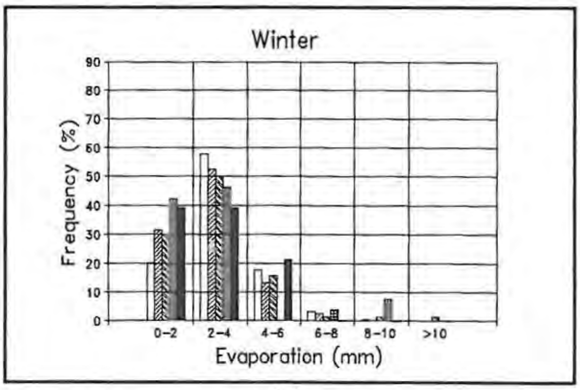
Figure 7.14 : **GLENDALE**
(Natal Coastal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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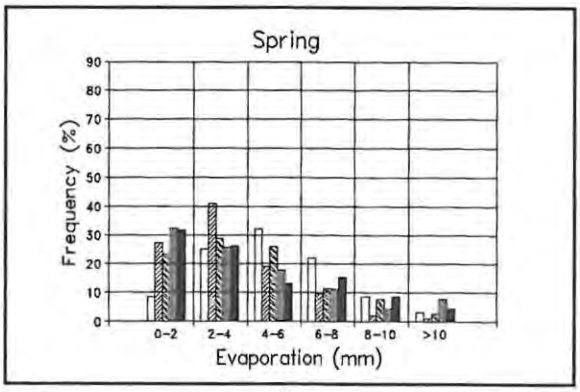

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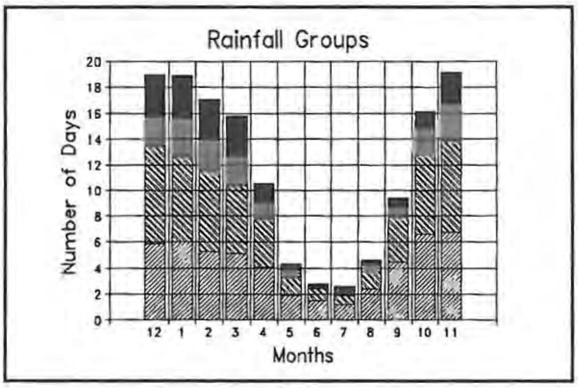

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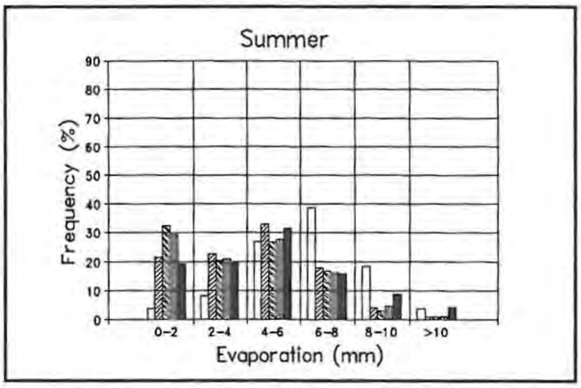

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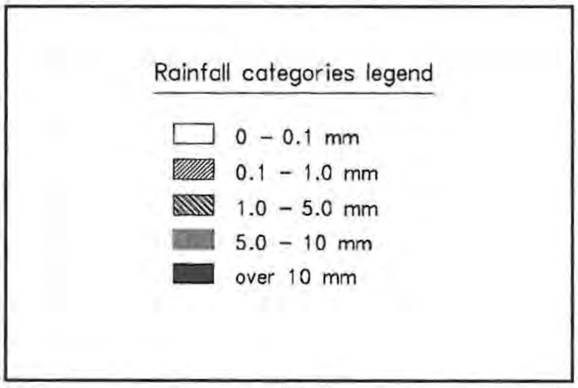

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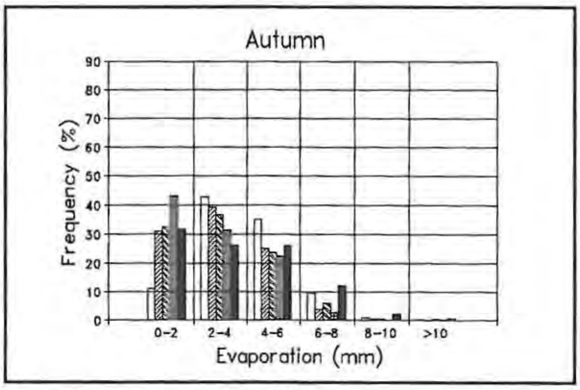

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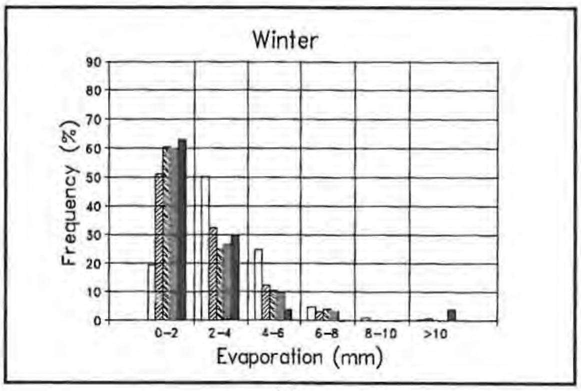

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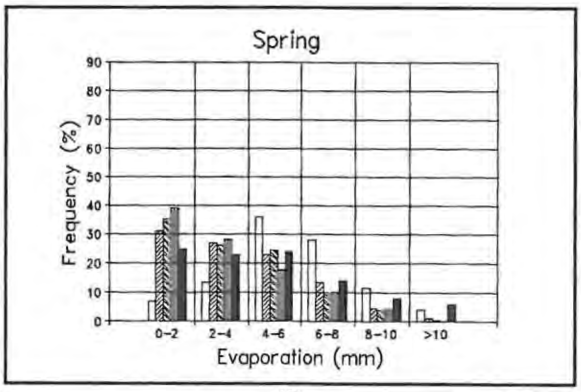

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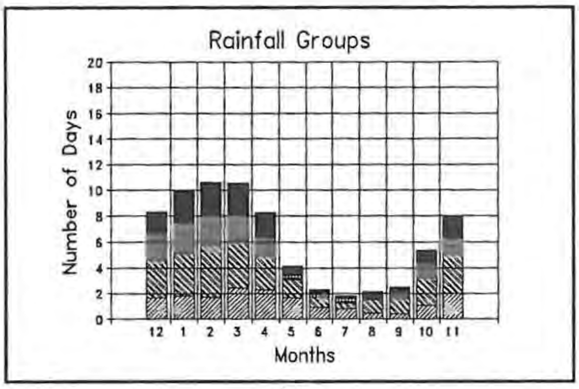
Figure 7.15 : **CEDARA AGR RES** (Natal Inland region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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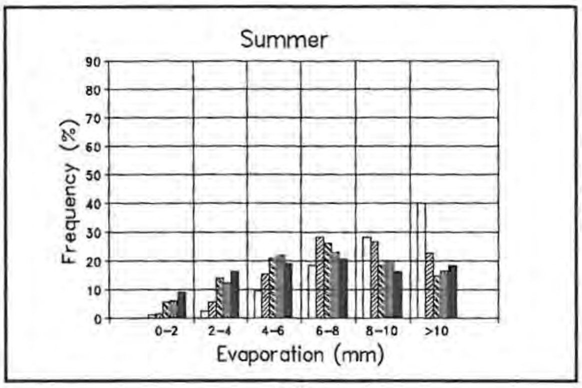

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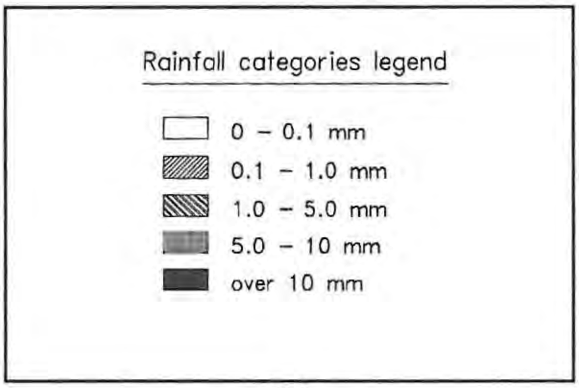

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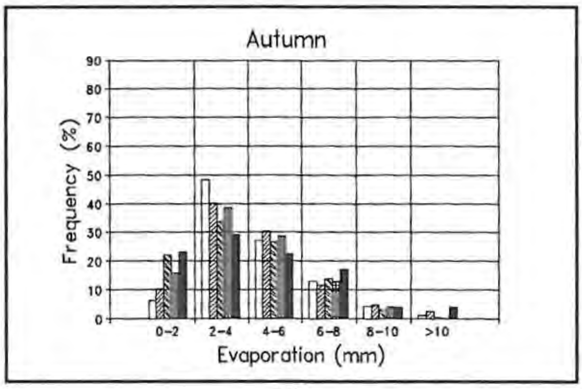


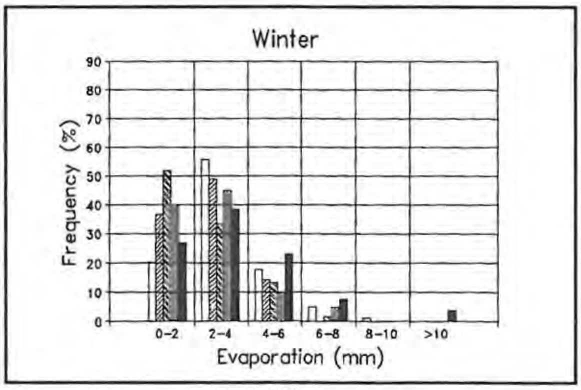
(d)

Figure 7.16 : **GLEN AGR COLL, BFN** (Orange Free State region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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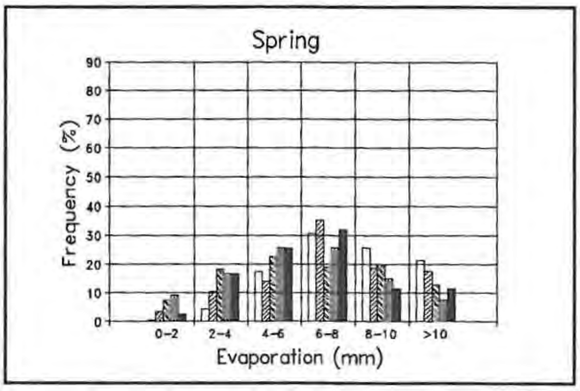

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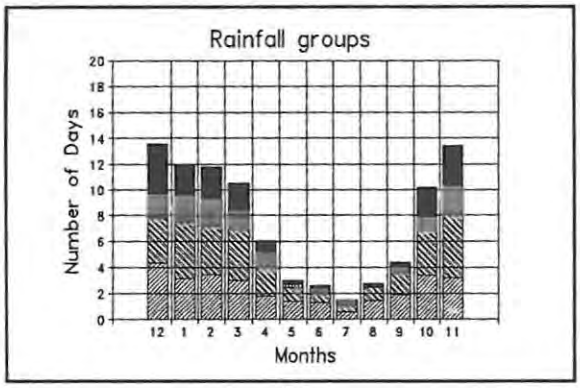

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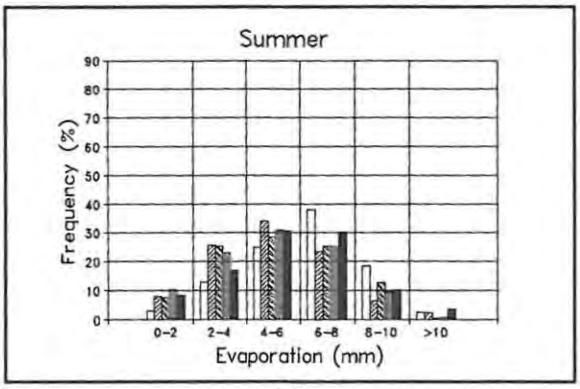

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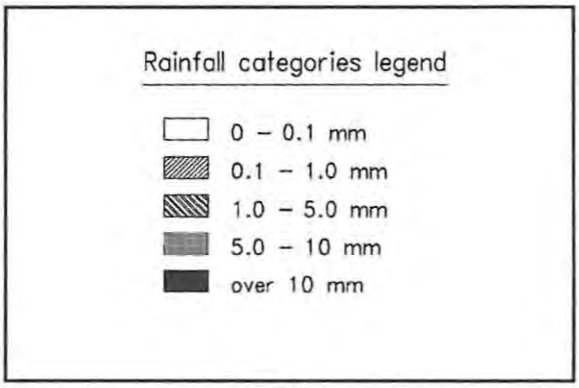

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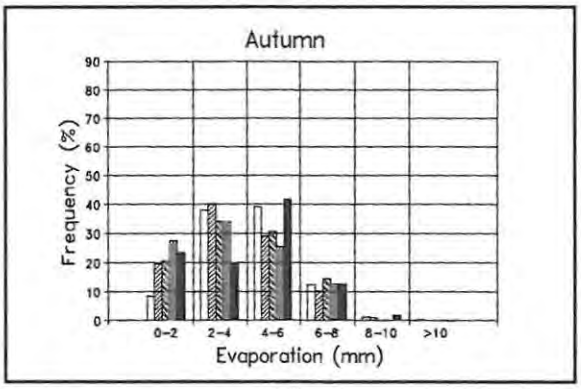


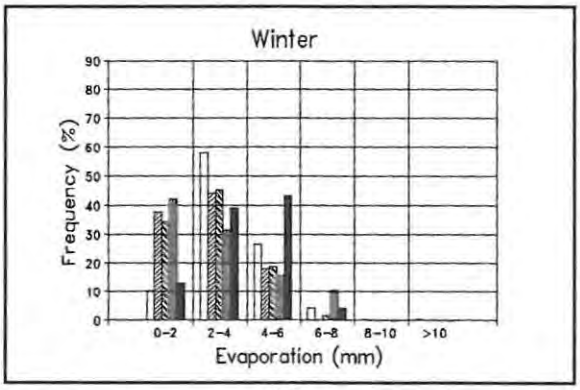
(d)

Figure 7.17 : **NELSPRUIT**
(Far eastern Transvaal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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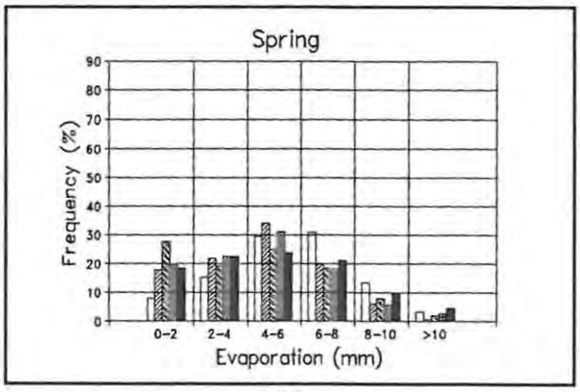

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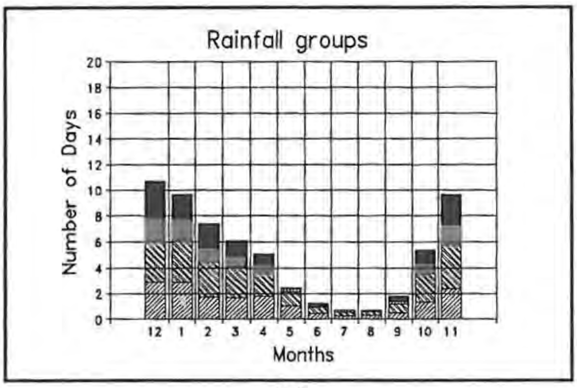

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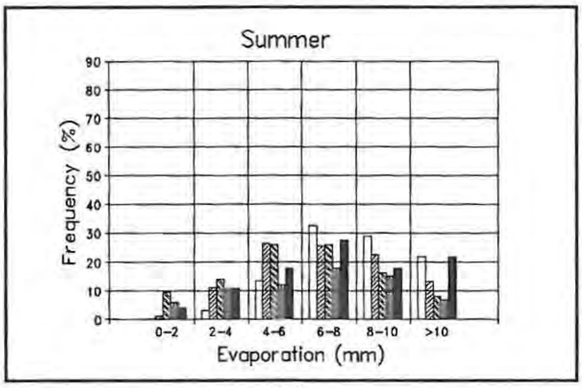

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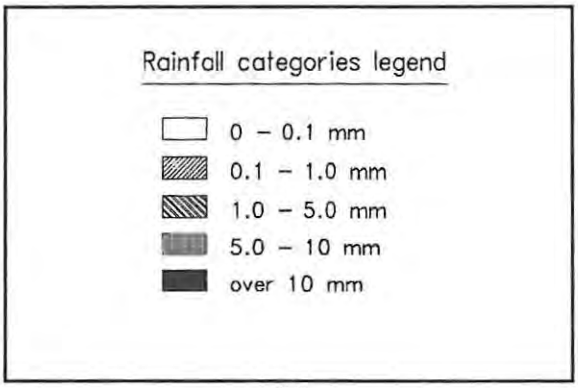

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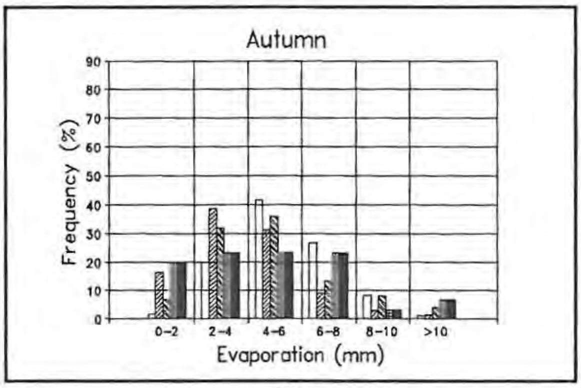


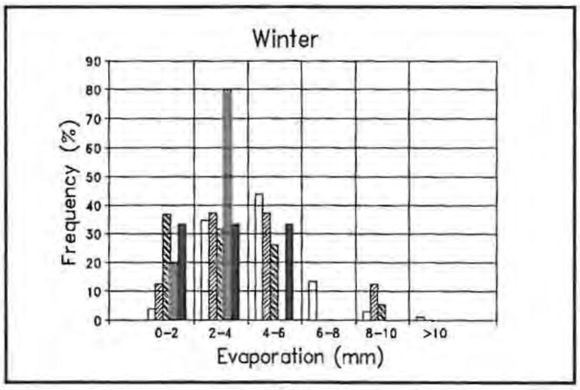
(d)

Figure 7.18 : **PIETERSBURG**
(Transvaal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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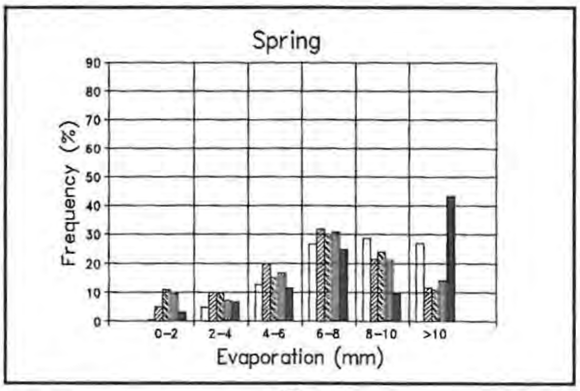

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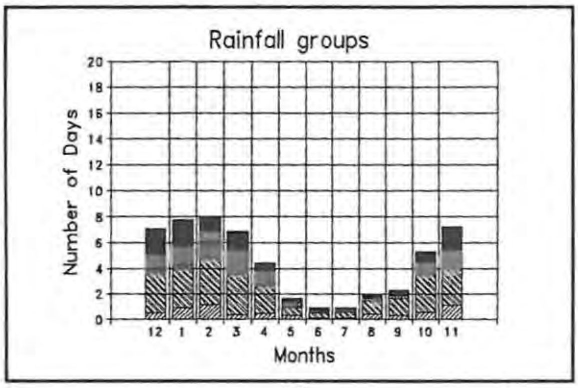

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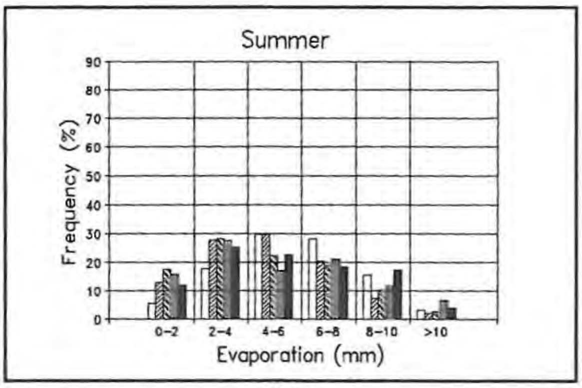

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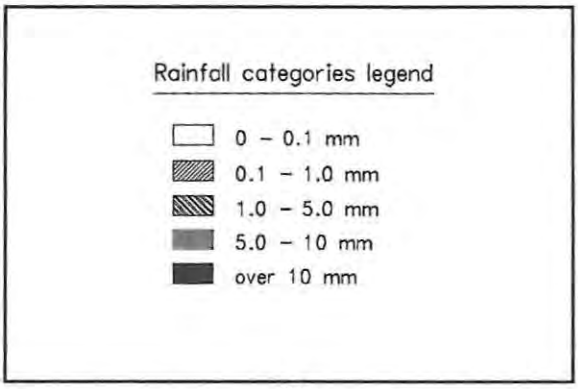

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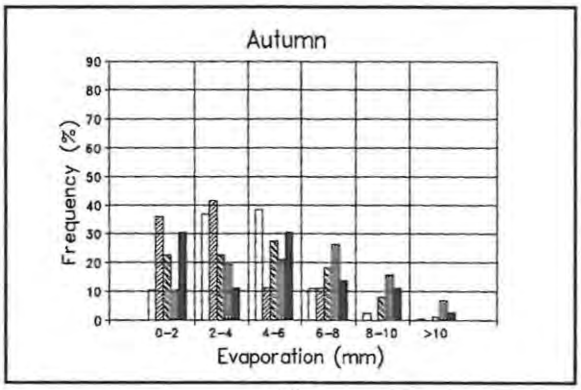


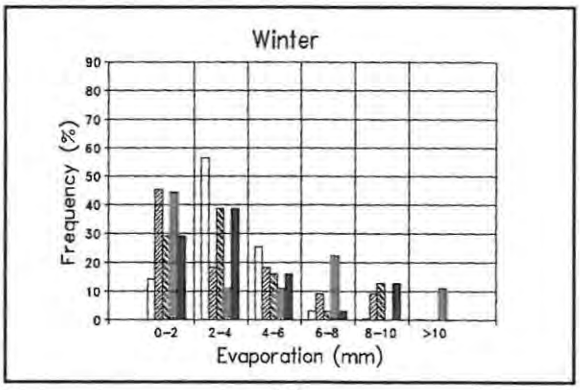
(d)

Figure 7.19 : **LETABA**
(Transvaal region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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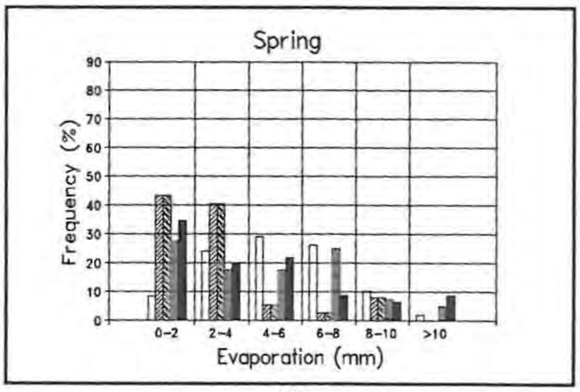

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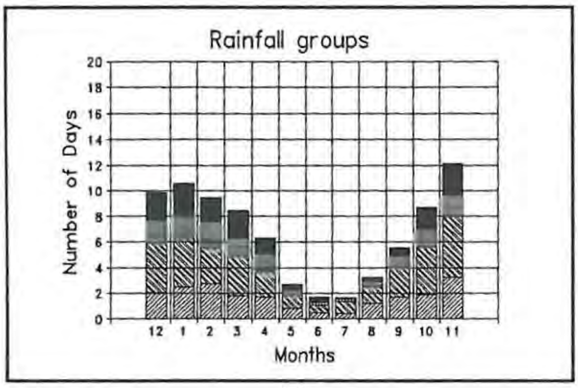

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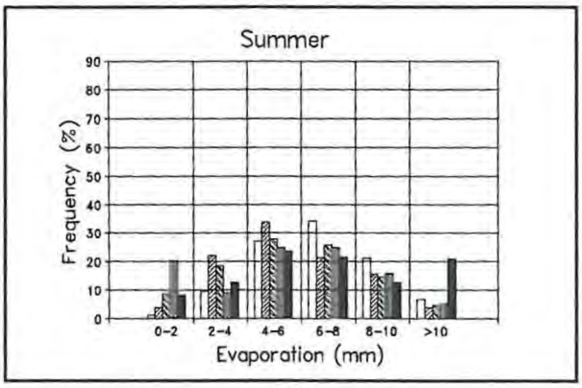

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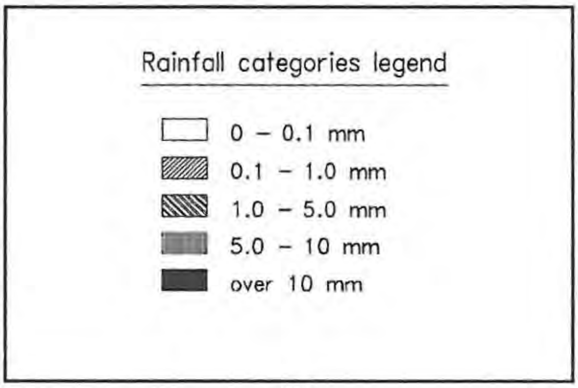

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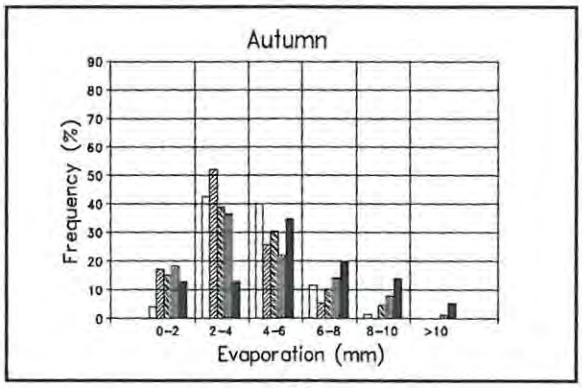

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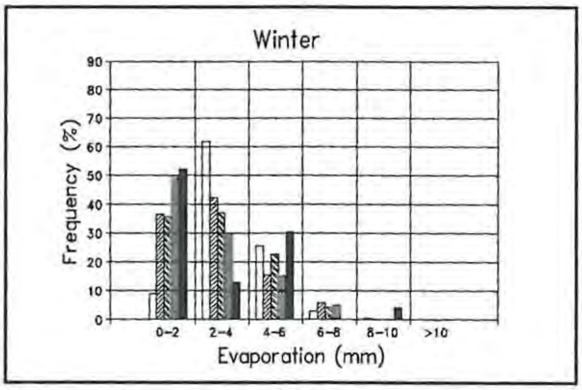

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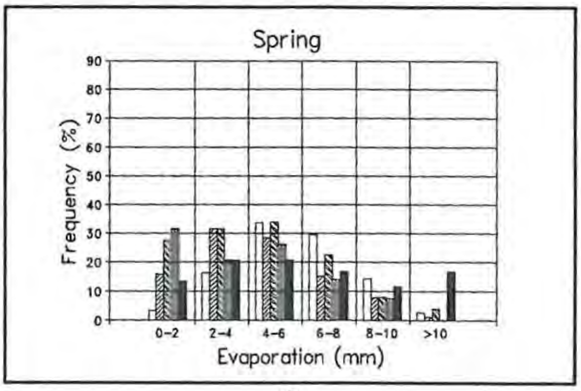


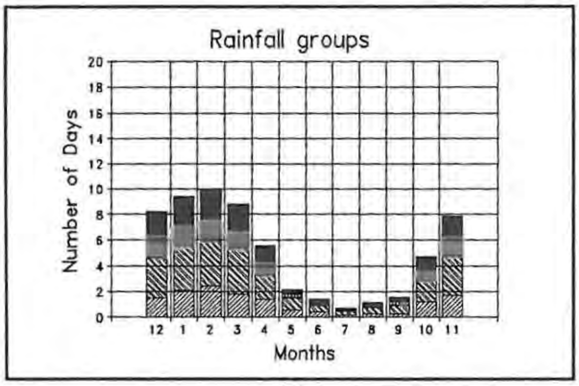
(f)

Figure 7.20 : **PONGOLA EXPT STN** (Northern Natal/Transvaal Border region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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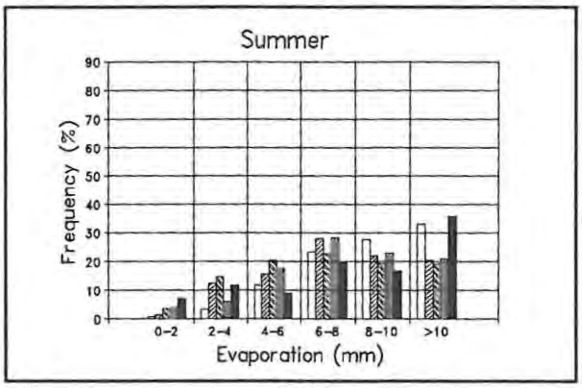

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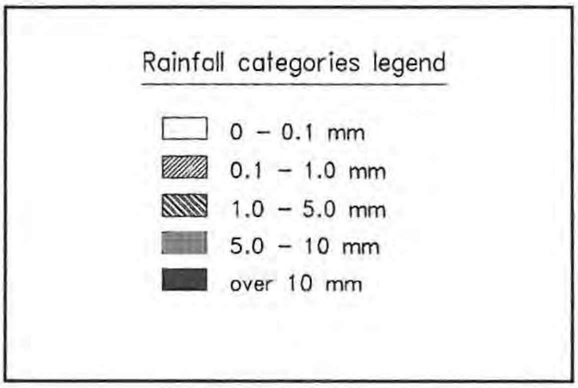

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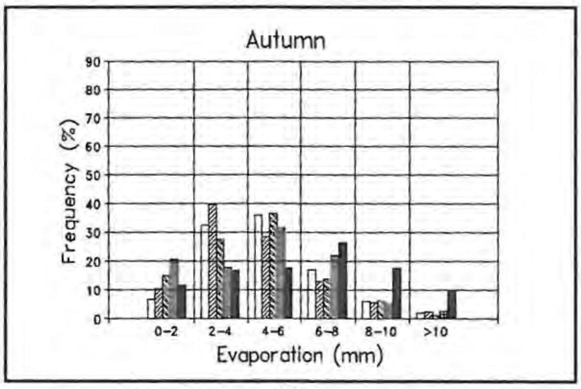


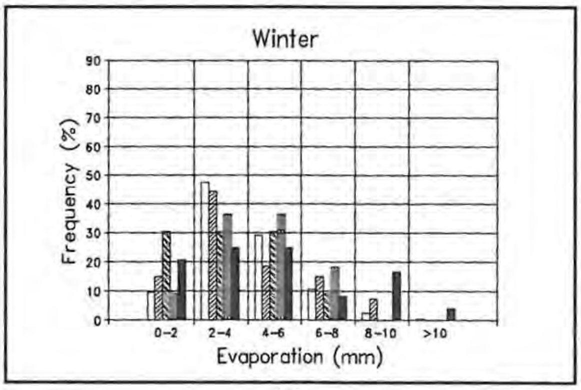
(d)

Figure 7.21 : **VRYBURG; ARMOEDSVLAKT STATION** (Northern Cape region)

(a) Distribution of mean monthly number of days with rainfall.

(b) Legend representing rainfall categories.

Evaporation frequency graphs for the evaporation and rainfall categories,
(c) summer
(d) autumn
(e) winter
(f) spring



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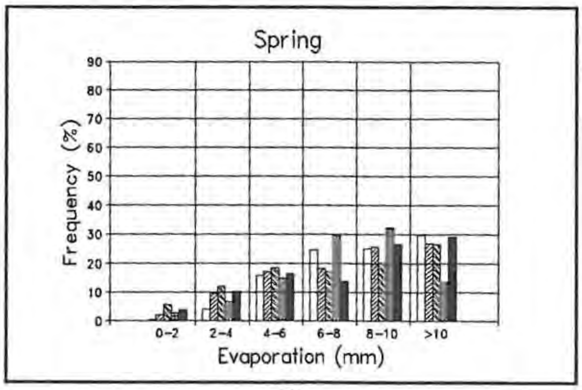


(f)

CHAPTER 8

8. COEFFICIENT OF EFFICIENCY ANALYSIS BASED ON DAILY DATA

8.1 INTRODUCTION

The coefficient of efficiency analysis based on the daily rainfall and evaporation data was conducted to determine the "goodness-of fit" between the observed and the simulated evaporation values. Program C, on the CCWR, calculates the coefficient of efficiency values for daily data. Input into the program includes the ordinary and transformed parameter files, and the daily rainfall and daily evaporation data files. This is an initial test of the validity of using raingroup based mean daily evaporation (the raingroup evaporation weights) over mean daily evaporation regardless of rainfall, and forms the basis of the monthly analysis. This procedure may also be used to infill missing evaporation data values. The results from the coefficient of efficiency analysis based on daily data were encouraging.

8.2 DISCUSSION OF RESULTS

The monthly and accumulative coefficient of efficiency values for all 14 representative stations are presented in tables 8.1 and 8.2, based on the ordinary and transformed data respectively.

A common characteristic of all the representative stations was that the coefficient of efficiency values were lower for the autumn/winter months and higher for the spring/summer months, when using both the ordinary and the transformed data. This indicates that the simulation program is working better when simulating monthly evaporation for the spring/summer months compared to the autumn/winter months. The reason for this may be related to the generally lower number of data points and the higher variability of evaporation values within the autumn/winter months.

TABLE 8.1 : COEFFICIENT OF EFFICIENCY ANALYSIS BASED ON DAILY DATA

(BASED ON THE ORDINARY PARAMETERS)

STATION	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Sum of Monthly
Prospect	0.424	0.422	0.411	0.307	0.208	0.111	0.141	0.090	0.168	0.058	0.341	0.420	3.101
Longdown	0.156	0.119	0.125	0.151	0.153	0.116	0.045	0.089	0.166	0.135	0.282	0.209	1.746
Oos-London W/K	0.208	0.213	0.140	0.106	0.074	0.086	0.059	0.029	0.066	0.118	0.221	0.284	1.604
Addo Sitrus NS	0.191	0.090	0.122	0.183	0.159	0.119	0.098	0.133	0.158	0.260	0.254	0.238	2.005
Queenstown	0.117	0.138	0.202	0.199	0.158	0.033	0.026	0.050	0.118	0.181	0.132	0.189	1.543
Experiment station	0.122	0.138	0.157	0.086	0.068	0.072	0.012	0.007	0.117	0.184	0.155	0.134	1.252
Glendale	0.051	0.125	0.042	0.049	0.013	0.022	0.010	0.005	0.017	0.103	0.044	0.057	0.538
Cedara Agr Res, Stn	0.190	0.212	0.236	0.178	0.113	0.023	0.076	0.042	0.106	0.228	0.284	0.206	1.894
Glen Agr Coll, Bfn	0.111	0.183	0.088	0.069	0.027	0.039	0.034	0.023	0.042	0.079	0.078	0.129	0.902
Letaba	0.053	0.035	0.044	0.042	0.043	0.066	0.055	0.087	0.009	0.085	0.059	0.037	0.615
Pietersburg	0.094	0.110	0.099	0.106	0.077	0.058	0.029	0.062	0.004	0.036	0.059	0.073	0.807
Nelspruit Res	0.130	0.172	0.127	0.101	0.114	0.080	0.125	0.095	0.169	0.196	0.260	0.120	1.689
Pongola Expt Stn	0.098	0.040	0.108	-0.005	-0.286	0.069	0.132	0.096	0.140	0.127	0.013	-0.14	0.395
Vryburg;Armoedsvlakt	0.033	0.053	0.067	0.062	0.020	0.018	0.006	0.006	0.004	0.019	0.029	0.062	0.379

TABLE 8.2 : COEFFICIENT OF EFFICIENCY ANALYSIS BASED ON DAILY DATA

(BASED ON THE TRANSFORMED PARAMETERS)

STATION	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Sum of Monthly
Prospect	0.438	0.429	0.413	0.322	0.201	0.161	0.200	0.202	0.230	0.091	0.315	0.394	3.396
Longdown	0.141	0.098	0.120	0.137	0.107	0.041	-0.063	0.001	0.091	0.068	0.265	0.188	1.194
Oos-London W/K	0.201	0.204	0.118	0.086	0.024	0.045	0.035	-0.001	0.042	0.083	0.213	0.270	1.320
Addo Sitrus NS	0.171	0.079	0.113	0.156	0.133	0.059	0.046	0.097	0.133	0.237	0.236	0.232	1.692
Queenstown	0.107	0.135	0.193	0.186	0.140	-0.006	-0.018	0.003	0.088	0.163	0.118	0.173	1.282
Experiment station	0.112	0.126	0.151	0.083	0.061	0.067	0.005	-0.007	0.107	0.176	0.149	0.120	1.150
Glendale	0.032	0.106	0.036	0.039	-0.002	-0.004	-0.004	-0.012	-0.004	0.093	0.025	0.042	0.347
Cedara Agr Res, Stn	0.241	0.255	0.271	0.224	0.173	0.087	0.124	0.052	0.121	0.222	0.304	0.237	2.311
Glen Agr Coll, Bfn	0.110	0.178	0.086	0.062	0.018	0.011	0.013	0.013	0.027	0.072	0.073	0.128	0.791
Letaba	0.046	0.026	0.036	0.035	0.029	0.024	0.044	0.083	-0.016	0.068	0.049	0.022	0.446
Pietersburg	0.090	0.106	0.097	0.097	0.065	0.047	0.014	0.057	-0.002	0.031	0.054	0.071	0.727
Nelspruit Res	0.127	0.166	0.121	0.093	0.103	0.074	0.120	0.087	0.163	0.186	0.241	0.110	1.591
Pongola Expt Stn	0.006	-0.188	0.016	-0.033	-0.056	-0.119	-0.089	-0.128	0.049	0.060	-0.090	-0.21	-0.779
Vryburg;Armoedsvlakt	0.031	0.052	0.061	0.056	0.013	0.004	-0.007	-0.003	-0.009	0.012	0.024	0.061	0.295

When using the ordinary parameters, the accumulative coefficient of efficiency values were positive for all 14 representative stations, indicating that the simulations of daily evaporation using the raingroup evaporation weights (REW's), were better than when the evaporation values (not corrected for rain) were used. When using the transformed parameters, the accumulative coefficient of efficiency values were lower than those values obtained when using the ordinary parameters, but still positive, except for Pongola Expt station. Therefore, when using either the ordinary or the transformed parameters, the program simulations were giving better results when using the REW's. However, best results were obtained when using the ordinary parameters (as opposed to using the parameters transformed to approximate a Normal distribution) for most stations except Prospect and Cedara Agr Res. The transformation does not seem to improve the model output, yet it is clear that the data is frequently skewed, and mainly positively skewed. This is surprising as it would be expected that because the transformed data closely approximates a normal distribution, these parameters should produce better simulations.

The coefficient of efficiency values were not high. This is because the defining formula does not represent a 1:1 relationship. Rather, the coefficient of efficiency represents a deviation ratio measurement of the simulated and mean evaporation values from the observed evaporation values. Therefore, when the coefficient of efficiency is positive, the simulation program is producing better results in comparison to simply using the mean evaporation values not corrected for rain, and these results are acceptable.

Highest coefficient of efficiency values were obtained for the stations representing the south-western Cape, eastern Cape coastal and inland regions, and the Natal coastal and inland regions. The lower coefficient of efficiency values were obtained for the stations representing the Orange Free State, Transvaal, Northern Natal/Transvaal border and the northern Cape regions. Therefore, the simulation program is tending to produce best results for stations in the southern and eastern Cape coastal regions, while the program is less effective when used on stations representing the northern and interior regions of South Africa. This is in aggreement with the findings in chapter 7. The rainfall/evaporation trends were more easily identifiable in the south-western Cape, and the eastern Cape and Natal coastal and inland regions compared to the more northern and interior regions. The program simulations are most probably affected by the higher variability and range of rainfall-producing systems and evaporation values, and ultimately does not perform as well in these regions.

Generally, as the program produced positive accumulative coefficient of efficiency values, it was decided to proceed with the analysis on a monthly basis. However, the accumulative coefficient of efficiency values in the monthly analysis were expected to be lower than those values obtained in the daily analysis as a result of other influencing factors such as the necessity to disaggregate monthly rainfall values to determine the number of days falling in each rainfall group and the relative simplicity of the procedure used to achieve this.

CHAPTER 9

9. COREVAP PROGRAMS

9.1 INTRODUCTION

The COREVAP programs were run on a PC and developed to simulate monthly evaporation from monthly rainfall and the parameters of the model. The COREVAP1 simulation program uses the straight-forward monthly mean evaporation multiplied by the estimated number of days in each raingroup (chapter 6). COREVAP3 uses a sample from the full distribution of evaporation values, while COREVAP2 uses a sample from one positive and one negative standard deviation of the mean evaporation value. The simulation programs COREVAP1, 2 and 3 were run for all 14 representative stations. Using the daily data (on the CCWR) the parameters were generated for the ordinary and transformed data. The daily evaporation data were infilled using the ordinary parameter file to obtain the monthly evaporation data (ordinary). Similarly, the daily evaporation data were infilled using the transformed parameter file to obtain the monthly evaporation data (transformed). The ordinary and the transformed monthly evaporation data were then used as observed data to compare with the results of the estimated evaporation (ordinary), (obtained from the monthly rainfall and ordinary parameter files); and the estimated evaporation (transformed), (obtained from the monthly rainfall and transformed parameter files).

The assessment of the performance of the COREVAP programs was based on a comparison between the observed and the simulated monthly evaporation values and the aim was to maximise the improvement over using the mean monthly evaporation regardless of rainfall group, that is, to maximise the improvement using the raingroup evaporation weights (REW's). It was important to determine the parameter set which minimized the difference between the observed and simulated outputs. An index was required to compare the sets of data in terms of the extent to which a change in one was or was not reflected by a change in the other data set. The coefficient of efficiency is such an index as explained in chapter 6. Another index reflecting the relationship between the observed and simulated mean evaporation values is the percentage error of mean evaporation, which is expressed as,

$$\%Eme=\sum \frac{(OBSme-SIMme)}{OBSme}\times 100$$

where,

%Eme = percentage error of mean evaporation
OBSme = observed mean evaporation
SIMme = simulated mean evaporation

The best performance of the COREVAP programs was decided on the basis of minimizing the percentage error of mean evaporation and maximizing the coefficients of efficiency.

In the first section of this chapter, the performance of the COREVAP programs is analyzed, with reference to the 14 representative stations. The second section represents a sensitivity analysis to determine the effect of changing the parameters of the model and the range over which the parameters of the model will vary when the model is used for predictive purposes.

9.2 PERFORMANCE OF THE COREVAP PROGRAMS

The performance of the COREVAP programs was analyzed in terms of the improvement effected by estimating evaporation using COREVAP1, 2 and 3, relative to estimating evaporation using the monthly evaporation (ME) regardless of rain. The accumulative coefficient of efficiency values are the sum of all the monthly coefficient of efficiency values and are presented in tables 9.1 to 9.3 for COREVAP1, 2 and 3 respectively. The percentage error of mean evaporation values are presented in table 9.4.

9.2.1 COREVAP1

For stations, **Prospect, Longdown, Addo Sitrus NS, Queenstown, Glen Agr Coll, Bfn, Pietersburg, Pongola Expt station and Vryburg;Armoedsvlakt** : When using the ordinary data the simulations of monthly evaporation (ME) values were close to the observed mean evaporation values for most months as indicated by the positive monthly and accumulative coefficient of efficiency values. Therefore, the simulation of monthly evaporation is better when using the REW's and the percentage error of monthly evaporation values are low.

When using the transformed data, the monthly evaporation values are slightly under-simulated for the winter months. This is evident in the higher percentage error of monthly evaporation values for the autumn/winter months, compared to the spring/summer months, although the annual value remains low. The monthly and accumulative coefficient of efficiency values are lower in comparison to when using the ordinary data. However, the accumulative coefficient of efficiency values still remain positive for all the above stations, except Longdown. Therefore, even when using the transformed data, the simulation of monthly evaporation is better when using the REW's compared to simply using the mean monthly evaporation values not corrected for rainfall.

For stations, **Oos-London W/K, Experiment station, Glendale, Cedara Agr Res, and Letaba** : When using the ordinary data, for most months, the monthly and accumulative coefficient of efficiency values were negative, indicating that the simulated monthly evaporation values were not as good as when the mean monthly evaporation value is used regardless of rain (tables 9.1 to 9.3). The worst coefficient of efficiency values were obtained for the summer months, and here the monthly evaporation values tend to be slightly under-simulated. However, the annual percentage error of monthly evaporation values remain low.

When using the transformed data, the monthly evaporation values are under-simulated for the winter months. This is evident in the higher percentage error of monthly evaporation values for the autumn/winter months in comparison to the spring/summer months, although the annual value is low (table 9.4). Generally, the percentage error of monthly evaporation values are higher than when using the ordinary data. The monthly coefficient of efficiency values are lower in comparison to when using the ordinary data, and the accumulative coefficient of efficiency values are negative. This indicates that when using the transformed data, the simulated values of mean monthly evaporation values are not as good as those obtained when the mean evaporation value is used, regardless of rainfall. In fact, the accumulated coefficient of efficiency values are worse (more negative) compared to those values obtained when using the ordinary data.

9.2.2 COREVAP2

For stations, **Addo Sitrus NS, Queenstown, Glen Agr Coll, Bfn, Pietersburg and Vryburg;Armoedsvlakt** : When using the ordinary data, the simulated monthly evaporation values are close to the observed mean evaporation values and the percentage error of monthly evaporation values are low. These values tend to be slightly over-simulated in the autumn/winter months, leading to negative monthly coefficient of efficiency values. This has consequently lead to lower monthly coefficient of efficiency values when compared to COREVAP1, and ultimately lower accumulative coefficient of efficiency values. However, the accumulative coefficient of efficiency values remain positive indicating that the simulation models are producing better results when using the REW's compared to simply using the mean monthly evaporation value that does not account for rainfall.

When using the transformed data, the mean evaporation values for the autumn/winter months tend to be slightly under-simulated. The monthly coefficient of efficiency values are not as high as those obtained when using the ordinary data, and slightly negative for the winter months. Consequently the accumulative coefficient of efficiency values are lower when using the transformed data, but still positive. The percentage error of mean evaporation values are higher for the autumn/winter months, although the annual values remain low.

For stations, **Prospect, Longdown, Oos-London W/K, Experiment station, Glendale, Cedara Agr Res, Letaba, Nelspruit and Pongola Experiment station** : When using the ordinary data, the accumulative coefficient of efficiency values were negative indicating that the simulation programs did not produce better results when using the REW's. Best monthly coefficient of efficiency values were obtained for the autumn/winter months while the spring/summer months displayed higher negative values. However, the percentage error of monthly evaporation values are low. When using the transformed data, the monthly evaporation values tend to be under-simulated (especially for the Natal and Transvaal stations) for the spring/summer months. Consequently, the monthly coefficient of efficiency values are negative, ultimately resulting in negative accumulative coefficient of efficiency values. The percentage error of monthly evaporation values are higher for the spring/summer months, although the annual values remain low. Therefore, the simulation program did not produce an improvement on simulation outputs when using the REW's. Comparing the outputs from the ordinary versus the transformed data, higher negative accumulative coefficient of efficiency values are obtained when using the transformed data, indicating that the program simulations perform better when using the ordinary data.

9.2.3 COREVAP3

For stations, **Prospect, Addo Sitrus NS, Queenstown, Glen Agr Coll, Bfn, Pietersburg, Pongola Expt station and Vryburg;Armoedsvlakt** : When using the ordinary data, the monthly coefficient of efficiency values are positive for most months, but slightly lower than those values obtained when using COREVAP1. Consequently, the accumulative coefficient of efficiency values are lower than for COREVAP1 (but still positive). The simulated monthly evaporation values are close to the observed mean evaporation values, except for Pietersburg and Vryburg;Armoedsvlakt. For Pietersburg, the monthly evaporation values are slightly over-simulated in the winter months, while for Vryburg;Armoedsvlakt the values are under-simulated for the autumn months, and over-simulated for the spring months (although the monthly coefficient of efficiency values remain positive). The percentage error of monthly evaporation values for all stations remain low.

When using the transformed data, the monthly evaporation values are slightly under-simulated in the autumn/winter months with negative monthly coefficient of efficiency values. However, these negative values were low, and ultimately the accumulative coefficient of efficiency values are still positive. Although monthly evaporation values are slightly under-simulated, the annual percentage error of monthly evaporation remain low. For all the above mentioned stations, except Vryburg;Armoedsvlakt, higher accumulative coefficient of efficiency values are obtained when using the ordinary data input. However, for both the ordinary and transformed data inputs, the accumulative coefficient of efficiency values are positive indicating that COREVAP3 is performing better when using the REW's.

For stations : **Longdown, Oos-London W/K, Experiment station, Glendale, Cedara Agr Res, Letaba, and Nelspruit** : When using the ordinary data, the monthly evaporation values are slightly under-simulated and worst monthly coefficient of efficiency values are obtained for the spring/summer months. This under-simulation of monthly evaporation tends to be higher for the Natal stations (Experiment station and Cedara Agr Res), culminating in higher negative accumulative coefficient of efficiency values (table 9.3). For the Transvaal stations (Letaba and Nelspruit), besides this under-simulation in the spring/summer months, the monthly evaporation values also tend to be over-simulated in the autumn months. However, for all the above stations, the percentage error of monthly evaporation values are low (and generally highest for the Natal and Transvaal stations) (table 9.4). As the accumulative coefficient of efficiency values are negative, COREVAP3 did not make any improvement in estimating evaporation when compared to simply using the monthly mean evaporation values not accounting for rainfall.

When using the transformed data, the accumulative coefficient of efficiency values are negative for all stations, with higher negative values for Longdown, Oos-London W/K and Letaba, and for the Natal stations (Experiment station, Glendale and Cedara Agr Res). The percentage error of monthly evaporation values for the above mentioned stations are higher compared to the other stations, although the overall values are still low. Higher percentage error of monthly evaporation values are obtained when using the transformed data as opposed to using the ordinary data. This is because the monthly evaporation values are under-simulated in the autumn/winter months to a greater extent than when using the ordinary data.

9.3 SUMMARY RESULTS OF THE COREVAP PROGRAMS

No program is better than the assumptions and data it relies on. The inconsistency of data is a basic problem. No conclusions and information extracted from past data records can be better than the quantity and quality of the available data. The programs use input data and parameter values which are subject to measurement and sampling errors as mentioned in chapter 6. For example, data recorded during extreme events are often unreliable. The 'noise' or randomness of the processes of rainfall and evaporation are an influencing factor. Perhaps some method is required to reduce this 'noise' in order to obtain a better definition of the processes occurring. For example, evaporation is influenced by a number of controlling factors and rainfall is just one process that is influencing the evaporation rate. Perhaps the inclusion of other factors such as temperature indices might give a better definition of the rainfall/evaporation relationships.

The program output resembles the main statistical characteristics of the historical hydrologic time series. However, the true statistical characteristics of hydrological series is never known because what is measured is only a finite (sample) number of years, and as a result, are only estimates of the true characteristics. Consequently, the statistical characteristics derived from the sample are only one possible estimate out of many others. This variability is evident when using different approaches, but the same data, for example, the difference in the performance of the COREVAP1, 2 and 3 programs.

For all representative stations, best simulation results are obtained when using the ordinary data. For stations, **Longdown, Prospect, Addo Sitrus NS, Queenstown, Glen Agr Coll, Bfn, Pietersburg, Nelspruit Res, Pongola Expt Stn**, and **Vryburg;Armoedsvlakt**, the COREVAP programs performed better when using the REW's than when the monthly mean evaporation value not corrected for rain, was used, as indicated by the positive monthly and accumulative coefficient of efficiency values. Best results are obtained when using COREVAP1 for the above stations, except for Vryburg;Armoedsvlakt, when COREVAP3 gave the best simulations of monthly evaporation.

Therefore, COREVAP1 produces best simulations of monthly evaporation. This is not surprising as the program uses the straight-forward mean evaporation value multiplied by the number of days to simulate the monthly evaporation values. Consequently, the simulated evaporation values are close to the observed evaporation values and the monthly and accumulative coefficient of efficiency values are positive. Results from COREVAP3 generally tended to be acceptable, although not as good as the simulations obtained when using COREVAP1. COREVAP3 uses a sample from the full distribution of evaporation values. Corevap2 produces the worst simulation of monthly evaporation values and uses a sample from one positive and one negative standard deviation of the mean evaporation value. These results are to be expected from COREVAP2 and 3 as here one is evaluating an estimate in comparison with the observed value at that time (month). This random sampling procedure may reproduce the statistics of the original data set quite well (as was the case with COREVAP3), but cannot be expected to reproduce individual values. For example, a sample from a specific distribution of possible evaporation values, will give you a monthly evaporation value that is dependent on the frequency of the occurrence of each observed value.

However, the data does tend to be frequently skewed, and it is evident that this will influence the random sampling procedure. More specifically, the simulated monthly evaporation values were not as close to the observed monthly evaporation values and the accumulated coefficient of efficiency values were lower than those obtained when using COREVAP1.

The COREVAP programs do not perform well when using the monthly evaporation data based on daily infilled values using the transformed parameters. For example, for stations, **Oos-London W/K, Experiment station, Glendale, Cedara Agr Res**, and **Letaba**, when using COREVAP1, 2 and 3, the accumulative coefficient of efficiency values are negative indicating that the program simulations are not producing better results when using the REW's than when using the monthly evaporation values not corrected for rain. Therefore, the transformations do not seem to improve the model when it is clear that the data are frequently skewed. This trend was also identified in the daily coefficient of efficiency analysis. The reason for this occurrence remains unexplainable.

A sensitivity analysis was conducted on COREVAP1 to determine which parameters of the model had the greatest influence on the simulations, and the results are presented in sub-section 9.4. The sensitivity analysis was only conducted on COREVAP1 using the ordinary data, as this program gave best results when compared with COREVAP2 and 3.

TABLE 9.1 : ACCUMULATIVE COEFFICIENTS OF EFFICIENCY : COREVAP1

STATION	Using the ordinary evaporation data		Using the transformed evaporation data	
	A	B	C	D
Prospect	0.246	0.250	0.059	0.068
Longdown	-0.024	0.062	-0.695	-0.485
Oos-London W/K	-0.298	-0.215	-0.639	-0.510
Addo Sitrus NS	0.182	0.182	0.124	0.124
Queenstown	0.292	0.291	0.139	0.138
Experiment station	-0.227	-0.019	-0.582	-0.532
Glendale	-0.128	-0.069	-0.613	-0.494
Cedara Agr Res, Stn	-0.444	-0.390	-1.181	-1.085
Glen Agr Coll, Bfn	0.232	0.235	0.216	0.220
Letaba	-0.230	-0.164	-0.698	-0.573
Pietersburg	0.120	0.123	0.095	0.099
Nelspruit Res	0.062	0.095	-0.201	-0.153
Pongola Expt Stn	0.166	0.202	0.041	0.095
Vryburg-Armoedsvlakt	0.107	0.108	0.122	0.124

A = Based on ordinary evaporation data and ordinary parameter files.

B = Based on ordinary evaporation data and transformed parameter files.

C = Based on transformed evaporation data and ordinary parameter files.

D = Based on transformed evaporation data and transformed parameter files.

TABLE 9.2 : ACCUMULATIVE COEFFICIENTS OF EFFICIENCY : COREVAP2

STATION	Using the ordinary evaporation data		Using the transformed evaporation data	
	A	B	C	D
Prospect	-0.006	-0.001	-0.062	-0.057
Longdown	-0.297	-0.207	-0.522	-0.440
Oos-London W/K	-0.551	-0.474	-0.585	-0.498
Addo Sitrus NS	0.010	0.010	0.031	0.031
Queenstown	0.205	0.203	0.187	0.185
Experiment station	-0.599	-0.560	-0.648	-0.606
Glendale	-0.335	-0.267	-0.452	-0.372
Cedara Agr Res, Stn	-0.642	-0.589	-0.757	-0.698
Glen Agr Coll, Bfn	0.151	0.154	0.156	0.159
Letaba	-0.665	-0.606	-0.926	-0.858
Pietersburg	0.037	0.040	0.035	0.037
Nelspruit Res	-0.230	-0.195	-0.275	-0.243
Pongola Expt Stn	-0.116	-0.072	-0.134	-0.086
Vryburg-Armoedsvlakt	0.130	0.132	0.130	0.132

A = Based on ordinary evaporation data and ordinary parameter files.

B = Based on ordinary evaporation data and transformed parameter files.

C = Based on transformed evaporation data and ordinary parameter files.

D = Based on transformed evaporation data and transformed parameter files.

TABLE 9.3 : ACCUMULATIVE COEFFICIENTS OF EFFICIENCY : COREVAP3

STATION	Using the ordinary evaporation data		Using the transformed evaporation data	
	A	B	C	D
Prospect	0.170	0.174	0.078	0.086
Longdown	-0.108	-0.023	-0.511	-0.336
Oos-London W/K	-0.383	-0.305	-0.573	-0.461
Addo Sitrus NS	0.120	0.120	0.106	0.106
Queenstown	0.265	0.263	0.182	0.181
Experiment station	-0.368	-0.331	-0.601	-0.554
Glendale	-0.165	-0.104	-0.483	-0.380
Cedara Agr Res, Stn	-0.433	-0.380	-0.894	-0.814
Glen Agr Coll, Bfn	0.207	0.210	0.205	0.209
Letaba	-0.381	-0.320	-0.641	-0.540
Pietersburg	0.114	0.116	0.104	0.107
Nelspruit Res	-0.044	-0.011	-0.205	-0.161
Pongola Expt Stn	0.068	0.107	-0.008	0.045
Vryburg-Armoedsvlakt	0.138	0.140	0.153	0.155

A = Based on ordinary evaporation data and ordinary parameter files.

B = Based on ordinary evaporation data and transformed parameter files.

C = Based on transformed evaporation data and ordinary parameter files.

D = Based on transformed evaporation data and transformed parameter files.

TABLE 9.4 : ANNUAL PERCENTAGE ERROR OF MONTHLY MEAN EVAPORATION

STATION	COREVAP 1		COREVAP 2		COREVAP 3	
	A	B	A	B	A	B
Prospect	0.16	2.29	-0.61	-0.33	-0.24	1.39
Longdown	1.29	7.01	0.09	-0.28	0.54	5.01
Oos-London W/K	2.76	7.69	1.49	2.44	2.04	5.74
Addo Sitrus NS	-0.53	2.55	-1.38	-1.00	-0.94	1.35
Queenstown	1.46	6.96	0.88	2.10	1.16	5.29
Experiment station	3.88	6.38	3.00	3.45	3.40	5.24
Glendale	3.32	8.39	2.44	3.37	2.84	6.55
Cedara Agr Res, Stn	4.57	9.42	3.33	4.36	3.84	7.43
Glen Agr Coll, Bfn	1.72	3.76	0.86	1.25	1.27	2.77
Letaba	2.03	6.41	0.55	1.02	1.20	4.40
Pietersburg	0.40	2.25	-0.38	-0.04	0.00	1.36
Nelspruit Res	3.02	5.10	2.05	2.12	2.52	4.01
Pongola Expt Stn	0.99	3.41	0.13	0.73	0.56	2.39
Vryburg;Armoedsvlakt	-3.03	-0.86	-3.58	-3.30	-3.28	-1.73

A = Based on the ordinary data.

B = Based on the transformed data.

9.4 SENSITIVITY ANALYSIS

9.4.1 INTRODUCTION

Sensitivity analysis is used to determine which parameters of a model or equation have the greatest influence on the results. The sensitivity analysis must be carried out in the context of the likely range over which the parameters of a model will vary when the model is used for predictive purposes. For example, if the value of a sensitive parameter is changed slightly, it will have a much larger effect on the model prediction than if the value of an insensitive parameter is altered by an equivalent amount. The sensitivity analysis was conducted by assessing the effect a fixed percentage change in each model parameter, would have on the model output, while holding all the other parameter values constant. However, a sensitivity analysis based on fixed percentage changes for each parameter value may be unrealistic with respect to the range of variation that may be observed in a particular parameter. This is shown by the lambda values in this study. Small percentage changes in lambda values resulted in negligible effects on the output parameters, while very high percentage changes resulted in only small changes in the output parameters.

The application of the relationships to areas where there are no observed data involves regionalisation of the parameters. The range of parameter values represented by all stations within a particular region therefore need to be viewed in the context of how sensitive the results are to similar changes to the parameters. This was done by conducting a sensitivity analysis, in terms of what effect a percentage increase or decrease in the original distribution statistics parameter files would have on the resultant simulated monthly evaporation and coefficient of efficiency values. The COREVAP program simulates the monthly evaporation given the specific data inputs and various program run combinations. It is important to identify all the possible combinations of the input and parameter files as to avoid any confusion and these have been identified in the first section of this chapter. Best simulations of monthly evaporation are obtained when using the ordinary data (chapter 9), and consequently the sensitivity analysis is based on COREVAP1 with an ordinary data input.

Before assessing the effect of percentage changes in the parameters lambda, mean monthly evaporation and mean monthly rainfall, certain characteristics of the data set and program simulations are to be expected. There will be no change in the mean monthly rainfall, observed mean monthly evaporation and file mean monthly evaporation values. These data inputs are fixed and are read the same way with each program run, and used as constants to compare the simulated monthly evaporation and accumulative coefficient of efficiency values.

It is important to note that changes to the mean monthly evaporation values do not change the actual mean monthly rainfall but the relative value for each raingroup (that is, only affecting the raingroup evaporation weights (REW's)). Similarly, the mean monthly rainfall changes are affecting the mean amount of rain within the raingroup (REW's). The changes in the simulated monthly evaporation values and the monthly and accumulative coefficient of efficiency values (when changing the input parameters) are an indication as to how well the COREVAP1 program simulations are performing.

Another index reflecting the relationship between the observed and simulated monthly evaporation is percentage error of monthly evaporation. The closer the percentage error of monthly evaporation value is to zero, the better the correlation between the observed and simulated monthly evaporation values. Graphs representing the percentage error of monthly evaporation values and the accumulative coefficient of efficiency values for all 14 representative stations are presented in figures 9.1 to 9.14.

With specific reference to the 14 representative regional stations, the effect a 5%, 15% and 25% increase or decrease in the

(i) lambda values (only applies when using the transformed data),

(ii) mean evaporation values (for each raingroup category and each month),

(iii) mean daily rainfall values (for each rainfall category and for each month), and the

(iv) number of raindays within each rainfall category (for each month),

will have on the simulated monthly evaporation values and the monthly and accumulative coefficient of efficiency values, will be assessed.

9.4.2 CHANGING THE LAMBDA VALUES.

Although the results of the sensitivity analysis of COREVAP1 using only the ordinary data are reported in this chapter, for 'completeness,' the effect of changing lambda values is briefly mentioned.

Percentage changes in the lambda values will only affect the transformed parameters and will therefore have no effect when using the ordinary data input files. With higher percentage increases in lambda values, the simulated monthly evaporation values decrease proportionately and the accumulative coefficient of efficiency values decrease. Conversely, with higher percentage decreases in lambda values the simulated monthly evaporation values increase proportionately, and the accumulative coefficient of efficiency values improve slightly. The accumulative coefficient of efficiency is represented by the equation,

$$\sum_{i=1}^{12} CE_i$$

where,

CE = accumulative coefficient of efficiency

i = month

This value represents the sum of the 12 monthly coefficient of efficiency values. The best accumulative coefficient of efficiency and simulated monthly evaporation values are obtained when using the higher percentage decreases in lambda values. However, for all 14 representative stations, changes as a result of percentage increases and decreases in lambda values are negligible and one may conclude that the lambda parameter is not sensitive to change. For the accumulative coefficient of efficiency value to show a slight improvement, a 50% decrease in lambda values was required. For example, Prospect (table 9.5), a 50% decrease in lambda values improved the accumulative coefficient of efficiency by only 0.038.

TABLE 9.5 : **PROSPECT** : Accumulative coefficient of efficiency values when changing the lambda values (using COREVAP1).

% dec/inc in the Lambda value	Accumulative Coefficient of Efficiency
50% dec	0.106
25% dec	0.077
15% dec	0.074
5% dec	0.069
Original value	**0.068**
5% inc	0.074
15% inc	0.069
25% inc	0.064
50% inc	0.049

9.4.3 CHANGING THE MEAN EVAPORATION VALUES.

For research stations : **Longdown, Prospect, Addo Sitrus NS, Queenstown, Glen Agr Coll, Bfn, Nelspruit Res, Pietersburg, Pongola Expt Stn, Vryburg;Armoedsvlakt** : Higher percentage increases and decreases in the mean evaporation values resulted in the simulated monthly evaporation values increasing and decreasing respectively. As a consequence, the simulated monthly evaporation values generally tend to be over- and under-simulated in comparison to the observed and file monthly evaporation values. Any percentage increase or decrease in the monthly evaporation values resulted in lower accumulative coefficients of efficiency (figures 9.1 to 9.14). Therefore, best simulated monthly evaporation values are obtained using the original mean evaporation values, and the percentage increases and decreases in the mean evaporation values were acceptable, as long as the accumulative coefficient of efficiency value remained positive.

For research stations : **Oos-London W/K, Glendale, Experiment station, Cedara Agr Res Stn, Letaba** : When using the original parameter inputs, the program simulations are worse than those obtained when using the monthly evaporation value not corrected for rain (the REW's), as indicated by the negative accumulative coefficient of efficiency values (figures 9.1 to 9.14). With a 5% increase in mean evaporation, the simulated monthly evaporation values increase and are closer to the file and observed monthly evaporation values when compared to running the program using the original mean evaporation values. The accumulative coefficient of efficiency values also improved. With a 15% increase, simulated monthly evaporation tends to be over-simulated in comparison to the observed and file monthly evaporation values, and the accumulative coefficient of efficiency values decrease. This problem is exacerbated with further percentage increases in mean evaporation values. In contrast, the higher the percentage decrease in mean evaporation, the higher the corresponding decrease in the simulated monthly evaporation values, which now tend to be under-simulated in comparison to the observed and file monthly evaporation. The accumulative coefficient of efficiency values decrease. Therefore, best accumulative coefficients of efficiency and simulated monthly evaporation values are obtained with a 5% increase in mean evaporation values, for each raingroup category, in each month. However, even with these better simulation results, the accumulative coefficient of efficiency values still remain negative. These changes in the mean evaporation values are therefore largely irrelevant, as the estimated parameters are not very useful.

For all 14 representative stations, the mean evaporation parameter is sensitive to change as indicated by the fairly steep percentage error of monthly evaporation line gradients (figures 9.1 to 9.14). As the graphs display insignificant differences between the summer and winter months, only the annual percentage error of monthly evaporation graphs have been included here. The relationship between the accumulated coefficient of efficiency and percentage error of monthly evaporation values with percentage increases and decreases in the mean evaporation parameter, are discussed under sub-section 9.5.

9.4.4 CHANGING THE MEAN RAINFALL VALUES.

For research stations, **Longdown**, **Nelspruit Res**, **Pongola Expt Stn**, and **Vryburg;Armoedsvlakt** : With a percentage increase in mean rainfall values, the simulated monthly evaporation values increase and progressively improve (figures 9.2, 9.12, 9.13 and

9.14). These values are more comparable to the observed and file monthly evaporation values, than when the original input parameter files are used. The accumulative coefficient of efficiency values have improved and are more positive. However, with a 25% increase in mean rainfall values, the evaporation values for some of the months tend to be slightly over-simulated, particularly for the spring and summer months. Therefore, any further percentage increases in mean rainfall values would lead to the over-simulation of monthly evaporation values. In contrast, percentage decreases in mean rainfall values, resulted in the under-simulation of monthly evaporation values in comparison to the observed monthly evaporation. This under-simulation is further exaggerated with higher percentage decreases in mean rainfall and is accompanied by lower accumulative coefficient of efficiency values.

For research stations, **Prospect** and **Addo Sitrus NS**, with a 15% and 25% increase in mean rainfall, simulated monthly evaporation tends to be over-simulated in comparison with the observed and file monthly evaporation values. However, a 5% increase in mean rainfall is acceptable and produces the best accumulative coefficient of efficiency values (figure 9.1 and 9.4 respectively). The above characteristics also apply to **Glen Agr Coll, Bfn** and **Pietersburg** stations, except that here a 5% to 15% increase in mean rainfall is permissible and generally the best accumulative coefficient of efficiency and simulated monthly evaporation values are obtained with a 15% increase (figures 9.9 and 9.11 respectively). In contrast, higher percentage decreases in mean rainfall values lead to the under-simulation of monthly evaporation.

For **Queenstown**, best simulated monthly evaporation values are obtained when using the original mean rainfall values (figure 9.5). Any increases in mean rainfall values and consequent increase in the accumulative coefficient of efficiency values are not justifiable when compared with the resultant over-simulation of monthly evaporation.

For research stations, **Oos-London W/K, Experiment station, Glendale, Cedara Agr Res, Stn**, and **Letaba** : With any percentage increase or decrease in rainfall values, the accumulative coefficient of efficiency values are negative, indicating that the simulation program did not improvement on the method of simply using the mean monthly evaporation value not corrected for rain. With higher percentage increases in mean rainfall the simulation of the monthly evaporation values did improve, and these values are more comparable to the observed mean evaporation (figures 9.3, 9.6, 9.7, 9.8 and 9.10). However, a 25% increase in mean rainfall, lead to the over-simulation of monthly evaporation. Therefore, any further percentage increase in mean rainfall values would lead to the further exaggeration of this over-simulation of monthly evaporation. Although the accumulative coefficient of efficiency values did improve, the values still remain negative. Therefore, for these stations, any changes to the mean rainfall parameter is largely irrelevant because at no time are the accumulative coefficient of efficiency values positive.

Considering the percentage error of monthly evaporation graphs, the mean rainfall parameter is less sensitive to change when compared with the mean evaporation parameter, as indicated by the gradual percentage error of monthly evaporation line gradients (figures 9.1 to 9.14). As there was very little difference between the summer and winter months, only the annual percentage error of monthly evaporation graphs have been included here. The relationship between the accumulative coefficient of efficiency and percentage error of monthly evaporation values, with percentage increases and decreases in the mean rainfall parameter, are discussed under section 9.5.

9.4.5 CHANGING THE MEAN NUMBER OF RAIN DAYS

It was not possible to simply use a standard increase or decrease in the mean number of raindays for each raingroup category and each month (as was the case with the lambda, mean evaporation and mean rainfall values) as, here the number of days in each raingroup must add up to the number of days within each month. Consequently, the sensitivity analysis was conducted slightly differently. Taking Prospect as an example, for January, no rainfall was recorded on 29.10 days of the month. The remaining 1.9 days are distributed amongst the 2 - 5 raingroup categories. The mean number of days in the 1st raingroup category (no rain) was decreased by 5%, to 27.6 days. The remaining 3.4 days are distributed amongst the 2 - 5 raingroup categories in proportion to the original distribution characteristics (table 9.6). This was done for each month of the year, and the resulting influence on the simulation of

TABLE 9.6 : **PROSPECT** : Changes in the mean number of days (ndays) for January, for each raingroup category.

Raingroup categories	Original mean ndays	5% change in mean ndays
0 - 0.1	29.10	27.60
0.1 - 1.0	0.50	0.90
1.0 - 5.0	0.67	1.20
5.0 - 10	0.22	0.40
>10.0	0.50	0.90

monthly evaporation and the accumulative coefficient of efficiency values is assessed. Changing the distribution of the mean number of days in the higher raingroup categories had only a limited effect on the accumulative coefficient of efficiency values. Generally, the accumulative coefficient of efficiency did not increase by more than 0.002. A further decrease in the mean number of days in the 'no rain' category (for example by 10%), and associated increase in the mean number of days in the higher rainfall categories would not be representative. This change would have the effect of increasing the number of higher magnitude rainfall events within each month and so would not be really representative of that station. In a way, the same situation could be accounted for by simply increasing the mean rainfall values, and it was decided that the time taken to change each value in proportion to the original distribution, and the very limited effect results had on the accumulative coefficient of efficiency values, did not warrant further investigation into changing this parameter value.

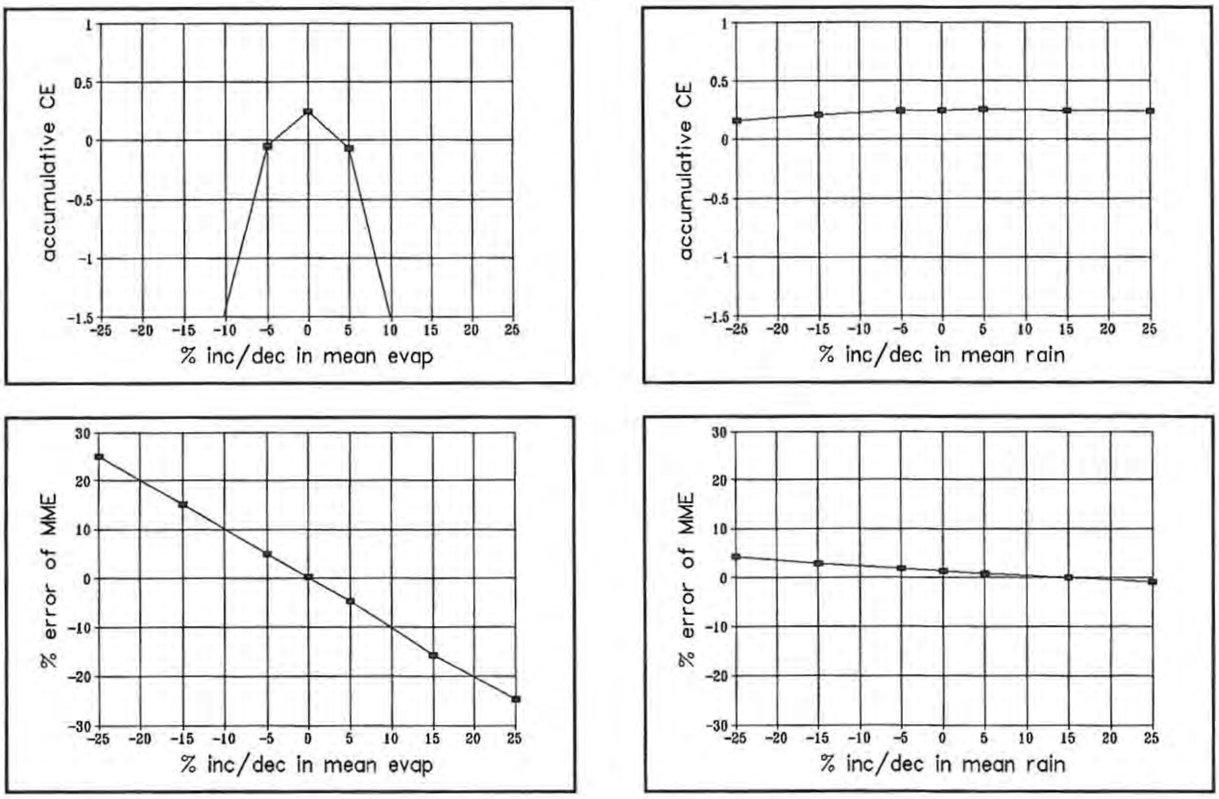


Figure 9.1 : **PROSPECT** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

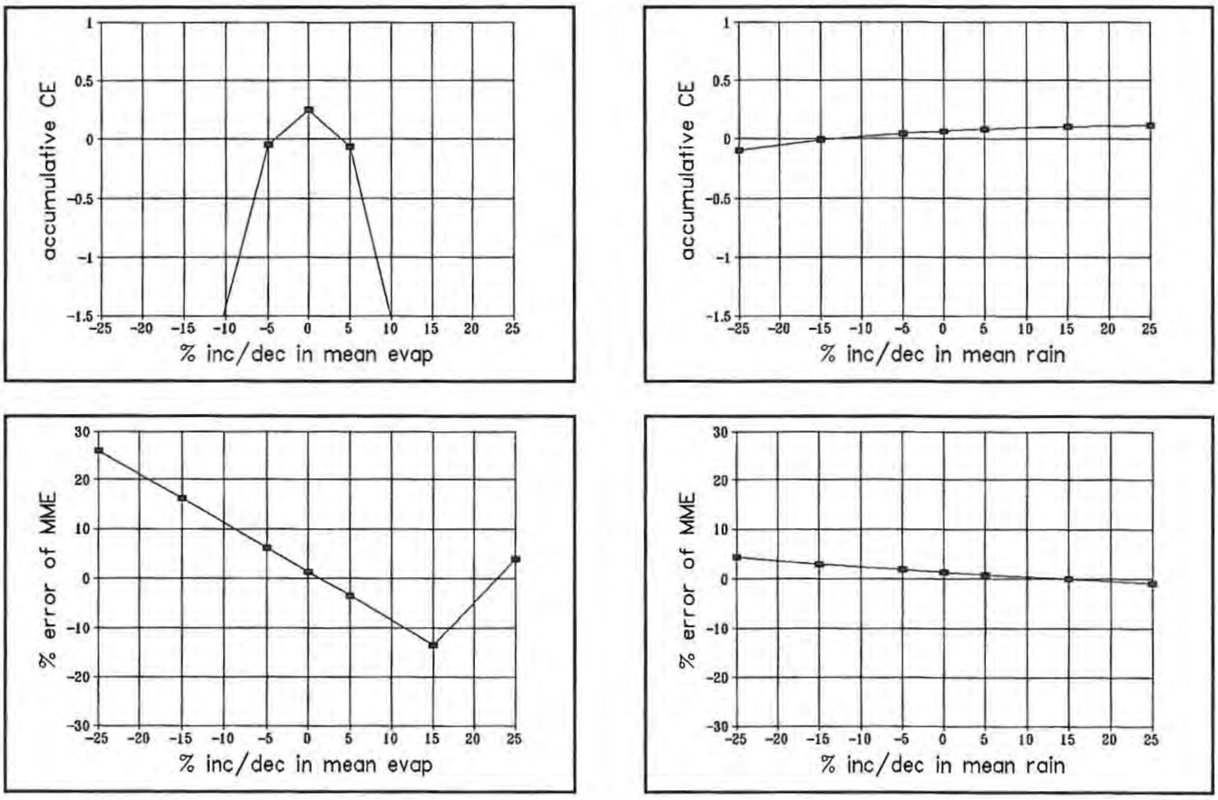


Figure 9.2 : **LONGDOWN** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

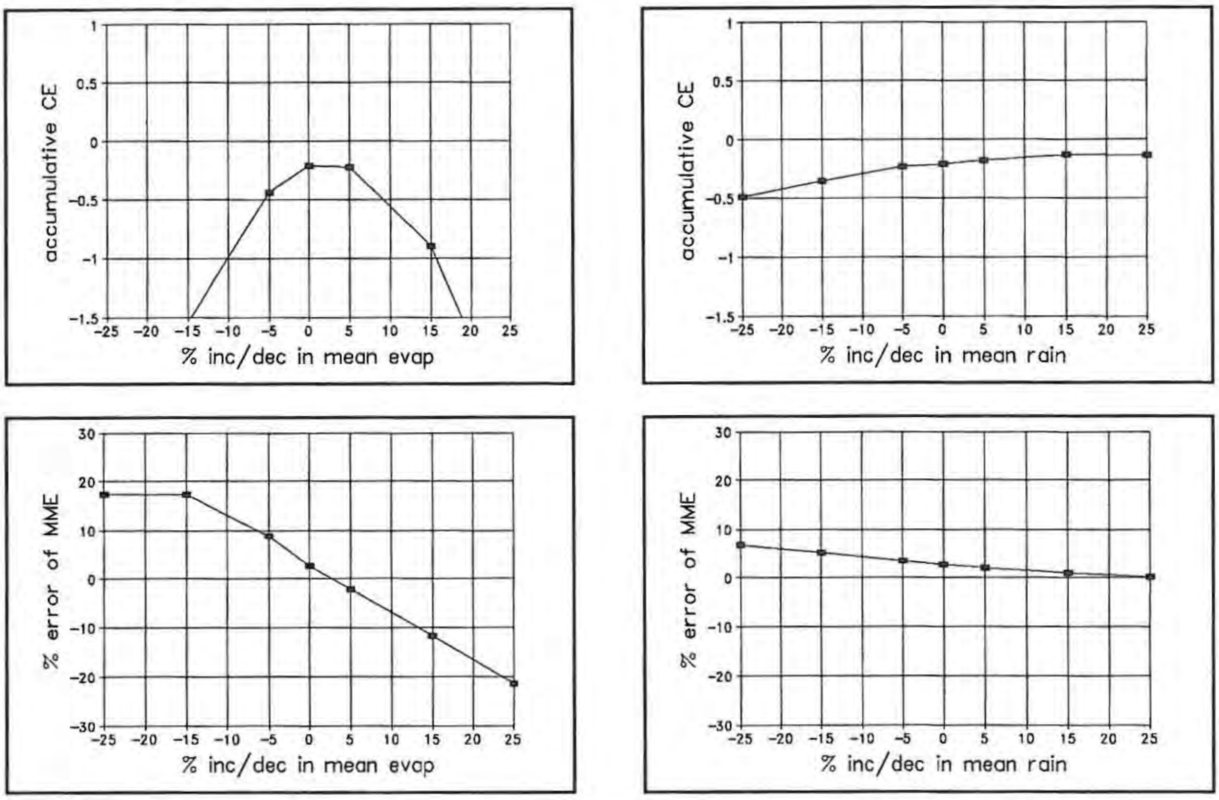


Figure 9.3 : **OOS-LONDON W/K** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

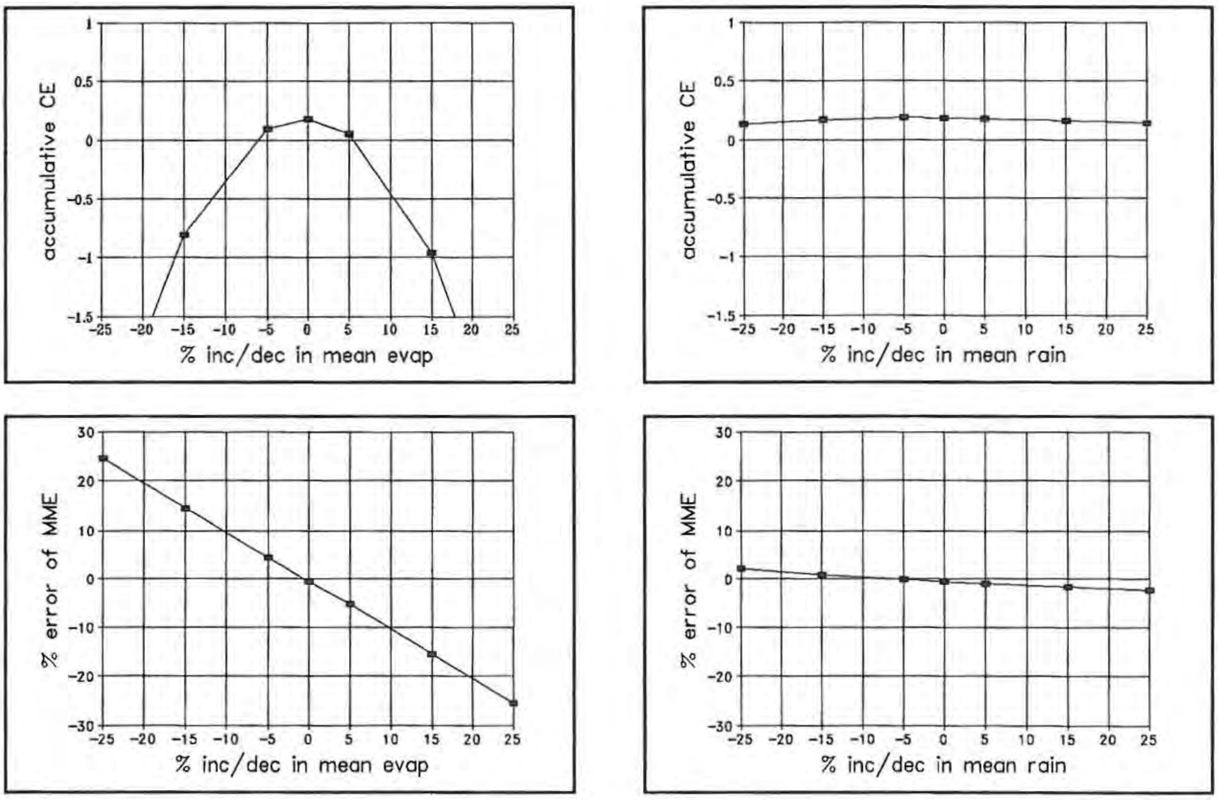


Figure 9.4 : **ADDO SITRUS NS** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

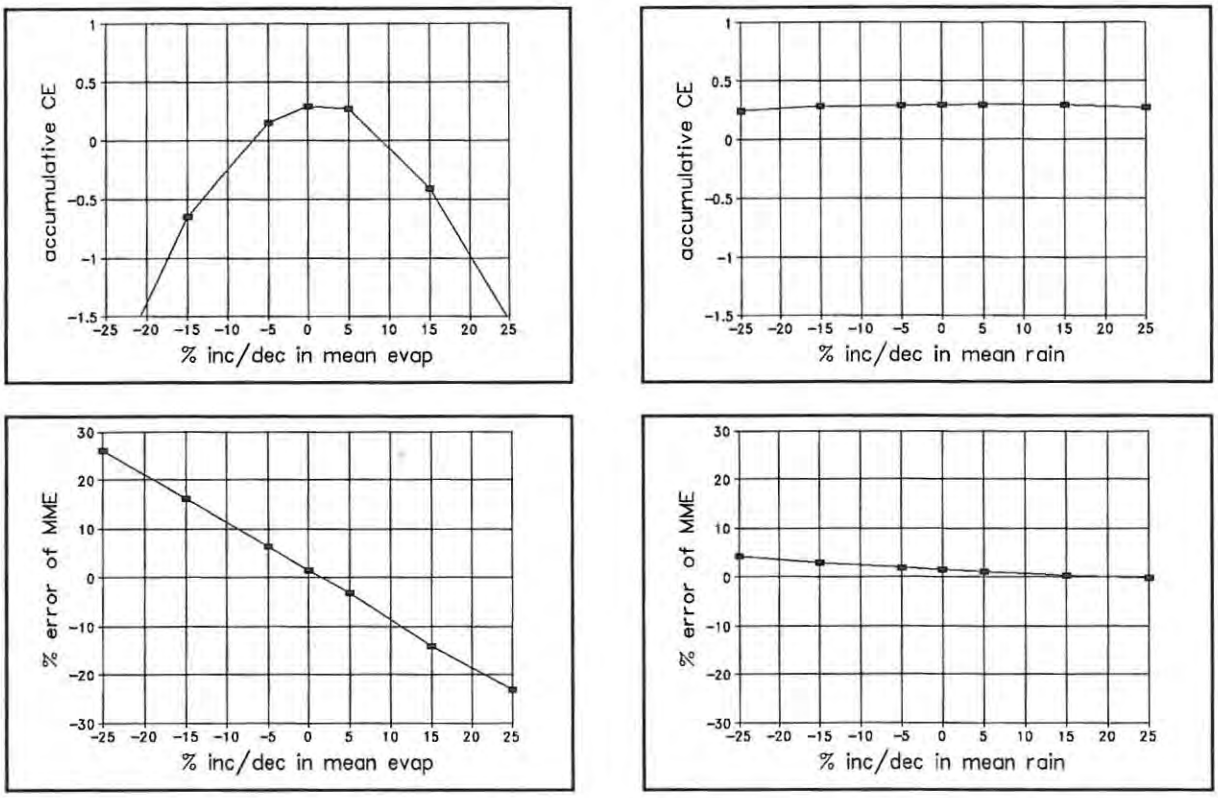


Figure 9.5 : **QUEENSTOWN** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

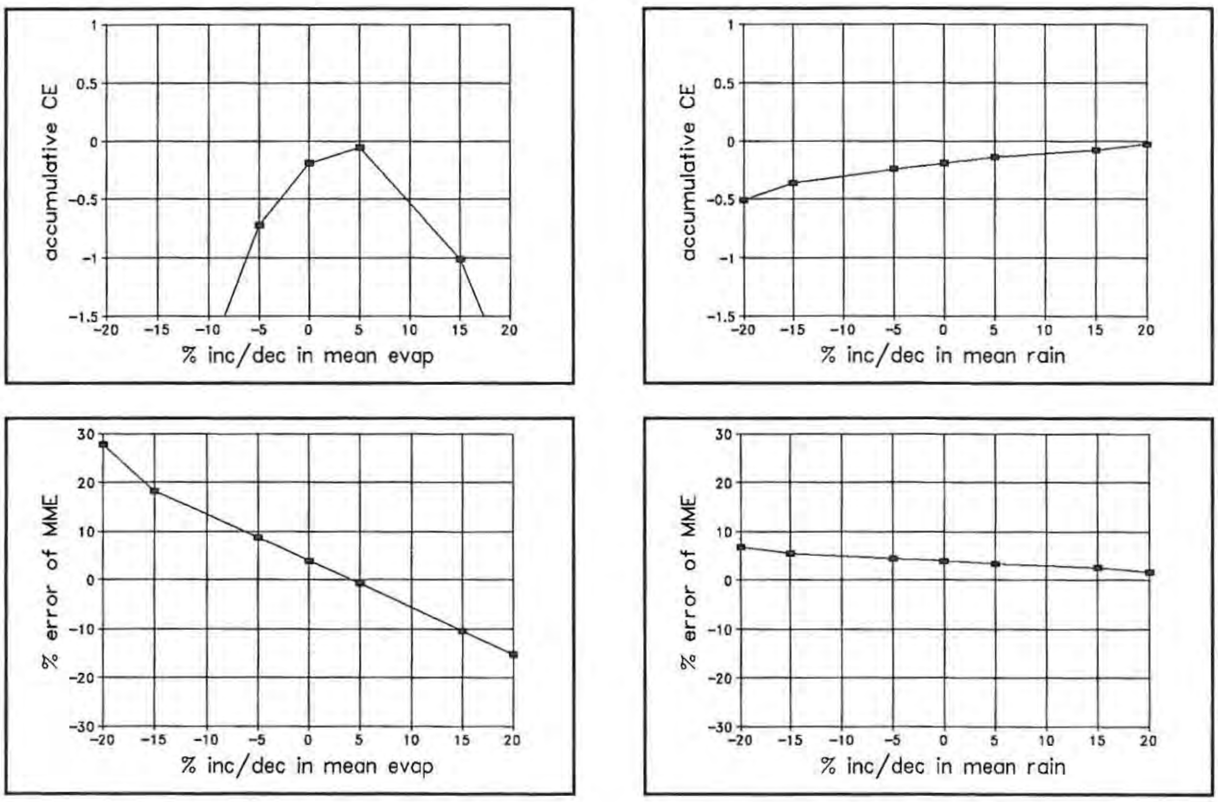


Figure 9.6 : **EXPERIMENT STATION** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

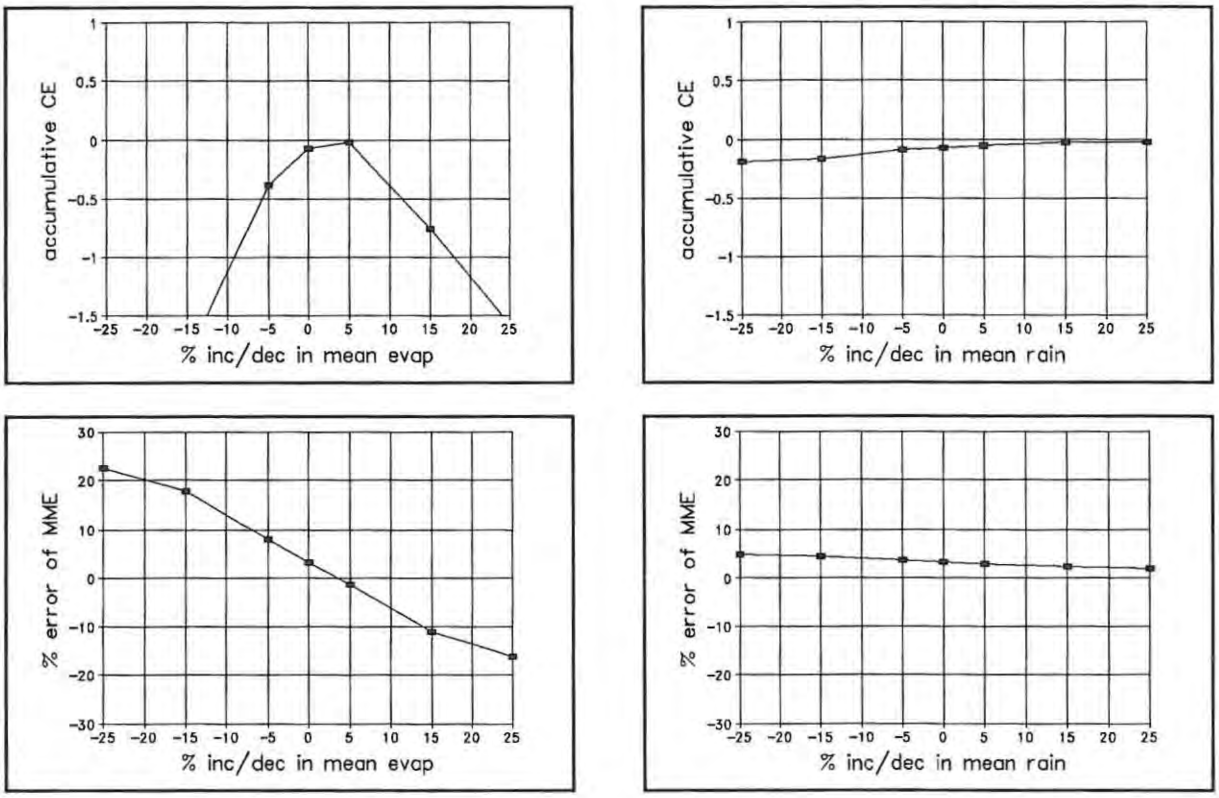


Figure 9.7 : **GLENDALE** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

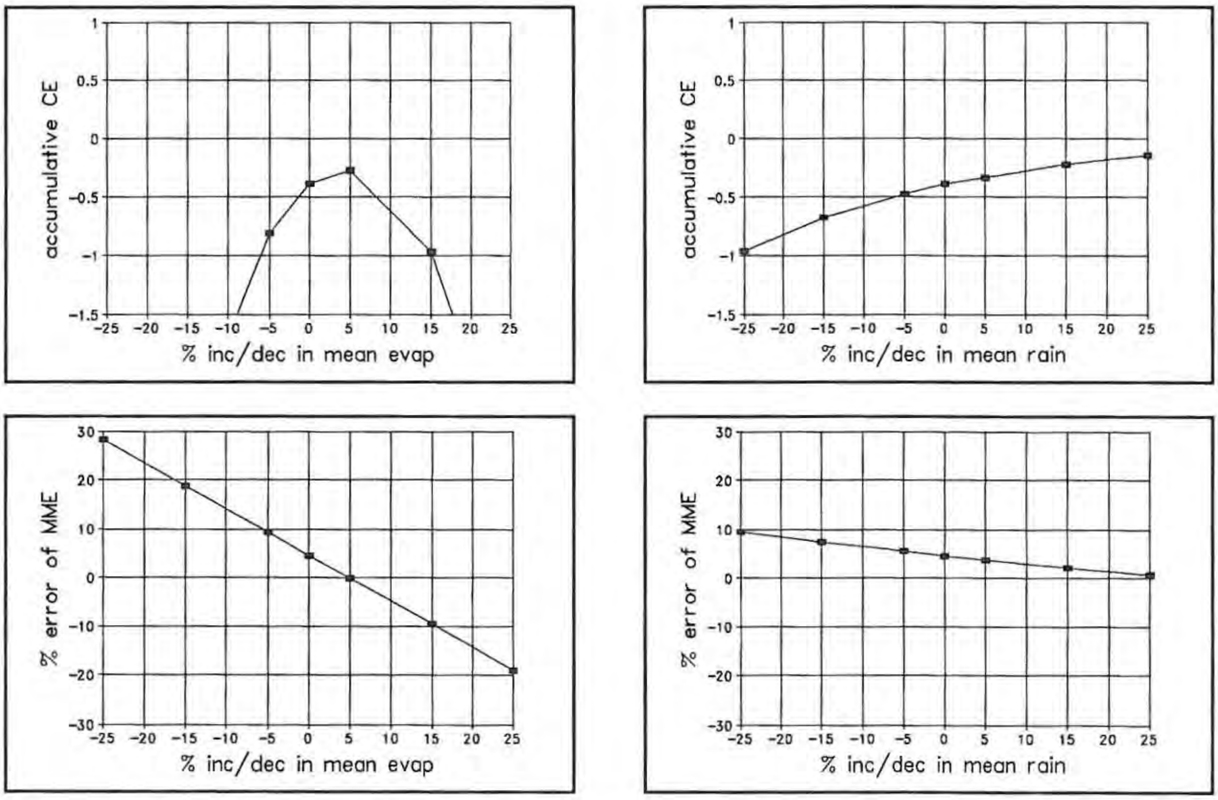


Figure 9.8 : **CEDARA AGR RES, STN** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

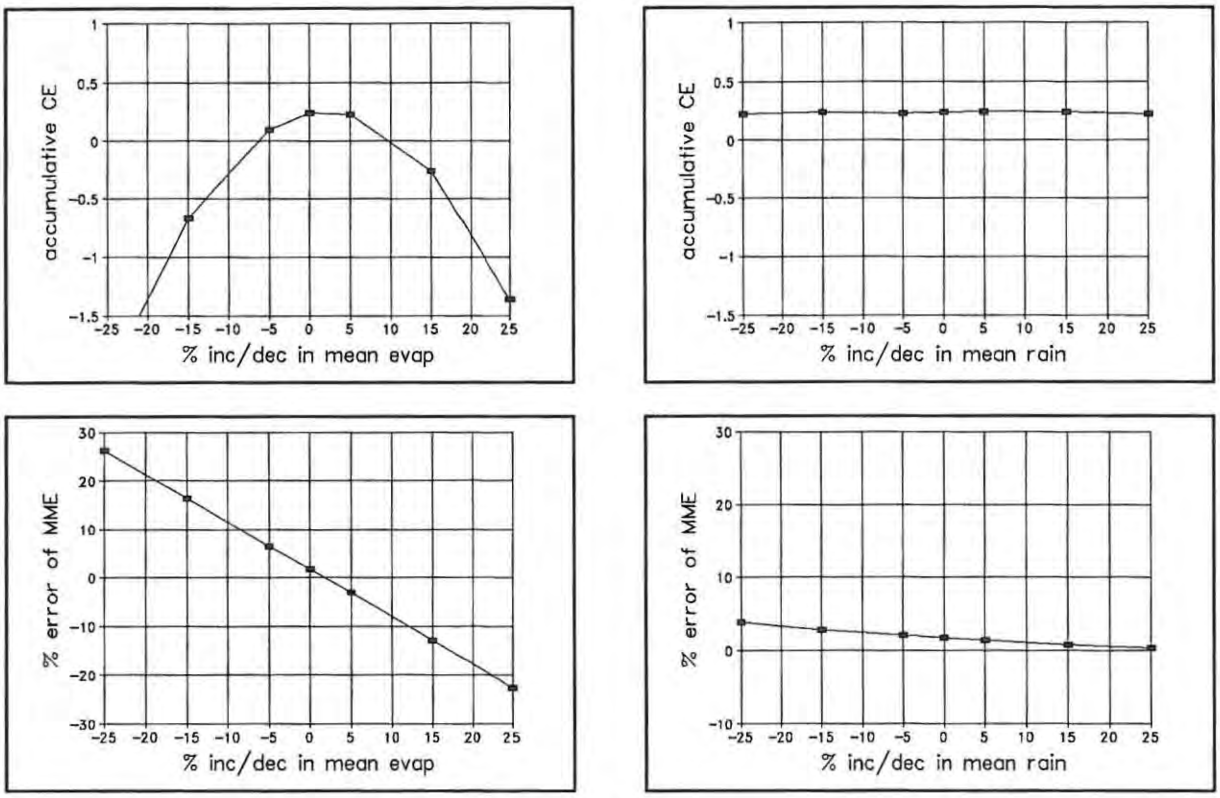


Figure 9.9 : **GLEN AGR COLL, BFN** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

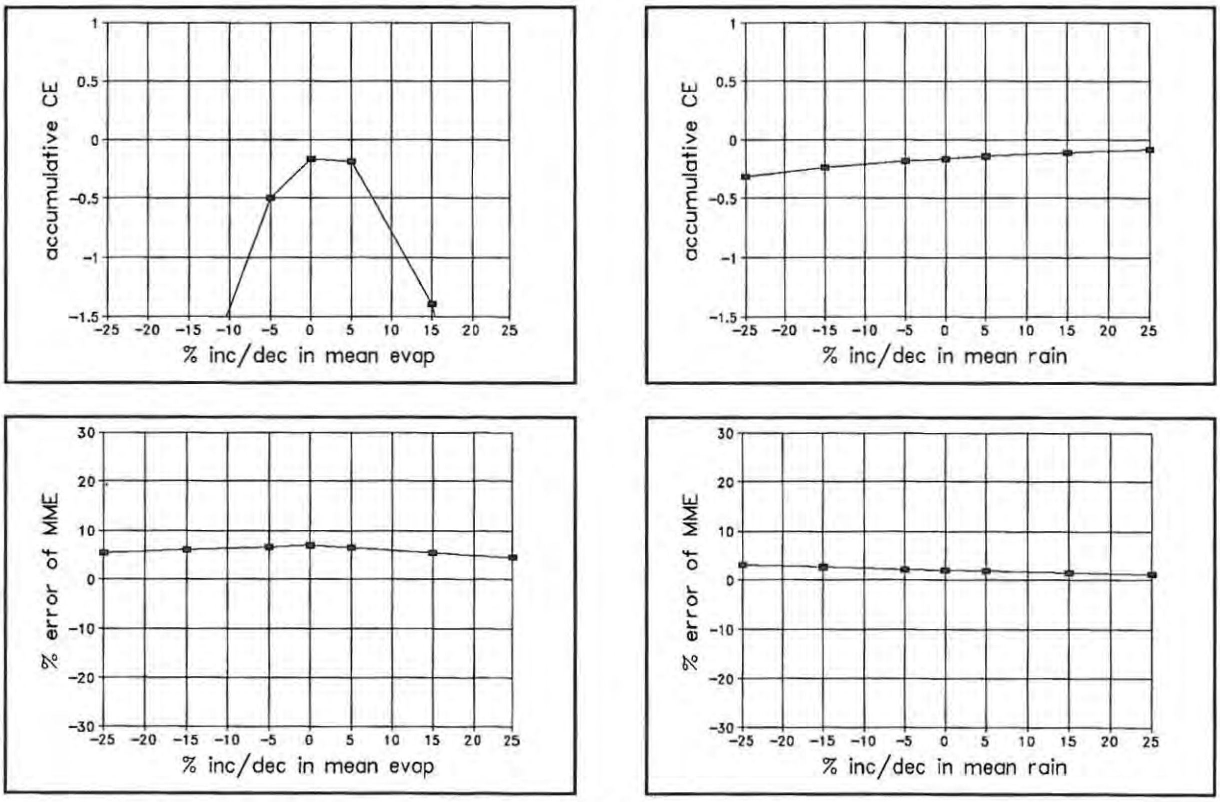


Figure 9.10 : **LETABA** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

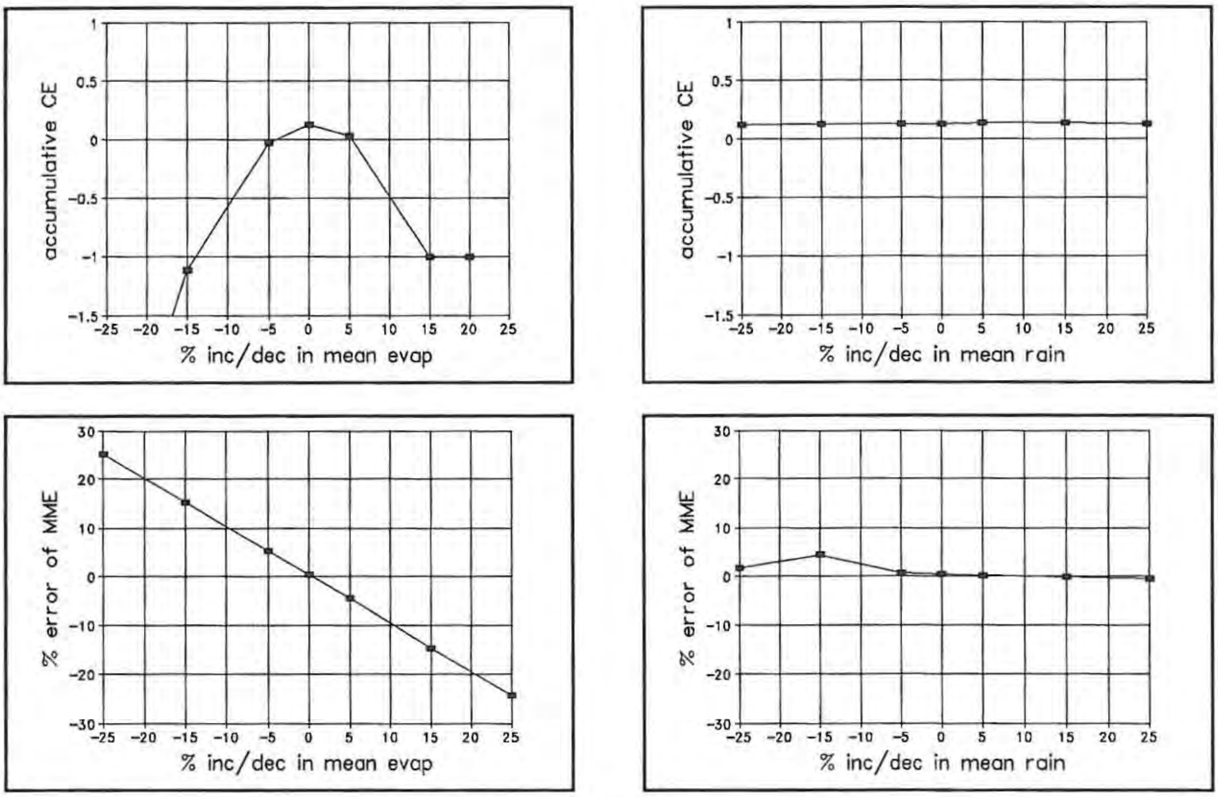


Figure 9.11 : **PIETERSBURG** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

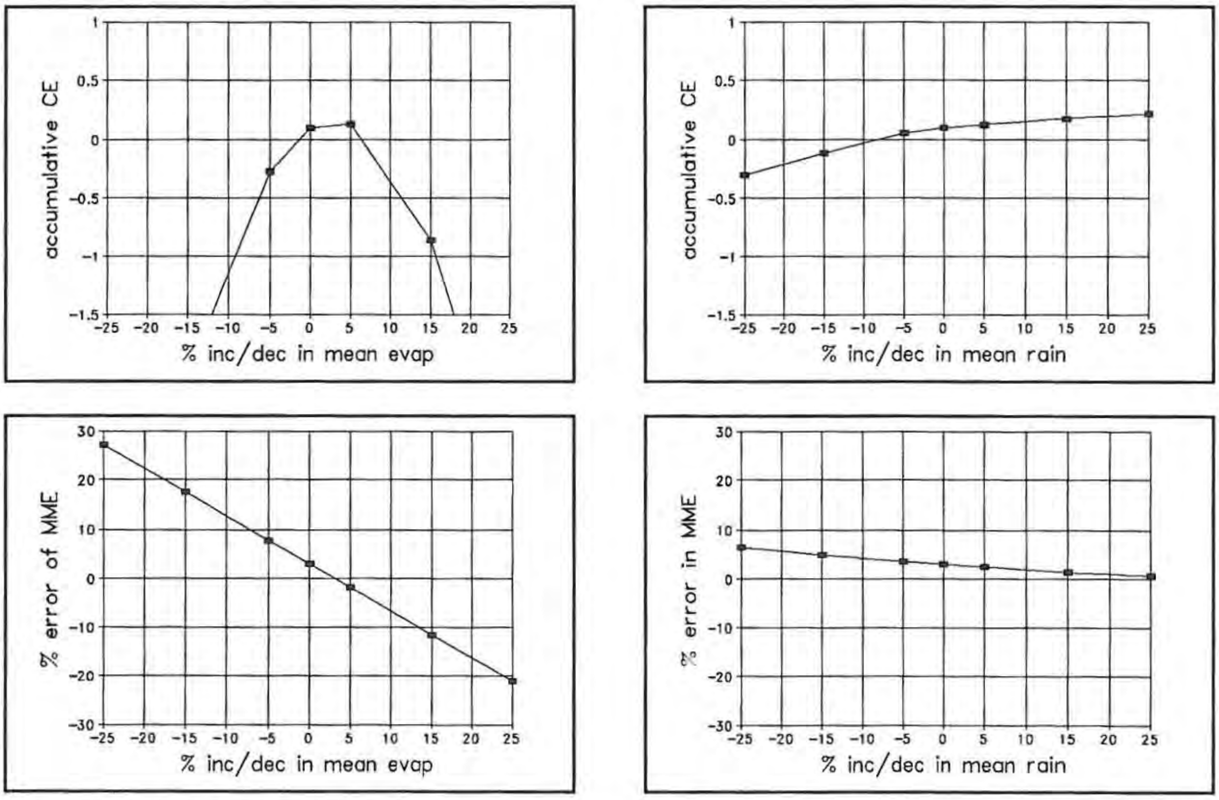


Figure 9.12 : **NELSPRUIT RES** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

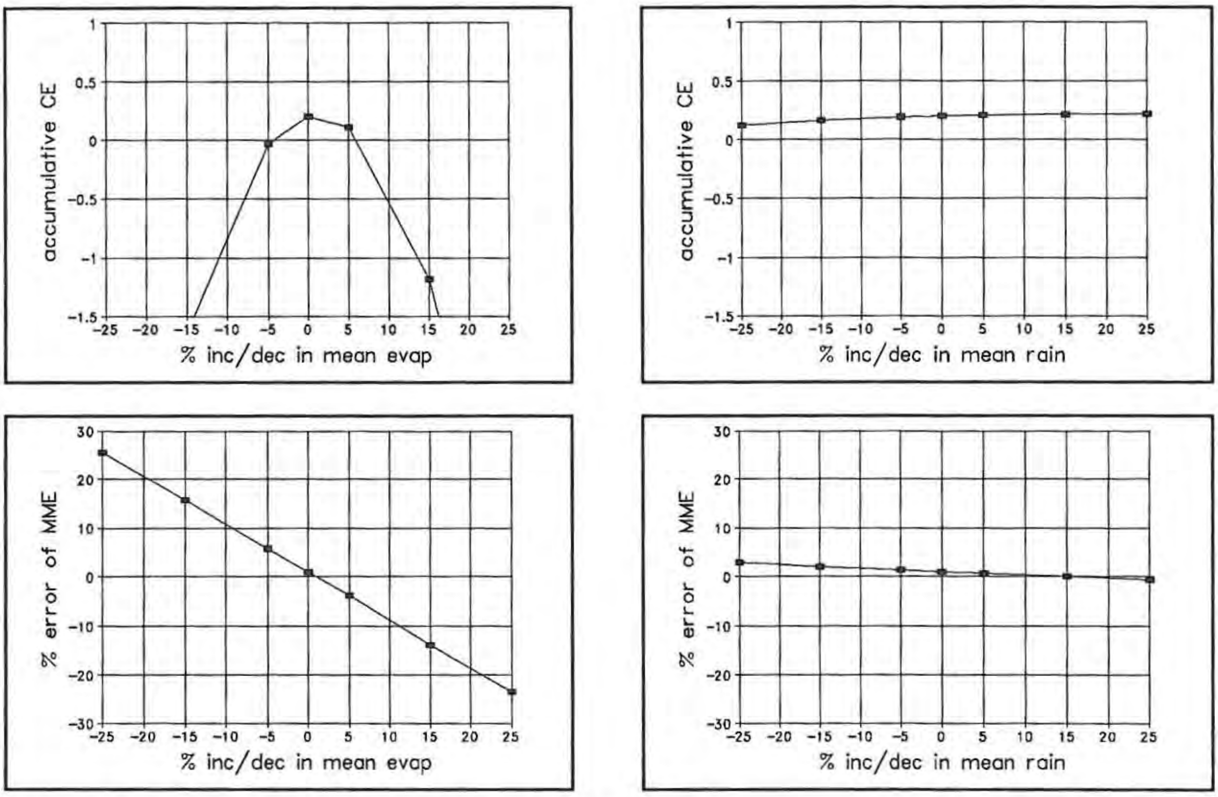


Figure 9.13 : **PONGOLA EXPT STN** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

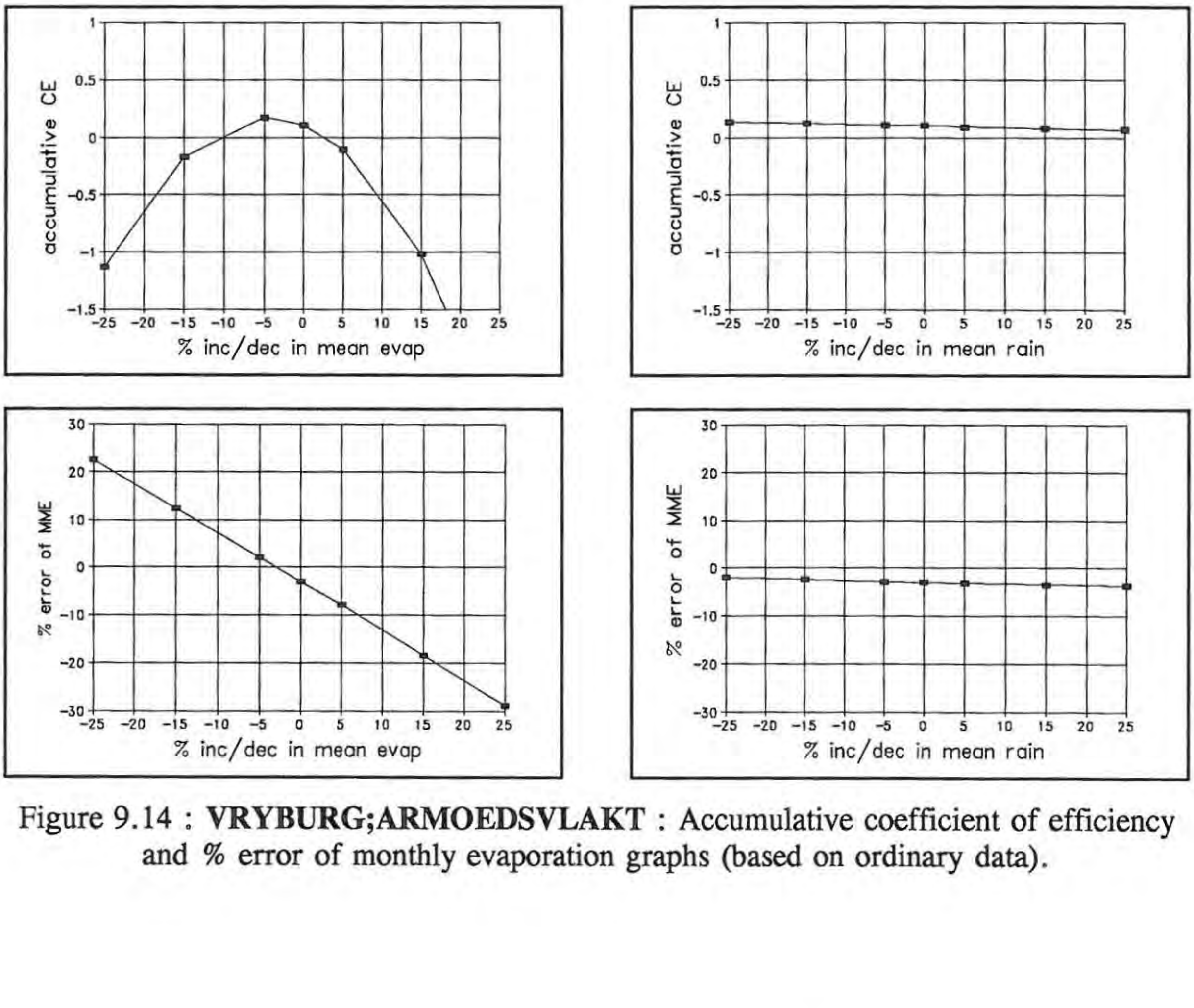


Figure 9.14 : **VRYBURG;ARMOEDSVLAKT** : Accumulative coefficient of efficiency and % error of monthly evaporation graphs (based on ordinary data).

9.5 SUMMARY RESULTS OF THE SENSITIVITY ANALYSIS

The point of the sensitivity analysis is to determine the extent to which the parameters can be changed before causing an adverse effect on the results. This is possible if the original coefficient of efficiency values are positive, as here the estimated parameters are producing better simulations than when using the mean monthly evaporation. However, if the original coefficient of efficiency values are negative, then the sensitivity analysis is largely irrelevant as the estimated parameters are not very useful. This applies for stations **Oos-London W/K, Experiment station, Glendale, Cedara Agr Res, Stn,** and **Letaba.** Any further percentage increases or decreases in the mean evaporation or mean rainfall values did not affect the accumulative coefficient of efficiency values to the extent that they became positive, and so are irrelevant.

Changing the mean evaporation values : For **Longdown** and **Prospect**, the accumulative coefficient of efficiency values are acceptable only when the mean evaporation parameter values are increased or decreased by approximately 4%. With higher percentage increases or decreases in mean evaporation values, the accumulative coefficient of efficiency values are negative, producing an adverse effect on simulation results (figures 9.1 and 9.2). The percentage error of monthly evaporation values are low (2 - 5%) for the above control limits, and are acceptable.

For **Addo Sitrus NS** (figure 9.4) a maximum of a 6% increase or decrease in mean evaporation was acceptable, producing positive coefficient of efficiency values. With this range, the percentage error of monthly evaporation was low (between 5 - 7%). This applies to **Queenstown** (figure 9.5) as well, except that the mean evaporation values can be decreased by up to 7% and increased by 9% before the coefficient of efficiency values become negative and unacceptable. Here, the percentage error of monthly evaporation is approximately 8%. The tolerance limit for **Glen Agr Coll, Bfn** (figure 9.9) was between a 6% decrease and a 10% increase in mean evaporation values. Therefore, this station has the highest tolerance level with regards to percentage increases in mean evaporation values, while the corresponding percentage error of monthly evaporation was still only approximately

8%. For **Pietersburg** (figure 9.11) and **Pongola Expt Stn** (figure 9.13), the tolerance limits are lower (4% decrease to 6% increase in mean evaporation), producing a 2 - 5% error of monthly evaporation. The tolerance limits for **Nelspruit Res** are more stringent, only allowing a 2% decrease and 6% increase in mean evaporation values. **Vryburg; Armoedsvlakt** station presents slightly different characteristics. A 10% decrease in mean evaporation values was acceptable, but only a 3% increase in mean evaporation values, and the percentage error of monthly evaporation values was between 6 - 8%. The reason why this station differs from the other stations discussed may be an indication of the unique skewness trends identified in chapter 7. Therefore, generally, the percentage increase/decrease in mean evaporation values that is acceptable for the representative stations is low.

Changing the mean rainfall values : For **Prospect**, **Longdown**, **Queenstown**, and **Pongola Expt Stn**, (figures 9.1, 9.2, 9.5 and 9.13), a higher percentage increase or decrease in mean rainfall does not produce much of an effect on the accumulative coefficient of efficiency values and the percentage error of monthly evaporation values remain low. One may conclude that this parameter is not as sensitive to change as the mean evaporation parameter. Best accumulative coefficient of efficiency values and lowest percentage error of monthly evaporation values are obtained with a 15% increase in mean rainfall values. However, for **Longdown** (figure 9.2) and **Nelspruit Res** (figure 9.12), with a decrease in the mean rainfall values of 10% or 7% respectively, the simulated monthly evaporation values are no longer an improvement and the accumulative coefficient of efficiency values are negative, coinciding with higher percentage error of monthly evaporation values.

For **Addo Sitrus NS**, with a 25% increase or decrease in mean rainfall values, the accumulative coefficient of efficiency values still remain positive. The highest accumulative coefficient of efficiency values coincided with the lower percentage error of monthly evaporation values, and are obtained with a 5% decrease in mean rainfall values.

For **Glen Agr Coll, Bfn** and **Pietersburg**, with any percentage increase or decrease in the mean rainfall value, the accumulative coefficient of efficiency values remained fairly similar (figures 9.9 and 9.11) and are clearly not sensitive to change. However, the percentage error of monthly evaporation values are lowest with a 20% to 25% increase in mean rainfall values. For **Vryburg;Armoedsvlakt** station, the percentage error of monthly evaporation values increased with higher percentage increases in mean rainfall and conversely, decrease with higher percentage decrease in mean rainfall values. The higher accumulative coefficient of efficiency values coincide with the higher percentage decreases in mean rainfall values. Therefore, in summary, it is evident that the simulation programs are not sensitive to changes in the mean rainfall parameter. In comparison to the results obtained when changing the mean evaporation values, it is evident that fairly high percentage changes in mean rainfall values are tolerated.

CHAPTER 10

10. REGIONALISATION OF PARAMETERS

10.1 INTRODUCTION

In many cases, especially in developing countries, not enough data is available to estimate the necessary parameters with the accuracy needed to arrive at reliable results. In some cases, there may not be enough data to estimate the parameters at all. Therefore, regional analysis is based on the assumption that certain properties are constant or vary in a predictable manner across a region. The regional analysis attempts to use data from several locations in a homogeneous region to develop relationships for ungauged points in that region. Therefore, the objective of this chapter is to determine whether general characteristics can be applied to some stations that are significantly different compared to other stations, so that the stations may be combined to represent separate regions. Therefore, the main aim is to verify the specific regions that have already been identified, on the basis of the mean daily evaporation values for each raingroup category (the raingroup evaporation weights, REW's) and the number of raindays data. It is important to consider the variance of the parameter set within each region and between regions to determine whether the regions are uniquely different in terms of variance, percentage error of monthly mean evaporation and the coefficient of efficiency analysis results. For example, do the data vary more for certain stations in some regions, although they have common characteristics, to the extent that sub-divisions within regions can be made; and do the data vary more within certain months or seasons, or is this variation uniform throughout the year. Eventually, what one wants to determine is that if the model is used, how much better will the results be compared to simply using the monthly mean evaporation values not corrected for rainfall? If located at a certain point in southern Africa, within which region will the station be located and therefore, which parameter set should be used to correct the mean monthly evaporation data?

10.2 REGIONALISATION OF PARAMETERS

This analysis was based on the daily and monthly mean evaporation values, the REW's and the number of days within each raingroup. For each station and region, the daily mean evaporation values for each month, the variance of the mean evaporation values and the number of days within each raingroup category are presented in appendices C, D and E respectively. Summaries of regional averages for the daily and relative monthly mean evaporation values are presented in tables 10.1 and 10.2, the number of days within each raingroup in table 10.3, and the regional mean evaporation values per raingroup, per season in table 10.4. The stations and demarcation of regions according to the evaporation parameter files are presented in figure 10.1. The range of variance values gives an indication as to the variation in the model parameters for each defined region. Intra- and inter-regional variability is analysed using the Kruskal-Wallis one-way analysis and the Friedman two-way analysis by ranks procedure.

10.2.1 DEMARCATION OF REGIONS ACCORDING TO INTER-STATION VARIABILITY (ONE-WAY ANALYSIS)

Regionalisation based on the raingroup evaporation weights (REW's), for each region, per season : For each region, the mean evaporation within each raingroup category, for each station, were compared on a seasonal basis. This comparison was not very effective as there was a lot of variability in the 2 to 5 raingroup categories, although values in the first raingroup category are similar. However, these variabilities are to be expected, as the synoptic conditions producing rainfall, and the factors influencing both rainfall and evaporation will be acting together to produce different meteorological conditions that may either favour or not favour evaporation. Besides the variability of mean evaporation within the higher raingroup categories, the values tended to be fairly similar within a region, and, in fact, there was not much difference between separate regions. Consequently, for each region the average regional evaporation values were compiled for each raingroup, per season, and are presented in table 10.4. The average regional evaporation values are ratio's of the mean evaporation for each raingroup divided by the mean evaporation for all groups.

The main distinguishing difference is between the summer and the winter-rainfall regions. For the winter rainfall region, the south-western Cape displays higher mean evaporation values in the 1st and 2nd raingroup categories, but thereafter, with higher magnitude rainfall events, the mean evaporation values decrease (table 10.4). Similarly, the eastern Cape coastal region displays lower evaporation values in the higher rainfall groups and tends to be transitional between the south-western and southern Cape and the summer-rainfall regions, as identified in chapter 7. In comparison, although the summer-rainfall regions record highest mean evaporation values in the first raingroup category, mean evaporation values remain high within the 2-5 rainfall groups, with a tendency to increase in the 5th raingroup category for the summer and autumn months.

Regionalisation based on the daily mean evaporation values per month, and the average number of days within each raingroup, per season : The coefficient of variation has been used as a general measure of the variability of daily mean evaporation values (on a monthly basis). Here, variance is expressed as a percentage of the daily mean evaporation value (appendix F1). More specifically, the analysis of variance (ANOVA) was conducted to determine whether intra- and inter-variability of daily evaporation between stations and regions was of an acceptable level to classify a particular region as a homogeneous region or whether there was too much variability to make regional divisions. This data set, however, does not satisfy the conditions under the ANOVA technique as the data would need to be normally distributed with equal variances. As identified earlier (chapter 6) and more specifically, by the regional normality probability plots (appendix F), the data is skewed and so a nonparametric (distribution-free) test is required. The nonparametric alternative to the ANOVA technique is the Kruskal-Wallis H test.

The Kruskal-Wallis analysis of variance analyses the effect of a classification factor for a balanced or unbalanced one-way design. This test is accounting for the variability between stations within each defined region (the intra-station variability). The test statistic, H, is used to test the hypothesis that the samples come from the same population, so that, H_0 : $Md_1 = Md_2 = ... = Md_k$ (as opposed to H_1 : not all Md_i's are equal). The H statistic is calculated using the formula,

$$H=\frac{12}{N(N+1)}[(\frac{R_1^2}{n_1}+\frac{R_2^2}{n_2}+.....+\frac{R_k^2}{n_k})-3(N+1)]$$

where,

n_i = various sample sizes

R_i = rank sums in each sample

N = total number of observations

If the test statistic is high, the hypothesis should be rejected and so if the test statistic is large, the significance level is small. If the null hypothesis is rejected, then multiple comparisons are made to determine the differences between pairs of treatments by comparing the mean ranks of the samples. The least significant difference between sample mean ranks is given by LSD,

$$LSD=Z_{\alpha/2s}\sqrt{N(N+1)/6n}$$

where,

s = number of comparisons and s = k(k-1)/2

n = common sample size

N = total number of observations

If the treatment means are greater than the LSD value, then we may conclude that there is a significant difference between the two treatments.

South-western Cape region : The daily mean evaporation values for each month were lower for stations Elgin (13), Chiltern Damwall (6), Longdown (22), Dwaalhoek (16), Boontjieskraal (14) and Riviersonderend Tyg (11). On this basis, the south-western Cape may be divided into two sub-divisions, A - that region with lower daily mean evaporation values and B - that region with higher daily mean evaporation values (appendix C1 and table 10.1). The relative mean monthly evaporation values were calculated (based on the daily data) to represent the accumulative differences (table 10.2 and figure 10.2). Clearly, these values are lower for sub-division A, with highest differences occurring in the spring/summer months (accumulative difference of 92.0mm and 123.3mm respectively). This is to be expected, as this is a winter rainfall region, experiencing moist cloudy conditions, conducive to low intensity continuous rainfall and corresponding lower evaporation rates (as identified in chapter 7).

The coefficients of variation indicate that the mean deviation of daily mean evaporation (for stations in sub-division A) are 8.82%, 4.30% 4.12% and 2.65% for summer, autumn, winter and spring respectively, culminating in a mean annual variation of 4.97% (table 10.5). This indicates relatively low variability of daily mean evaporation between stations within this region. This is supported by the Kruskal-Wallis test (table 10.6). The H test statistic indicates that the variability of daily evaporation values for the data stations within sub-division A, is acceptable and may be classified as a single homogeneous unit. Taking into account the number of days falling into each raingroup category (appendix E1 and table 10.3), a lower number of days were recorded in the first raingroup category than for sub-division B, with this trend being more pronounced in the spring/summer months. Consequently, a higher number of days fall into the second and third raingroups indicating that sub-division A receives slightly higher magnitude rainfall events.

For sub-division B, the relative variability of daily mean evaporation is higher with an annual variation of 9.95% (table 10.5)). However, the H test indicates that this variability is still acceptable. In fact, the H test indicates that there is little variability in daily evaporation values between all stations in the south-western Cape, and although differences between sub-division A and B have been identified, this variability is not sufficiently significant to justify any sub-divisions within this region.

Eastern Cape coastal region : The slightly more inland stations, Patensie (23) and Addo Sitrus NS (25) display lower daily mean evaporation values for the autumn/winter months. This is also evident for Port Elizabeth W/K but only for the winter months (appendix C2). If the region is demarcated into two sub-divisions, the difference in daily mean evaporation values is low for the spring/summer months but much higher in the autumn/winter months (table 10.1). This difference is exaggerated when the daily mean evaporation values are converted to monthly equivalents (table 10.2 and figure 10.3). Taking into account the number of days within each raingroup category, per season, the number of days in the first raingroup are significantly higher for Addo Sitrus NS and Patensie, and lower in the 2nd, 3rd, 4th and 5th raingroup categories for all seasons (appendix E2 and table 10.3).

However, results obtained from the H test, indicate that, although possible sub-divisions have been identified, the combination of all stations representing a single homogeneous unit is also acceptable. Considering the effect of berg wind and other meteorological influences (chapter 3), it is surprising that the variability of daily mean evaporation values between inland versus the coastal stations, is so insignificant. However, only 6 data stations are representing this region which may be an influential factor.

Eastern Cape inland region : Stations in sub-division A (Queenstown (29), Welverdiend (30) and Grootfontein (35)) display higher daily mean evaporation values for each month (tables 10.1 and 10.2). The coefficients of variation indicate high variability of daily mean evaporation values in sub-division A, particularly in winter (average variability of 20.98%). This is supported by the H test statistic which indicates that the variability of daily mean evaporation and REW's between stations is significant and consequently warrants sub-divisions within this region (table

10.6 and appendix G). Taking into account multiple comparisons, the LSD test indicates that the variability responsible for the high H test statistic is confined to the differences in daily mean evaporation between stations in sub-division A, and the rest of the stations representing this region. A definite distinction between stations nearer the coast and those further inland is evident (figure 10.1). This result is further supported by the fact that the number of days in the 1st raingroup are significantly higher for stations in sub-division A, but lower in the remaining raingroup categories (appendix E3 and table 10.3).

Natal Coastal region : Daily mean evaporation values tended to be similar for all stations and no clear sub-divisions could be distinguished (appendix C4 and figure 10.5). The H test, however, indicates that there are definitely significant differences in daily mean evaporation values. On the basis of the mean rank values for each station (appendix G) and the LSD test, stations may be grouped into sub-division A, (Powerscourt (42), Cedara Agr Res (39), Umzimkulu Mill (37), Sezela; Sugar Mill (52), Esperanza (40), Chakas Kraal Auto (47), Experiment station (55) and Tongaat (45)) with the remaining stations in sub-division B. However, taking into account the number of days within each raingroup category, stations Powerscourt (42), Ukulinga Agr Res Stn (51), Windy Hill (54) and Cedara Agr Res (39) display lower number of days in the 1st raingroup and higher number of days in the 3rd raingroup for the spring/summer months. For the autumn/winter months, all stations display similar trends (appendix E4 and table 10.3). Considering the location of these stations (figure 10.1), there is no evident central locality. Thus, although divisions have been identified, based on the daily mean evaporation values and REW's, actually defining boundaries is not practical.

Natal inland region : The relative variability of daily mean evaporation is higher for the spring/summer months - a seasonal average of 10.58% and 13.46% respectively, compared to the autumn/winter months which display approximately half this variability (figures 10.6 and 10.7 and table 10.5). The H test indicates that the differences in daily mean evaporation between stations is significant (table 10.6). From the ranks values (appendix G) and LSD test, three sub-divisions may be distinguished, sub-division A (Baynesfield Estates (58), and Stoke, Mid-Illovo (57)), sub-division B (Melmoth (Golden Reef) (65), and Entumeni Mill (64)) and sub-division C (Seven Oaks-Ryhill (62), Union Mill, Seven OA (61), Crammond (60) and Sun Valley, Weenen (63)). However, taking into account the number of days within each raingroup, two sub-divisions can be distinguished. Stations Sun Valley Weenen (63), Union Mill (61) and Melmoth (65) form the 1st sub-division and are characterized by having the highest number of days in the 1st raingroup (indicating the higher frequency of lower intensity rainfall events). The second sub-division includes stations Entumeni Mill (64), Seven Oaks (62), Crammond (60) and Baynesfield (58) which display fewer number of days in the 1st raingroup (indicating that larger rainfall events are more common). The third sub-division includes stations Cedara Agr Res (59) and Stoke, Mid-Illovo (57) where the number of days in the 1st raingroup are lower in comparison to the stations already mentioned, yet higher for the 2nd and 3rd raingroups (appendix E5 and table 10.3). It is not clear why these stations are displaying different trends and one cannot make assumptions based on the limited data available. It is possible that the variability of evaporation rates is influenced by other meteorological conditions, micro-scale influences and locality.

Orange Free State region : Stations Meshlynn Kamberg (77) and Cathedral Peak (71) display lower daily and monthly mean evaporation values. Also, the number of days in the first raingroup are lower in comparison to the other stations, yet significantly higher in the 2nd to 5th raingroups (appendix E6). These stations are also at a higher altitude. Kestell Pol (72) and Bethlehem;Loch Lomon (66) stations display intermediate characteristics, and the remaining stations display higher daily mean evaporation values (appendix C6 and figure 10.7). The further inland the locality the higher the daily mean evaporation values and REW's, as clearly indicated by the difference in the relative mean monthly evaporation values especially for the spring/summer months - a difference of 287.3mm and 182.9mm respectively (table 10.2), and the coefficient of variation values (table 10.5). The H statistic indicates that the variability of daily mean evaporation between stations is significant. From the average ranks and LSD test, two sub-divisions could be identified. Sub-division A includes stations Cathedral Peak (71), Meshlynn (77), Kestell-Pol (72), Loch Lomon, Bethlehem (66) while the remainder of the stations are assigned to sub-division B. The H test was conducted on each sub-division, and it was found that the variability within sub-division A and B is not significant. Therefore, it is acceptable to define each as a separate homogeneous unit. Considering the locality of these stations, it is clear that stations in sub-division B are further inland.

Transvaal region : Considering the number of days within each raingroup, the values do not differ to the extent that sub-divisions could be identified. However, Levubu (81) and Letaba (78) stations record lower daily mean evaporation values (appendix C7 and figure 10.8). The H test indicates that the variability of daily mean evaporation between stations is high, and not acceptable (table 10.6). The LSD test indicate that this region may be divided into sub-division A (which includes stations Levubu (81) and Letaba (78)), and the remainder of the stations in sub-division B (appendix G). However, stations Vaalwater (82) and Rustenburg (83) tend to show transitional characteristics. For this reason, when the H test was conducted on each sub-division, the variability of daily mean evaporation values is acceptable for stations in sub-division A but not for sub-division B. The multiple range test indicates that the stations responsible for this variability were Vaalwater and Rustenburg. The reason for this is not evident and these stations are not located close to each other.

Eastern Transvaal region : All the stations in this region show similar daily mean evaporation values and REW's for all seasons and the coefficients of variation are low (appendix C8, figure 10.9 and table 10.5). The H test (table 10.6) confirms that the variability of daily mean evaporation between stations is not significant and this region may be classified as a single homogeneous unit. However, stations Nelspruit Res (89), Nelspruit Freidenheim (95) and Lydenburg Vis (97) do display slightly lower number of days in the 1st raingroup and higher number of days in the 2nd and in some cases the 3rd raingroup (appendix E8 and table 10.3). These stations are slightly further inland and at higher altitudes (figure 10.1).

Northern Natal/Transvaal border region : The H test indicates that the variability of daily mean evaporation values between stations is significant (table 10.6). Further, the multiple range test indicates that this region may be divided into a number of sub-divisions. Firstly, Piet Retief Mun (105) and Kangela Mtubatuba (108) clearly display lower daily mean evaporation values, especially in the autumn/winter months. The reason for this is not clear as one station is located near the coast, while the other is further inland and situated at a much higher altitude. Secondly, according to the LSD tests, stations Seven Oaks (111), Mkuze Game Reserve (102), Bokel, Bloodriver (104), Bundu-Hluhluwe (107), Mtubatuba Mill (99), and Pongola Expt station (98) may be grouped into a second sub-division. The third sub-division includes stations Athole Proefplaas (106), Dundee Agric Res (110), Empangeni Mill (100), Mkuze estates (101), Big Bend (Wisselrode) (109) and Makatini (103) which display higher daily mean evaporation values (appendix G). However, actually defining boundaries for these sub-divisions is impractical as, the stations, (although representing different sub-divisions on the basis of the daily mean evaporation values), are located fairly close to each other.

Northern Cape region : The daily mean evaporation values and REW's for stations representing this region are similar (appendix C10), displaying highest variability in the spring and especially the summer months, as indicated by the coefficients of variation (table 10.5). The relative mean monthly evaporation values are high in comparison to the other regions (table 10.2). In fact, the number of days within each raingroup are also similar for all stations (appendix E10). A common characteristic is that the number of days within the 1st raingroup are very high compared to the rest of the regions (table 10.3), and especially high for the winter months. The H test indicates that the variability of daily mean evaporation between stations is not significant.

In summary, on the basis of the Kruskal-Wallis and LSD tests, stations have been grouped into regions, as representing similar REW's and number of days within each raingroup characteristics. The Friedman test was conducted to determine the extent of the variability of the rainfall/evaporation characteristics between the above defined regions. The representative regional raingroup evaporation weights (REW's) have been used in the Friedman test.

10.2.2 DEMARCATION OF REGIONS ACCORDING TO INTER-REGION VARIABILITY (TWO-WAY ANALYSIS)

The Friedman two-way analysis procedure analyzes the effect of two classification factors for analysis of data with a balanced randomized block design. This test is accounting for the variability between specific regions (inter-regional variability). This statistic, Fr, tests the hypothesis that the distributions for each grouping are identical and is calculated using the formula,

$$Fr=\frac{12}{nk(k-1)}\sum_j R_j^2-3n(k+1)$$

where,

n = number of blocks

k = number of treatments

R_j = rank sum values for each sample

If the test statistic is high, H_0 will be rejected and multiple comparisons can be made using the Bonferroni approach (as was the case when using the H test). Here, the least significant difference (LSD) is calculated using the equation,

$$LSD=Z_{\alpha/2s}\sqrt{k(k+1)/6n}$$

where,

n = common sample size

s = number of comparisons and s = k(k-1)/2

k = number of treatments

Again, if the treatment means are greater than the LSD value then the difference between treatment means is significant.

The results are summarized in table 10.7. The Fr statistic indicates that for all regions except, Orange Free State and the Transvaal (sub-division A), the null hypothesis may be rejected. Thus, the regional REW's are significantly different and (on this basis), the regions defined earlier in the Kruskal-Wallis H test, may be classified as representing individual homogeneous rainfall/evaporation regions. Multiple range comparisons were made to determine whether the null hypothesis was rejected as a consequence of the specific region in question being 'significantly different' to only one or two regions, or whether this region is 'significantly different' to all other defined regions. The results of the LSD test are presented in appendix G. It is clear that, for each region, in most cases the difference between the mean ranks of the sample are greater than the LSD value, and one may conclude that there are significant differences between the regional REW's. The Friedman analysis was not conducted on the number of days falling within each raingroup category as this data tended to be too variable to identify any specific trends (appendix E).

In summary, it has been demonstrated that general characteristics can be applied to stations that are significantly different, and so the parameters of the model may be regionalised.

10.3 PERFORMANCE OF COREVAP1 USING REGIONAL PARAMETERS

The COREVAP1 program was run using the regional parameters to determine whether the regional parameters still provide estimates that compare favourably with mean monthly evaporation rates. This analysis was conducted on the following basis : (i) the original REW's were replaced by the regional REW's; (ii) the original number of days within each raingroup category were replaced by the regional number of days within each raingroup category, and (iii)

COREVAP1 was run using the complete regional parameter file. This analysis was conducted on the original 14 representative stations and the results are presented in table 10.8.

The performance of COREVAP1 is analysed in terms of the accumulative coefficients of efficiency. The results are not conclusive. For stations Longdown, Oos-London W/K, Glendale, Cedara Agr Res and Letaba, whether the regional parameters resulted in an improvement of the simulated mean monthly evaporation values or not is largely irrelevant, as the accumulative coefficient of efficiency values still remain negative.

For stations Prospect, Pietersburg, Vryburg;Armoedsvlakt, Nelspruit, Pongola Expt Farm and Queenstown, when using the regional parameter sets, the simulations of mean monthly evaporation were still acceptable as the accumulative coefficients of efficiency remained positive. However, for stations Addo and Glen Agr Coll, Bfn, the accumulative coefficients of efficiency were acceptable using the original parameter file and the regional REW's parameter file, but accumulative coefficient of efficiency values became negative when using the regional number of days within each raingroup category parameter file. For Experiment station, the accumulative coefficient of efficiency value was negative when using the original parameter file, but there is an improvement when using the regional REW's and the complete regional parameter files, to the extent that the accumulative coefficient of efficiency values are now positive.

TABLE 10.1 : REGIONAL AVERAGES FOR THE DAILY MEAN EVAPORATION VALUES (mm)

Region	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Annual Average
South-western Cape													
Sub-division A	7.83	8.24	7.28	5.63	3.73	2.43	1.97	1.96	2.43	3.41	5.04	6.79	4.73
Sub-division B	9.26	9.52	8.63	6.64	4.49	2.87	2.25	2.31	2.85	4.15	6.12	8.00	5.59
Eastern Cape Coastal													
Sub-division A	6.95	7.05	6.12	4.81	3.58	2.74	2.27	2.45	3.03	3.74	4.92	6.04	4.48
Sub-division B	7.04	6.93	6.33	5.26	4.30	3.71	3.40	3.42	3.91	4.51	5.37	6.20	5.03
Eastern Cape Inland													
Sub-division A	8.92	8.94	7.30	5.82	4.40	3.75	3.05	3.48	4.60	5.74	6.67	7.85	5.88
Sub-division B	5.75	5.46	5.08	4.30	3.58	3.01	2.64	3.05	3.95	4.52	4.88	5.30	4.29
Natal Coastal	5.46	5.92	5.73	5.12	4.17	3.43	3.08	3.27	4.00	4.52	5.16	5.46	4.61
Natal Inland	5.66	5.39	5.32	4.79	4.02	3.38	2.96	3.37	4.18	4.77	5.05	5.27	4.51
Orange Free State													
Sub-division A	5.90	5.60	5.20	4.52	3.86	3.44	3.05	3.48	4.51	5.34	5.59	5.52	4.67
Sub-division B	9.26	9.14	7.73	6.12	4.56	3.47	2.80	3.08	4.47	6.42	7.55	8.51	6.09
Transvaal													
Sub-division A	5.80	6.01	5.61	5.09	4.34	3.84	3.48	3.69	4.47	5.41	5.57	5.79	4.93
Sub-division B	8.03	7.85	7.08	6.33	5.22	4.56	3.87	4.31	5.78	7.44	8.42	8.46	6.45
Eastern Transvaal	6.37	6.52	6.14	5.31	4.33	3.60	3.12	3.47	4.42	5.46	5.92	5.92	5.05
Northern Natal/Transvaal Border	6.60	6.53	6.13	5.37	4.39	3.63	3.19	3.47	4.40	5.18	5.71	6.02	5.05
Northern Cape	10.75	10.52	8.66	6.93	5.27	4.19	3.39	3.79	5.23	7.32	8.87	10.22	7.10

TABLE 10.2 : REGIONAL RELATIVE MEAN MONTHLY EVAPORATION VALUES (mm)

(BASED ON DAILY DATA)

Region	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
South-western Cape												
Sub-division A	242.7	255.4	211.1	174.5	111.9	75.3	89.0	58.8	75.3	102.3	156.2	203.7
Sub-division B	287.1	295.1	250.3	205.8	134.7	89.0	69.8	69.3	88.4	124.5	189.7	240.0
Eastern Cape Coastal												
Sub-division A	215.5	218.6	177.5	149.1	107.4	84.9	70.4	73.5	93.9	112.2	152.5	181.2
Sub-division B	218.2	214.8	183.6	163.1	129.0	115.0	105.4	102.6	121.2	135.3	166.5	186.0
Eastern Cape Inland												
Sub-division A	276.5	277.1	211.7	180.4	132.0	116.3	94.6	104.4	142.6	172.2	206.8	235.5
Sub-division B	178.3	169.3	147.3	133.3	107.4	93.3	81.8	91.5	122.5	135.6	151.3	159.0
Natal Coastal	169.3	183.5	166.2	158.7	125.1	106.3	95.5	98.1	124.0	135.6	160.0	163.8
Natal Inland	175.5	167.1	154.3	148.5	120.6	104.8	91.8	101.1	129.6	143.1	156.6	158.1
Orange Free State												
Sub-division A	182.9	173.6	150.8	140.1	115.8	106.6	94.6	104.4	139.8	160.2	173.3	165.6
Sub-division B	287.1	283.3	224.2	189.7	136.8	107.6	86.8	92.4	138.6	192.6	234.1	255.3
Transvaal												
Sub-division A	179.8	186.3	162.7	157.8	130.2	119.0	107.9	110.7	138.6	162.3	172.7	173.7
Sub-division B	248.9	243.3	205.3	196.2	156.6	141.4	120.0	129.3	179.2	223.2	261.0	253.8
Eastern Transvaal	197.5	202.1	178.1	164.6	129.9	111.6	96.7	104.1	137.0	163.8	183.5	177.6
Northern Natal/Transvaal Border	204.6	202.4	177.8	166.5	131.7	112.5	98.9	104.1	136.4	155.4	177.0	180.6
Northern Cape	333.3	326.1	251.1	214.8	158.1	129.9	105.1	113.7	162.1	219.6	275.0	306.6

TABLE 10.3 : REGIONAL AVERAGES FOR THE NUMBER OF DAYS WITHIN EACH RAINGROUP

Region	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
South-western Cape																				
Sub-division A	25.67	1.58	2.24	0.71	0.68	23.48	1.39	3.05	1.21	1.28	22.43	1.68	3.37	1.55	1.98	23.51	1.71	3.35	1.39	1.05
Sub-division B	28.54	0.52	1.07	0.44	0.43	26.24	0.93	1.96	0.96	0.91	24.24	1.13	2.83	1.35	1.45	26.45	1.03	2.11	1.64	0.59
Eastern Cape Coastal																				
Sub-division A	25.55	1.26	2.57	0.89	1.04	25.15	1.15	2.95	0.95	0.82	26.14	0.97	2.37	0.85	0.70	24.61	1.35	2.77	0.96	1.31
Sub-division B	20.13	3.62	4.11	1.68	1.47	22.26	2.71	3.39	1.31	1.34	24.93	1.86	2.22	0.90	1.09	20.38	3.32	3.95	1.65	1.71
Eastern Cape Inland																				
Sub-division A	21.71	2.11	3.35	1.62	2.21	24.43	1.98	2.23	0.98	1.38	27.94	0.99	1.10	0.33	0.64	24.31	1.71	2.31	1.11	1.55
Sub-division B	13.79	4.48	6.32	2.73	3.68	20.95	3.09	3.59	1.64	1.73	27.87	1.22	1.24	0.37	0..31	18.34	4.08	4.86	1.86	1.87
Natal Coastal																				
Sub-division A	15.07	3.12	6.95	2.80	3.12	22.32	2.16	3.47	1.41	1.64	27.56	0.98	1.50	0.52	0.46	17.54	2.98	6.02	2.33	2.15
Sub-division B	19.47	1.71	5.10	2.32	2.62	24.22	1.07	2.81	1.35	1.55	27.01	0.63	1.83	0.73	0.87	19.24	1.51	4.61	2.29	2.19
Natal Inland																				
Sub-division A	19.84	0.65	4.71	2.44	3.36	25.69	0.38	2.35	1.14	1.49	28.69	0.31	1.09	0.47	0.44	21.37	0.82	4.40	1.95	2.46
Sub-division B	15.48	1.75	6.96	3.17	3.65	22.88	1.35	3.52	1.66	1.63	27.53	0.63	1.68	0.64	0.53	18.17	1.53	5.94	2.74	2.59
Sub-division C	12.91	5.96	7.07	2.49	2.58	20.87	3.90	3.44	1.35	1.45	27.06	1.83	1.30	0.40	0.41	15.77	5.63	5.91	2.18	1.40
Orange Free State																				
Sub-division A	11.82	4.07	6.85	3.30	4.98	22.00	2.45	3.04	1.58	1.94	27.99	0.79	1.20	0.55	0.48	17.56	3.38	5.20	3.05	1.82
Sub-division B	22.30	1.38	3.19	2.04	2.26	25.11	1.18	2.14	1.12	1.51	29.32	0.42	0.70	0.31	0.25	25.44	1.01	2.05	1.15	1.35
Transvaal	21.82	1.39	3.45	2.01	2.32	26.51	0.87	1.87	0.94	0.83	29.83	0.32	0.51	0.18	0.15	25.36	0.97	2.20	1.10	1.30
Eastern Transvaal	21.74	1.75	3.30	1.80	2.38	25.87	1.19	1.92	0.96	1.06	29.39	0.45	0.75	0.21	0.20	23.80	1.49	2.84	1.38	1.49
Northern Natal / Transvaal Border	20.61	1.97	3.89	1.79	2.75	24.73	1.33	2.47	1.17	1.31	28.02	0.86	1.24	0.48	0.40	21.83	2.06	3.69	1.45	1.92
Northern Cape	23.82	1.45	2.78	1.49	1.58	26.14	0.99	1.90	1.00	0.97	29.88	0.30	0.46	0.18	0.19	25.21	0.82	1.58	0.95	0.90

TABLE 10.4 : RAINGROUP EVAPORATION WEIGHTS (REW's), PER REGION, PER SEASON

Region	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
South-western Cape	1.04	0.76	0.72	0.60	0.52	1.08	0.75	0.68	0.63	0.58	1.09	0.78	0.71	0.69	0.72	1.08	0.77	0.67	0.55	0.46
Eastern Cape Coastal	1.11	0.91	0.72	0.62	0.68	1.09	0.85	0.71	0.65	0.61	1.06	0.89	0.70	0.66	0.59	1.13	0.80	0.67	0.62	0.55
Eastern Cape Inland	1.13	0.85	0.82	0.79	0.92	1.07	0.83	0.79	0.82	0.91	1.03	0.74	0.75	0.79	0.87	1.12	0.82	0.72	0.69	0.78
Natal Coastal	1.10	0.79	0.84	0.82	0.94	1.04	0.84	0.84	0.87	1.04	1.02	0.81	0.84	0.86	0.96	1.10	0.82	0.80	0.76	0.91
Natal Inland	1.16	0.82	0.80	0.80	0.99	1.07	0.83	0.76	0.72	0.98	1.03	0.70	0.71	0.70	1.01	1.16	0.76	0.75	0.70	0.89
Orange Free State	1.07	0.84	0.85	0.82	0.88	1.04	0.81	0.79	0.85	0.90	1.02	0.67	0.69	0.76	0.85	1.07	0.76	0.74	0.79	0.78
Transvaal	1.05	0.89	0.84	0.88	0.94	1.03	0.77	0.80	0.92	0.92	1.01	0.54	0.72	0.59	0.89	1.04	0.79	0.78	0.77	0.82
Eastern Transvaal	1.05	0.76	0.82	0.90	1.06	1.02	0.82	0.81	1.01	1.11	1.02	0.60	0.72	0.67	0.95	1.05	0.66	0.72	0.85	0.93
Northern Natal/Transvaal Border	1.07	0.84	0.83	0.84	0.95	1.04	0.81	0.83	0.84	0.97	1.03	0.71	0.73	0.71	0.75	1.09	0.78	0.73	0.74	0.86
Northern Cape	1.06	0.88	0.76	0.79	0.83	1.03	0.87	0.82	0.81	1.07	1.00	0.69	0.84	0.88	0.98	1.03	0.82	0.75	0.77	0.81

TABLE 10.5 : RELATIVE VARIABILITY OF DAILY MEAN EVAPORATION VALUES (VARIANCE EXPRESSED AS A PERCENTAGE OF THE DAILY MEAN EVAPORATION VALUE)

Region	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
South-western Cape												
Sub-division A	9.20	9.71	7.55	5.33	4.29	3.29	4.57	3.57	3.70	2.64	3.97	1.33
Sub-division B	13.07	14.60	20.28	14.46	9.13	3.48	5.33	4.76	2.80	3.86	8.00	14.50
Eastern Cape Coastal												
Sub-division A	0.58	1.13	0.00	0.00	0.00	1.09	2.64	3.67	0.33	0.00	0.00	0.99
Sub-division B	7.95	6.20	3.16	4.56	3.49	9.97	15.88	10.53	4.86	4.21	3.17	4.19
Eastern Inland												
Sub-division A	9.75	9.84	6.99	3.61	4.77	12.27	20.98	25.00	16.96	16.20	15.44	14.78
Sub-division B	6.78	4.40	3.54	0.93	4.19	10.30	9.47	9.84	6.33	3.10	5.33	8.30
Natal Coastal	13.37	7.77	6.63	5.66	4.32	4.66	6.17	6.73	5.75	4.87	5.43	6.23
Natal Inland	15.55	12.62	12.22	7.31	5.22	5.62	4.73	6.53	6.70	9.85	10.50	11.39
Orange Free State												
Sub-division A	5.42	5.71	6.35	1.55	0.52	0.29	0.98	2.30	2.22	10.86	5.90	11.05
Sub-division B	19.33	20.68	15.39	7.52	5.92	4.90	5.36	4.87	7.16	10.28	16.29	22.68
Transvaal												
Sub-division A	0.00	0.17	0.18	0.79	1.15	0.00	0.57	2.17	3.58	9.06	3.77	2.07
Sub-division B	7.85	8.54	7.49	9.48	7.09	6.36	5.68	4.41	4.50	6.85	8.67	7.21
Eastern Transvaal	2.83	4.57	2.00	2.42	1.36	1.41	1.92	2.54	2.30	4.44	5.43	10.76
Northern Natal / Transvaal Border	9.70	11.03	11.42	11.17	8.88	10.47	12.54	12.68	14.55	15.83	11.91	8.64
Northern Cape	12.00	15.40	11.55	7.79	6.45	4.77	2.36	2.37	5.54	8.20	8.23	8.71

TABLE 10.6 : KRUSKAL-WALLIS H TEST RESULTS FOR DIFFERENT REGIONS

Region	Test Statistic	Significance level
South-western Cape		
Sub-division A	2.2974	0.8067
Sub-divsion B	7.0645	0.9558
Regional	5.6301	0.0177
Eastern Cape Coastal		
Sub-division A	0.0133	0.9081
Sub-division B	2.7613	0.4299
Regional	4.1802	0.5238
Eastern Cape Inland		
Sub-division A	1.8393	0.3987
Sub-division B	4.9988	0.2874
Regional	18.5471	0.0097
Natal Coastal		
Regional	31.6111	0.0346
Natal Inland		
Regional	22.0400	0.0048
Orange Free State		
Sub-division A	2.1126	0.3477
Sub-division B	6.0467	0.6420
Regional	14.0158	0.2321
Transvaal		
Sub-division A	0.6080	0.4355
Sub-division B	10.6847	0.2202
Regional	25.1871	0.0050
Eastern Transvaal		
Regional	6.8757	0.5501
Northern Natal/Transvaal Border		
Regional	35.9357	0.0006
Northern Cape		
Regional	2.8385	0.7249

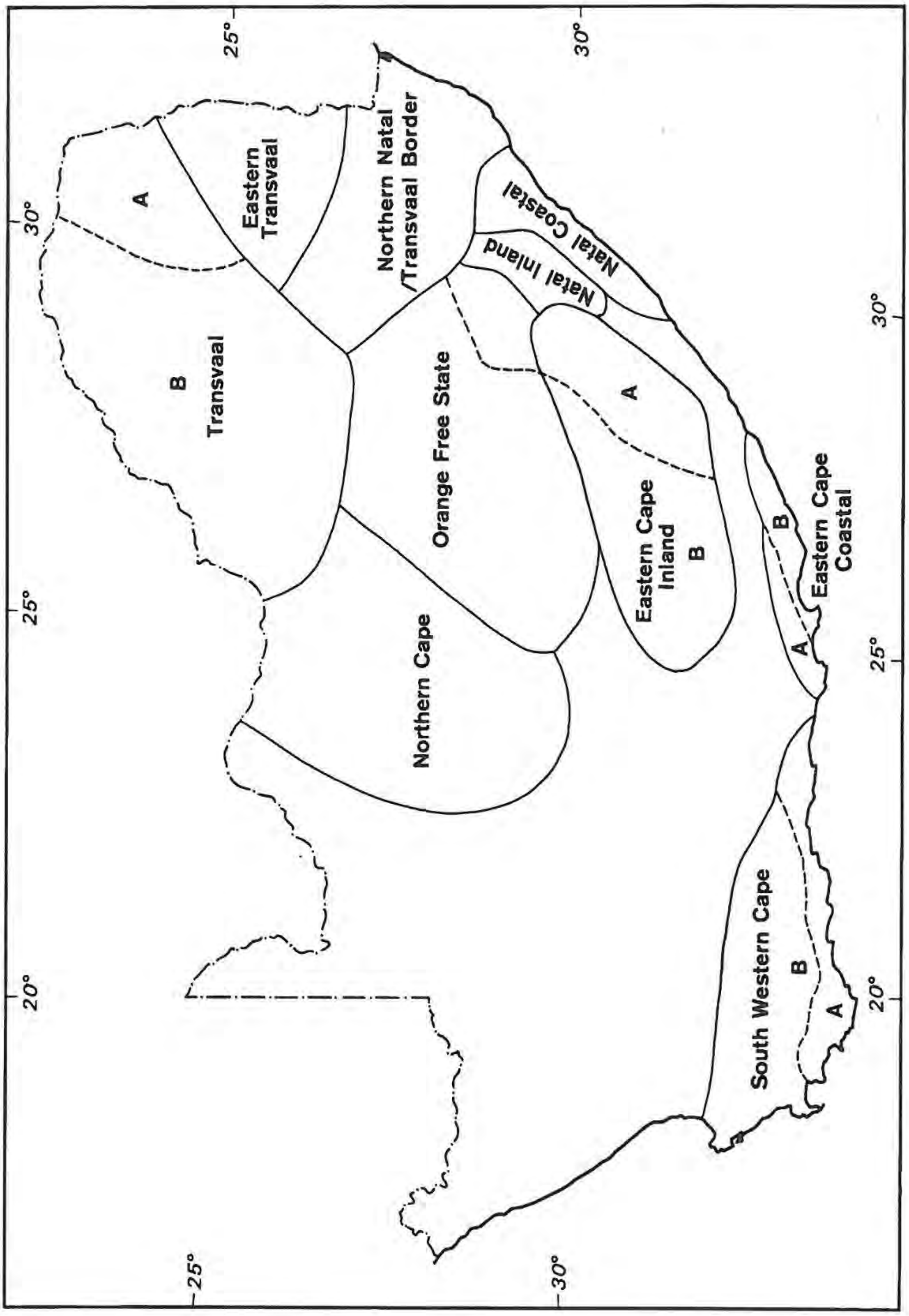


FIGURE 10.1 : Demarcation of rainfall/evaporation regions according to the daily mean evaporation and number of days within each raingroup category parameter files

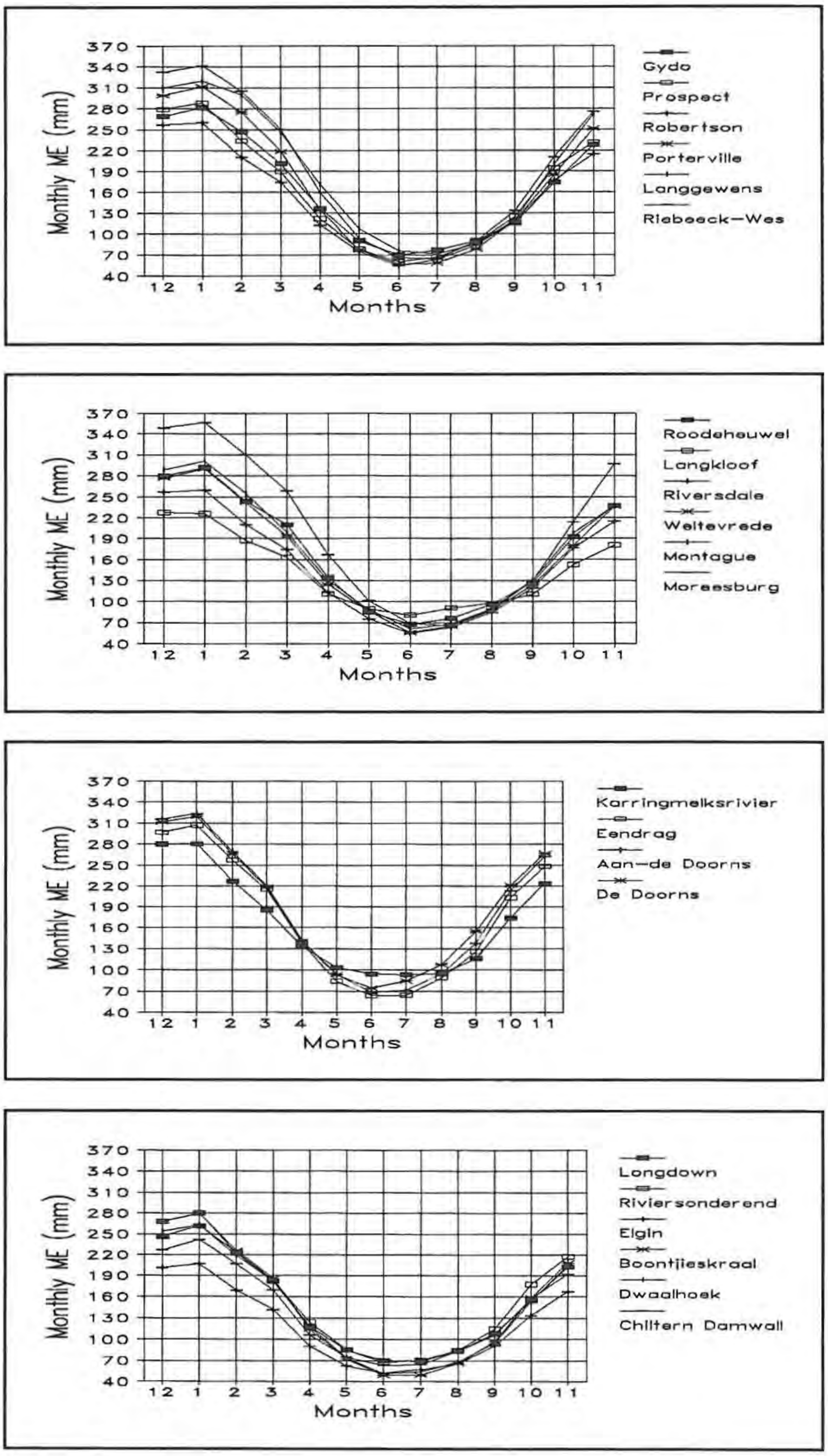


FIGURE 10.2 : **SOUTH-WESTERN CAPE** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

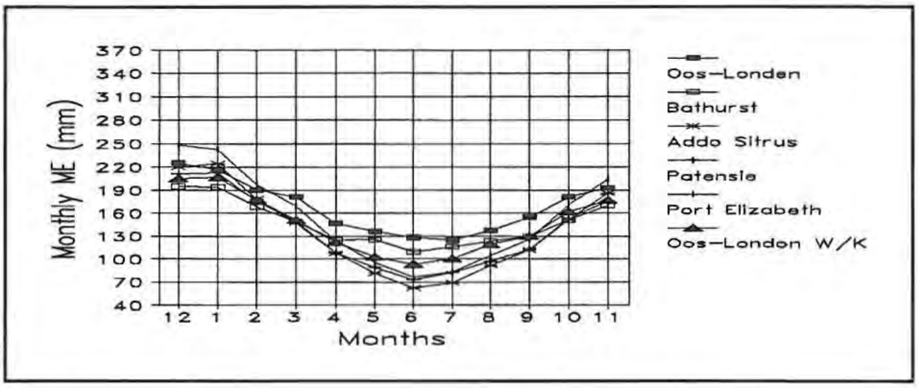


FIGURE 10.3 : **EASTERN CAPE COASTAL** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

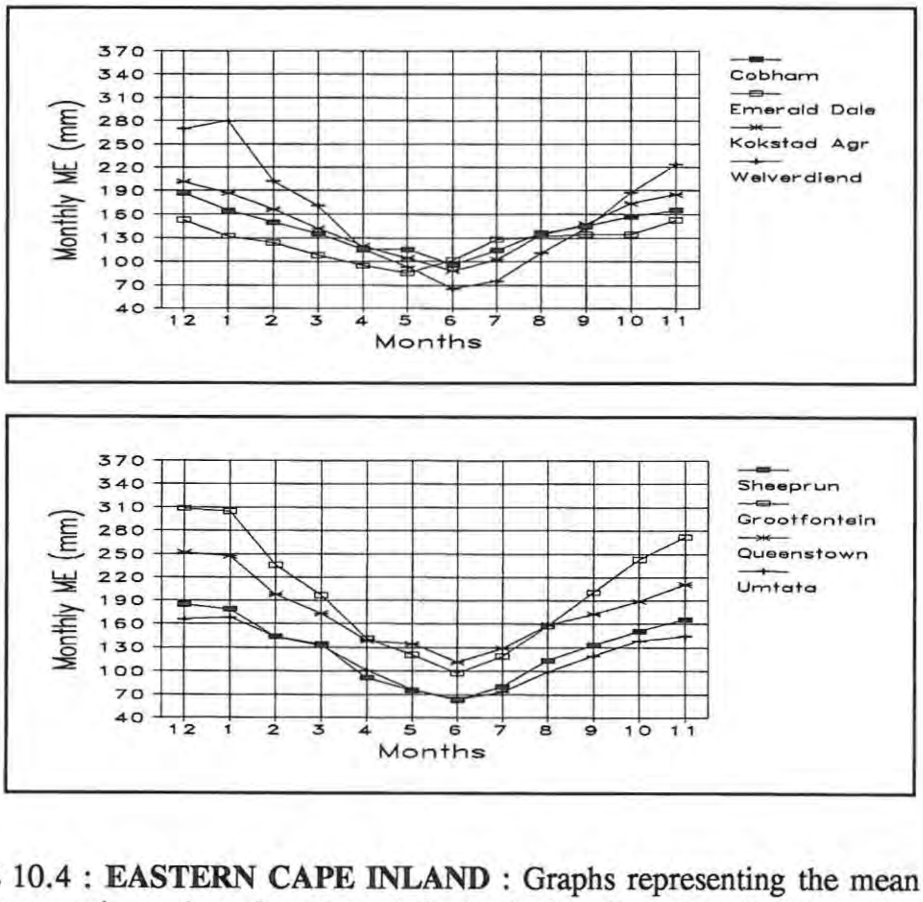


FIGURE 10.4 : **EASTERN CAPE INLAND** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

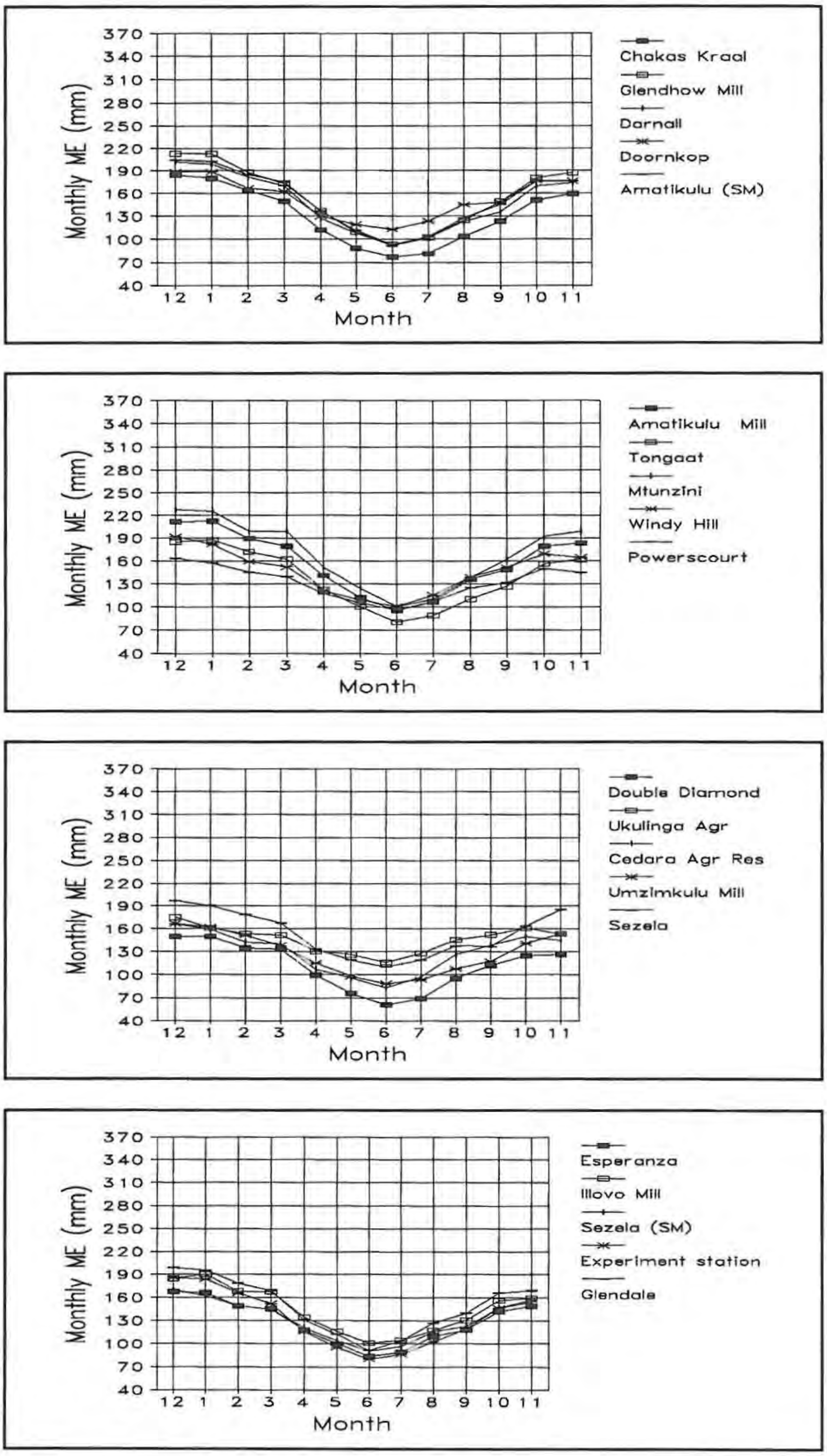


FIGURE 10.5 : **NATAL COASTAL** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

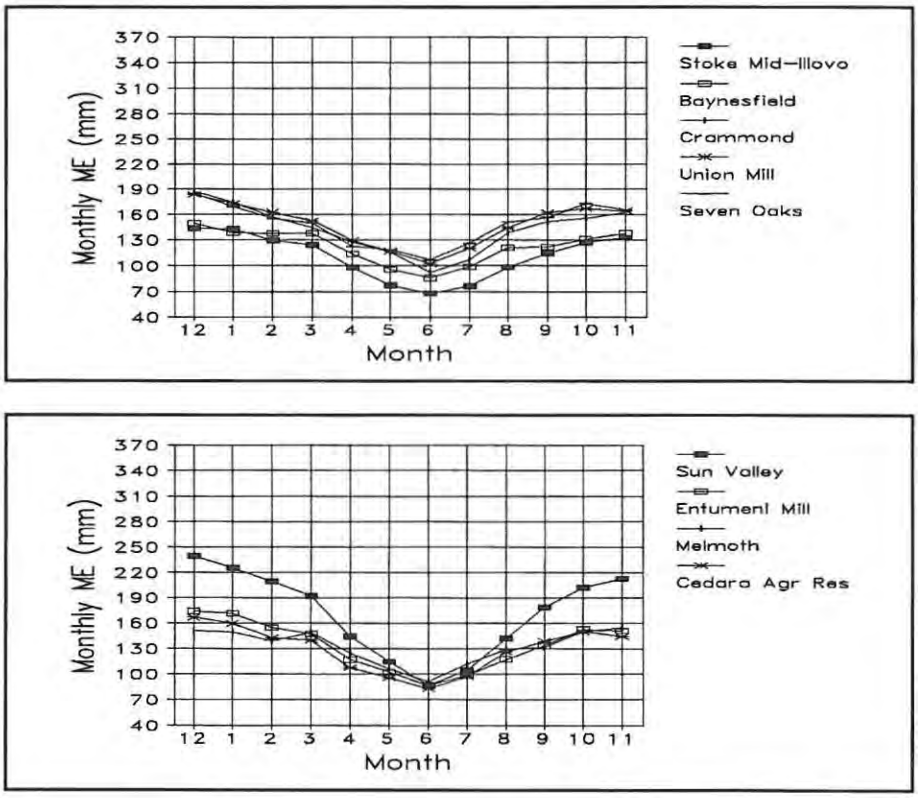


FIGURE 10.6 : **NATAL INLAND** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

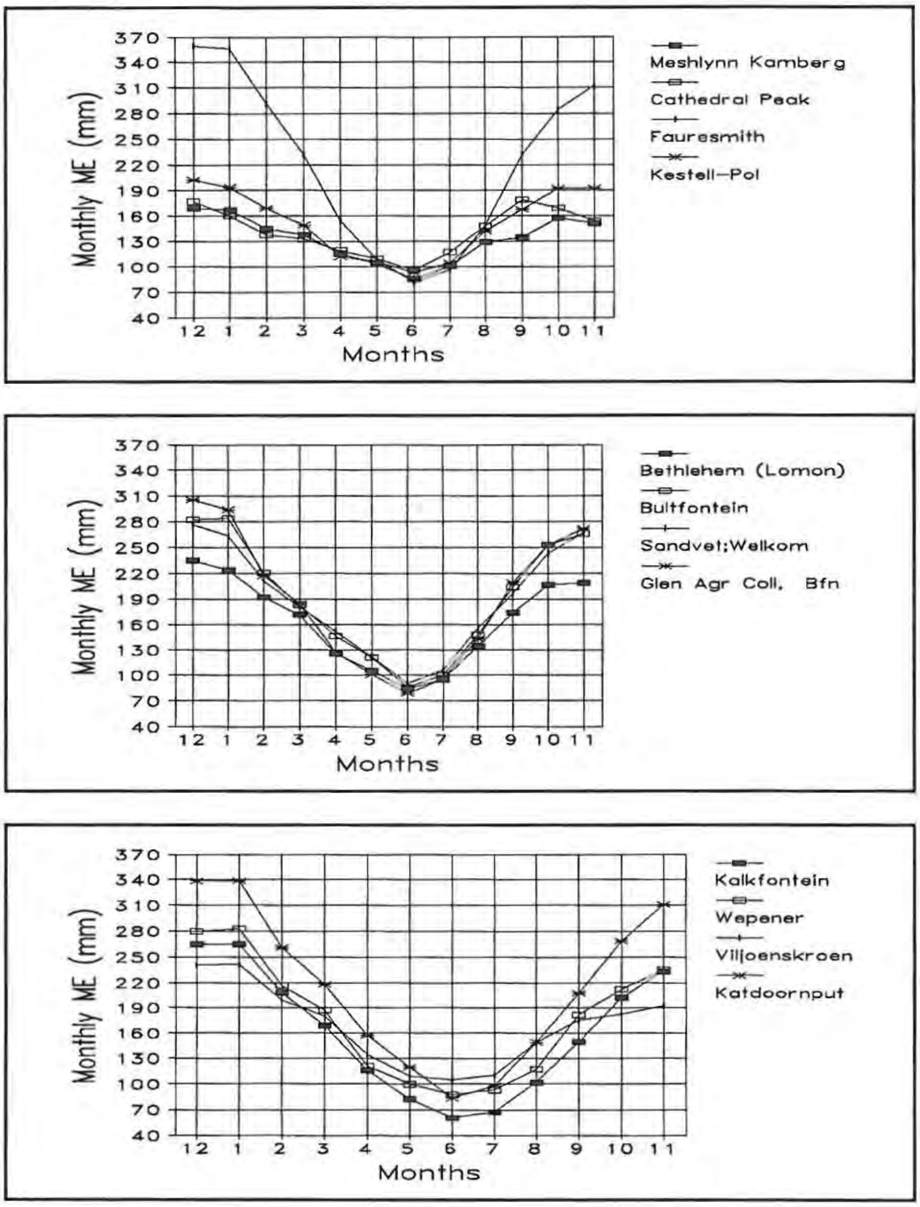


FIGURE 10.7 : **ORANGE FREE STATE** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

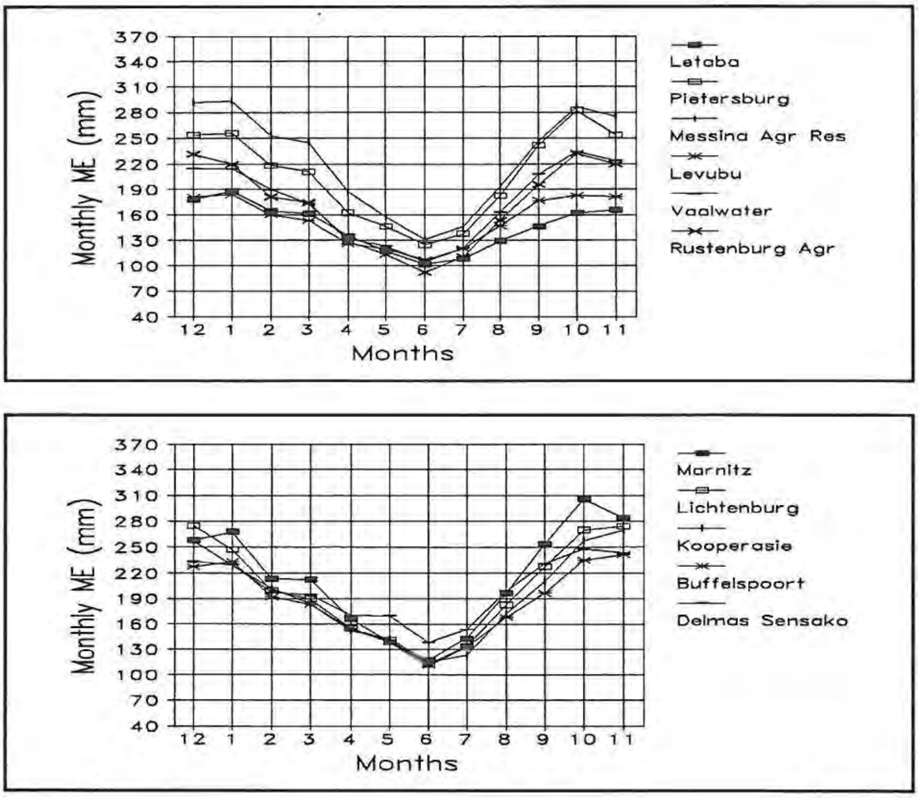
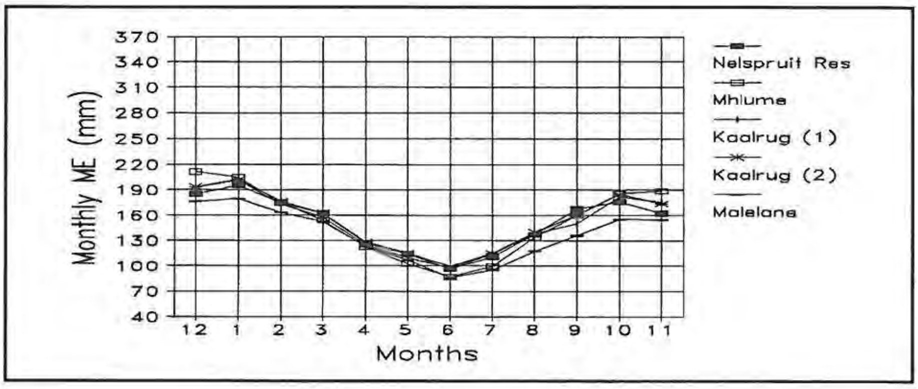


FIGURE 10.8 : **TRANSVAAL** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.



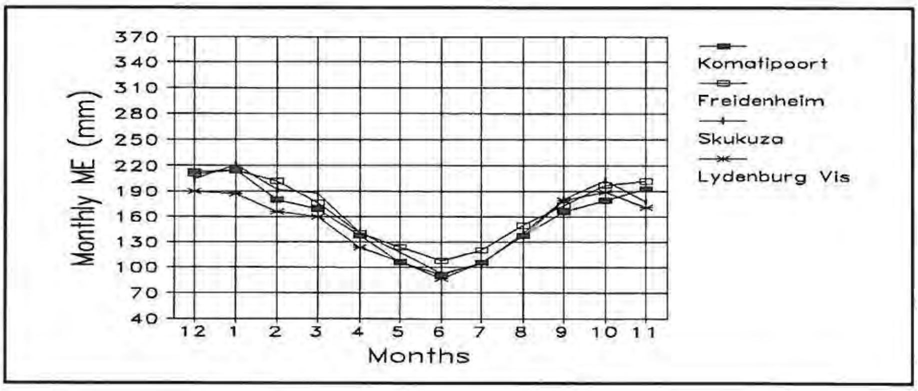


FIGURE 10.9 : **EASTERN TRANSVAAL** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

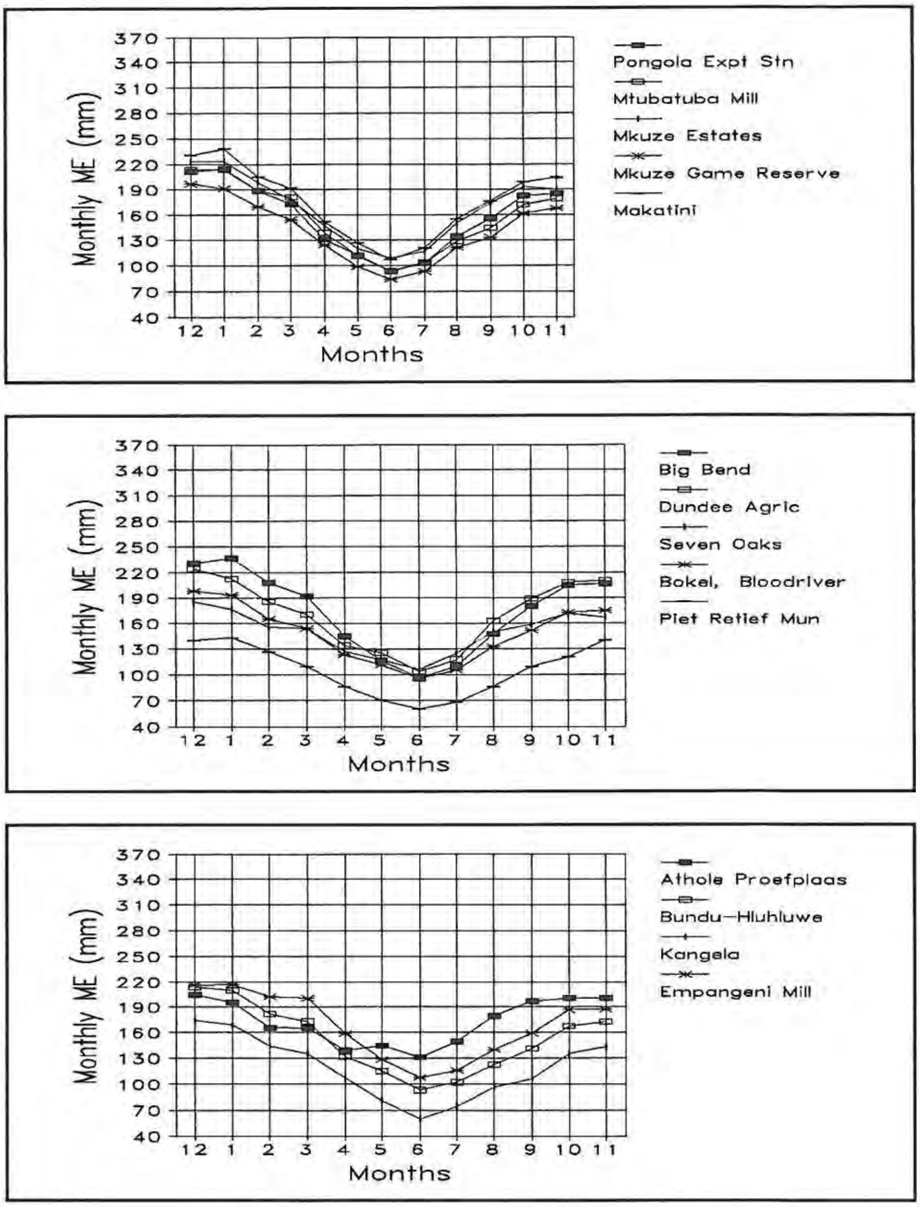


FIGURE 10.10 : **NORTHERN NATAL/TRANSVAAL BORDER** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

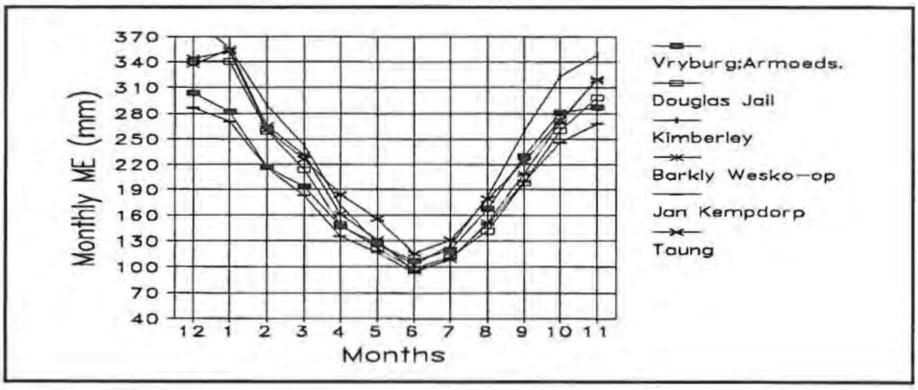


FIGURE 10.11 : **NORTHERN CAPE** : Graphs representing the mean monthly evaporation values (based on daily data), for all stations in this region.

TABLE 10.7 : FRIEDMAN TWO-WAY ANALYSIS (Fr) RESULTS FOR DIFFERENT REGIONS

REGION	Fr TEST STATISTIC
South-western Cape	66.3572
Eastern Cape coastal	29.3198
Eastern Cape inland	
Sub-division A	10.6667
Sub-division B	31.8667
Natal coastal	168.1880
Natal inland	78.2710
Orange Free State	
Sub-division A	8.1667
Sub-division B	51.3380
Transvaal	
Sub-division A	1.3333
Subdivision B	76.8456
Eastern Transvaal	52.2726
Northern Natal/Transvaal border	118.3770
Northern Cape	40.5238

TABLE 10.8 : PERFORMANCE OF COREVAP1 USING THE REGIONAL PARAMETERS

REGION AND STATION	USING ORIGINAL PARAMETER FILE (annual coefficient of efficiency)	USING THE REGIONAL DAILY MEAN EVAPORATION PARAMETER FILE (annual coefficient of efficiency)	USING THE REGIONAL NUMBER OF DAYS WITHIN EACH RAINGROUP CATEGORY PARAMETER FILE (annual coefficient of efficiency)	USING THE COMPLETE REGIONAL PARAMETER FILE (annual coefficient of efficiency)
South-western Cape				
Longdown	-0.024	-0.090	-0.039	-0.136
Prospect	0.246	0.190	0.245	0.167
Eastern Cape Coastal				
Addo Sitrus NS	0.182	0.173	-2.615	-2.548
Oos-London W/K	-0.298	-0.053	-0.276	-0.076
Eastern Cape inland				
Queenstown	0.292	0.233	0.295	0.247
Natal Coastal				
Glendale	-0.128	-0.316	-0.278	-0.493
Experiment station	-0.227	0.011	-0.169	0.048
Natal inland				
Cedara Agr Res, Stn	-0.440	-0.300	-0.195	-0.260
Orange Free State				
Glen Agr Coll, Bfn	0.232	0.165	-0.229	0.173
Transvaal				
Letaba	-0.230	-0.102	-0.461	-0.248
Pietersburg	0.120	0.071	0.119	0.096
Eastern Transvaal				
Nelspruit Res	0.109	0.146	0.118	0.172
Northern Natal/Transvaal border				
Pongola Expt Farm	0.166	0.065	0.186	0.102
Northern Cape				
Vryburg;Armoedsvlakt	0.107	0.099	0.100	0.092

CHAPTER 11

11. CONCLUSIONS AND RECOMMENDATIONS

Processes such as rainfall and evaporation are influenced by a number of factors and are irregular in space and time. Attempting to clarify the relationship between these two processes is difficult, as a combination of factors are responsible for the development of specific weather systems which are inherently highly variable and complex. This is further complicated by the fact that in many cases, different synoptic systems occur simultaneously to produce a different set of conditions. Consequently, no one set of conditions can be related to produce a specific rainfall/evaporation relationship. The point is that rainfall is occurring in association with a wide range of other conditions (temperature, humidity, wind) that affect evaporation rates. Perhaps a more extensive analysis of weather parameters is required. In fact, an attempt was made to investigate the inclusion of temperature indices into the rainfall/evaporation relationship analysis, to determine the variability of evaporation trends before and after rainfall events such as frontal, orographic and convective thunderstorm activity. Unfortunately, the available database on temperature indices was simply not adequate (in general, only minimum and maximum daily temperature was available) for the intended purpose. However, this is beyond the original aims and objectives of this study.

The availability of data, and inconsistencies within the data set itself has complicated matters. The quality of data is a basic problem because it determines the reliability of extrapolated information from past observations to future use. No model is better than the assumptions and data it relies on. Awareness of the limitations of the data must be developed. The extent to which each region is adequately represented by the data stations is important, as the higher the number of stations representing a region, the more reliable will be the eventual regionally identified characteristics. The south-western Cape is represented by 22 stations. However, the remaining regions are represented by far fewer stations, and this situation is exacerbated where regions represented by only a few stations, are further divided into sub-divisions. For example, the eastern Cape coastal region is divided into sub-divisions A and B which are represented by only 2 and 4 stations respectively. Similarly, the eastern Cape inland region is divided into sub-divisions A and B which are represented by only 3 and 5 stations respectively. The Natal inland region is represented by 9 stations, Orange Free State by 13 (sub-division A (4); sub-division B (9)), Transvaal by 11 (sub-division A (2); sub-division B (9)), eastern Transvaal by 9, northern Natal/Transvaal border region by 14 and the northern Cape by 6 stations. It is clear that using so few data points for some regions to define rainfall/evaporation trends for an extensive area is hazardous, and it is not surprising that difficulties have been encountered when attempting to develop regional rainfall/evaporation relationships. Unfortunately, no further data stations satisfied the basic requirements as stipulated in chapter 6.

Although regional differences in the rainfall/evaporation relationships have been identified, and related to some extent, to the prevailing synoptic conditions, these are not always distinct. The variability in the rainfall/evaporation relationships for the winter versus the summer rainfall regions and the transitional zone between the winter and summer rainfall regions are clearly discernable. However, it is more difficult to pin-point or account for differences between regions that fall within the summer rainfall zone. For example, accounting for the differences in the rainfall/evaporation trends between the Natal coastal, Natal inland and the north-eastern and northern regions of South Africa (Orange Free State, Transvaal, eastern Transvaal, northern Natal/Transvaal and northern Cape). These regions are affected by similar synoptic systems, yet still display highly variable evaporation trends.

The coefficient of efficiency analysis based on daily data, was conducted to determine the "goodness-of-fit" between the observed and the simulated mean monthly evaporation values. The analysis indicated that best results were obtained for stations in the southern and eastern Cape coastal and inland regions, while the program was less effective when used on stations representing the northern and interior regions of southern Africa. This is in agreement with the rainfall/evaporation trends that were more easily identified for the southern and eastern Cape coastal regions. Generally, the program produced positive accumulative coefficient of efficiency values and so the analysis was conducted on a monthly basis. However, the accumulative coefficient of efficiency values in the monthly analysis were expected to be lower than those values obtained in the daily analysis as a result of other influencing factors such as the necessity to disaggregate monthly rainfall values to determine the number of days falling in each raingroup and the relative simplicity of the procedure used to carry this out.

COREVAP1 produced the best simulations of monthly evaporation. This is not surprising as the program uses the straight-forward mean evaporation value multiplied by the number of days to simulate the monthly evaporation values. However, the coefficient of efficiency analysis indicated that for some stations the program simulations were not producing an improvement when using the REW's compared to simply using the monthly evaporation value not corrected for rain. Thus, a sensitivity analysis was conducted to determine which parameters of the model had the greatest influence on the simulations. The sensitivity analysis indicated that generally, the percentage increase/decrease in mean evaporation values that was acceptable for the representative stations was low, while fairly high percentage changes in mean rainfall values was tolerated.

A need had been identified for the regionalisation of parameters to represent regions displaying different rainfall/evaporation trends. Thus the regional analysis would be an attempt to use data from several locations in a homogeneous region to develop relationships for ungauged points in a specific region. This is important as in many cases, especially in developing countries, not enough data is available to estimate the necessary parameters with the accuracy needed to arrive at reliable results. The basic aim was to determine that if the model is used, would the results still be comparable, or even better than simply using the monthly mean evaporation values not corrected for rainfall. Also, if located at a certain point in southern Africa, within which region will the station be located and therefore, which parameter set should be used to correct the mean monthly evaporation data?

COREVAP1 was run using the regional parameters to determine whether the regional parameters still provide estimates that compare favourably with the mean monthly evaporation rates. Unfortunately, the results obtained from the regionalisation of parameters are neither encouraging or conclusive. For stations Longdown, Oos-London W/K, Glendale, Cedara Agr Res and Letaba, whether the regional parameters produced acceptable simulations of mean monthly evaporation is largely irrelevant as the accumulative coefficient of efficiency values remained negative. For the remaining stations (9), running COREVAP1 using the regional parameter files did still produce acceptable results, as indicated by the positive accumulative coefficient of efficiency values. However, stations Addo Sitrus NS, Glen Agr Coll, Bfn and Experiment station were sensitive to the regional parameter file where only the regional number of days within each raingroup category were substituted. These results are not surprising as,

- there was no linear relationship between daily rainfall and daily evaporation,
- the regional rainfall/evaporation relationships that were identified were not well defined, and in some cases impossible to identify,
- the results obtained from the coefficient of efficiency analysis based on daily data was encouraging, but was not as good when monthly data was used,
- the sensitivity analysis did not display any major regional differences,
- the regionalisation of parameters was difficult because of the inherent variability of rainfall and evaporation and in many cases the delimitation of regions was based on too few data stations,
- the results obtained when substituting the regional parameters were not encouraging.

However, there is no one evaporation equation that can be readily used with a high degree of confidence and at the same time having input data requirements that can be readily met from available data. Existing Water Resource Estimation Models use published regionalised mean monthly pan evaporation values which result in the overestimation or underestimation of the actual evaporation that is occurring depending on the actual amount of rain occurring in a specific month. The approach in this thesis has been an attempt to correct these mean evaporation values for the amount of rainfall that occurs in a specific month, in a specific region. Unfortunately, it is clear that this method did not work very well, and is not really feasible because of the inherent variability of the physical processes under study. These processes and their interrelationships probably need to be more closely defined. The study relies on 117 data stations to develop the generalized regional rainfall/evaporation relationships for southern Africa. The spatial distribution of these stations is not adequate in order to develop regional parameters.

Recommendations

- Further investigation of the inclusion of temperature indices into the rainfall/evaporation relationship analysis : This would assist with the determination of the variability of evaporation trends before and after rainfall events such as frontal, orographic and convective thunderstorm activity. This is important, as whether the mean temperature is closer to the minimum or the maximum temperature, will have a direct influence on the evaporation rates. However, the database needed to compile the temperature indices must be readily available. For example, a continuous temperature record for the day would be required and not simply the mean of the maximum and minimum temperature values. An indication of the humidity indexes would also be helpful. However, once again it must be stressed that, as was the case with the more empirical equations, if the meteorological data inputs become too extensive, problems will arise when applying the approach more generally and satisfying the more extensive data requirements. Also, users of the model will not want to spend hours collecting data when they could simply extract the mean monthly evaporation values from published regionalised tables (and forego more accurate values that take rainfall into account, such as the REW's).

- Disaggregation of rainfall procedure : In the model, the disaggregation of monthly rainfall values (to determine the number of days falling into each raingroup) is a simple procedure, and there is possibly a more effective way in which this could be achieved.

- More extensive use of COREVAP2 and COREVAP3 : Since COREVAP2 and 3 take into account a wider range of evaporation values compared to simply using the mean value as is the case with COREVAP1, COREVAP2 and 3 may give a better indication of the variability of the rainfall/evaporation relationship. (COREVAP2 uses a random sampling procedure to draw $Ndays_i$ samples from between minus and plus one standard deviation of the mean. COREVAP3 uses a similar procedure but samples from the full distribution of the daily evaporation distribution for each raingroup). These programs use a simple stochastic method of achieving the above, and it is possible that an improvement of the sampling procedure could lead to improved results. However, although COREVAP2 and 3 will give a better indication of the wider range of values associated with the rainfall/evaporation relationship, the fact is that these programs will be directly influenced by skewed data and outliers, which will affect their outputs. COREVAP2 and 3 can not be expected to simulate observed mean monthly evaporation as closely as COREVAP1 but they may reproduce statistics of the relationship between rainfall and evaporation more closely.

Although the proposed method did not 'work', it is clear that the original aims and objectives of the thesis have been fulfilled - the attempt to derive and develop meaningful relationships between daily rainfall and daily evaporation, to possibly quantify these relationships, and to assess the usefulness of incorporating these variations into existing simple Water Resource Estimation Models. Finally, this thesis concludes with the first golden rule of applied mathematics, "an approximate answer to the right question is worth a great deal more than a precise answer to the wrong question".

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APPENDICES

APPENDIX A

APPENDIX A : DAILY RAINFALL AND DAILY EVAPORATION DATA STATIONS

STATION NAME	MAP NO.	LAT.	LONG.	ALT (m).	RECORD OF DAILY RAINFALL DATA (yrs)	RECORD OF DAILY EVAPORATION DATA (yrs)	RECORD OF CONCURRENT DAILY RAINFALL AND EVAPORATION DATA (yrs)	NUMBER OF DATA POINTS
SOUTH WESTERN CAPE								
Longdown	22	34° 03'	19° 10'	335	1973 - 1989	1973 - 1989	1973 - 1989	5744
Prospect	5	33° 51'	20° 03'	160	1971 - 1989	1971 - 1989	1971 - 1989	6477
Elgin	13	34° 00'	19° 02'	281	1963 - 1989	1964 - 1989	1964 - 1989	8932
Boontjieskraal	14	34° 12'	19° 21'	122	1920 - 1989	1973 - 1989	1973 - 1989	5752
Dwaalhoek	16	34° 08'	19° 31'	400	1973 - 1989	1973 - 1989	1973 - 1989	6068
Riviersonderend Tyg	11	34° 08'	19° 54'	295	1932 - 1989	1973 - 1989	1973 - 1989	5714
Langkloof (nivv)	9	33° 47'	23° 35'	723	1966 - 1989	1966 - 1989	1966 - 1989	7018
De Doorns (niww)	18	33° 28'	19° 40'	510	1901 - 1990	1965 - 1989	1965 - 1989	8934
Robertson (nivv)	1	33° 50'	19° 54'	170	1954 - 1989	1965 - 1989	1965 - 1989	8933
Aan-De-Doorns	17	33° 42'	19° 29'	220	1970 - 1989	1970 - 1989	1970 - 1989	7132
Gydo	3	33° 13'	19° 20'	1080	1972 - 1989	1972 - 1989	1972 - 1989	6226
Porterville - Mun	2	33° 01'	19° 01'	137	1973 - 1989	1973 - 1989	1973 - 1989	5827
Moreesburg	20	33° 09'	18° 41'	189	1973 - 1989	1973 - 1989	1973 - 1989	5917
Langgewens (wrs)	4	33° 17'	18° 42'	170	1931 - 1989	1972 - 1989	1972 - 1989	6317
Karringmelksrivier	15	34° 08'	20° 46'	160	1973 - 1989	1973 - 1989	1973 - 1989	5493
Riversdale	10	34° 06'	21° 16'	128	1877 - 1989	1963 - 1978	1963 - 1978	5194
Eendrag	21	33° 41'	19° 33'	245	1970 - 1984	1970 - 1984	1970 - 1984	5285
Roodeheuwel (wrs)	8	33° 38'	22° 15'	297	1970 - 1989	1970 - 1989	1970 - 1989	7158

Riebeeck-Wes	7	33^{0} 21'	18^{0} 52'	198	1969 - 1990	1973 - 1989	1973 - 1989	4557
Montague Police	19	33^{0} 48'	20^{0} 08'	223	1883 - 1990	1979 - 1989	1979 - 1989	3486
Chiltern Damwal	6	34^{0} 03'	19^{0} 09'	312	1973 - 1989	1973 - 1989	1973 - 1989	5289
Weltevrede	12	33^{0} 56'	20^{0} 37'	411	1965 - 1989	1972 - 1989	1972 - 1989	4233
EASTERN CAPE COASTAL								
Patensie	23	33^{0} 47'	24^{0} 50'	55	1954 - 1990	1979 - 1989	1979 - 1989	4342
Port Elizabeth W/K	24	33^{0} 59'	25^{0} 36'	60	1937 - 1975	1959 - 1975	1959 - 1975	6019
Addo Sitrus NS	25	33^{0} 34'	25^{0} 42'	150	1965 - 1989	1975 - 1989	1975 - 1989	5098
Bathurst NS	26	33^{0} 31'	26^{0} 49'	210	1970 - 1989	1976 - 1989	1976 - 1989	5205
Oos-London W/K	27	33^{0} 02'	27^{0} 50'	120	1960 - 1990	1960 - 1989	1960 - 1989	6295
Oos-Londen	28	33^{0} 01'	27^{0} 48'	140	1967 - 1986	1968 - 1986	1968 - 1986	5134
EASTERN CAPE INTERIOR								
Queenstown	29	31^{0} 54'	26^{0} 52'	1067	1884 - 1989	1979 - 1989	1979 - 1989	3578
Welverdiend An	30	30^{0} 43'	26^{0} 43'	1333	1974 - 1989	1979 - 1989	1979 - 1989	3488
Sheeprun	31	30^{0} 59'	28^{0} 23'	1213	1962 - 1973	1963 - 1973	1963 - 1973	3731
Kokstad Agr Res Stn	32	30^{0} 31'	29^{0} 25'	1363	1932 - 1989	1973 - 1989	1973 - 1989	4772
Cobham, Himeville	33	29^{0} 41'	29^{0} 25'	1750	1965 - 1989	1975 - 1989	1975 - 1989	4073
Emerald Dale Donnyb	34	29^{0} 57'	29^{0} 58'	1158	1935 - 1989	1976 - 1989	1976 - 1989	4840
Grootfontein	35	31^{0} 29'	25^{0} 01'	1250	1916 - 1989	1957 - 1989	1957 - 1989	12320
Umtata	36	31^{0} 35'	28^{0} 47'	692	1911 - 1971	1958 - 1971	1958 - 1971	4717
NATAL COASTAL								
Umzimkulu Mill	37	30^{0} 43'	30^{0} 25'	19	1924 - 1990	1967 - 1988	1967 - 1988	7101
Sezela	38	30^{0} 25'	30^{0} 39'	90	1976 - 1990	1976 - 1988	1976 - 1988	4053
Cedara Agr Res Stn	39	29^{0} 32'	30^{0} 17'	1067	1914 - 1989	1960 - 1989	1960 - 1989	8907

Esperanza	40	30^0 18'	30^0 38'	195	1968 - 1990	1968 - 1988	1968 - 1988	6739
Illovo Mill	41	30^0 06'	30^0 49'	15	1930 - 1990	1966 - 1988	1966 - 1988	7903
Powerscourt	42	29^0 58'	30^0 38'	631	1967 - 1990	1967 - 1988	1967 - 1988	7471
Double Diamond, Cato	43	29^0 48'	30^0 30'	650	1964 - 1989	1964 - 1989	1964 - 1989	7047
Glendhow Mill	44	29^0 21'	31^0 18'	33	1920 - 1990	1967 - 1988	1967 - 1988	7673
Tongaat	45	29^0 34'	31^0 08'	72	1966 - 1989	1966 - 1988	1966 - 1988	8034
Doornkop	46	29^0 12'	31^0 14'	442	1933 - 1990	1967 - 1988	1967 - 1988	5454
Chakas Kraal Auto	47	29^0 27'	31^0 11'	50	1951 - 1990	1966 - 1988	1966 - 1988	8037
Darnall	48	29^0 16'	31^0 23'	85	1966 - 1989	1966 - 1988	1966 - 1988	7909
Sugar Mill, Amatikulu	49	29^0 03'	31^0 32'	70	1973 - 1988	1973 - 1988	1973 - 1988	5342
Mtunzini (Prop farm)	50	28^0 56'	31^0 42'	151	1966 - 1990	1966 - 1988	1966 - 1988	8018
Ukulinga Agr Res Stn	51	29^0 40'	30^0 24'	775	1950 - 1989	1973 - 1989	1973 - 1989	5499
Sugar Mill, Sezela	52	30^0 20'	30^0 35'	160	1973 - 1988	1973 - 1988	1973 - 1988	5419
Amatikulu (Mill)	53	29^0 02'	31^0 31'	45	1924 - 1990	1967 - 1988	1967 - 1988	7707
Windy Hill	54	29^0 29'	30^0 34'	988	1932 - 1990	1966 - 1986	1966 - 1986	7015
Experiment Station	55	29^0 42'	31^0 02'	96	1901 - 1990	1927 - 1988	1927 - 1988	9438
Glendale	56	29^0 18'	31^0 07'	129	1966 - 1989	1967 - 1988	1967 - 1988	6982
NATAL INLAND								
Stoke Mid-Illovo	57	29^0 56'	30^0 30'	670	1964 - 1989	1979 - 1989	1979 - 1989	4099
Baynesfield Estates	58	29^0 45'	30^0 20'	846	1964 - 1989	1979 - 1989	1979 - 1989	4036
Cedara Agr Res Stn	59	29^0 32'	30^0 17'	1067	1914 - 1989	1960 - 1989	1960 - 1989	8907
Crammond	60	29^0 24'	30^0 25'	823	1971 - 1990	1977 - 1988	1977 - 1988	3980
Union Mill, Seven OA	61	29^0 21'	30^0 41'	975	1953 - 1989	1966 - 1988	1966 - 1988	4277
Seven Oaks - Ryhill	62	29^0 14'	30^0 37'	1066	1970 - 1990	1973 - 1988	1973 - 1988	5388

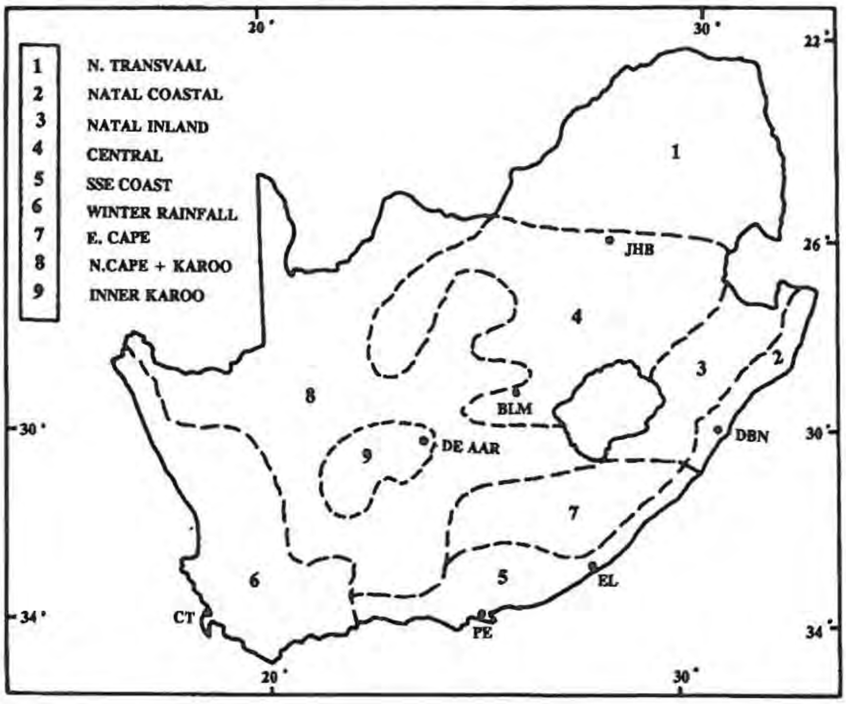
Sun Valley, Weenen	63	28° 50'	30° 05'	880	1974 - 1989	1976 - 1989	1976 - 1989	4620
Entumeni Mill	64	28° 54'	31° 18'	587	1932 - 1990	1968 - 1988	1968 - 1988	7028
Melmoth (Golden Reef)	65	28° 36'	31° 23'	790	1967 - 1989	1967 - 1983	1967 - 1983	4304
ORANGE FREE STATE								
Bethlehem, Loch Lomon	66	28° 10'	28° 18'	1638	1948 - 1989	1959 - 1989	1959 - 1989	11392
Bultfontein Arbeidskroon	67	28° 11'	26° 04'	1320	1905 - 1990	1978 - 1989	1978 - 1989	4378
Welkom ; Sandvet	68	28° 08'	26° 41'	1290	1932 - 1989	1975 - 1989	1975 - 1989	5678
Glen Agr Coll, Bfn	69	28° 57'	26° 20'	1295	1922 - 1989	1958 - 1989	1958 - 1989	9283
12C5E02 Kalkfontein	70	29° 30'	25° 13'	1234	1939 - 1967	1942 - 1967	1942 - 1967	9335
Cathedral Peak	71	28° 57'	29° 14'	1463	1973 - 1989	1975 - 1989	1975 - 1989	2809
Kestell - POL	72	28° 19'	28° 42'	1682	1907 - 1989	1968 - 1989	1968 - 1989	5492
Wepener	73	29° 44'	27° 02'	1430	1890 - 1990	1958 - 1976	1958 - 1976	6153
Viljoenskroen Rietpan	74	27° 10'	26° 55'	1371	1955 - 1989	1978 - 1989	1978 - 1989	1620
Katdoornput	75	28° 59'	25° 30'	1215	1913 - 1990	1978 - 1989	1978 - 1989	4277
Fauresmith	76	29° 46'	25° 19'	1524	1959 - 1990	1977 - 1988	1977 - 1988	4748
Meshlynn, Kamberg	77	29° 20'	29° 43'	1539	1968 - 1989	1979 - 1989	1979 - 1989	1951
TRANSVAAL								
Letaba	78	23° 52'	30° 19'	609	1973 - 1989	1973 - 1989	1973 - 1989	5346
Pietersburg	79	23° 52'	29° 27'	1234	1951 - 1973	1957 - 1973	1957 - 1973	5795
Messina Agr Res	80	22° 16'	29° 54'	522	1933 - 1989	1959 - 1989	1959 - 1989	8339
Levubu	81	23° 05'	30° 17'	650	1940 - 1989	1966 - 1989	1966 - 1989	7537
Vaalwater	82	24° 17'	28° 03'	1170	1964 - 1990	1979 - 1989	1979 - 1989	3907
Rustenburg Agr	83	25° 43'	27° 18'	1155	1903 - 1989	1958 - 1989	1958 - 1989	7646
Marnitz	84	23° 10'	28° 13'	944	1944 - 1971	1957 - 1971	1957 - 1971	4908

Lichtenburg, Sensako	85	26° 10'	26° 10'	1477	1960 - 1990	1977 - 1989	1977 - 1989	4252
Koster Kooperasie	86	25° 50'	26° 55'	1553	1911 - 1990	1977 - 1989	1977 - 1989	3967
Buffelspoort	87	25° 45'	27° 29'	1203	1925 - 1989	1976 - 1989	1976 - 1989	2950
Delmas, Sensako	88	26° 06'	28° 40'	1548	1907 - 1990	1977 - 1989	1977 - 1989	4610
EASTERN TRANSVAAL								
Nelspruit Res	89	25° 27'	30° 58'	659	1960 - 1989	1960 - 1989	1960 - 1989	6764
Mhlume 428	90	26° 05'	31° 49'	249	1976 - 1988	1976 - 1988	1976 - 1988	4918
Kaalrug (1)	91	25° 37'	31° 34'	365	1975 - 1989	1975 - 1989	1975 - 1989	5231
Kaalrug (2)	92	25° 37'	31° 32'	366	1919 - 1989	1973 - 1988	1973 - 1988	5480
Malelane	93	25° 30'	31° 30'	310	1938 - 1990	1966 - 1989	1966 - 1989	4586
Komatipoort Tenbosch	94	25° 24'	31° 58'	140	1972 - 1989	1976 - 1989	1976 - 1989	5127
Nelspruit Friedenheim	95	25° 26'	30° 59'	737	1973 - 1989	1973 - 1989	1973 - 1989	6110
Skukuza	96	24° 59'	31° 36'	274	1911 - 1990	1960 - 1975	1960 - 1975	3890
Lydenburg Vis	97	25° 06'	30° 28'	1412	1960 - 1986	1962 - 1976	1962 - 1976	3738
NORTHERN NATAL / TRANSVAAL BORDER								
Pongola Expt Stn	98	27° 24'	31° 35'	308	1967 - 1990	1967 - 1988	1967 - 1988	7798
Mtubatuba Mill	99	28° 26'	32° 11'	46	1951 - 1990	1967 - 1988	1967 - 1988	8086
Empangeni (Mill)	100	28° 45'	31° 54'	74	1924 - 1984	1967 - 1983	1967 - 1983	4987
Mkuze Estates	101	27° 38'	32° 03'	120	1958 - 1989	1969 - 1980	1969 - 1980	2488
Mkuze Game Reserve	102	27° 36'	32° 13'	152	1950 - 1989	1979 - 1989	1979 - 1989	2523
Makatini	103	27° 24'	32° 10'	59	1966 - 1989	1969 - 1988	1969 - 1988	7102
Bokel, Bloodriver	104	27° 51'	30° 32'	1200	1960 - 1989	1979 - 1989	1979 - 1989	4130
Piet Retief Mun	105	27° 00'	30° 48'	1250	1959 - 1977	1959 - 1976	1959 - 1976	7250
Athole Proefplaas	106	26° 36'	30° 35'	1324	1936 - 1989	1974 - 1989	1974 - 1989	4372

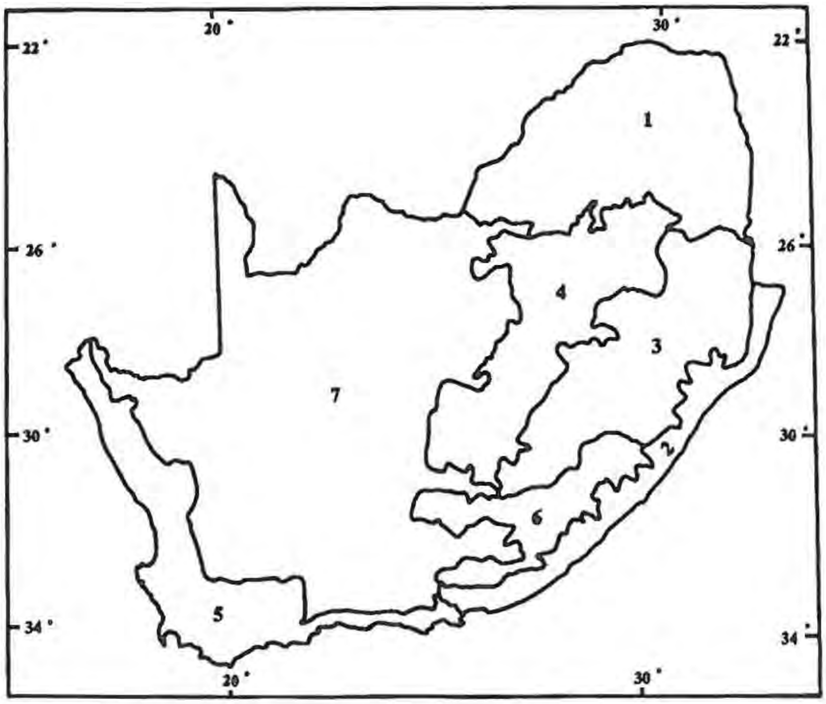
Bundu-Hluhluwe	107	$28^0 08'$	$32^0 17'$	45	1958 - 1989	1966 - 1989	1966 - 1989	8378
Kangela, Mtubatuba	108	$28^0 24'$	$32^0 12'$	60	1914 - 1989	1979 - 1989	1979 - 1989	2643
Big Bend (Wissel Rode)	109	$26^0 51'$	$31^0 55'$	100	1922 - 1989	1968 - 1988	1968 - 1988	8123
Dundee Agric Res	110	$28^0 10'$	$30^0 19'$	1259	1931 - 1989	1967 - 1989	1967 - 1989	7768
Seven Oaks	111	$29^0 14'$	$30^0 36'$	1057	1966 - 1990	1966 - 1988	1966 - 1988	8421
NORTHERN CAPE								
Vryburg;Armoedsvlakt	112	$26^0 57'$	$24^0 38'$	1240	1920 - 1989	1959 - 1989	1959 - 1989	10822
Douglas Jail	113	$29^0 04'$	$23^0 45'$	984	1976 - 1989	1976 - 1989	1976 - 1989	4585
Taung	114	$27^0 33'$	$24^0 44'$	1113	1898 - 1990	1979 - 1989	1979 - 1989	3077
Kimberley	115	$28^0 48'$	$24^0 46'$	1196	1932 - 1972	1957 - 1976	1957 - 1972	5579
Barkly Wes Ko-op	116	$28^0 30'$	$24^0 30'$	1127	1950 - 1989	1976 - 1989	1976 - 1989	4436
Jan Kempdorp;Vaalhar	117	$27^0 57'$	$24^0 50'$	1143	1938 - 1989	1958 - 1989	1958 - 1989	11275

APPENDIX B

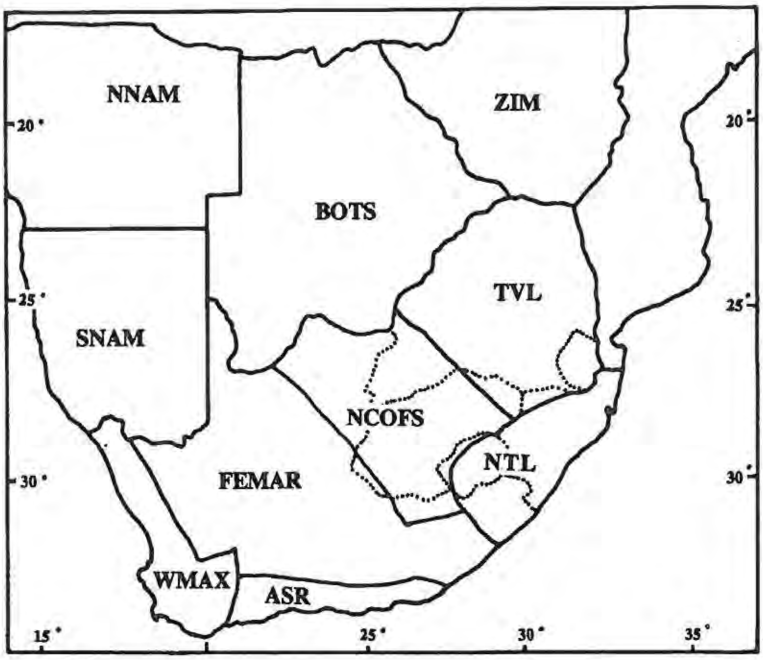
APPENDIX B : REGIONALIZED EVAPORATION, WIND AND VEGETATION MAPS FOR SOUTHERN AFRICA.



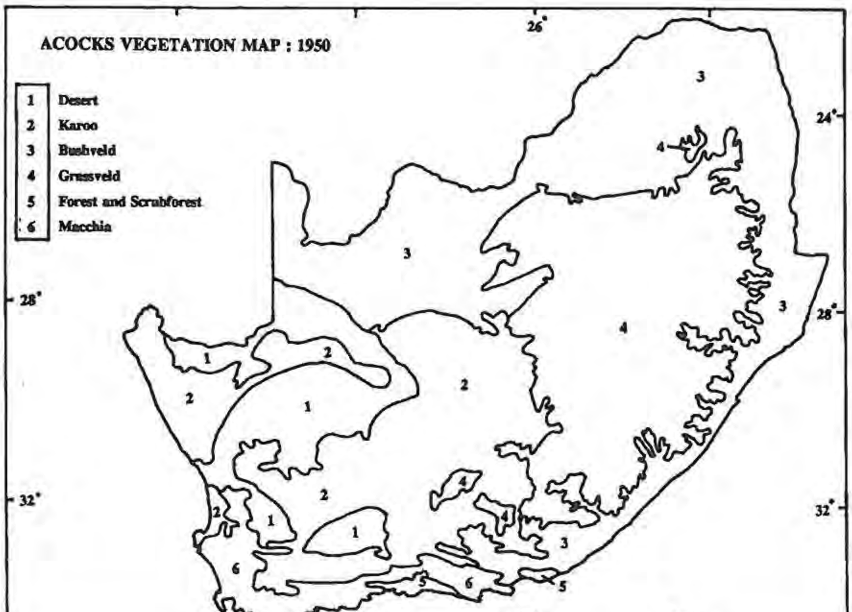
Evaporation regions over southern Africa (After, Clemence, 1986).



Delimitation of major wind regions in southern Africa (After, Dent, Schulze and Angus, 1988).



Delimitation of rainfall regions in southern Africa (After, Taljaard and Steyn, 1991).



Regional vegetation map of southern Africa (Acocks, 1975).

APPENDIX C

APPENDIX C1 : SOUTH-WESTERN CAPE - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Elgin	6.51	6.67	5.84	4.58	3.00	2.01	1.74	1.85	2.13	3.05	4.33	6.51
Chiltern Damwall	7.13	7.80	7.12	5.47	3.54	2.41	2.10	2.06	2.69	3.52	5.10	6.41
Longdown	7.94	8.45	7.71	5.91	3.94	2.73	2.34	2.24	2.70	3.61	5.00	6.76
Dwaalhoek	8.17	8.46	7.54	5.88	3.91	2.38	1.72	1.75	2.20	3.18	4.96	6.83
Boontjieskraal	8.62	9.02	7.79	6.01	3.83	2.32	1.63	1.59	2.14	3.23	5.12	6.95
Riviersonderend	8.62	9.04	7.66	5.90	4.14	2.75	2.26	2.27	2.73	3.84	5.73	7.25
Average for sub-division A	**7.83**	**8.24**	**7.28**	**5.63**	**3.73**	**2.43**	**1.97**	**1.96**	**2.43**	**3.41**	**5.04**	**6.79**
Riversdale	7.15	7.21	6.11	4.83	3.41	2.52	2.14	2.17	2.45	3.47	4.69	5.90
Langkloof	7.34	7.29	6.47	5.27	3.69	2.87	2.68	2.92	3.14	3.67	4.92	6.01
Robertson	8.28	8.38	7.25	5.63	3.74	2.42	1.81	2.04	2.71	3.95	5.69	7.15
Gydo	8.66	9.09	8.51	6.49	4.55	2.89	2.32	2.47	2.29	3.87	5.61	7.59
Karringsmelkrivier	9.03	9.05	7.84	5.98	4.45	3.34	3.14	3.00	3.08	3.88	5.62	7.45
Prospect	8.99	9.29	8.05	6.11	4.05	2.53	1.98	2.15	2.82	4.16	6.28	7.71
Weltevrede	8.93	9.37	8.34	6.25	4.13	2.79	1.85	2.11	2.81	4.11	5.81	7.89
Roodeheuwel (wrs)	9.01	9.42	8.41	6.78	4.47	2.73	2.25	2.44	3.09	4.24	6.21	7.92
Porterville - mun	9.64	10.05	9.48	7.06	4.47	2.49	1.89	1.87	2.51	3.98	5.98	8.36
Langgewens (wrs)	9.99	10.31	10.34	7.93	5.71	3.47	2.52	2.30	2.74	4.00	6.44	9.05
De Doorns (niww)	10.04	10.31	9.17	7.03	4.67	3.01	2.50	2.72	3.47	5.17	7.12	8.90
Montague Police	9.30	9.69	8.77	6.42	4.34	2.85	2.05	2.18	2.90	4.36	6.40	7.94
Eendrag	9.58	9.92	8.87	6.94	4.59	2.71	2.12	2.07	2.88	4.21	6.55	8.27
Aan-de-Doorns	10.18	10.44	9.29	7.10	4.75	3.03	2.28	2.29	3.04	4.59	6.87	8.74
Riebeek-wes	10.72	11.03	10.51	8.07	5.31	3.02	2.17	2.05	2.89	4.45	6.80	9.19
Moreesburg	11.27	11.51	10.69	8.33	5.57	3.26	2.29	2.11	2.85	4.31	6.88	9.91
Average for sub-division B	**9.26**	**9.52**	**8.63**	**6.64**	**4.49**	**2.87**	**2.25**	**2.31**	**2.85**	**4.15**	**6.12**	**8.00**
Regional Average	**8.87**	**9.17**	**8.26**	**6.36**	**4.28**	**2.75**	**2.17**	**2.21**	**2.77**	**3.95**	**5.82**	**7.63**

APPENDIX C2 : EASTERN CAPE COASTAL - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Addo Sitrus NS	7.09	7.24	6.16	4.77	3.57	2.61	2.09	2.23	2.94	3.72	4.90	6.21
Patensie	6.81	6.85	6.07	4.84	3.59	2.87	2.45	2.66	3.11	3.76	4.93	5.87
Average for sub-division A	**6.95**	**7.05**	**6.12**	**4.81**	**3.58**	**2.74**	**2.27**	**2.45**	**3.03**	**3.74**	**4.92**	**6.04**
Bathurst NS	6.31	6.27	5.81	4.82	4.16	4.04	3.66	3.75	3.97	4.34	4.88	5.67
Oos-londen	7.26	6.98	6.58	5.85	4.88	4.39	4.27	4.03	4.44	5.16	5.85	6.44
Oos-London W/K	6.61	6.66	6.13	4.88	4.05	3.32	3.11	3.24	3.85	4.34	5.24	5.90
Port Elizabeth W/K	7.99	7.82	6.81	5.48	4.11	3.08	2.56	2.67	3.37	4.19	5.52	6.79
Average for sub-division B	**7.04**	**6.93**	**6.33**	**5.26**	**4.30**	**3.71**	**3.40**	**3.42**	**3.91**	**4.51**	**5.37**	**6.20**
Regional average	**7.01**	**6.97**	**6.26**	**5.11**	**4.06**	**3.39**	**3.02**	**3.10**	**3.61**	**4.25**	**5.22**	**6.15**

APPENDIX C3 : EASTERN CAPE INLAND - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Queenstown	8.11	7.96	6.81	5.60	4.61	4.34	3.73	4.17	5.13	5.77	6.10	7.03
Welverdiend An	8.71	9.03	6.98	5.52	3.87	3.01	2.17	2.42	3.58	4.76	6.06	7.46
Grootfontein 11	9.94	9.83	8.12	6.35	4.71	3.90	3.26	3.85	5.09	6.69	7.84	9.07
Average for sub-division A	**8.92**	**8.94**	**7.30**	**5.82**	**4.40**	**3.75**	**3.05**	**3.48**	**4.60**	**5.74**	**6.67**	**7.85**
Emerald Dale, Donnyb	4.92	4.75	4.57	3.99	3.62	3.06	2.83	3.27	4.12	4.41	4.34	4.48
Cobham, Himeville	6.02	5.31	5.16	4.36	3.85	3.72	3.19	3.69	4.40	4.84	5.08	5.50
Umtata	5.35	5.44	4.98	4.27	3.37	2.48	2.12	2.36	3.21	3.99	4.47	4.83
Sheeprun	5.97	5.77	4.97	4.32	3.04	2.43	2.10	2.59	3.68	4.44	4.88	5.52
Kokstad Agr Res Stn	6.51	6.03	5.73	4.57	4.00	3.35	2.94	3.32	4.33	4.93	5.61	6.18
Average for sub-division B	**5.75**	**5.46**	**5.08**	**4.30**	**3.58**	**3.01**	**2.64**	**3.05**	**3.95**	**4.52**	**4.88**	**5.30**
Regional Average	**6.94**	**6.77**	**5.92**	**4.87**	**3.88**	**3.29**	**2.79**	**3.21**	**4.19**	**4.98**	**5.55**	**6.26**

APPENDIX C4 : NATAL COASTAL - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Double Diamond, Cato	4.84	4.84	4.64	4.31	3.32	2.44	2.03	2.22	3.07	3.73	4.03	4.22
Powerscourt	5.27	5.07	5.02	4.48	3.89	3.40	3.21	3.45	4.03	4.39	4.84	4.83
Cedara Agr Res	5.36	5.15	4.92	4.51	3.57	3.08	2.76	3.13	4.07	4.61	4.84	4.81
Ukulinga Agr Res	5.64	5.18	5.28	4.89	4.36	4.06	3.87	4.12	4.69	5.07	5.18	5.11
Umzimkulu Mill	5.36	5.24	5.21	4.45	3.84	3.15	2.95	3.02	3.48	3.92	4.54	5.11
Sezela, Sugar Mill	5.47	5.26	5.15	4.67	4.01	3.36	3.01	3.11	3.75	4.09	4.72	5.14
Esperanza	5.41	5.36	5.13	4.68	3.92	3.23	2.81	2.88	3.56	3.93	4.58	4.98
Chakas Kraal Auto	5.94	5.80	5.66	4.83	3.72	2.85	2.57	2.61	3.33	4.10	4.87	5.32
Windy Hill	6.20	5.87	5.49	4.90	4.03	3.51	3.36	3.71	4.49	5.06	5.46	5.48
Experiment Station	5.99	5.91	5.71	4.90	3.87	3.06	2.66	2.78	3.32	3.99	4.72	5.25
Tongaat	5.95	6.06	5.94	5.24	4.09	3.22	2.68	2.86	3.56	4.23	5.03	5.39
Doornkop	6.10	6.09	5.76	5.25	4.33	3.85	3.77	4.00	4.68	4.94	5.71	5.88
Illovo Mill	5.96	6.14	5.80	5.40	4.48	3.73	3.37	3.37	3.80	4.35	5.06	5.32
Sezela	6.35	6.15	6.14	5.40	4.45	3.84	3.67	3.85	4.43	4.56	5.27	6.18
Glendale	6.41	6.30	6.15	5.46	4.36	3.63	3.05	3.35	4.11	4.67	5.37	5.64
Darnall	6.51	6.41	6.26	5.47	4.24	3.48	3.07	3.28	3.97	4.51	5.49	5.79
Amatikulu Sugar Mill	6.60	6.54	6.38	5.65	4.55	3.59	3.08	3.33	4.13	4.84	5.67	5.86
Amatikulu Mill	6.84	6.85	6.54	5.79	4.69	3.60	3.17	3.44	4.37	4.96	5.78	6.11
Glendhow Mill	6.85	6.85	6.49	5.59	4.57	3.51	3.12	3.29	4.03	4.98	5.83	6.22
Mtunzini (prop farm)	7.32	7.27	6.85	6.41	5.06	4.01	3.37	3.54	4.45	5.40	6.19	6.63
Regional Average	**5.46**	**5.92**	**5.73**	**5.12**	**4.17**	**3.43**	**3.08**	**3.27**	**4.00**	**4.52**	**5.16**	**5.46**

APPENDIX C5 : NATAL INLAND - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Baynesfield estates	4.84	4.47	4.73	4.44	3.79	3.09	2.85	3.18	3.90	4.06	4.21	4.60
Stoke, Mid-Illovo	4.63	4.62	4.46	4.02	3.26	2.49	2.25	2.46	3.16	3.83	4.11	4.43
Melmoth (Golden Reef)	4.87	4.82	4.80	4.79	4.16	3.42	3.03	3.60	4.16	4.38	4.86	5.15
Cedara Agr Res	5.36	5.15	4.92	4.51	3.57	3.08	2.76	3.13	4.07	4.61	4.84	4.81
Seven Oaks - Ryhill	5.95	5.45	5.37	4.83	4.09	3.83	3.55	4.06	4.87	5.22	5.59	5.50
Entumeni Mill	5.61	5.51	5.32	4.74	3.90	3.29	2.90	3.18	3.79	4.44	4.93	5.03
Union Mill, Seven OA	5.92	5.56	5.61	4.92	4.32	3.77	3.41	3.89	4.65	5.42	5.38	5.47
Crammond	6.05	5.63	5.43	4.66	4.26	3.73	3.07	3.45	4.47	5.06	5.04	5.41
Sun Valley, Weenen	7.73	7.27	7.22	6.19	4.81	3.70	2.87	3.37	4.57	5.94	6.53	7.07
Regional Average	**5.66**	**5.39**	**5.32**	**4.79**	**4.02**	**3.38**	**2.96**	**3.37**	**4.18**	**4.77**	**5.05**	**5.27**

APPENDIX C6 : ORANGE FREE STATE - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Cathedral Peak	5.71	5.16	4.74	4.28	3.98	3.56	3.20	3.80	4.78	5.96	5.46	5.12
Meshlynn, Kamberg	5.45	5.39	5.02	4.46	3.88	3.33	2.84	3.26	4.17	4.49	5.09	5.03
Kestell-Pol	6.53	6.24	5.84	4.81	3.71	3.42	3.10	3.37	4.59	5.58	6.21	6.42
Average for sub-division A	**5.90**	**5.60**	**5.20**	**4.52**	**3.86**	**3.44**	**3.05**	**3.48**	**4.51**	**5.34**	**5.59**	**5.52**
Loch Lomon, Bethlehem	7.58	7.22	6.63	5.54	4.19	3.41	2.81	3.05	4.35	5.81	6.66	6.96
Rietpan, Viljoenskroon	7.77	7.79	6.87	5.83	4.48	3.52	3.49	3.57	4.81	5.87	5.89	6.42
Sandvet;Welkom	8.92	8.50	7.29	5.84	5.05	3.94	3.00	3.42	5.02	6.56	7.86	8.92
12C5E02 Kalkfontein	8.54	8.54	7.18	5.46	3.86	2.65	2.01	2.16	3.30	4.99	6.54	7.78
Wepener	9.02	9.13	7.49	6.05	4.04	3.23	2.92	3.00	3.80	6.08	6.83	7.86
Arbeidskroon, Bultfontein	9.11	9.15	7.61	5.91	4.88	3.91	2.86	3.22	4.77	6.82	8.15	8.85
Glen Agr Coll, Bfn	9.85	9.48	7.50	5.96	4.23	3.25	2.62	3.08	4.61	6.98	8.15	9.05
Katdoornput	10.91	10.94	8.99	7.04	5.25	3.86	2.78	3.15	4.81	6.91	8.67	10.38
Fauresmith	11.60	11.48	10.04	7.48	5.12	3.49	2.70	3.11	4.79	7.73	9.18	10.41
Average for sub-division B	**9.26**	**9.14**	**7.73**	**6.12**	**4.56**	**3.47**	**2.80**	**3.08**	**4.47**	**6.42**	**7.55**	**8.51**
Regional Average	**8.42**	**8.25**	**7.10**	**5.72**	**4.39**	**3.46**	**2.86**	**3.18**	**4.48**	**6.15**	**7.06**	**7.77**

APPENDIX C7 : TRANSVAAL - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Levubu	5.85	5.94	5.53	4.95	4.18	3.88	3.58	3.88	4.75	5.90	5.89	6.03
Letaba	5.74	6.07	5.68	5.22	4.50	3.80	3.38	3.49	4.18	4.91	5.24	5.54
Average for sub-division A	**5.80**	**6.01**	**5.61**	**5.09**	**4.34**	**3.84**	**3.48**	**3.69**	**4.47**	**5.41**	**5.57**	**5.79**
Vaalwater	6.92	6.90	6.56	5.58	4.39	3.99	3.48	3.92	5.28	6.92	7.52	7.45
Rustenburg Agr	7.46	7.08	6.24	5.62	4.30	3.67	3.07	3.58	4.97	6.53	7.47	7.31
Kooster Kooperasie	8.28	7.38	6.97	5.94	5.05	4.60	3.84	3.98	5.56	7.02	8.31	9.00
Delmas Sensako	7.52	7.42	6.82	6.28	5.67	5.48	4.61	4.96	6.42	7.71	7.99	8.11
Buffelspoort	7.34	7.53	6.62	5.92	5.17	4.45	3.69	4.29	5.42	6.55	7.59	8.04
Lichtenburg, Sensako	8.86	7.97	6.90	6.11	5.17	4.55	3.74	4.30	5.90	7.59	8.70	9.12
Pietersburg	8.17	8.25	7.51	6.79	5.43	4.72	4.17	4.46	5.90	8.05	9.10	8.44
Marnitz	8.33	8.63	7.36	6.85	5.52	4.47	3.91	4.61	6.36	8.45	9.85	9.47
Messina Agr Res	9.40	9.46	8.71	7.89	6.25	5.10	4.35	4.73	6.25	8.17	9.23	9.18
Average for subdivision B	**8.03**	**7.85**	**7.08**	**6.33**	**5.22**	**4.56**	**3.87**	**4.31**	**5.78**	**7.44**	**8.42**	**8.46**
Regional Average	**7.62**	**7.51**	**6.81**	**6.10**	**5.06**	**4.43**	**3.80**	**4.20**	**5.54**	**7.07**	**7.90**	**7.97**

APPENDIX C8 : EASTERN TRANSVAAL - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Malelane	5.67	5.78	5.63	4.92	4.10	3.44	2.86	3.05	3.79	4.55	5.01	5.17
Lydenburg Vis	6.14	6.02	5.72	5.16	4.11	3.44	2.90	3.39	4.43	5.99	6.10	5.69
Nelspruit Res	5.98	6.32	6.01	5.24	4.24	3.70	3.21	3.57	4.44	5.58	5.67	5.41
Kaalrug (1)	6.22	5.85	5.86	5.02	4.47	3.68	3.23	3.56	4.17	5.09	5.98	6.50
Kaalrug (2)	6.24	5.79	5.95	5.34	4.52	3.72	3.31	3.72	4.28	5.25	6.09	6.53
Mhlume 428	6.82	6.30	5.99	5.33	4.33	3.21	2.89	3.31	4.09	4.96	6.03	6.59
Nelspruit Freidenheim	6.80	6.74	6.37	5.79	4.83	3.89	3.58	4.00	4.68	5.69	6.98	6.91
Komatipoort Tenbosch	6.85	6.44	5.78	5.53	4.44	3.41	3.03	3.43	4.58	5.46	6.21	6.93
Skukuza	6.60	5.93	6.54	6.01	4.52	3.36	3.09	3.81	4.71	6.05	6.61	7.12
Regional Average	**6.37**	**6.13**	**5.98**	**5.317**	**4.340**	**3.54**	**3.12**	**3.54**	**4.35**	**5.40**	**6.08**	**6.32**

APPENDIX C9 : NORTHERN NATAL/TRANSVAAL BORDER - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Piet Retief Mun	4.52	4.62	4.36	3.54	2.88	2.27	2.00	2.19	2.79	3.66	3.89	4.67
Kangela, Mtubatuba	5.62	5.45	4.98	4.38	3.55	2.60	1.99	2.40	3.12	3.54	4.36	4.78
Seven Oaks	5.97	5.70	5.36	4.96	4.23	3.77	3.54	4.03	4.84	5.28	5.55	5.56
Mkuze Game Reserve	6.35	6.17	5.87	4.98	4.14	3.18	2.80	3.01	3.91	4.44	5.22	5.58
Bokel, Bloodriver	6.40	6.25	5.70	4.97	4.11	3.59	3.17	3.40	4.28	5.05	5.56	5.83
Athole Proefplaas	6.59	6.31	5.72	5.33	4.63	4.67	4.38	4.83	5.78	6.57	6.49	6.70
Bundu - Hluhluwe	6.89	6.78	6.28	5.58	4.40	3.71	3.11	3.29	3.96	4.71	5.41	5.75
Dundee Agric Res Sta	7.24	6.86	6.41	5.50	4.46	4.04	3.46	3.80	5.26	6.30	6.71	7.01
Mtubatuba Mill	6.88	6.89	6.53	5.85	4.63	3.59	3.12	3.35	4.16	4.81	5.55	5.96
Pongola Expt Stn	6.81	6.90	6.53	5.56	4.37	3.63	3.10	3.34	4.34	5.19	5.89	6.17
Empangeni Mill	6.98	7.00	6.97	6.46	5.29	4.14	3.59	3.74	4.51	5.30	6.03	6.24
Mkuze estates	7.22	7.22	6.86	5.74	4.92	3.87	3.63	3.77	4.85	5.82	6.25	6.36
Big Bend (Wissel Rode)	7.43	7.62	7.16	6.20	4.83	3.75	3.19	3.54	4.77	6.00	6.61	6.87
Makatini	7.44	7.68	7.07	6.20	5.08	4.08	3.58	3.91	5.02	5.89	6.41	6.79
Regional Average	**6.60**	**6.53**	**6.13**	**5.37**	**4.39**	**3.63**	**3.19**	**3.47**	**4.40**	**5.18**	**5.71**	**6.02**

APPENDIX C10 : NORTHERN CAPE - DAILY MEAN EVAPORATION (mm)

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Jan Kempdorp;Vaalhar	9.23	8.72	7.45	5.89	4.52	3.77	3.10	3.55	4.84	6.64	7.91	8.93
Vryburg;Armoedsvlakt	9.81	9.08	7.49	6.25	4.93	4.06	3.57	3.87	5.42	7.65	9.06	9.56
Douglas Jail	10.99	10.99	8.93	6.88	4.98	3.94	3.26	3.59	4.58	6.60	8.37	9.93
Taung	11.11	11.37	8.98	7.28	6.13	5.04	3.86	4.23	5.77	7.44	8.78	10.62
Barkly Wes ko-op	10.87	11.45	9.15	7.45	5.38	4.25	3.16	3.50	4.89	6.96	8.68	10.68
Kimberley	12.50	11.50	9.98	7.81	5.71	4.11	3.42	4.03	5.87	8.65	10.42	11.59
Regional Average	**10.75**	**10.52**	**8.66**	**6.93**	**5.27**	**4.19**	**3.39**	**3.79**	**5.23**	**7.32**	**8.87**	**10.22**

APPENDIX D

APPENDIX D1 : SOUTH-WESTERN CAPE - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Elgin	1.74	2.46	2.07	1.10	0.53	0.18	0.05	0.01	0.09	0.13	0.50	0.08
Chiltern Damwall	0.49	0.19	0.03	0.03	0.04	0.00	0.02	0.01	0.07	0.01	0.00	0.14
Longdown	0.01	0.04	0.18	0.08	0.04	0.09	0.14	0.08	0.07	0.04	0.00	0.00
Dwaalhoek	0.12	0.05	0.07	0.06	0.03	0.00	0.06	0.04	0.05	0.05	0.01	0.00
Boontjieskraal	0.62	0.61	0.26	0.14	0.01	0.01	0.12	0.14	0.08	0.03	0.01	0.03
Riviersonderend	0.62	0.64	0.14	0.07	0.17	0.10	0.08	0.10	0.09	0.18	0.48	0.21
Variance for sub-division A	**0.72**	**0.80**	**0.55**	**0.30**	**0.16**	**0.08**	**0.09**	**0.07**	**0.09**	**0.09**	**0.20**	**0.09**
Riversdale	4.45	5.34	6.35	3.28	1.17	0.12	0.01	0.02	0.16	0.46	2.04	4.41
Langkloof	3.69	4.97	4.67	1.88	0.64	0.00	0.18	0.37	0.08	0.23	1.44	3.96
Robertson	0.96	1.30	1.90	1.02	0.56	0.20	0.19	0.07	0.02	0.04	0.18	0.72
Gydo	0.36	0.18	0.01	0.02	0.00	0.00	0.00	0.03	0.31	0.08	0.26	0.17
Karringsmelkrivier	0.05	0.22	0.62	0.44	0.00	0.22	0.79	0.48	0.05	0.07	0.25	0.30
Prospect	0.07	0.05	0.34	0.28	0.19	0.12	0.07	0.03	0.00	0.00	0.26	0.08
Weltevrede	0.11	0.02	0.08	0.15	0.13	0.01	0.16	0.04	0.00	0.00	0.10	0.01
Roodeheuwel (wrs)	0.06	0.01	0.05	0.02	0.00	0.02	0.00	0.02	0.06	0.01	0.01	0.01
Porterville - mun	0.14	0.28	0.72	0.18	0.00	0.14	0.13	0.19	0.12	0.03	0.02	0.13
Langgewens (wrs)	0.53	0.62	2.92	1.66	1.49	0.36	0.07	0.00	0.01	0.02	0.10	1.10
De Doorns (niww)	0.61	0.62	0.29	0.15	0.03	0.02	0.06	0.17	0.38	1.04	1.00	0.81
Montague Police	0.00	0.03	0.02	0.05	0.02	0.00	0.04	0.02	0.00	0.04	0.08	0.00
Eendrag	0.10	0.16	0.06	0.09	0.01	0.03	0.02	0.06	0.00	0.00	0.18	0.07
Aan-de-Doorns	0.84	0.85	0.43	0.21	0.07	0.03	0.00	0.00	0.04	0.19	0.56	0.55
Riebeek-wes	2.13	2.28	3.53	2.04	0.68	0.03	0.01	0.07	0.00	0.09	0.46	1.42
Moreeesburg	4.04	3.96	4.24	2.86	1.17	0.15	0.00	0.04	0.00	0.03	0.58	3.65
Variance for sub-division B	**1.21**	**1.39**	**1.75**	**0.96**	**0.41**	**0.10**	**0.12**	**0.11**	**0.08**	**0.16**	**0.49**	**1.16**

APPENDIX D2 : EASTERN CAPE COASTAL - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Addo Sitrus NS	0.02	0.04	0.00	0.00	0.00	0.02	0.03	0.05	0.01	0.00	0.00	0.03
Patensie	0.02	0.04	0.00	0.00	0.00	0.02	0.03	0.04	0.01	0.00	0.00	0.03
Variance for sub-division A	**0.04**	**0.08**	**0.00**	**0.00**	**0.00**	**0.03**	**0.06**	**0.09**	**0.01**	**0.00**	**0.00**	**0.06**
Bathurst NS	0.53	0.44	0.27	0.19	0.02	0.11	0.07	0.11	0.00	0.03	0.24	0.28
Oos-Londen	0.05	0.00	0.06	0.35	0.34	0.46	0.76	0.37	0.28	0.42	0.23	0.06
Oos-London W/K	0.18	0.07	0.04	0.14	0.06	0.15	0.08	0.03	0.00	0.03	0.02	0.09
Port Elizabeth W/K	0.90	0.79	0.23	0.05	0.04	0.40	0.71	0.56	0.29	0.10	0.02	0.35
Variance for sub-division B	**0.56**	**0.43**	**0.20**	**0.24**	**0.15**	**0.37**	**0.54**	**0.36**	**0.19**	**0.19**	**0.17**	**0.26**

APPENDIX D3 : EASTERN CAPE INLAND - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Queenstown	0.66	0.96	0.24	0.05	0.04	0.35	0.46	0.48	0.28	0.00	0.32	0.67
Welverdiend An	0.04	0.01	0.10	0.09	0.28	0.55	0.77	1.12	1.04	0.96	0.37	0.15
Grootfontein 11	1.04	0.79	0.67	0.28	0.10	0.02	0.04	0.14	0.24	0.90	1.37	1.49
Variance for sub-division A	**0.87**	**0.88**	**0.51**	**0.21**	**0.21**	**0.46**	**0.64**	**0.87**	**0.78**	**0.93**	**1.03**	**1.16**
Emerald Dale, Donnyb	0.69	0.50	0.26	0.10	0.00	0.00	0.04	0.05	0.03	0.01	0.29	0.67
Cobham, Himeville	0.07	0.02	0.01	0.00	0.07	0.50	0.30	0.41	0.20	0.10	0.04	0.04
Umtata	0.16	0.00	0.01	0.00	0.04	0.28	0.27	0.48	0.55	0.28	0.17	0.22
Sheeprun	0.05	0.10	0.01	0.00	0.29	0.34	0.29	0.21	0.07	0.01	0.00	0.05
Kokstad Agr Res Stn	0.58	0.32	0.42	0.07	0.18	0.12	0.09	0.07	0.14	0.17	0.53	0.77
Variance for sub-division B	**0.39**	**0.24**	**0.18**	**0.04**	**0.15**	**0.31**	**0.25**	**0.30**	**0.25**	**0.14**	**0.26**	**0.44**

APPENDIX D4 : NATAL COASTAL - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Double Diamond, Cato	0.38	1.17	1.19	0.66	0.72	0.98	1.10	1.10	0.86	0.62	1.28	1.54
Powerscourt	0.04	0.72	0.50	0.41	0.08	0.00	0.02	0.03	0.00	0.02	0.10	0.40
Cedara Agr Res	0.01	0.59	0.66	0.37	0.36	0.12	0.10	0.02	0.00	0.01	0.10	0.42
Ukulinga Agr Res	0.03	0.55	0.20	0.05	0.04	0.40	0.62	0.72	0.48	0.30	0.00	0.12
Umzimkulu Mill	0.01	0.46	0.27	0.45	0.11	0.08	0.02	0.06	0.27	0.36	0.38	0.12
Sezela, Sugar Mill	0.00	0.43	0.34	0.20	0.03	0.00	0.00	0.03	0.06	0.18	0.19	0.10
Esperanza	0.00	0.31	0.36	0.19	0.06	0.04	0.07	0.15	0.19	0.35	0.34	0.23
Chakas Kraal Auto	0.23	0.01	0.00	0.08	0.20	0.34	0.26	0.44	0.45	0.18	0.08	0.02
Windy Hill	0.55	0.00	0.06	0.05	0.02	0.01	0.08	0.19	0.24	0.29	0.09	0.00
Experiment Station	0.28	0.00	0.00	0.05	0.09	0.14	0.18	0.24	0.46	0.28	0.19	0.04
Tongaat	0.24	0.02	0.04	0.01	0.01	0.04	0.16	0.17	0.19	0.08	0.02	0.00
Doornkop	0.41	0.03	0.00	0.02	0.03	0.18	0.48	0.53	0.46	0.18	0.30	0.18
Illovo Mill	0.25	0.05	0.00	0.08	0.10	0.09	0.08	0.01	0.04	0.03	0.01	0.02
Sezela	0.79	0.05	0.17	0.08	0.08	0.17	0.35	0.34	0.18	0.00	0.01	0.52
Glendale	0.90	0.14	0.18	0.12	0.04	0.04	0.00	0.01	0.01	0.02	0.04	0.03
Darnall	1.10	0.24	0.28	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.11
Amatikulu Sugar Mill	1.30	0.38	0.42	0.28	0.14	0.03	0.00	0.00	0.02	0.10	0.26	0.16
Amatikulu Mill	1.90	0.86	0.66	0.45	0.27	0.03	0.01	0.03	0.14	0.19	0.38	0.42
Glendhow Mill	1.93	0.86	0.58	0.22	0.16	0.01	0.00	0.00	0.00	0.21	0.45	0.58
Mtunzini (prop farm)	3.46	1.82	1.25	1.66	0.79	0.34	0.08	0.07	0.20	0.77	1.06	1.37
Variance for region	**0.73**	**0.46**	**0.38**	**0.29**	**0.18**	**0.16**	**0.19**	**0.22**	**0.23**	**0.22**	**0.28**	**0.34**

APPENDIX D5 : NATAL INLAND - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Baynesfield estates	0.67	0.85	0.35	0.12	0.05	0.08	0.01	0.04	0.08	0.50	0.71	0.45
Stoke, Mid-Illovo	1.06	0.59	0.74	0.59	0.58	0.79	0.50	0.83	1.04	0.88	0.88	0.71
Melmoth (Golden Reef)	0.62	0.32	0.27	0.00	0.02	0.00	0.00	0.05	0.00	0.15	0.04	0.01
Cedara Agr Res	0.09	0.06	0.16	0.08	0.20	0.09	0.04	0.06	0.01	0.03	0.04	0.21
Seven Oaks -Ryhill	0.08	0.00	0.00	0.00	0.00	0.20	0.35	0.48	0.48	0.20	0.29	0.05
Entumeni Mill	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.04	0.15	0.11	0.01	0.06
Union Mill, Seven OA	0.07	0.03	0.08	0.02	0.09	0.15	0.20	0.27	0.22	0.42	0.11	0.04
Crammond	0.15	0.06	0.01	0.02	0.06	0.12	0.01	0.01	0.08	0.08	0.00	0.02
Sun Valley, Weenen	4.28	3.53	3.61	1.96	0.62	0.10	0.01	0.00	0.15	1.37	2.19	3.24
Variance value for region	**0.88**	**0.68**	**0.65**	**0.35**	**0.21**	**0.19**	**0.14**	**0.22**	**0.28**	**0.47**	**0.53**	**0.60**

APPENDIX D6 : ORANGE FREE STATE - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Cathedral Peak	0.04	0.19	0.21	0.06	0.01	0.01	0.02	0.10	0.07	0.38	0.02	0.16
Meshlynn, Kamberg	0.20	0.04	0.03	0.00	0.00	0.01	0.04	0.05	0.12	0.72	0.25	0.24
Kestell-Pol	0.40	0.41	0.41	0.08	0.02	0.00	0.00	0.01	0.01	0.06	0.38	0.81
Variance for sub-division A	0.32	0.32	0.33	0.07	0.02	0.01	0.03	0.08	0.10	0.58	0.33	0.61
Loch Lomon, Bethlehem	2.82	3.69	1.21	0.34	0.14	0.00	0.00	0.00	0.01	0.37	0.79	2.40
Rietpan, Viljoenskroon	2.22	1.82	0.74	0.08	0.01	0.00	0.48	0.24	0.12	0.30	2.76	4.37
Sandvet;Welkom	0.12	0.41	0.19	0.08	0.24	0.22	0.04	0.12	0.30	0.02	0.10	0.17
12C5EO2 Kalkfontein	0.52	0.36	0.30	0.44	0.49	0.67	0.62	0.85	1.37	2.04	1.02	0.53
Wepener	0.06	0.00	0.06	0.00	0.27	0.06	0.01	0.01	0.45	0.12	0.52	0.42
Arbeidskroon, Bultfontein	0.02	0.00	0.01	0.04	0.10	0.19	0.00	0.02	0.09	0.16	0.36	0.12
Glen Agr Coll, Bfn	0.35	0.12	0.05	0.03	0.11	0.05	0.03	0.00	0.02	0.31	0.36	0.29
Katdoornput	2.72	3.24	1.59	0.85	0.48	0.15	0.00	0.00	0.12	0.24	1.25	3.50
Fauresmith	5.48	5.48	5.34	1.85	0.32	0.00	0.01	0.00	0.10	1.72	2.66	3.61
Variance for sub-division B	**1.79**	**1.89**	**1.19**	**0.46**	**0.27**	**0.17**	**0.15**	**0.15**	**0.32**	**0.66**	**1.23**	**1.93**

APPENDIX D7 : TRANSVAAL - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Levubu	0.00	0.00	0.01	0.02	0.03	0.00	0.01	0.04	0.08	0.24	0.10	0.06
Letaba	0.00	0.00	0.00	0.02	0.03	0.00	0.01	0.04	0.08	0.25	0.11	0.06
Variance for sub-division A	**0.00**	**0.01**	**0.01**	**0.04**	**0.05**	**0.00**	**0.02**	**0.08**	**0.16**	**0.49**	**0.21**	**0.12**
Vaalwater	1.23	0.90	0.27	0.27	0.69	0.32	0.15	0.15	0.25	0.27	0.81	1.02
Rustenburg Agr	0.32	0.59	0.71	0.23	0.85	0.79	0.64	0.53	0.66	0.83	0.90	1.32
Kooster Kooperasie	0.06	0.22	0.01	0.03	0.03	0.00	0.00	0.11	0.05	0.18	0.01	0.29
Delmas Sensako	0.26	0.18	0.07	0.03	0.20	0.85	0.55	0.42	0.41	0.07	0.18	0.12
Buffelspoort	0.48	0.10	0.21	0.03	0.00	0.01	0.03	0.00	0.13	0.80	0.69	0.18
Lichtenburg, Sensako	0.69	0.01	0.03	0.00	0.00	0.00	0.02	0.00	0.01	0.02	0.08	0.44
Pietersburg	0.02	0.16	0.18	0.48	0.04	0.03	0.09	0.02	0.01	0.37	0.46	0.00
Marnitz	0.09	0.61	0.08	0.56	0.09	0.01	0.00	0.09	0.34	1.02	2.04	1.02
Messina Agr Res	1.88	2.59	2.66	3.20	1.07	0.29	0.23	0.18	0.22	0.53	0.66	0.52
Variance for sub-division B	**0.63**	**0.67**	**0.53**	**0.60**	**0.37**	**0.29**	**0.22**	**0.19**	**0.26**	**0.51**	**0.73**	**0.61**

APPENDIX D8 : EASTERN TRANSVAAL - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Malelane	0.49	0.55	0.26	0.15	0.05	0.03	0.07	0.18	0.40	0.83	0.83	0.56
Lydenburg Vis	0.05	0.25	0.18	0.02	0.05	0.03	0.05	0.01	0.00	0.28	0.03	0.05
Nelspruit Res	0.15	0.04	0.02	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.06	0.26
Kaalrug (1)	0.02	0.45	0.08	0.08	0.02	0.01	0.01	0.01	0.06	0.14	0.00	0.34
Kaalrug (2)	0.02	0.53	0.04	0.00	0.04	0.01	0.04	0.06	0.02	0.04	0.03	0.37
Mhlume 428	0.20	0.05	0.02	0.00	0.00	0.15	0.05	0.03	0.11	0.25	0.01	0.45
Nelspruit Freidenheim	0.18	0.05	0.05	0.23	0.25	0.08	0.21	0.28	0.07	0.05	1.12	0.98
Komatipoort Tenbosch	0.23	0.01	0.13	0.05	0.01	0.04	0.01	0.01	0.03	0.00	0.08	1.02
Skukuza	0.05	0.35	0.16	0.49	0.04	0.06	0.00	0.12	0.08	0.35	0.48	1.44
Variance for region	**0.18**	**0.28**	**0.12**	**0.13**	**0.06**	**0.05**	**0.06**	**0.09**	**0.10**	**0.24**	**0.33**	**0.68**

APPENDIX D9 : NORTHERN NATAL/TRANSVAAL BORDER - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Piet Retief Mun	4.33	3.65	3.13	3.35	2.28	1.85	1.42	1.64	2.59	2.31	3.31	1.82
Kangela, Mtubatuba	0.96	1.17	1.32	0.98	0.71	1.06	1.44	1.14	1.64	2.69	1.82	1.54
Seven Oaks	0.40	0.69	0.59	0.17	0.03	0.02	0.12	0.31	0.19	0.01	0.03	0.21
Mkuze Game Reserve	0.06	0.13	0.07	0.15	0.06	0.20	0.15	0.21	0.24	0.55	0.24	0.19
Bokel, Bloodriver	0.04	0.08	0.18	0.16	0.08	0.00	0.00	0.00	0.01	0.02	0.02	0.04
Athole Proefplaas	0.00	0.05	0.17	0.00	0.06	1.08	1.42	1.85	1.90	1.93	0.61	0.46
Bundu - Hluhluwe	0.08	0.06	0.02	0.04	0.00	0.01	0.01	0.03	0.19	0.22	0.09	0.07
Dundee Agric Res Sta	0.41	0.11	0.08	0.02	0.00	0.17	0.07	0.11	0.74	1.25	1.00	0.98
Mtubatuba Mill	0.08	0.13	0.16	0.23	0.06	0.00	0.00	0.01	0.06	0.14	0.03	0.00
Pongola Expt Stn	0.04	0.14	0.16	0.04	0.00	0.00	0.01	0.02	0.00	0.00	0.03	0.02
Empangeni Mill	0.14	0.22	0.71	1.19	0.81	0.26	0.16	0.07	0.01	0.01	0.10	0.05
Mkuze estates	0.38	0.48	0.53	0.14	0.28	0.06	0.19	0.09	0.20	0.41	0.29	0.12
Big Bend (Wissel Rode)	0.69	1.19	1.06	0.69	0.19	0.01	0.00	0.00	0.14	0.67	0.81	0.72
Makatini	0.71	1.32	0.88	0.69	0.48	0.20	0.15	0.19	0.38	0.50	0.49	0.59
Variance for region	**0.64**	**0.72**	**0.70**	**0.60**	**0.39**	**0.38**	**0.40**	**0.44**	**0.64**	**0.82**	**0.68**	**0.52**

APPENDIX D10 : NORTHERN CAPE - VARIANCE VALUES FOR DAILY MEAN EVAPORATION

Station	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Jan Kempdorp;Vaalhar	2.31	3.24	1.46	1.08	0.56	0.18	0.08	0.06	0.15	0.46	0.92	1.66
Vryburg;Armoedsvlakt	0.88	2.07	1.37	0.46	0.12	0.02	0.03	0.01	0.04	0.11	0.04	0.44
Douglas Jail	0.06	0.22	0.07	0.00	0.08	0.06	0.02	0.04	0.42	0.52	0.25	0.08
Taung	0.13	0.72	0.10	0.12	0.74	0.72	0.22	0.19	0.29	0.01	0.01	0.16
Barkly Wes ko-op	0.01	0.86	0.24	0.27	0.01	0.00	0.03	0.08	0.12	0.13	0.04	0.21
Kimberley	3.06	0.96	1.74	0.77	0.19	0.01	0.00	0.06	0.41	0.77	2.40	1.88
Variance for region	**1.29**	**1.62**	**1.00**	**0.54**	**0.34**	**0.20**	**0.08**	**0.09**	**0.29**	**0.60**	**0.73**	**0.89**

APPENDIX E

APPENDIX E1 : SOUTH-WESTERN CAPE - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Langkloof (nivv)	24.00	1.92	2.88	1.19	1.01	23.51	1.62	3.20	1.47	1.19	24.30	1.66	2.87	1.06	1.11	22.64	1.91	3.58	1.75	1.12
Riversdale	24.59	2.27	2.91	0.88	0.50	22.75	1.72	4.26	1.17	1.09	22.38	1.67	4.22	1.74	0.99	22.73	2.20	3.78	1.26	1.04
Riviersonderend Tyg.	24.20	2.58	2.40	1.17	0.66	23.39	2.65	2.97	1.10	0.89	22.70	2.71	3.25	1.40	0.94	23.08	2.89	3.20	1.30	0.53
Elgin	24.81	1.60	2.45	1.06	1.08	22.66	1.69	3.01	1.45	2.19	20.00	1.79	3.52	1.86	3.87	22.26	2.12	2.93	1.50	2.18
Boontjieskraal	25.22	3.07	1.77	0.53	0.41	23.05	3.43	2.61	1.07	0.84	20.15	3.34	4.08	1.53	1.91	22.26	2.12	2.93	1.50	2.18
Karringmelksrivier	26.77	0.70	1.85	0.98	0.70	25.33	0.67	3.06	1.01	0.93	24.75	0.54	2.98	1.47	1.26	25.10	0.46	3.02	1.62	0.80
Dwaalhoek	26.31	0.62	2.90	0.56	0.60	24.16	0.73	3.38	1.41	1.31	22.13	0.96	4.15	1.69	2.07	23.57	0.82	4.18	1.47	0.96
Chiltern Damwall	27.20	1.00	1.41	0.68	0.70	24.55	1.04	2.61	1.02	1.78	22.46	1.49	2.32	1.53	3.21	24.77	0.86	3.01	1.02	1.33
Longdown	27.96	0.47	1.62	0.50	0.44	25.14	0.92	2.39	1.22	1.34	23.01	0.95	2.94	1.68	2.42	24.77	1.14	2.87	1.34	0.87
Gydo	27.81	0.43	1.34	0.63	0.78	25.21	1.01	2.09	1.36	1.33	22.98	1.14	3.00	1.46	2.43	25.22	1.19	2.33	1.15	1.11
Robertson (nivv)	28.02	1.11	1.00	0.46	0.41	25.62	1.62	2.34	0.69	0.72	24.13	1.89	2.81	1.29	0.87	25.67	2.02	2.31	0.54	0.46
Weltevrede	28.14	0.62	1.16	0.36	0.71	26.09	1.07	2.21	0.85	0.77	24.02	1.50	3.28	1.16	1.04	25.87	1.09	2.61	0.94	0.50
Langgewens (wrs)	28.25	0.48	1.40	0.54	0.32	25.33	0.93	2.22	1.47	1.05	21.93	1.42	3.90	1.72	2.02	25.43	1.11	2.72	1.01	0.71
Riebeek-Wes	28.29	0.52	1.21	0.49	0.49	25.13	0.73	1.99	1.40	1.76	22.18	0.61	3.01	2.29	2.90	25.07	0.85	2.82	1.23	1.03
Roodeheuwel (wrs)	27.89	0.85	1.27	0.56	0.42	26.57	1.00	2.13	0.81	0.49	26.12	1.21	2.38	0.71	0.57	26.61	1.17	2.07	0.76	0.40
Porterville - Mun	28.38	0.44	1.17	0.55	0.47	25.87	0.71	1.96	1.22	1.25	23.96	0.83	2.69	1.60	1.93	25.71	1.25	2.21	1.12	0.72
Moreesburg	28.50	0.45	1.15	0.61	0.29	25.60	0.73	2.44	1.27	0.92	23.42	0.75	3.44	1.69	1.71	25.70	1.01	2.65	1.17	0.48
Prospect	28.35	0.84	0.96	0.34	0.50	26.11	1.39	1.89	0.81	0.80	24.70	1.63	2.76	1.08	0.83	26.50	1.40	2.02	0.61	0.46
Montague Police	29.12	0.15	1.02	0.30	0.41	27.07	0.59	1.97	0.71	0.67	25.37	0.72	2.83	1.05	1.03	27.16	0.56	1.93	0.85	0.49
Eendrag	29.41	0.26	0.72	0.37	0.23	27.49	0.99	1.34	0.58	0.60	25.71	1.01	2.17	1.25	0.86	28.53	0.49	1.24	0.38	0.35
Aan-de-Doorns	29.35	0.37	0.80	0.25	0.23	27.78	0.63	1.41	0.55	0.63	25.10	1.22	2.39	1.01	1.27	28.25	0.58	1.30	0.38	0.50
De Doorns (niww)	29.53	0.23	0.75	0.23	0.27	27.22	0.69	1.48	0.81	0.81	25.47	0.81	2.08	1.25	1.39	28.18	0.70	1.21	0.41	0.50

APPENDIX E2 : EASTERN CAPE COASTAL - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Addo Sitrus NS	25.51	0.60	2.86	1.05	0.98	25.34	0.47	3.24	1.06	0.89	25.89	0.48	2.94	0.93	0.77	25.07	0.81	2.71	0.99	1.42
Patensie	25.58	1.32	2.28	0.73	1.09	24.95	1.83	2.65	0.83	0.74	26.38	1.45	1.79	0.76	0.63	24.15	1.89	2.82	0.93	1.20
Port Elizabeth W/K	22.01	4.02	3.12	1.11	0.74	21.72	3.34	3.33	1.51	1.11	23.33	2.52	2.94	1.17	1.05	20.47	4.15	3.84	1.54	1.00
Bathurst NS	20.57	3.20	3.99	1.49	1.74	22.85	2.31	3.11	1.31	1.42	24.61	1.73	2.27	0.98	1.41	19.98	2.59	4.48	1.81	2.14
Oos-Londen	19.58	3.10	4.18	2.29	1.85	22.91	2.02	3.39	1.23	1.44	25.72	1.41	1.88	0.77	1.21	21.16	2.59	3.61	1.46	2.18
Oos-London W/K	18.35	4.17	5.14	1.81	1.53	21.53	3.15	3.74	1.19	1.39	26.07	1.76	1.80	0.67	0.69	19.91	3.94	3.86	1.77	1.52

APPENDIX E3 : EASTERN CAPE INLAND - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Emerald Dale, Donnyb	11.08	6.23	7.60	2.90	3.17	20.86	3.24	3.93	1.25	1.72	27.73	1.20	1.51	0.31	0.26	15.89	5.49	5.90	1.85	1.87
Cobham, Himeville	11.34	3.36	6.79	3.77	5.73	20.79	2.43	3.44	2.24	2.10	28.38	1.01	0.73	0.54	0.34	17.47	3.30	4.91	2.56	2.77
Sheeprun	13.59	5.46	6.09	2.28	3.58	19.84	4.17	3.88	1.59	1.52	27.53	1.59	1.25	0.32	0.31	18.36	4.37	4.92	1.74	1.62
Kokstad Agr Res Stn	16.27	3.35	5.08	2.55	3.76	21.53	2.92	3.27	1.47	1.80	27.84	1.27	1.37	0.22	0.29	19.41	3.70	4.18	1.94	1.78
Umtata	16.69	4.00	6.03	2.13	2.14	21.72	2.68	3.44	1.64	1.51	27.88	1.03	1.32	0.44	0.33	20.55	3.52	4.40	1.21	1.32
Welverdiend AN	21.37	1.52	3.62	2.10	2.39	24.57	1.73	2.07	1.20	1.43	27.78	0.73	1.22	0.38	0.90	24.06	1.33	2.63	0.91	2.06
Queenstown	20.62	2.42	3.71	1.68	2.57	24.29	1.85	2.56	0.84	1.45	28.10	0.88	1.12	0.28	0.63	22.70	2.06	2.74	1.65	1.85
Grootfontein 11	23.14	2.40	2.73	1.07	1.66	24.43	2.36	2.06	0.89	1.25	27.95	1.36	0.95	0.33	0.40	26.16	1.74	1.57	0.77	0.75

APPENDIX E4 : NATAL COASTAL - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Glendale	21.45	3.73	4.79	2.26	2.12	25.87	0.35	2.24	1.33	1.21	28.44	0.24	1.41	0.46	0.44	22.91	0.60	4.11	1.73	1.65
Sugar Mill, Sezela	20.87	0.40	5.52	1.99	2.22	25.16	0.11	3.28	1.23	1.22	27.92	0.05	1.62	0.58	0.83	22.16	0.06	4.70	2.30	1.78
Esperanza	20.07	1.11	5.26	2.26	2.30	25.06	0.75	2.65	1.30	1.24	28.42	0.28	1.19	0.57	0.54	21.24	0.69	4.65	2.61	1.80
Mtunzini (prop farm)	20.50	0.52	4.44	2.17	3.37	23.69	0.32	2.80	1.78	2.40	25.71	0.22	2.33	1.22	1.51	20.58	0.47	4.20	2.38	3.37
Glendhow Mill	20.70	0.53	4.51	2.27	3.13	24.61	0.33	2.70	1.65	1.89	26.79	0.24	2.10	0.95	0.92	21.33	0.58	4.32	2.48	2.29
Darnall	20.01	1.15	4.36	2.67	2.81	23.74	1.06	3.19	1.30	1.72	26.27	0.60	1.97	1.17	2.19	20.70	1.54	3.86	2.64	2.27
Sezela	20.60	0.72	5.07	2.20	2.41	25.65	0.49	2.39	1.31	1.16	28.47	0.15	1.30	0.60	0.48	21.93	0.47	4.08	2.56	1.96
Chakas Kraal Auto	18.98	2.03	5.04	2.52	2.42	23.44	1.45	3.29	1.27	1.54	26.39	0.98	2.01	0.90	0.71	19.87	2.28	4.56	2.08	2.21
Illovo Mill	18.82	2.25	5.25	2.55	2.15	23.92	1.30	3.03	1.34	1.41	27.01	0.97	1.62	0.62	0.78	19.70	2.37	4.94	2.40	1.83
Tongaat	18.87	1.78	5.24	2.60	2.53	23.39	1.35	3.06	1.41	1.80	26.52	0.96	2.08	0.64	0.81	19.72	1.79	4.89	2.58	2.02
Amatikulu Mill	18.79	2.21	5.00	2.20	2.80	23.56	1.80	2.39	1.37	1.87	25.96	1.10	2.08	0.85	1.01	19.33	2.48	4.46	2.25	2.47
Double Diamond, Cato	19.18	1.15	6.12	2.03	2.58	24.40	0.82	2.91	1.38	1.49	27.83	0.62	1.77	0.34	0.43	20.20	1.38	5.62	1.82	1.98
Experiment station	18.23	3.11	4.83	2.49	2.35	23.50	2.02	2.71	1.23	1.55	26.82	0.98	1.78	0.59	0.83	18.93	3.17	4.57	2.13	2.20
Sugar Mill, Amatikulu	19.10	2.22	4.61	2.26	2.81	24.40	1.81	2.18	1.08	1.53	25.77	1.11	2.29	0.83	1.00	18.94	2.72	4.39	2.47	2.48
Umzimkulu Mill	17.21	3.20	6.03	2.22	2.34	23.13	2.48	2.67	1.30	1.42	27.02	0.96	1.48	0.70	0.85	19.60	2.40	4.91	2.00	2.09
Doornkop	18.15	1.30	5.48	2.49	3.59	23.99	0.73	3.54	1.30	1.43	26.80	0.67	2.29	0.63	0.61	19.63	1.15	5.44	2.19	2.57
Powerscourt	16.25	0.66	7.63	3.66	2.80	23.12	0.55	4.13	1.65	1.55	27.13	0.38	2.16	0.65	0.68	18.01	0.51	6.91	3.24	2.33
Ukulinga Agr Res Stn	15.90	3.67	6.66	2.21	2.56	23.23	2.35	3.11	0.99	1.31	28.14	0.87	1.33	0.34	0.32	18.47	2.99	5.70	1.82	2.02
Windy Hill	15.39	2.51	6.55	2.82	3.93	22.11	2.06	3.23	1.62	1.98	27.25	1.08	1.48	0.74	0.46	17.59	2.54	5.83	2.31	2.74
Cedara Agr Res	12.74	5.62	6.96	2.49	3.18	20.81	3.68	3.41	1.39	1.70	27.70	1.57	1.04	0.33	0.36	16.08	5.86	5.63	1.93	1.50

APPENDIX E5 : NATAL INLAND - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Sun Valley, Weenen	20.92	1.07	4.13	1.71	3.18	26.73	0.61	1.81	0.84	1.01	29.56	0.30	0.57	0.35	0.22	23.95	1.32	2.79	1.38	1.56
Union Mill, Seven OA	19.47	0.52	4.76	2.55	3.70	25.14	0.26	2.58	1.36	1.81	28.07	0.48	1.25	0.57	0.63	20.06	0.46	5.22	2.49	2.77
Melmoth (Golden Reef)	19.12	0.36	5.25	3.07	3.20	25.19	0.28	2.65	1.23	1.64	28.45	0.15	1.45	0.48	0.47	20.10	0.69	5.18	1.98	3.04
Entumeni Mill	15.93	2.30	6.08	2.74	3.95	22.65	1.78	3.20	1.69	1.68	26.18	1.02	2.08	0.98	0.74	17.01	2.51	5.86	2.76	2.73
Seven Oaks - Ryhill	15.92	2.48	6.43	2.89	3.28	22.98	1.82	3.36	1.35	1.49	28.14	0.68	1.10	0.62	0.46	19.03	2.01	5.01	2.61	2.34
Crammond	14.81	0.95	6.74	3.87	4.64	23.67	0.61	3.09	1.81	1.98	28.34	0.15	1.42	0.52	0.58	18.49	0.69	5.30	3.36	3.16
Baynesfield estates	15.27	1.26	8.59	3.16	2.71	22.21	1.20	4.42	1.80	1.37	27.44	0.68	2.11	0.42	0.35	18.16	0.91	7.58	2.23	2.13
Cedara Agr Res	12.74	5.62	6.96	2.49	3.18	20.81	3.68	3.41	1.39	1.70	27.70	1.57	1.04	0.33	0.36	16.08	5.86	5.63	1.93	1.50
Stoke Mid-Illovo	13.08	6.29	7.18	2.48	1.97	20.92	4.11	3.47	1.30	1.20	26.42	2.09	1.56	0.47	0.46	15.45	5.40	6.18	2.42	1.29

APPENDIX E6 : ORANGE FREE STATE - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Viljoenskroen Rietpan	24.60	0.07	1.54	2.21	2.59	27.49	0.07	0.49	0.68	2.28	30.69	0.00	0.09	0.16	0.07	27.33	0.00	0.78	1.22	1.66
12C5E02 Kalkfontein	24.55	0.83	2.54	1.36	1.71	25.01	0.78	2.71	1.03	1.48	29.19	0.38	0.84	0.32	0.26	27.19	0.43	1.55	0.84	0.98
Katdoornput	24.03	0.94	2.97	2.73	1.89	26.47	0.57	1.97	0.88	1.10	29.18	0.34	0.66	0.44	0.38	26.37	0.67	2.09	1.20	0.67
Fauresmith	23.42	2.30	2.88	0.92	1.48	24.17	2.03	2.44	1.11	1.25	28.86	0.71	0.99	0.25	0.20	25.64	2.22	1.58	0.64	0.91
Welkom;Sandvet	23.51	0.34	3.01	1.96	2.18	26.08	0.38	1.91	1.23	1.41	29.61	0.02	0.81	0.35	0.20	25.69	0.28	2.08	1.36	1.59
Bultfontein Arbeidskroon	21.57	2.07	3.46	2.10	1.81	25.28	1.26	2.16	1.42	0.87	29.07	0.56	0.70	0.49	0.19	24.59	1.50	2.29	1.12	1.50
Glen Agr Coll,Stn	21.35	1.71	3.46	2.22	2.25	23.27	2.09	2.62	1.25	1.76	28.91	0.72	0.76	0.27	0.34	25.71	1.14	2.16	0.93	1.07
Kestell - Pol	21.59	0.73	3.43	2.00	3.25	26.42	0.39	1.86	0.89	1.44	29.73	0.25	0.45	0.25	0.32	24.72	0.65	2.29	1.34	1.99
Wepener	19.21	2.56	4.21	2.43	2.58	22.49	2.24	3.00	1.33	1.93	28.64	0.84	0.93	0.28	0.30	24.38	1.40	2.56	1.23	1.42
Bethlehem, Loch Lomon	19.13	2.24	4.35	2.44	2.84	24.41	1.36	2.22	1.41	1.61	29.32	0.42	0.77	0.25	0.24	22.77	1.82	3.11	1.61	1.70
Meshlynn, Kamberg	12.36	4.07	7.17	2.63	4.78	22.72	1.94	3.02	1.42	1.90	27.87	1.02	1.03	0.57	0.51	17.15	4.14	5.18	2.99	1.54
Cathedral Peak	11.27	4.06	6.52	3.97	5.17	21.28	2.96	3.06	1.73	1.98	28.10	0.55	1.37	0.53	0.44	17.97	2.62	5.22	3.10	2.10

APPENDIX E7 : TRANSVAAL - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Messina Agr Res	25.11	1.00	2.43	1.04	1.41	28.64	0.55	1.03	0.39	0.38	30.58	0.16	0.22	0.01	0.03	28.15	0.52	1.07	0.55	0.72
Letaba	23.90	0.78	3.11	1.59	1.62	26.95	0.32	1.90	1.13	0.70	29.68	0.21	0.68	0.19	0.23	25.88	0.71	2.48	0.96	0.96
Marnitz	23.17	1.56	2.95	1.54	1.78	27.54	1.13	1.51	0.42	0.56	30.28	0.26	0.41	0.03	0.03	26.68	1.09	1.41	0.81	1.01
Vaalwater	22.68	0.42	3.12	2.41	2.36	27.04	0.34	1.92	0.75	0.95	29.90	0.15	0.49	0.23	0.23	26.33	0.24	1.71	1.00	1.72
Lichtenburg, Sensako	22.98	0.20	3.24	2.21	2.36	27.55	0.09	1.26	0.89	1.22	30.37	0.03	0.21	0.20	0.20	26.75	0.14	1.38	1.61	1.12
Kooster Kooperasie	21.86	0.66	3.66	1.98	2.84	26.63	0.60	1.69	1.28	0.81	30.02	0.03	0.38	0.27	0.30	25.10	0.50	2.76	1.34	1.31
Pietersvburg	21.72	2.49	3.05	1.51	2.22	26.43	1.51	1.74	0.64	0.68	30.08	0.34	0.41	0.11	0.07	25.33	1.41	2.09	0.89	1.26
Delmas, Sensako	20.75	0.71	4.12	2.65	2.77	26.70	0.23	1.90	1.37	0.79	29.74	0.15	0.54	0.35	0.22	24.10	0.42	2.74	1.61	2.13
Buffelspoort	20.50	1.31	3.87	2.68	2.63	25.84	0.71	2.10	1.38	0.98	29.38	0.55	0.72	0.23	0.12	24.88	0.74	2.35	1.63	1.40
Levubu	18.68	3.41	4.49	1.74	2.69	23.37	2.72	3.00	0.91	1.00	28.13	1.29	1.12	0.28	0.19	22.44	3.01	3.23	0.51	1.18
Rustenburg Agr	18.69	2.78	3.91	2.81	2.81	24.93	1.40	2.47	1.19	1.01	29.98	0.37	0.47	0.10	0.08	23.28	1.94	3.03	1.22	1.53

APPENDIX E8 : EASTERN TRANSVAAL - NUMBER OF DAYS WITHIN EACH RAINGROUP

Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Komatipoort Tenbosch	23.95	0.90	2.60	1.70	1.85	26.58	0.79	1.54	1.18	0.90	29.50	0.33	0.60	0.31	0.26	25.33	0.94	2.26	1.27	1.21
Skukuza	22.79	2.22	2.56	1.50	1.61	26.70	1.63	1.54	0.44	0.70	29.24	0.56	0.80	0.14	0.26	25.21	1.77	2.03	1.00	1.00
Kaalrug (1)	23.33	0.25	2.91	1.93	2.59	26.88	0.17	1.62	1.06	1.28	29.71	0.04	0.86	0.15	0.24	24.68	0.38	2.94	1.53	1.47
Kaalrug (2)	23.61	0.12	2.78	1.83	2.66	27.06	0.18	1.62	0.96	1.19	29.76	0.04	0.87	0.21	0.12	24.82	0.34	3.25	1.40	1.20
Malelane	22.65	1.80	2.76	1.71	2.08	26.04	1.26	1.57	0.98	1.15	29.75	0.36	0.65	0.08	0.15	24.30	1.43	2.71	1.16	1.40
Mhlume 428	22.83	1.58	3.28	1.59	1.72	25.43	1.22	2.19	0.95	1.20	29.08	0.43	0.97	0.25	0.27	23.92	1.53	3.00	1.23	1.33
Nelspruit Res	18.71	3.58	3.83	2.01	2.88	24.55	2.10	2.33	0.95	1.07	28.69	1.08	0.79	0.30	0.14	21.55	2.79	3.45	1.24	1.98
Nelspruit Freidenheim	18.38	3.24	4.66	1.75	2.97	24.45	1.95	2.42	1.06	1.12	29.11	0.88	0.67	0.16	0.17	21.93	2.98	3.06	1.46	1.57
Lydenburg Vis	19.37	2.06	4.34	2.18	3.05	25.18	1.41	2.41	1.03	0.97	29.63	0.35	0.55	0.29	0.17	22.50	1.25	2.83	2.15	2.28

APPENDIX E9 : NORTHERN NATAL/TRANSVAAL BORDER - NUMBER OF DAYS WITHIN EACH RAINGROUP

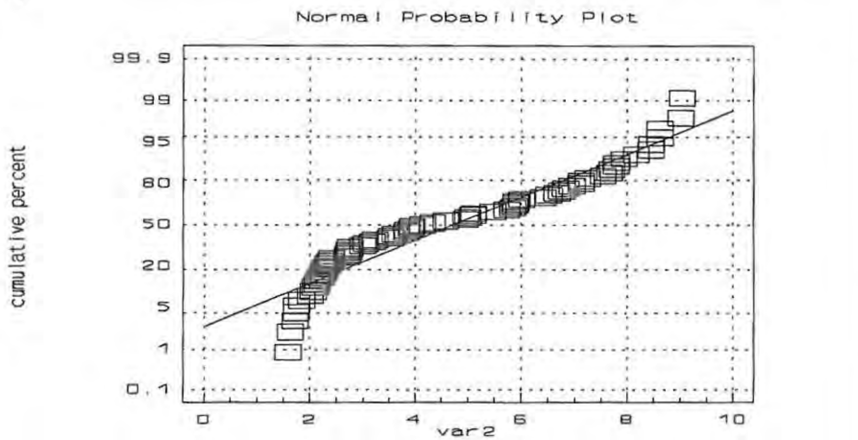
Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Mkuze estates	26.92	0.21	1.86	0.93	1.09	27.66	0.18	1.83	0.67	0.66	29.79	0.05	0.84	0.23	0.09	27.90	0.23	1.87	0.59	0.41
Big Bend (Wissel Rode)	24.37	0.85	2.73	1.20	1.87	26.46	0.52	1.95	0.90	1.17	29.22	0.34	0.83	0.28	0.33	25.25	0.66	2.40	0.96	1.73
Makatini	22.50	1.91	3.20	1.59	1.81	25.92	1.05	2.27	1.04	0.72	29.16	0.49	0.85	0.31	0.18	23.66	2.06	2.95	1.08	1.25
Empangeni (Mill)	21.81	0.65	4.02	1.92	2.60	23.37	0.52	3.02	1.91	2.19	26.04	0.62	2.30	1.11	0.93	21.11	0.85	4.23	1.96	2.85
Mkuze Game Reserve	22.67	2.23	2.73	1.21	2.17	24.94	1.63	2.42	0.88	1.14	28.44	0.98	0.88	0.37	0.32	22.45	2.63	3.65	0.99	1.29
Bundu-Hluhluwe	20.91	2.47	3.69	1.54	2.40	24.77	1.61	2.17	1.02	1.43	27.35	0.96	1.61	0.49	0.60	22.05	2.24	3.57	1.39	1.75
Pongola Expt Stn	21.11	2.39	3.36	1.95	2.19	25.25	1.45	1.93	1.08	1.29	28.83	0.67	0.93	0.29	0.26	22.03	2.28	3.56	1.38	1.74
Mtubatuba	20.73	2.46	3.87	1.67	2.27	23.55	1.82	2.68	1.43	1.52	26.11	1.58	1.96	0.82	0.54	20.81	2.96	4.09	1.57	1.56
Piet Retief Mun	19.00	2.05	3.75	1.89	4.32	24.50	1.25	2.01	1.35	1.89	28.70	0.59	1.05	0.26	0.39	21.82	1.57	3.47	1.63	2.50
Kangela, Mtubatuba	18.94	3.37	5.23	1.57	1.89	22.86	2.55	3.13	1.32	1.14	25.13	2.72	1.76	0.91	0.49	17.04	4.75	5.50	1.54	2.17
Dundee Agric Res	19.52	1.52	3.90	1.97	4.09	25.12	1.19	2.36	1.18	1.16	28.85	0.66	0.83	0.37	0.29	22.98	1.57	2.80	1.52	2.14
Bokel, Bloodriver	17.56	2.80	4.53	2.32	3.79	24.78	1.70	2.69	0.88	0.95	28.23	0.90	0.93	0.50	0.44	20.93	3.12	3.54	1.33	2.08
Seven Oaks	15.80	2.63	6.44	2.82	3.31	22.37	2.04	3.33	1.51	1.75	27.83	0.88	1.31	0.51	0.48	18.49	2.34	5.41	2.53	2.23
Athole Proefplaas	16.70	2.00	5.11	2.51	4.68	24.65	1.04	2.76	1.21	1.34	28.57	0.56	1.32	0.25	0.30	19.71	1.57	4.63	1.86	3.23

APPENDIX E10 : NORTHERN CAPE - NUMBER OF DAYS WITHIN EACH RAINGROUP

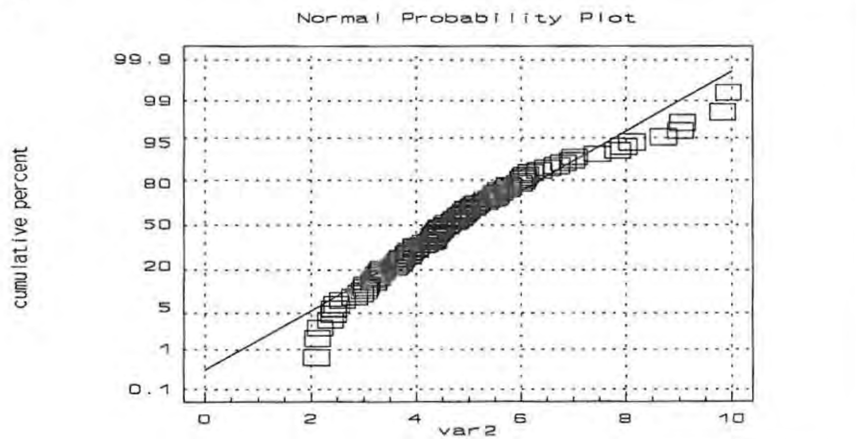
Station	Summer					Autumn					Winter					Spring				
	RG1	RG2	RG3	RG4	RG5	RG1	R27	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5	RG1	RG2	RG3	RG4	RG5
Douglas Jail	25.25	1.30	2.43	1.09	0.93	26.68	0.83	1.74	1.00	0.74	30.04	0.27	0.43	0.13	0.13	27.13	0.76	1.60	0.69	0.82
Barkly Wes ko-op	25.74	0.24	2.21	1.56	1.48	27.69	0.09	1.31	1.12	0.80	30.25	0.00	0.31	0.31	0.13	18.42	0.26	1.37	0.94	0.78
Taung	24.63	0.86	2.48	1.73	1.30	27.52	0.34	1.44	0.96	0.74	30.03	0.14	0.40	0.14	0.29	26.97	0.31	1.27	1.17	1.28
Jan Kempdorp;Vaalhar	23.28	1.69	3.05	1.62	1.78	25.76	0.95	2.18	1.07	1.05	29.82	0.33	0.55	0.22	0.08	26.49	0.80	1.78	1.09	0.84
Vryburg;Armoedsvlakt	21.73	2.04	3.39	1.75	2.08	25.50	1.25	2.19	0.87	1.20	29.83	0.29	0.45	0.13	0.30	26.19	1.03	1.86	0.93	0.99
Kimberley	22.27	2.56	3.10	1.19	1.88	23.68	2.50	2.56	0.98	1.28	29.29	0.75	0.64	0.13	0.19	26.11	1.76	1.60	0.87	0.67

APPENDIX F

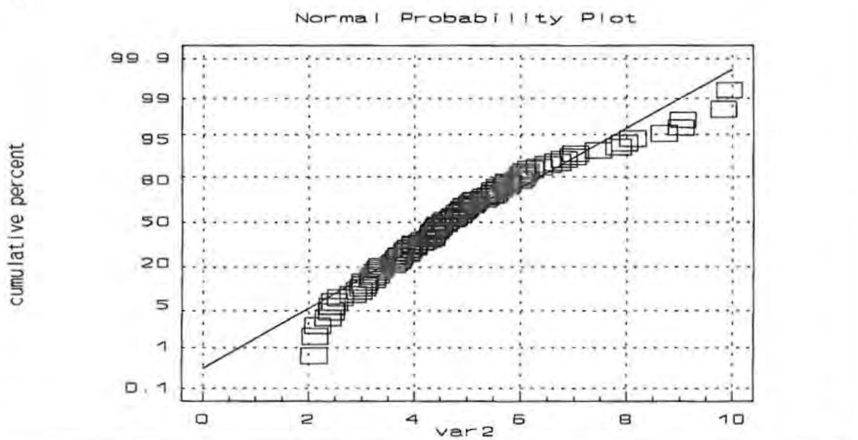
(F1)



(F2)



(F3)

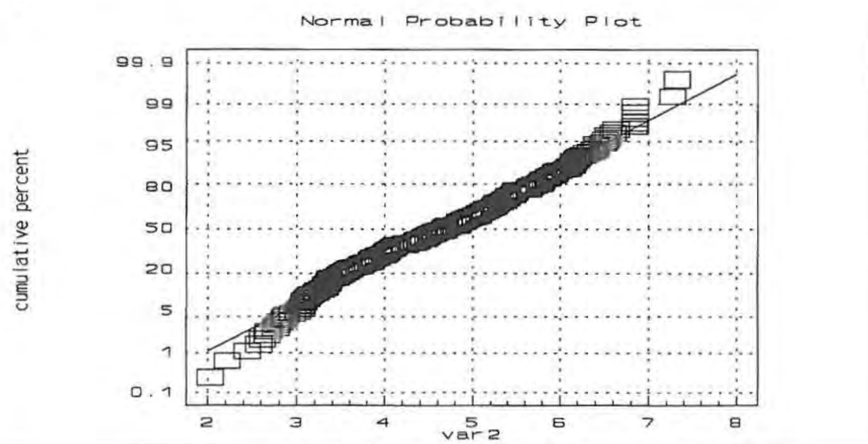


NORMAL PROBABILITY PLOTS FOR DAILY MEAN EVAPORATION FOR REGIONS :

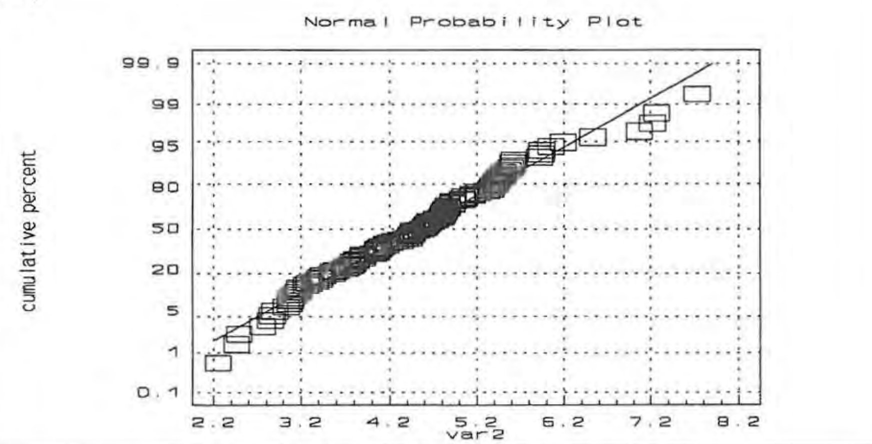
(F1) South-western Cape
(F2) Eastern Cape Coastal
(F3) Eastern Cape Inland
(F4) Natal Coastal
(F5) Natal Inland
(F6) Orange Free State
(F7) Transvaal
(F8) Eastern Transvaal
(F9) Northern Natal/Transvaal Border
(F10) Northern Cape

X-axis represents daily mean evaporation values
Y-axis represents probability (cumulative percent)

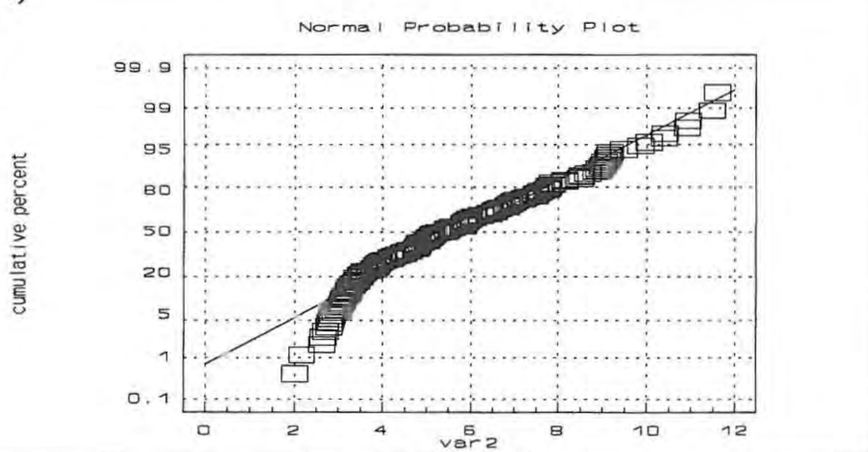
(F4)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
2
3
4
5
6
7
8
var2

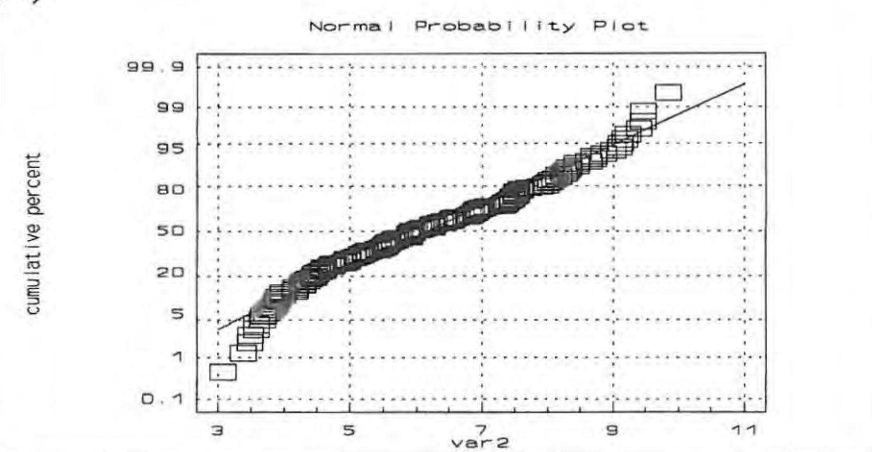
(F5)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
2.2
3.2
4.2
5.2
6.2
7.2
8.2
var2

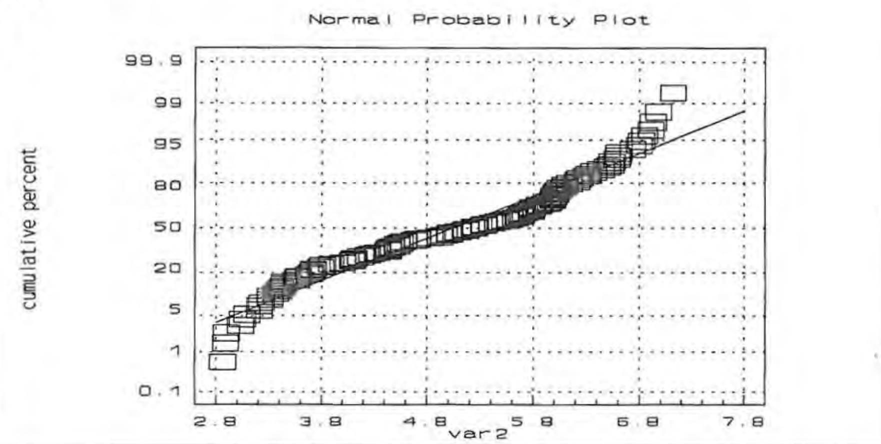
(F6)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
0
2
4
6
8
10
12
var2

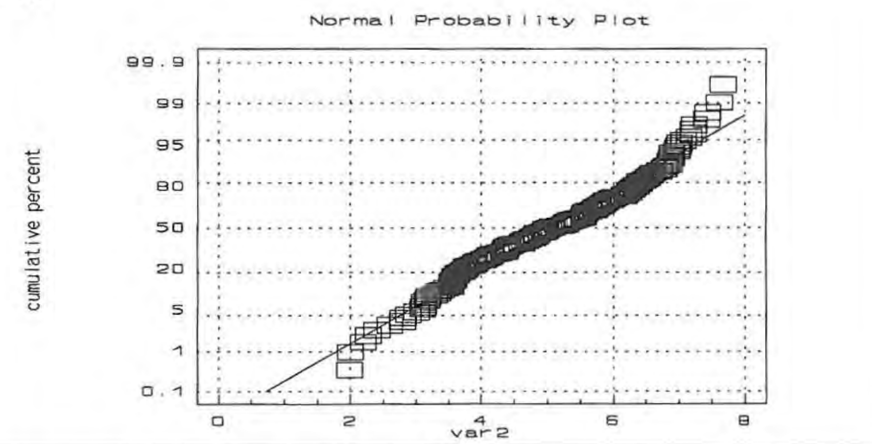
(F7)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
3
5
7
9
11
var2

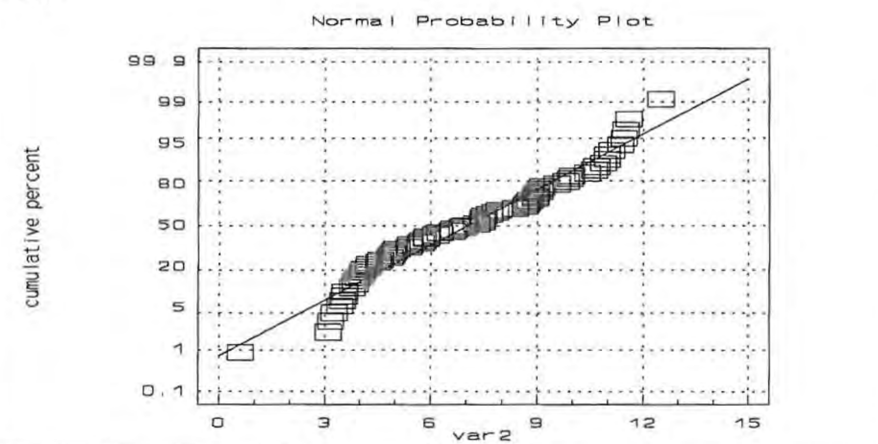
(F8)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
2.8
3.8
4.8
5.8
6.8
7.8
var2

(F9)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
0
2
4
6
8
var2

(F10)


Normal Probability Plot
cumulative percent
99.9
99
95
80
50
20
5
1
0.1
0
3
6
9
12
15
var2

APPENDIX G

APPENDIX G1 : NON-PARAMETRIC KRUSKAL-WALLIS H TEST RESULTS (MEAN RANKS AND TEST STATISICS)

SOUTH-WESTERN CAPE	
Sub-division A	**Average rank**
Elgin	29.5000
Chiltern Damwal	35.6667
Longdown	39.6250
Dwaalhoek	36.0833
Boontjieskraal	36.7083
Riviersonderend	41.4167
TEST STATISTIC	2.29739
Sub-division B	
Riversdale	73.4167
Langkloof	84.5417
Robertson (nivv)	81.3333
Gydo	92.2917
Karringmelksrivier	99.5833
Prospect	90.3333
Weltevrede	90.4583
Roodeheuwel (wrs)	97.2083
Porterville - Mun	95.0000
Langgewens (wrs)	108.917
De Doorns (niww)	110.250
Montague Police	96.6667
Eendrag	97.7500
Aan-De-Doorns	106.250
TEST STATISTIC	7.06445
Regional comparison	
Sub-division A	114.292
Sub-division B	139.328
TEST STATISTIC	5.63006
EASTERN CAPE INLAND	
Sub-division A	
Queenstown	18.5000
Welverdiend An	15.5833

EASTERN CAPE COASTAL	
Sub-division A	**Average rank**
Addo Sitrus NS	12.3333
Patensie	12.6667
TEST STATISTIC	0.01333
Sub-division B	
Bathurst NS	21.8750
Oos-Londen	30.1667
Oos-london W/K	22.1250
Port Elizabeth W/K	23.8333
TEST STATISTIC	2.76132
Regional comparison	
Sub-division A	31.5000
Sub-division B	39.0000
TEST STATISTIC	2.05506
NATAL INLAND	
Baynesfield estates	38.1250
Stoke, Mid-Illovo	29.3750
Melmoth (Golden Reef)	49.9167
Cedara Agr Res	47.5000
Seven Oaks - Ryhill	67.7917
Entumeni Mill	53.0417
Union Mill, Seven OA	67.5833
Crammond	62.0417
Sun Valley, Weenen	75.1250
TEST STATISTIC	22.0400
ORANGE FREE STATE	
Sub-division A	
Cathedral Peak	18.5833
Meshlynn, Kamberg	15.3333
Kestell-Pol	21.5833
TEST STATISTIC	2.11261

Grootfontein 11	21.4167
TEST STATISTIC	1.83934
Sub-division B	
Emerald Dale Donnyb	25.5883
Cobham, Himeville	35.0833
Umtata	25.2917
Sheeprun	28.8333
Kokstad Agr Res Stn	37.7083
TEST STATISTIC	4.99878
Regional comparison	
Sub-division A	61.6667
Sub-division B	40.6000
TEST STATISTIC	12.8686
NATAL COASTAL	
Double Diamond, Cato	63.9167
Powerscourt	99.2083
Cedara Agr Res Stn	94.7917
Ukulinga Agr Res Stn	130.333
Umzimkulu Mill	91.1250
Sugar Mill, Sezela	99.7917
Esperanza	93.9167
Chakas Kraal Auto	101.875
Windy Hill	131.750
Experiment station	103.083
Tongaat	114.583
Doornkop	144.333
Illovo Mill	126.375
Sezela	143.125
Glendale	134.708
Darnall	134.250
Sugar Mill, Amatikulu	142.458
Amatikulu (Mill)	149.250
Glendhow Mill	145.542
Mtunzini (Prop farm)	165.583
TEST STATISTIC	31.6111

Sub-division B	
Loch Lomon, Bethlehem	44.9167
Rietpan, Viljoenskroon	48.6667
Sandvet;Welkom	56.9167
12C5EO2 Kalkfontein	43.8750
Wepener	51.5000
Arbeidskroon, Bultfontein	57.7917
Glen Agr Coll, Bfn	56.7917
Katdoornput	63.7500
Fauresmith	66.2917
TEST STATISTIC	6.04661
TRANSVAAL	
Sub-division A	
Levubu	13.6250
Letaba	11.3750
TEST STATISTIC	0.60803
Sub-division B	
Rustenburg Agr	39.2083
Kooster Kooperasie	52.7500
Delmas Sensako	57.2500
Buffelspoort	47.1667
Lichtenburg, Sensako	56.8750
Pietersburg	60.4167
Marnitz	63.8750
Messina Agr Res	71.2917
Vaalwater	41.6667
TEST STATISTIC	10.6847
EASTERN TRANSVAAL	
Malelane	38.5417
Lydenburg Vis	51.4583
Nelspruit Res	50.3750
Kaalrug (1)	52.1250
Kaalrug (2)	55.0417
Mhlume 428	53.4583

NORTHERN NATAL/TRANSVAAL BORDER		Nelspruit Freidenheim	67.4167
Piet Retief Mun	31.8750	Komatipoort Tenbosch	57.7500
Kangela, Mtubatuba	45.7917	Skukuza	64.3333
Seven Oaks	77.3333	TEST STATISTIC	6.87568
Mkuze Game Reserve	69.4583		
Bokel, Bloodriver	76.4167	**NORTHERN CAPE**	
Athole Proefplaas	106.667	Jan Kempdorp;Vaalhar	29.8333
Bundu - Hluhluwe	81.5833	Vryburg;Armoedsvlakt	34.8333
Dundee Agric Res Sta	103.417	Douglas Jail	34.3750
Mtubatuba Mill	86.0417	Taung	40.1667
Pongola Expt Stn	87.0833	Barkly Wes ko-op	37.1250
Empangeni Mill	101.542	Kimberley	42.6667
Mkuze estates	102.083	TEST STATISTIC	2.83851
Big Bend (Wissel Rode)	104.792		
Makatini	108.917		
TEST STATISTIC	35.9357		

APPENDIX G2 : FRIEDMAN TWO-WAY ANALYSIS AND MULTIPLE COMPARISON LEAST SIGNIFICANCE DIFFERENCE TEST (LSD) RESULTS

Multiple range comparisons (inter-regional comparison)	LSD results	Multiple range comparisons (inter-regional comparison)	LSD results
South-western Cape	Difference is significant if /Ri-Rj/ > LSD	**Eastern Cape coastal**	Difference is significant if /Ri-Rj/ > LSD
Eastern Cape coastal	1.09 < LSD	Eastern Cape inland (sub-division A)	4.46 > LSD
Eastern Cape inland (sub-division A)	3.37 > LSD	Eastern Cape inland (sub-division B)	3.12 > LSD
Eastern Cape inland (sub-division B)	4.21 > LSD	Natal coastal	0.70 < LSD
Natal coastal	1.79 > LSD	Natal inland	1.91 > LSD
Natal inland	3.00 > LSD	Orange Free State (sub-division A)	0.00 < LSD
Orange Free State (sub-division A)	1.09 < LSD	Orange Free State (sub-division B)	4.00 > LSD
Orange Free State (sub-division B)	2.91 > LSD	Transvaal (sub-division A)	2.09 > LSD
Transvaal (sub-division A)	1.00 < LSD	Transvaal (sub-division B)	6.42 > LSD
Transvaal (sub-division B)	5.33 > LSD	Eastern Transvaal	2.84 > LSD
Eastern Transvaal	1.75 > LSD	Northern Natal/Transvaal Border	2.38 > LSD
Northern Natal/Transvaal Border	1.29 < LSD	Northern Cape	7.42 > LSD
Northern Cape	6.33 > LSD	FRIEDMAN TEST STATISTIC	29.3198
FRIEDMAN TEST STATISTIC	66.3572	**Eastern Cape inland (sub-division B)**	
Eastern Cape inland (sub-division A)		Natal coastal	2.42 > LSD
Eastern Cape inland (sub-division B)	7.58 > LSD	Natal inland	1.21 < LSD
Natal coastal	5.16 > LSD	Orange Free State (sub-division A)	3.12 > LSD
Natal inland	6.37 > LSD	Orange Free State (sub-division B)	7.12 > LSD
Orange Free State (sub-division A)	4.46 > LSD	Transvaal (sub-division A)	5.21 > LSD
Orange Free State (sub-division B)	0.46 < LSD	Transvaal (sub-division B)	9.54 > LSD
Transvaal (sub-division A)	2.37 > LSD	Eastern Transvaal	5.96 > LSD
Transvaal (sub-division B)	1.96 > LSD	Northern Natal/Transvaal Border	5.50 > LSD
Eastern Transvaal	1.62 = LSD	Northern Cape	10.54 > LSD
Northern Natal/Transvaal Border	2.08 > LSD	FRIEDMAN TEST STATISTIC	31.8667
Northern Cape	2.96 > LSD	**Natal Coastal**	
FRIEDMAN TEST STATISTIC	10.6667	Natal inland	1.21 < LSD
Natal Inland		Orange Free State (sub-division A)	0.70 < LSD
Orange Free State (sub-division A)	1.91 > LSD	Orange Free State (sub-division B)	4.70 > LSD
Orange Free State (sub-division B)	5.91 > LSD	Transvaal (sub-division A)	2.79 > LSD
Transvaal (sub-division A)	4.00 > LSD	Transvaal (sub-division B)	7.12 > LSD
Transvaal (sub-division B)	8.33 > LSD	Eastern Transvaal	3.54 > LSD
Eastern Transvaal	4.75 > LSD	Northern Natal/Transvaal Border	3.08 > LSD

Northern Natal/Transvaal Border	4.29 > LSD
Northern Cape	9.33 > LSD
FRIEDMAN TEST STATISTIC	78.2710
Orange Free State (sub-division A)	
Orange Free State (sub-division B)	4.00 > LSD
Transvaal (sub-division A)	2.09 > LSD
Transvaal (sub-division B)	6.42 > LSD
Eastern Transvaal	2.84 > LSD
Northern Natal/Transvaal Border	2.38 > LSD
Northern Cape	7.42 > LSD
FRIEDMAN TEST STATISTIC	8.1667
Transvaal (sub-division B)	
Eastern Transvaal	3.58 > LSD
Northern Natal/Transvaal Border	4.04 > LSD
Northern Cape	1.00 < LSD
FRIEDMAN TEST STATISTIC	76.8456
Northern Natal/Transvaal Border	
Northern Cape	5.04
FRIEDMAN TEST STATISTIC	118.3770

Northern Cape	8.12 > LSD
FRIEDMAN TEST STATISTIC	168.1880
Orange Free State (sub-division B)	
Transvaal (sub-division A)	4.00 > LSD
Transvaal (sub-division B)	6.42 > LSD
Eastern Transvaal	2.84 > LSD
Northern Natal/Transvaal Border	2.38 > LSD
Northern Cape	7.42 > LSD
FRIEDMAN TEST STATISTIC	51.3380
Transvaal (sub-division A)	
Transvaal (sub-division B)	4.33 > LSD
Eastern Transvaal	0.75 < LSD
Northern Natal/Transvaal Border	0.29 < LSD
Northern Cape	5.33 > LSD
FRIEDMAN TEST STATISTIC	1.3333
Eastern Transvaal	
Northern Natal/Transvaal Border	0.46 < LSD
Northern Cape	4.58 > LSD
FRIEDMAN TEST STATISTIC	52.2726