CROP WATER REQUIREMENTS FOR IRRIGATION PLANNING IN SOUTH AFRICA

MARK CLIFFORD DENT

Submitted in partial fulfilment of the
requirements for the degree of
Ph.D.

Department of Agricultural Engineering
University of Natal
1988

ABSTRACT

Irrigation in 1980 accounted for approximately 52 per cent of the water consumed in Southern Africa. The need for planning water resources in the agricultural sector is therefore apparent. Much of Southern Africa's arable farming is carried out on land which, in terms of soil moisture availability to crops, can be described as marginal. Information on soil moisture is therefore valuable to the agriculturalist for planning irrigation schemes and for dryland farming.

The objectives of this study were to provide the information mentioned above. This was achieved by producing a detailed delimitation of 712 zones throughout Southern Africa, of more or less homogeneous climate and by providing estimates of crop water requirements under dryland and irrigated conditions in each zone. At the same time the bulk of information which is normally forthcoming from such an analysis involving a large number of combinations of possible input, i.e. crops, soils and planting dates, was reduced, whilst the essential information content was retained. The study provided inter alia an estimate of the frequency of non-exceedance of certain levels of irrigation requirement, based on analyses of soil moisture budgets using long daily rainfall records. The soil moisture budgeting models which were used to estimate the above information were verified inter alia using field measurements of soil moisture.

The irrigation analysis was designed such that the results should not become redundant when the inevitable improvement occurs in the estima-

tion of crop factors or soil moisture variables nor if the farming practices change with respect to planting dates.

A dryland soil moisture budget analysis for a range of crops and soils was performed in addition to the abovementioned irrigation analysis. The need for this latter study stemmed from the belief that irrigation should not be considered in isolation but rather as one of a range of options, many of them involving dryland farming, facing the agriculturalist.

In addition to the dissertation, this study produced a map of Southern Africa on which the 712 homogeneous climate zones are depicted. For each of these zones four pages of computer printout were produced. These pages contain the results of the crop water requirements study for irrigated conditions and the crop water requirement deficit, runoff and an index of stress days for a range of crops, soils and planting dates, under dryland conditions.

I wish to certify that the work reported in this thesis is my own original and unaided work except where specific acknowledgement is made.

Signed ....

25 September 1988

ACKNOWLEDGEMENTS

This study was only possible through the co-operation of many individuals and organisations. I wish therefore to record my sincere thanks to the following:

Professor P Meiring, Head, Department of Agricultural Engineering, University of Natal for his encouragement and support and for making this research possible through his Department;

Professor R E Schulze, Department of Agricultural Engineering, University of Natal who supervised this research, for his encouragement, guidance and support which has meant so much to me in this study and in my career in general;

The research in this dissertation emanated from a project funded by the **Water Research Commission.** The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee, especially **Dr G C Green, Mr D W H Cousens, Professor J M de Jager, Dr A L du Pisani** and **Dr R Mottram,** is acknowledged gratefully;

Department of Environment Affairs, South African Weather Bureau: in particular Mr J S van Rhyn and Mr J Koch, for rainfall data;

Department of Agriculture and Water Supply, Soil and Irrigation Research Institute: particularly Messrs J Erasmus, J Myburgh, J Hoon, D Turner, S Barrow and D Rowswell, for rainfall, temperature, evaporation and altitude data; Mr A Nel, for climatic and soil moisture data from field plots of wheat at Roodeplaat; Dr R Mottram of the Department of Agriculture and Water Supply, Summer Grain Centre for climatic and soil moisture data from field plots of soybeans at Cedara;

Computing Centre for Water Research: a venture by ISM (Pty) Limited, the Water Research Commission and the University of Natal for the provision of a computing facility dedicated to water research at the University of Natal, Pietermaritzburg. This facility was of great benefit to this project.

University of Natal, Computer Services Division: for assistance and advice in computing;

University of the Witwatersrand's erstwhile Hydrological Research Unit: Professor D C Midgley and Dr W V Pitman, for providing a large portion of the grid of co-ordinates and altitudes covering Southern Africa;

Department of Environment Affairs: South African Forestry Research Institute, Mr J Bosch and Mr F Rogers for rainfall data in the Jonkershoek and Cathedral Peak areas;

South African Sugar Association Experiment Station: Dr G Thompson, Mr M Murdoch and Mr R Harding for providing rainfall and temperature data;

University of Natal: Pietermaritzburg, Department of Geography for the loan of maps;

Mr G R Angus, Department of Agricultural Engineering, University of Natal, who assisted greatly with the programming to automate the execution of the dryland analysis;

Mrs M Maharaj, Department of Agricultural Engineering, University of Natal, who was responsible for a considerable amount of computer programming and data processing in this study;

Mr H Tarboton, formerly of the Department of Agricultural Engineering, University of Natal, who was largely responsible for the dedicated task of delimiting the climate zones and computer programming related to these zones;

Mr S D Lynch, Department of Agricultural Engineering, University of Natal, for assistance with the plotting programs;

Dr P T Adamson, Department of Water Affairs, who assisted in commissioning the daily rainfall generator at the Computing Centre for Water Research;

Mr S Piper, Department of Land Surveying and Mapping, University of Natal, Durban, for providing the grid of altitudes covering Natal;

Mesdames K M Temple, J M Whyte, K Wiercx and H M M Wills, all of the Department of Agricultural Engineering, University of Natal, who worked on the project at various times with patience and diligence;

Mrs J Swanepoel who typed much of this document with commendable speed and accuracy;

My wife, **Kerry** and my children **Lloyd** and **Roslyn** for their unstinting support and encouragement throughout the long years of this study.

TABLE OF CONTENTS

2. SELECTED TOPICS RELATED TO THE ESTIMATION OF IRRIGATION REQUIREMENTS FOR PLANNING IN SOUTHERN AFRICA

3. DELIMITATION OF HOMOGENEOUS CLIMATE ZONES

4. THE ACRU AND IRRIGATION SOIL MOISTURE BUDGET MODELS

5. VERIFICATION OF THE OUTPUT OF THE MODELS

6. CLIMATIC DATA INPUT TO THE SOIL MOISTURE BUDGET MODELS

7. APPLICATION OF THE MODELS AND THEIR OUTPUT

LIST OF TABLES

Page

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

The drought of the 1980s over Southern Africa, coupled with the mounting demand for water by all sectors has emphasised the continuing need for detailed water resources planning in this region. Since irrigation in 1980 accounted for approximately 52 per cent of the total water demand in South Africa (Department of Water Affairs, 1986) the need for planning of water resources in the agricultural sector is apparent.

In the view of the increasing demand for water by the urban and industrial sectors, all indications are that agriculture will have to improve the efficiency of its water usage, and in this regard an accurate estimation of irrigation water requirement plays a very important role.

> "Small savings in the large amounts of water used for irrigation can release significant quantities of water" (Department of Water Affairs, 1986).

In the agricultural sector a large portion of the increased demand for water may be ascribed to the practice of supplementary irrigation. There are several reasons for this increase. First, crops are being introduced into areas which are marginal climatically. Secondly, development corporations in the National States are promoting total and supplementary irrigation schemes. Thirdly, crop yields are boosted by supplementary irrigation and the practice of irrigation is being used as a measure for ensuring consistent crop yields. Furthermore, the production of crops under irrigation, primarily for more intensive feeding of livestock is becoming an increasingly widespread phenomenon in parts of Southern Africa (Coordinating Committee for Irrigation Research, 1986). According to Green (1984) just over a million hectares of land is under irrigation in South Africa and he describes this irrigation as a vital stabilizing factor in agriculture.

Much of Southern Africa's arable farming is carried out on land which, in terms of soil moisture availability to crops, can be described as marginal. To emphasise this point one need only to consider that the average mean annual rainfall in South Africa is 472 mm and only 12 per cent of the country receives more than 800 mm per annum. The rainfall is unreliable and strongly seasonal and the evaporation ranges from 1 500 - 3 000 mm over most parts of South Africa. Information on soil moisture is therefore valuable to the agriculturalist for planning supplementary irrigation and for dryland farm planning. Apart from the individual farmer's need to plan, it is also necessary to estimate irrigation water requirements for potential development of entire regions. Consumption of water by dryland crops and natural vegetation is also important since these affect runoff to different degrees.

At present the standard text used by many planners of irrigation schemes is a publication entitled "Estimated irrigation requirements of crops in South Africa" edited by Green (1985). In that publication a daily soil moisture budget approach was used to generate estimated irrigation requirements, at 118 climate stations in South Africa, for a range of crops, soils, planting times, irrigation cycle times and application amounts. The approach followed by Green (1985) in that publication has the following shortcomings;

(a) relatively sparse coverage of climate stations, thereby requiring the user to extrapolate the results over large areas,

(b) many short climate records which reduce the value of risk analyses based on these short records,

(c) fixed combinations of locality, crop and planting dates which therefore exclude the possibility of considering combinations of the above, other than those chosen.

Some of the objectives of this study aim at addressing these shortcomings albeit by following a different approach.

In Southern Africa a few planners of irrigation schemes employ daily soil moisture budgeting models in which daily climatic data and site specific crop, soil and planting time information are used. However, such use of daily soil moisture budgeting models is not common. In many instances monthly mean rainfall and pan evaporation or some probabilistic value of monthly rainfall is used to obtain a coarse estimate of crop water requirements for planning purposes.

The areas in which the major crops are being grown in Southern Africa have, in the past, been determined by a number of factors among which economics played a dominant role. Climatological disadvantages were often masked by economic factors which resulted in crops being grown "profitably" in regions where they are unsuited climatically. Profitability, although understandably a dominant factor in decision making, is also an unreliable and fickle phenomenon which can alter very suddenly. A change in the pricing structure of inputs, transport or products may result in the need to seek alternative crops. The more market oriented approach to the maize price in South Africa in 1987 is a particularly dramatic example of the above point. At times when the need for alternative crops is most pressing, research such as that described in this study is valuable.

One of the primary elements of a preliminary survey of agricultural potential is information on the crop water requirements and in particular to what extent these requirements are met by natural rainfall. Cuenca (1982) emphasises this point very strongly when he states;

> "The crop water requirement is the single most important piece of data upon which all the other irrigation system design parameters are based" p 140.

However, a practical solution to the problem of estimating and presenting the monthly crop water requirements for supplementary irrigation and for dryland crops, in the form of a manual, for planning, is complicated by the numerous interacting factors which influence that requirement. The crop water requirement is primarily a function of the rainfall amount and rainfall frequency in association with evapotranspiration, soil texture and depth, crop type, time of planting, plant population density as well as the stage of growth of the crop and its root depth and root density. The high spatial variability of the soil alone indicates the large number of possible combinations of the above. The following quotation from Green (1984) emphasises the complexity of the problem;

> "Climatic diversity and also the wide variety of soil conditions in South Africa, add much complexity to agricultural research in our country. On the one hand a wide variety of crops are grown and on the other, certain crops are produced over an astoundingly wide range of climatic and soil conditions." p 31 (Green, 1984).

The agricultural planner, therefore, is often faced with a large number of possible crop, soil and risk management options which must be considered. Comprehensive planning requires an appraisal of the crop water requirements associated with the many combinations of the aforementioned variables. The presentation of estimated irrigation or dryland crop water requirements for all possible combinations of these variables may be very cumbersome. It was therefore essential to reduce the volume of this output without reducing the content and spatial coverage of the information. This need thus formed a primary objective of the study.

1.2 Objectives

This study had several primary objectives related to the estimation of crop water requirements under irrigated conditions. In addition the investigation of aspects of crop water requirements and runoff under dryland conditions formed a secondary objective.

The primary objectives are stated briefly as follows;

(a) to provide a detailed delimitation of zones throughout Southern Africa, of more or less homogeneous climate and to provide estimates of crop water requirements under irrigated conditions in each zone,

(b) to reduce the bulk, whilst retaining the essential content, of information which is normally forthcoming from such an analysis involving a large number of combinations of possible input, i.e. crops, soils and planting dates,

(c) to provide an estimate of the frequency of non-exceedence of certain levels of irrigation requirement, based on analyses of soil moisture budgets using long daily rainfall records,

(d) to enable the results of these analyses to remain relevant in the future, despite improved estimates of crop factors and soil moisture variables and if farming practices change with respect to planting dates,

(e) to provide the above information in a form which is easy and quick to consult whilst remaining flexible and relevant in a facet of agriculture, viz. irrigation which is expanding rapidly in Southern Africa,

(f) to verify the soil moisture budgeting models which were used to estimate the above information.

A secondary objective in this study stemmed from the belief that irrigation should not be considered in isolation but rather as one of a range of options, many of them involving dryland farming, facing the agriculturalist. The dryland farming option should also be considered in the preliminary stages of a feasibility study involving possible irrigation. The secondary objective therefore was to estimate the deficiency in crop water supply under rainfed conditions and the runoff emanating from such soil moisture budgets. The estimates of the above should cover a range of crops, soils and planting dates and should be performed within the context of objectives (a), (b) and (e) outlined above.

An objective which embraced almost every facet of the above and the pursuance of which was essential to the successful completion of this study was that of automation. The large volumes of data and information which were processed in this study made the development of computerised systems obligatory. Furthermore such systems may be used for a rapid revision of this study in the light of better data, for example.

1.3 Overview of methodology

Invariably the potential user of the information generated in this study will need to apply the information to sites other than that of the rainfall station used. To assist such users and to provide a rational way of selecting the required rainfall stations, the region surrounding the rainfall station and for which the selected rainfall/temperature station is considered representative, was delimited. To this end 712 homogeneous climate zones were identified and delimited in Southern Africa. A long term daily rainfall station was selected for each of these zones. This station then provided the daily rainfall input data for both the irrigation and dryland approaches.

In the information reduction process the variables can be divided into two categories viz. those which are specific to an area and those which are specific to a site. Whereas the high spatial variability of daily rainfall is appreciated, the location of existing gauges with records of long duration means that rainfall has, for practical purposes, to be considered specific to or to pertain to a relatively large area. In this study, area specific variables are daily rainfall and potential evaporation; and the site-specific variables are soil and crop type, time of planting, stage of growth and rooting depth. The planner is normally well informed as to the soil conditions at the sites as well as the other variables pertaining to the cropping scheme which is being considered, i.e. the site-specific variables. The planner also requires maximum flexibility of choice with respect to these site-specific variables so that a wide range of options may be considered.

A soil moisture budgeting model was developed to estimate the possible crop water requirements under irrigated conditions. In this model, which catered for daily rainfall interception, actual evapotranspiration, rooting depth and soil texture, the irrigation water was applied when the soil moisture reached 50 per cent of the plant available moisture (PAM). The monthly summations of such water applications and the change in soil moisture storage between the first and last day of the month constituted the crop water requirement from irrigation. These values, for the entire daily rainfall record at each station, were ranked and the 50, 80 and 90 percentile values were extracted. The results of these analyses are useful for estimating irrigation requirements and the risk attendant to planning for these potential requirements.

To fulfill the secondary objective viz. modelling soil moisture under dryland farming conditions, the ACRU model (Schulze, 1984b; 1986) was used. It was assumed that daily rainfall was the only soil water input. Thus, in the event of no rainfall, the model allowed the soil to dry to the point where the vegetation was unable to extract moisture from the root zone at the potential rate. The difference between the potential evapotranspiration and the actual evapotranspiration was estimated. In addition to the evapotranspiration deficit the ACRU model was used to estimate runoff and occurrence of stress days. Such information complements the estimates of evapotranspiration deficit and is useful for the delimitation of agricultural areas which for a variety of crops are potentially good or stress prone. In addition runoff into for example, small farm dams which are used for irrigation was estimated. Key crops and soils have been selected and the soil moisture budget simulated for growth patterns on major soil types under the normal first world management practices associated with these crops. The dryland study thus includes parameters of soil type, vegetation type, stage of growth, rooting depth and distribution as well as risk analysis. The potential evaporation estimate was provided by the Linacre (1977) equation and used monthly mean temperature (converted to daily values) at a station which was representative of each zone. Wind and day length correction factors were applied to the Linacre (1977) equation on a regional basis.

The results of this study include a map of Southern Africa on which the 712 homogeneous climate zones are depicted. For each of these zones four pages of computer printout were produced. These pages contain the results of the crop water requirements study for irrigated conditions and the crop water requirement deficit, runoff and an index of stress days for a range of crops, soils and planting dates, under dryland conditions.

1.4 Note on terminology and conventions

This thesis contains a number of tables which were generated by a computer and printed out directly through a laser printer. In addition to these tables a very large amount of information was generated in computer compatible media. The decimal point was therefore used throughout in preference to the decimal comma.

For the purposes of this document southern Africa is defined as the Republic of South Africa, the TBVC States, Lesotho and parts of Swaziland.

The term soil moisture has been used throughout this thesis in preference to soil water. Both terms are used in a wide variety of refereed international journals. It is conceded that some researchers may prefer the term soil water. However, the Soil Science Society of America (1979) glossary of soil science terms defines soil moisture as water contained in the soil. The term soil moisture is discussed further in Appendix G.

2 SELECTED TOPICS RELATED TO THE ESTIMATING OF IRRIGATION REQUIREMENTS FOR PLANNING IN SOUTHERN AFRICA

This chapter contains discussion on a number of topics related to the estimation of irrigation requirements for planning in Southern Africa. These topics have been presented collectively in this chapter for one or more of the following reasons. First, they serve as an extension to the introduction and some contain a brief literature overview. Secondly, each topic, though important, did not warrant a separate chapter. Thirdly, some of these topics form necessary background and elaboration which if presented in the midst of an explanation of methodology, for example, would disrupt the reader's train of thought.

The following are some of the topics discussed in this Chapter;

(a) a brief review of past research relating to the estimation of irrigation requirements in Southern Africa;

(b) the shift in emphasis towards irrigation in the more humid regions in Southern Africa;

(c) a clarification of the distinction between estimating irrigation requirements for planning as opposed to scheduling;

(d) some comments on the complexity of hydrological models, with particular reference to the complexity necessary for this study;

(e) selected components of the soil moisture modelling process with particular reference to

  - rainfall intensity and effective rainfall
  - irrigation timing and amount
  - crop factors and the estimation of actual evapotranspiration (AET)
  - root distribution and water uptake
  - drainage of soil water to groundwater

(f) the selection of objective functions to be used in verification of soil moisture budget modelling.

2.1 Past research covering the estimation of irrigation requirements in Southern Africa

There are currently two publications which report on research into the estimation of irrigation requirements for the whole of Southern Africa. These publications by the Department of Agricultural Technical Services (1973) and Green (1985) follow a different approach to that pursued in this study. The publication of the Department of Agriculture, edited by Green (1985) supercedes the publication entitled "Beraamde besproeiingsbehoeftes van gewasse in Suid-Afrika" by the Department of Agriculture (1975). Discussion on these publications will therefore be confined to Green (1985).

In that study the 118 climate stations, the locations of which are shown in Figure 2.1, were selected from the records of the South African Weather Bureau, Department of Agriculture and the Department of Water Affairs. Green (1985) estimated the daily irrigation requirement at each of these stations for a range of depths of water applied per application, crop and planting date combinations using a soil moisture budgeting procedure in which the climatic inputs were daily rainfall and daily Class A-pan evaporation. The decision to use daily A-pan evaporation held both advantages and disadvantages. The advantages were that the short periods of highest evaporation would be reflected in the maximum requirements whereas had the monthly mean or mean monthly pan evaporations been used the maximum estimated requirements would have been lower. The other advantage was that all the crop factors which are published by Green (1985) and which are the result of contributions from many agronomic scientists in South Africa, relate PET to Class A-pan evaporation estimates. The disadvantages of the decision to use only daily pan evaporation are that some of the records are short, eg. 5 years and hence in the humid areas in particular the frequency analysis of the estimated irrigation requirement is not very meaningful. A further disadvantage stemmed from the fact that evaporation pans are often located at agricultural research stations, Department of Water Affairs dam sites or established irrigation areas only. The

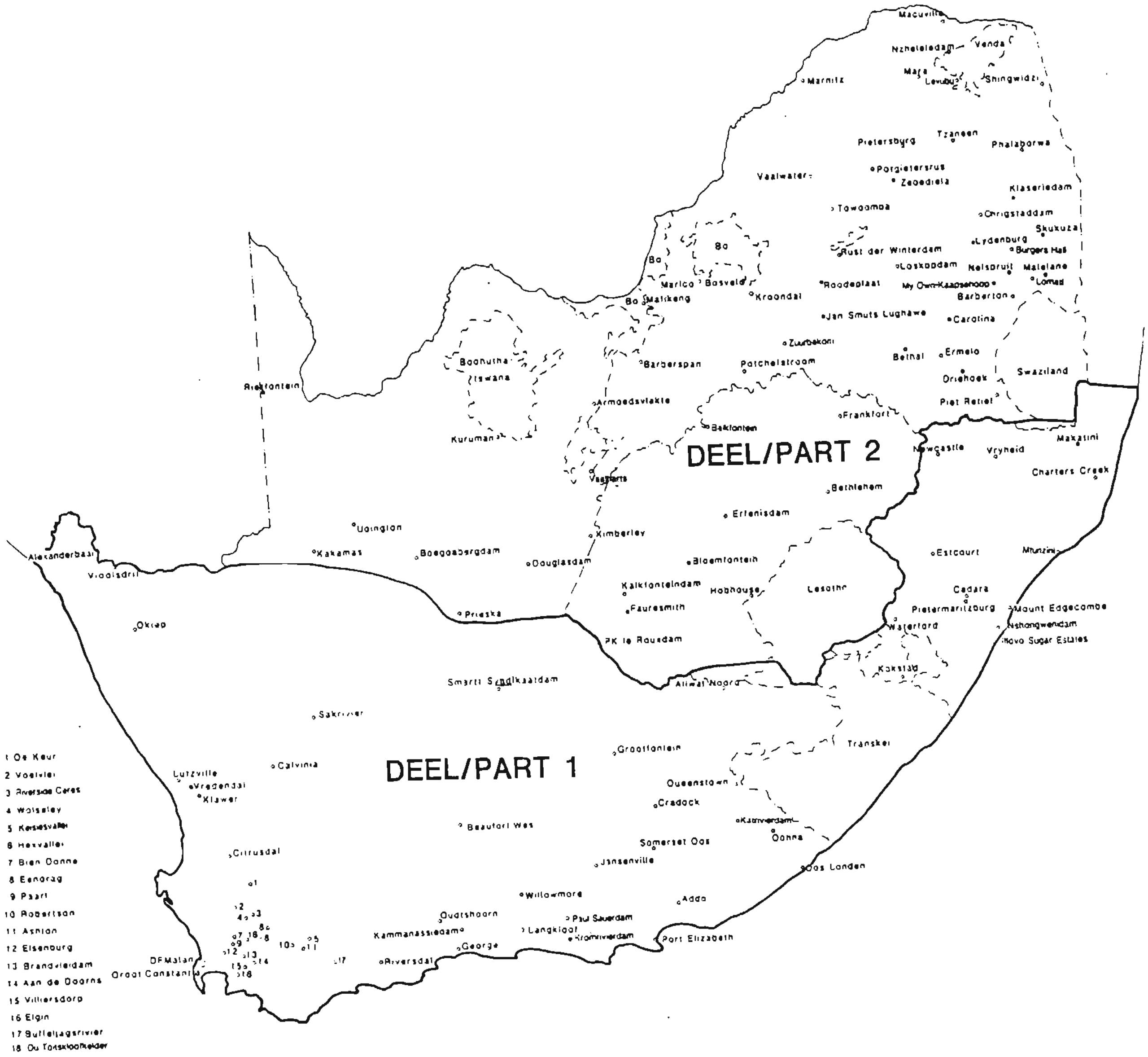


Figure 2.1 Location of the climate stations used in the irrigation study by Green (1985)

spatial coverage of pans is therefore sparse or non existent in many areas. Green (1985) notes that although the evaporation pan data used were fairly free of error it is nevertheless difficult to evaluate how representative the data are of the majority of irrigated areas in the region served by the chosen site. Green (1985) therefore warns against unsound extrapolation of the results to areas in which the microclimate and terrain form differs from the A-pan measuring site due to the moistness of the surrounds, altitude, shelter from winds, aspect or slope. The study by Green (1985) did not delimit the extent of the area which could be represented by the stations at which the analyses were performed. This is a major difference between that study and the one reported in this document.

Green (1985) presented several pages of tables for each station. These tables contained for each time period in the crop growth cycle and for irrigation applications of 5, 10, 15, 25, 50, 75 and 100 mm the estimated evapotranspiration, effective rainfall, irrigation requirement and the mean cycle length i.e. the mean interval between applications as determined by his soil moisture budgeting model. In addition a frequency analysis of the minimum irrigation intensity (mm/day) is presented for each of the application depths. The results of the study by Green (1985) are used widely in Southern Africa. However, the coverage of stations in the more humid areas tended to be sparse whilst at the same time Midgley (1983) and Green (1984) indicated the advantages to be gained from and tendencies towards irrigation in the more humid parts of Southern Africa.

2.2 Change in emphasis towards irrigation in humid regions in Southern Africa

As was mentioned in Section 1.1 there has been a marked increase in irrigation in the more humid regions of Southern Africa. This shift in irrigation development has been both foreseen and supported by Midgley (1983) and Green (1984). The section which follows is drawn largely from papers by Midgley (1983) and Green (1984) which relate to this topic. Midgley (1983) makes the point that supplementary irrigation can make do with low assurance supplies of water whereas this is not the case in areas of total irrigation. Midgley (1983) adds furthermore that the economy in water utilization becomes apparent when one considers that the annual supplementary irrigation requirement can be as low as 300 mm in supplementary areas and as high as 3 000 mm in the arid areas of total irrigation. Midgley (1983) does concede however that two or three crops may be grown in the arid areas, per annum, but that such double cropping is only achieved at considerable expense in terms of water transpiration and water losses in transit.

Whilst supporting generally the sentiments expressed by Midgley (1983), Green (1984) makes some counter points which provoke thought. For example since radiation intensities are less in the more humid areas it follows that potential productivity will also be lower. Furthermore Green (1984) points out that preferential utilization of water for irrigation in the higher reaches of major rivers will only allow the lower parts to use surplus water. Thus the risk associated with the irrigation water supply in such lower reach, arid areas, may be too high to attract irrigation farmers and consequently surplus water may go to waste.

The results of this study contribute to the debate outlined above inter alia by providing estimates of the extent and frequency of supplementary irrigation requirements in the humid and arid areas. An estimate of the savings in irrigation water may therefore be gained. It is particularly in these humid areas that the long records of daily rainfall used in this study are so necessary as was shown by Furniss (1987).

2.3 Distinction between estimating irrigation requirements for planning and for scheduling

Somewhat surprisingly there is still a good deal of confusion amongst potential users of the results of this study as to their application to scheduling. The results of this study are not intended for use in scheduling and will not be of any use to persons wishing to use them for that purpose. Arising from the abovementioned misconception the need was felt to draw a clear distinction between estimating irrigation requirements for planning as opposed to on farm scheduling purposes. Several reasons exist for performing such a comparison. Important among these reasons is that the choice of model structure and the approach adopted for this aspect of the study depended on maintaining a clear distinction between these two purposes.

First, the planning function often has an exploratory facet whereas this is not generally the case for scheduling. Secondly, the estimation of irrigation water requirements is normally regarded as a quick operation as far as professional time is concerned, whereas, for example, the design of the pump, piping and sprinkler aspects of the system is not. Thirdly, it is often necessary to assess the irrigation requirements of a number of alternative crop schemes. Fourthly, techniques of estimation used in planning require historical climatic data. Design estimates are often based on what would be sufficient, should the past climatic record be repeated. These estimates are naturally more coarse than those used at the time of scheduling since they are required to cover a wide range of possible situations. In addition to this, each design estimate carries with it an associated probability of exceedance. Engineering is essentially the art of taking calculated risks and the process of estimating supplementary irrigation requirements for planning purposes is no exception in this regard.

Estimating supplementary irrigation requirements for scheduling purposes is a different process to that of estimating for planning purposes. Once an investment has been made in the equipment, water supply and crop, the irrigator must apply adequate water and should apply it in time to extract the maximum benefit from the scheme. Extra investment both in terms of money and time should be made to equip and operate a basic meteorological station. Daily data could then be processed through an irrigation model in a micro computer. Such action would put the irrigator in an informed decision making position, with regard to scheduling. Perhaps this may sound futuristic but when one considers the investment in crops, fertiliser and equipment then the cost of these scheduling aids is not unreasonable. In choosing a moisture budgeting model for this scheduling exercise the cost/benefit of accumulating and maintaining this data base to protect and enhance the investment is more self evident and hence easier to motivate than in the case of planning estimates. In addition only one set of soil and crop conditions are under investigation.

The need for good planning estimates may be questioned if one is to go to the above lengths to schedule correctly. However, the point is that the design must be adequate in terms of equipment and water supply once the scheduling decision has been made. Over design on the equipment and water supply aspects on the other hand is wasteful.

2.4 Comment on the complexity of soil moisture budgeting models

Soil moisture budgeting models have various degrees of complexity and hence input data requirements. These data cover both the climatic as well as the crop/soil variable used in the models. One of the many decisions which face the planner in estimating irrigation requirements is that of the complexity of the model and its inputs. Generally the more complex physically based models have more detailed inputs and should yield more accurate estimates, if the additional complexity is at all justified. However, an important factor to consider in a planning exercise is that there is often a diminishing return to increased accuracy of the estimation. This is especially so in an environment in which the inputs, for example, climatic, are uncertain and difficult to quantify. Cost/benefit trends will also influence the choice of model.

Engman (1986) in a penetrating and thought provoking review of hydrologic research, states;

> "One interesting aspect of recent hydrologic research is that although we feel we know more about the physical process, use sophisticated analysis techniques and can produce very elaborate output, we have not been able to demonstrate

> consistently improved accuracy or reproducibility." p5

Studies by Naef (1985) show that although simple rainfall-runoff models may produce satisfactory results in certain cases, either or both the complex and the simple models tested by Naef (1985) are reported to have failed in certain cases because none of them could describe adequately, the rainfall-runoff process. Naef (1985), adds that it could not be proved that complex models give better results than simpler ones.

Loague and Freeze (1981) studied the performance of three event based rainfall-runoff models viz. a quasi-physically based model, a unit hydrograph model and a regression model. Data sets involving 269 events from small upland catchments were used. Surprisingly poor model efficiencies were the result, for all three models on all the data sets. Loague and Freeze (1981) speculated that the performance of physically based models may be impeded by the problems of scale which are associated with the unmeasurable spatial variability of soil hydraulic properties and of rainfall.

The findings _inter alia_ of Loague and Freeze (1981) and Naef (1985) were reviewed by Engman (1986) and prompted the following comment;

> "The fact that simpler, less data intensive models provided as good or better predictions than a physically based model is food for thought. If one accepts these studies as indicators of the effectiveness of recent hydrologic research results, one should ask, Why? Why is it that more complex and more physically based models do not give us better results? There is perhaps no clear answer, but I would speculate that lack of the proper amounts and types of data may be a large part of the answer." p 6

The exercise of gathering data is costly in terms of professional time and in many instances the data are simply not available. Faced with a choice of models and the range of available data, the irrigation planner for example is often forced to opt for one of two solutions. Either a complex model is used with data from a site, which is remote from the design site, but which has the required data. The irrigation requirements are then extrapolated to the design site. Alternatively a simplified model is used with the available simple data, from the design site. In many instances methods other than modelling are employed. These methods require only simple data from at or near the design site. Should the data be available then the time invested in using a complex model may be justified if only one cropping operation is being investigated. However, in many instances the feasibility of several alternative crops and systems are under review. In these cases the returns may not justify the use of models which require complex input data. Ritchie (1981) supports this view when he states that models should not depend on the input of weather records that are difficult to obtain. The models which were used in this study and are discussed in Chapter 4 were designed to accommodate simple inputs whilst retaining their flexibility and versatility.

2.5 Selected components of the soil moisture modelling process

According to Green (1986) the cause of disagreement between observed and estimated soil moisture, when using the more conventional irrigation scheduling models, may often be traced to one or more of the following;

(a) inaccurate estimation of both rainfall and runoff under rainfed conditions;
(b) crop coefficients, for converting reference evapotranspiration (ET) to crop ET, which are non-applicable;
(c) the effect of perched water tables and the incorrect estimation of field drainage rates;
(d) uncertainty regarding root zone development; and
(e) inaccurate estimation of the drying rate of the soil surface.

Most of these important points are discussed in the Sections 2.5.1 to 2.5.5 which follow.

2.5.1 Rainfall intensity and effective rainfall

According to Johns and Smith (1975) factors such as runoff and runon under conditions of high rainfall intensity probably account for much of the discrepancy between observed and computed deficits. This is a view which is shared by a great many researchers and indeed the amount of research which addresses this topic is testimony to its importance.

In approaching the problem of rainfall intensity and its effect on runoff one is inclined to look towards infiltration equations. However, Ritchie (1981) cautions that infiltration equations which require precipitation data for less than 24 hour periods may not be useful for many operational models because of the paucity of autographic rainfall data. Indeed the paucity of autographic data, both temporal and spatial, excluded the use of such data in this study.

The term effective rainfall will mean different things to different people. Effective rainfall for the irrigation scientist or farmer is that rainfall which enters and is retained in the soil moisture store in the active root zone. Effective rainfall to the civil engineer who has built a dam for supplying water to a town is that rainfall which runs off and finds its way into his dam. An appropriate definition of effective rainfall for the purposes of irrigation engineering is according to Hershfield (1964), that portion of rainfall that contributes to meeting the evapotranspiration requirement of a crop.

It is evident that the estimation of effective rainfall is of prime importance to the estimation of irrigation water requirements in areas of frequent rainfall. According to Burman, Cuenca and Weiss (1982) one of the most common methods used in the USA for estimating effective rainfall is the US-SCS method involving water balance calculations. The above method was used in this study as discussed in Section 4.1.2 and Section 4.2.3.

2.5.2 Irrigation timing and amount

Linacre and Till (1969) present an extensive review on the subject of irrigation timing and amount. These are crucial questions in both scheduling and planning irrigation, since the planned estimate of irrigation requirements must be based on a set of assumptions with regard to when and how much irrigation water should be applied.

When considering the question of how much to apply Linacre and Till (1969) refer *inter alia* to papers which advocate either irrigating to less than field capacity in the root zone or more than the amount required to fill the root zone to field capacity (FC). However, Linacre and Till (1969) conclude that "it is normal practice to apply just sufficient water to re-wet the root zone completely" p176.

The application of frequent and shallow waterings is undesirable for three reasons;

(a) operations input and control is increased;

(b) interception loss as a percentage of the water applied is increased;

(c) and, shallow root growth is encouraged (Meyer *et al.*, 1987),

and therefore a very reliable irrigation system is required.

The question of deficit irrigation was considered. Deficit irrigation is the intentional under-irrigation of crops with the objective of either water conservation or increased profitability over the long term. Green (1986) reporting on the work of several irrigation experts in respect of deficit irrigation, highlighted several questions, the answers to which are still not evident and hence deficit irrigation was considered too new a concept to include in the models described in Chapter 4 and used in this study. The questions concerned the optimum level of deficit irrigation, the circumstances in which it would be profitable, whether the multiple-year allocation of a fixed volume of water instead of an equivalent single season quota would enable growers to increase returns and reduce risk and the management guidelines necessary to achieve optimised deficit irrigation scheduling.

Furniss (1987) estimated irrigation requirement at several locations in South Africa, using the ACRU model developed by Schulze (1986) and concluded that, in areas of high rainfall, deficit irrigation resulted in marked savings in water. Deficit irrigation appears to hold much promise for the future, however, in the light of the still many unanswered questions with regard to deficit irrigation it was decided to simulate irrigation up to field capacity in this study.

With regard to the desired degree of soil moisture depletion before irrigation should be applied Linacre and Till (1969) conclude that it is commonly recognised that irrigation is required when the soil water deficit in the root zone reaches 50 per cent of the plant available moisture. This view is supported inter alia by Green (1985). Linacre and Till (1969) go on to refer, however, to studies which show that the abovementioned level of 50 per cent could vary by up to 20 per cent either way depending on the particular crop/soil combination. The level of 50 per cent was accepted as being the level at which irrigation water was applied in this study.

Implied in the above statement is the fact that demand mode irrigation was assumed in this study. Demand mode is the term which has been introduced to describe the practice of irrigating only when the soil moisture has been depleted to a pre-determined level. This is distinct from a fixed cycle irrigation practice in which irrigation is applied at fixed intervals and amounts irrespective of the soil moisture status. Furniss (1987) showed that in the wet season in humid areas of Southern Africa, substantial water savings could be effected by applying irrigation in demand mode and thus making optimum use of any rain which may fall and save an irrigation setting.

The exact timing of such demand mode irrigation settings means that the irrigator needs to know the soil moisture status of the irrigated field. There are a number of methods of estimating this soil moisture. These methods fall into two broad categories viz. measurement of soil moisture by direct or indirect technique or by estimating soil moisture through modelling. On first considering the problem of estimating soil moisture one would think that direct measurement was by far the best and most accurate. However, this is not necessarily so since the soil itself is so variable and hence soil moisture may vary markedly within a small space.

It is therefore necessary to make a number of scattered measurements of soil moisture in order to determine a representative value for the soil moisture status of a field. A study by Devitt _et al._ (1983) compared several methods of estimating the soil moisture status with the objective of controlling leaching. Soil moisture modelling using _inter alia_ the Penman equation for estimating evapotranspiration was by far the most accurate method used. Other methods which were used by Devitt _et al._ (1983) to estimate the water loss through the plants were pan evaporation, a tensiometer, neutron probe and leaf water potential. The weekly evapotranspiration predictions were all compared with those from a weighing lysimeter which was considered to give the "true" value.

Ziska and Hall (1983) investigated several soil and plant measurements for determining when to irrigate cowpeas and concluded that modelling soil water depletion based on predicted evapotranspiration appeared to be the most practical procedure for scheduling irrigation of cowpeas. This conclusion that modelling offers one of the best methods of estimating soil moisture and hence when to irrigate is supported by Calder _et al._ (1983) and Devitt _et al._ (1983).

The final word on methods for estimating the correct timing of irrigation application is provided by Green (1986) who summarised the opinions expressed at a national conference in the U.S.A. to discuss advances in evapotranspiration estimation. Green (1986) states that "scheduling based solely on soil water monitoring can demand a frequency of sampling and a level of instrumentation which is too time-consuming and expensive for many farmers to consider seriously". p11

2.5.3 Crop factors and the estimation of actual evapotranspiration

To hydrologists, engineers, agriculturalists and many others the ability to estimate soil moisture status without recourse to direct measurement is of great interest. However, to do this they must, inter alia, estimate AET which according to Green (1986) is possibly the most difficult process to measure or estimate albeit one of the most important processes in dryland agriculture, irrigation and hydrology. The successful estimation of AET depends primarily on the ability to estimate PET, the crop factor or crop coefficient and the relationship between soil moisture status, PET and AET. The estimation of PET is discussed in Chapter 6 and will therefore not be discussed in this Section which will concentrate on the crop factor and the relationship between PET, soil moisture and AET.

According to Green (1986) the crop factor is a variable to which soil moisture balances are very sensitive generally, and as such it constitutes a potential weak link in such modelling. In this study the abovementioned weakness was recognised and consequently the irrigation requirements estimation technique described in Chapters 4 and 5 was designed to accommodate this sensitivity. The effect of any future changes in recommended crop factors will not render these estimates, of crop water requirement from irrigation, redundant.

Green (1986) notes that the assumption that the crop factor for a particular crop is a varying constant which depends only on the time elapsed since planting date is not valid. Such an assumption implies, according to Green (1986), a unique development rate, independent of climate and a non-variable plant population density. All the above assumptions are invalid to some degree and caution should be exercised in applying crop factors. A further factor which should be considered is the effect of plant stress which may reduce the crop factor permanently. For most crops it is unrealistic to assume that the crop factor will return to the pre-stressed levels as soon as the soil moisture is no longer limiting.

If the atmospheric demand is high, plants may also alter their crop factor effectively by partial or total stomatal closure, even if soil water is not limiting. This is a well known phenomenon and it was also evident in the field plot simulations of soil moisture described in Chapter 5.

Estimation of PET based on Class A-pan evaporation is, in South Africa, the most tried and tested of all the empirical methods available (Green, 1985). Crop factors which are the constant of proportionality between the Class A-pan evaporation and PET were therefore used by Green (1985). The crop factors for most common crops in South Africa are presented in Green (1985). These crop factors and those obtained from Schulze (1987) were used in this study. Both Green (1985) and Schulze (1987) obtained these crop factors from various sources and those factors which were obtained from South African studies were given priority over those estimated elsewhere. Green (1985) and Schulze (1987) caution that these estimates of crop factor should be regarded as first approximation working estimates and by implication this means that they may be refined with further research. Green (1985) reflects on a number of factors which can and do affect the crop factor and for which no adjustment was made in his or this study, for example, if there is significant nocturnal pan evaporation when the plant stomata are closed, if there is excessive atmospheric demand which forces stomatal closure, retardance of crop factor due to previous stress history, the inability to adjust crop factors to specific seasonal and climatic conditions.

These problems of estimating the correct crop factor are not as important in a dryland analysis due to the negative feedback loop described by Johns and Smith (1975) and Calder et al. (1983) and presented later in this Section 2.5.3. With respect to the irrigation analyses in this study the approach adopted ensures flexibility in the use of the crop factor on condition that the crop factor is taken as the constant of proportionality between the Class A-pan evaporation and PET.

Data from weighing lysimeters are used generally to provide the basis for the performance of various methods of estimating reference AET (Green, 1986). However, Green (1986) did caution that some researchers have found that AET estimated by lysimeter studies were sometimes significantly larger than those from field water balance studies.

Notwithstanding the above note of caution it is considered relevant to present the following findings of Devitt et al., (1983) in Table 2.1.

Table 2.1 Standard error of estimate of weekly evapotranspiration predictions compared to weighing lysimeter (N=17)* (Devitt et al., 1983)

Method	Standard error (mm/wk)	Percentage error
Penman Equation	4,7	15
Pan evaporation	8,1	23
Tensiometer - field plots	8,1	23
Neutron probe - lysimeter	8,2	24
Neutron probe - field plots	12,5	36
Leaf water potential	16,5	48

*N = number of data pairs

Devitt et al. (1983) conclude from their study that atmospheric modelling should require far less replication than methods which monitor soil water status directly, since climatological conditions are usually fairly uniform over large areas of land compared to conditions within the soil. It is interesting to note from this study that predictions based on pan evaporation performed relatively well. Doorenbos and Pruitt (1977) also grade pan evaporation (under the correct conditions) as the next best method after Penman of estimating reference crop evapotranspiration.

The ratio AET/PET is not constant but is a function of available soil moisture. Research to determine the nature of this function has been conducted inter alia by Denmead and Shaw (1962), Linacre (1963), Shaw (1964), Eagleman and Decker (1965), Baier and Robertson (1966), Wu (1967), Eagleman (1971) and Slabbers (1980). Figure 2.2 shows a graphical representation of various of these proposed functional relationships.

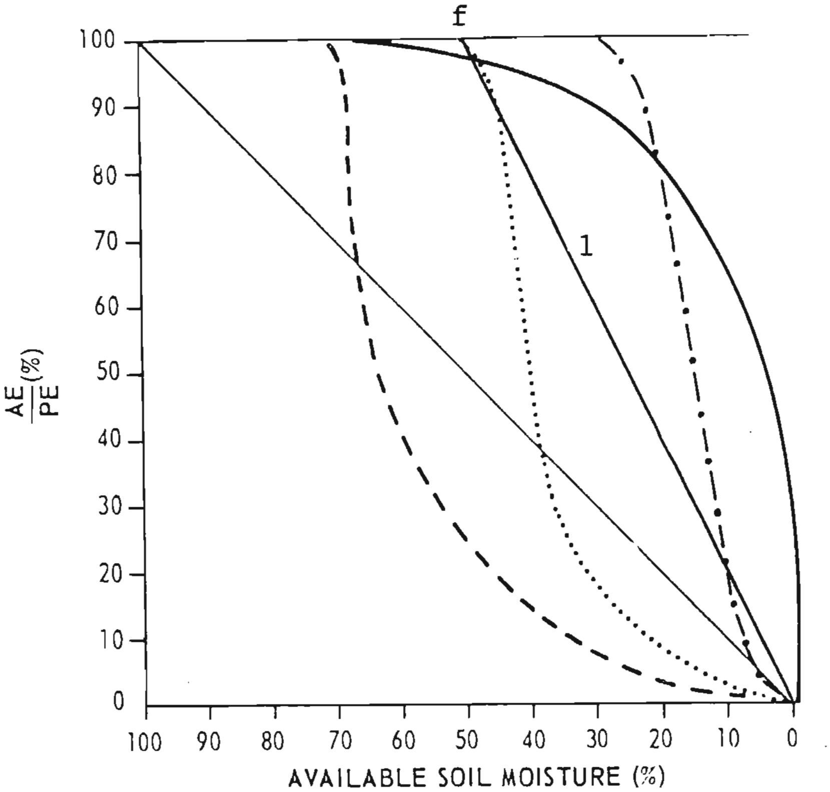


Figure 2.2 Various proposals for the relationship between AET/PET and available soil moisture (after Baier and Robertson, 1966)

The form of the function which was chosen in this study is discussed in Section 4.1.1. The effect of this decreasing AET/PET ratio is to introduce an apparent conservatism into soil moisture budget modelling under dryland conditions. This conservatism is due largely to the negative feedback mechanism which begins to operate in soil moisture budget model when AET/PET<1. The mechanism has been discussed <u>inter alia</u> by Johns and Smith (1975) and Calder <u>et al</u>. (1983). When AET/PET<1 the negative feedback mechanism ensures that, if the AET is overestimated in one period, then in the next period the soil moisture is underestimated which in turn produces an underestimate of AET/PET and hence a reduction in the soil moisture depletion in that period. The mechanism also works in the reverse direction if an initial underestimation of AET is made. The modelling mechanism is thus self compensating or is said to have a negative feedback loop. In addition AET is limited above by stomatal action and below by unavailable soil moisture i.e. at wilting point (WP). Johns and Smith (1975) found that when the appropriate value of (f) in Figure 2.2 was used then the simple function (1) as described in Figure 2.2 was as good or better than the other more complex functions for estimating AET.

The purpose of irrigation is to hold AET/PET equal to one by providing the correct quantities of water when it is needed. Hence the issue of negative feedback loops and the decline in AET/PET with decreasing levels of plant available moisture (PAM) should really only be an issue of significance in the dryland analysis.

2.5.4 Root distribution and water uptake by roots

Root distribution and the process of water uptake by roots is a complex and difficult subject to study. However, since it is so important for plant growth and for the modelling of plant growth, as well as soil moisture budget modelling, it has been the subject of many studies, some of which are discussed in this section.

The results of studies by Baker and Van Bavel (1986) form an interesting prelude to this discussion on roots since they indicate the complexity of the root/soil water system. Experimentation by Baker and Van Bavel (1986) found that at night moisture was moved through the plant from roots which were in wet soil and exuded from roots which were in dry soil. In this way the soil on the dry side was kept moist to the extent that one half of the transpiration needs of the Bermuda grass which was used in the experiment, could be met by this mechanism. This finding was not new since Kirkham (1983) had developed a physical model which showed the abovementioned phenomenon namely that a plant could take up, transfer and exude water in response to gradients of soil water content.

However, despite the complexity of the root distribution/water uptake system there are certain patterns which have been well known for many years and are reconfirmed regularly by experimentation which is reported in the literature. For example in most plants the major portion of the roots are to be found in the top 300 to 500 mm and these roots are more active than those in the lower zones in that they take up water available to them first,. before the lower roots began taking up appreciable quantities of water. One or both of the above conclusions may be drawn from the work inter alia of Bloodworth et al. (1958), Ogata et al. (1960), Gardner (1964), Baier and Robertson (1966), Ritchie et al. (1972) and Johns and Smith (1975). Baier and Robertson (1966) introduced the above concept into a multi-layer model in that they assumed that all soil water from the uppermost layer was evapotranspired first until the soil moisture was reached where AET/PET<1 and then only did moisture begin to be withdrawn from the lower zones. The ACRU model of Schulze (1984b; 1986) and which is discussed in Section 4.1, takes a slightly different approach in apportioning the AET to the two root zones in the same ratio as the root distributions in these zones. There is also evidence to suggest that the lower zone roots do not extract water down to the same moisture contents as is the case with upper zone roots. Ritchie et al. (1972) and Johns and Smith (1975) show that there is no clearly defined depth of rooting from above which all water which is available at potentials above wilting point (WP) will be extracted. Rather, the lowest moisture content to which roots can dry the soil gradually increases with depth until finally that minimum moisture content is very close to field capacity. Ritchie (1981) followed up these ideas and stated that the incomplete extraction of apparently available soil water limited productivity in many rainfed agricultural regions. Ritchie (1981) suggests that the enhancement of deep rooting is a possibility for increasing the availability of soil water. Mottram (1986) found that for maize, wheat and soybeans growing in a Bainsvlei Metz soil at Cedara the upper 600 mm was active in terms of changes in soil moisture. Below this level little change occurred under supplementary irrigation conditions.

The distribution of roots depends largely on the plant and soil type. However, there are several other factors, some of which can be controlled by man, which also influence the root distribution. For example, a great deal of experimental and observational evidence reported in the literature, shows that frequent shallow irrigations increase the root growth in the upper soil zone. This is a phenomenon which increases the risk of crop water stress should an irrigation application be omitted. Roots may also be restricted by the presence of water tables and plough or other hard pans. These are mentioned since the assumptions made in both the irrigation and dryland analyses discussed in Chapters 4 and 7 do not make provision for these extraordinary cases.

Taylor and Klepper (1978) in an extensive review of root distribution and water uptake by roots, concluded with the view that;

> "All current models of water uptake by root systems contain assumptions that are not strictly valid for everyday field situations." p120

Whereas this is undoubtedly true, one still needs to use models and therefore it is necessary to make simplifying assumptions. The assumptions regarding root distribution and the uptake of water by roots in the ACRU model follow the broad path of consensus in this regard.

2.5.5 Drainage of soil water to groundwater

Perhaps three of the most important questions in relation to this aspect of soil moisture budget modelling are:

(a) the amount of soil pore space above FC for the various textured soils;

(b) the rate at which this water drains to groundwater i.e. below the active root zone; and

(c) does one assume that evapotranspiration is occurring from this surplus water source whilst it is draining.

The total porosity, FC and WP values, for the various textured soils, which were used in this study are presented in Table 4.1. The values in that table were deduced by Schulze _et_ _al_. (1987) from publications by Dunne and Leopold (1978), Brakensiek, Engleman and Rawls (1981), Hutson and Joubert (1983) and Hutson (1984). The amount of pore space above FC may be obtained from Table 4.1.

The rate at which the soil water above FC drains to groundwater depends on the soil texture of the upper zone as well as that of the lower zone below the root zone. These rates vary from several hours in sandy, well drained soils to a week or more in clay soils. According to Wilcox (1960) most of the literature up to that time shows that moist arable soils drain to field capacity in 1 to 4 days. However, Wilcox (1960) does state that some researchers have found longer periods than 4 days. For the purposes of modelling in this study the recommendations of Ritchie and Otter (1984) were accepted. They assumed that the moisture which is held in the soil at levels above FC drains to groundwater at a rate of 50 per cent of the remaining excess water per day. This rate was also adopted by Schulze (1984) in the 1984 version of the ACRU model.

Johns and Smith (1975) assumed that water which was applied whilst the soil moisture was above field capacity was lost either as runoff or deep percolation. Wilcox (1960) and Bartels (1965) on the other hand showed that consumptive use during this period was from the excess water which would otherwise have drained away. The latter was the approach adopted in this study in both the ACRU and the irrigation models.

2.6 Choice of objective functions for verification of soil moisture budget models

The choice of objective function when comparing the observed and simulated soil moisture is a difficult one for several reasons. First, in a continuous simulation such as a soil moisture budget model an error introduced by a single discrete event such as a large rainfall for which runoff is not estimated correctly may result in a displacement of the simulated and observed soil moistures. Such a stepped change will have a long carry over or memory period with respect to the soil moisture. The observed and simulated data are therefore not independent of such an error event although subsequent to such an event the budgeting routine may be simulating accurately albeit with a displacement in soil moisture content.

Secondly, the change in moisture content between observations is often small and especially so when compared with the total soil moisture content in the root zone. The active root zone is also difficult to determine accurately.

Thirdly, the range in moisture content is often also small and hence both plots of accumulated observed and accumulated simulated soil moisture and regression analyses yield less information as objective functions than, for example, variables which have a smaller mean value and a larger range.

Shaw (1964) and Baier and Robertson (1966) used the correlation coefficient between the observed and simulated soil moisture as a measure of the accuracy of the simulated budget. However, as Johns and Smith (1975) explain, this is not correct for two reasons. First, the correlation coefficient related variation accounted for by the simulation to the variation in the observations and as such it is a relative parameter only. Therefore no absolute estimate of the error is given and hence it is not possible to compare the accuracies of simulations conducted under different situations. Secondly, the existence of bias is not taken into account by the correlation coefficient. It is possible to have a regression intercept and slope which are markedly different from 0 and 1 respectively and yet still have a correlation coefficient which is high. Johns and Smith (1975) recommend that since the root mean square error (RMSE) value does not have the above shortcomings, that it should be used as a measure of the accuracy of prediction.

In this study the RMSE, regression slope and intercept, correlation coefficient, time series plots of observed and simulated soil moisture and also the coefficient of efficiency following Aitken (1973) were used to assess the performance of the ACRU and the irrigation models, as discussed in Chapter 5.

3 DELIMITATION OF HOMOGENEOUS CLIMATE ZONES

Climate is determined primarily by the two major meteorological variables, namely, rainfall and temperature. Wind, humidity and solar radiation are also meteorological variables which contribute to the description of climate at a particular location. However, these variables are only measured at relatively few locations in South Africa and hence detailed delimitations of homogeneous climate zones must of necessity be made without reference to measurements of these variables in many cases. Since the zones which were delimited in this study are mostly relatively small, the variation of wind, humidity and solar radiation are of consequence only at the micro scale. The delimitation of homogeneous climate zones was therefore performed only in terms of trends in rainfall and temperature.

3.1 Need for homogeneous climate zones

A primary objective of this study was to provide reasonable estimates of crop water requirements at any locality in Southern Africa. To achieve this objective, soil moisture budgets needed to be simulated using data from a large number of daily rainfall stations. Unfortunately, no matter how many stations may be used in such an analysis, it would still not be feasible to model the soil moisture budget at every possible future design site. The station most appropriate to the design site would then have to be chosen by the planner or designer. The local farmer may know which station's data would be most representative for use at his site. However, the planner who is not familiar with the area would need additional information before making this decision. Spatial proximity of rainfall stations could be misleading in many instances.

Computer time and publication space placed a constraint on processing all the daily data from rainfall stations in Southern Africa through the models for both the irrigation and the dryland analyses. It was therefore evident that a compromise was required between limiting the number of rainfall stations utilized and the objective of providing adequate coverage of the country. The value of a study which contained simply the results of moisture budget simulation at a number of stations without delimiting their zone of applicability would have been limited. It was therefore decided to delimit zones of more or less homogeneous climate surrounding the chosen daily rainfall stations. Several existing delimitations of rainfall zones and the reasonably homogeneous farming areas as defined by Scheepers, Smit and Ludick (1984) were investigated as a point of departure.

3.2 Existing delimitations of rainfall zones

Southern Africa has been classified into rainfall zones at different times in the past. The most notable of these classifications are those by the South African Weather Bureau (SAWB) in 1960 and 1972 and that by Welding and Havenga (1974). The Welding and Havenga (1974) zones were considered an improvement on those of the SAWB (1960; 1972) for several reasons. First, the Welding and Havenga (1974) delimitation used 1549 stations for the period 1931 to 1966, which is more than double the number used by the SAWB (1972) for the same period. Secondly, Welding and Havenga (1974) used monthly data in a correlation procedure which formed the basis for the hierarchical classification technique of McQuitty (1960). This technique is considered to be statistically more sensitive to the influence of variation in monthly rainfall from year to year than that of the SAWB (1972), which used the distribution of mean monthly rainfall. Welding and Havenga (1974) took cognizance of topographic features, as did SAWB (1972). Welding and Havenga (1974) delimit 114 regions compared to the 34 of the SAWB (1972). In Natal, for example, the Welding and Havenga (1974) regions show reasonable agreement with those proposed by Schulze (1983). The overall goal of the Welding and Havenga (1974) classification was to identify similar regions for agricultural purposes. It was therefore assumed that Welding and Havenga (1974) took cognizance of physiographic features as well, and that it was not purely an exercise in which the correlations

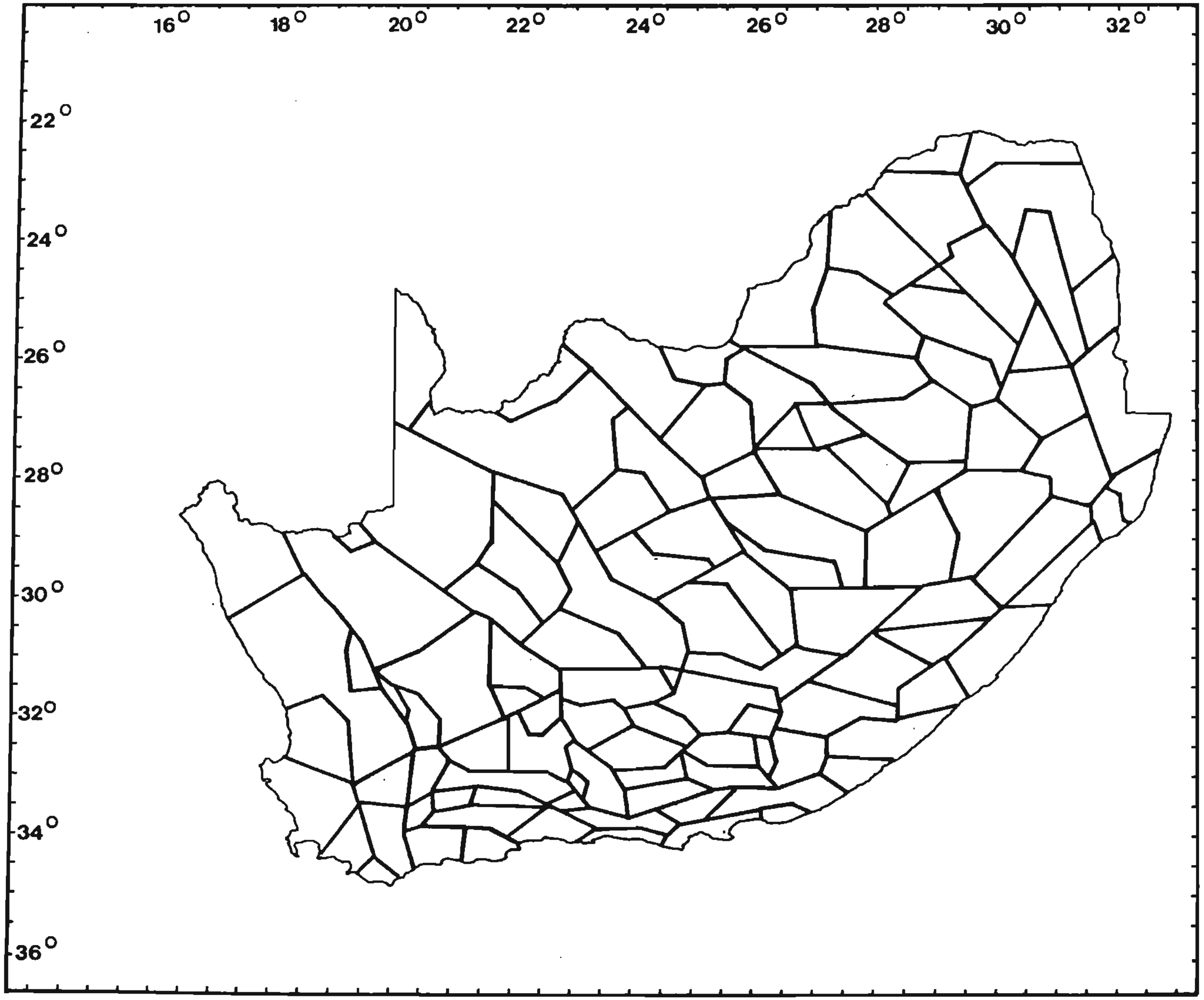


Figure 3.1 Rainfall regions (114) of Southern Africa (after Welding and Havenga, 1974)

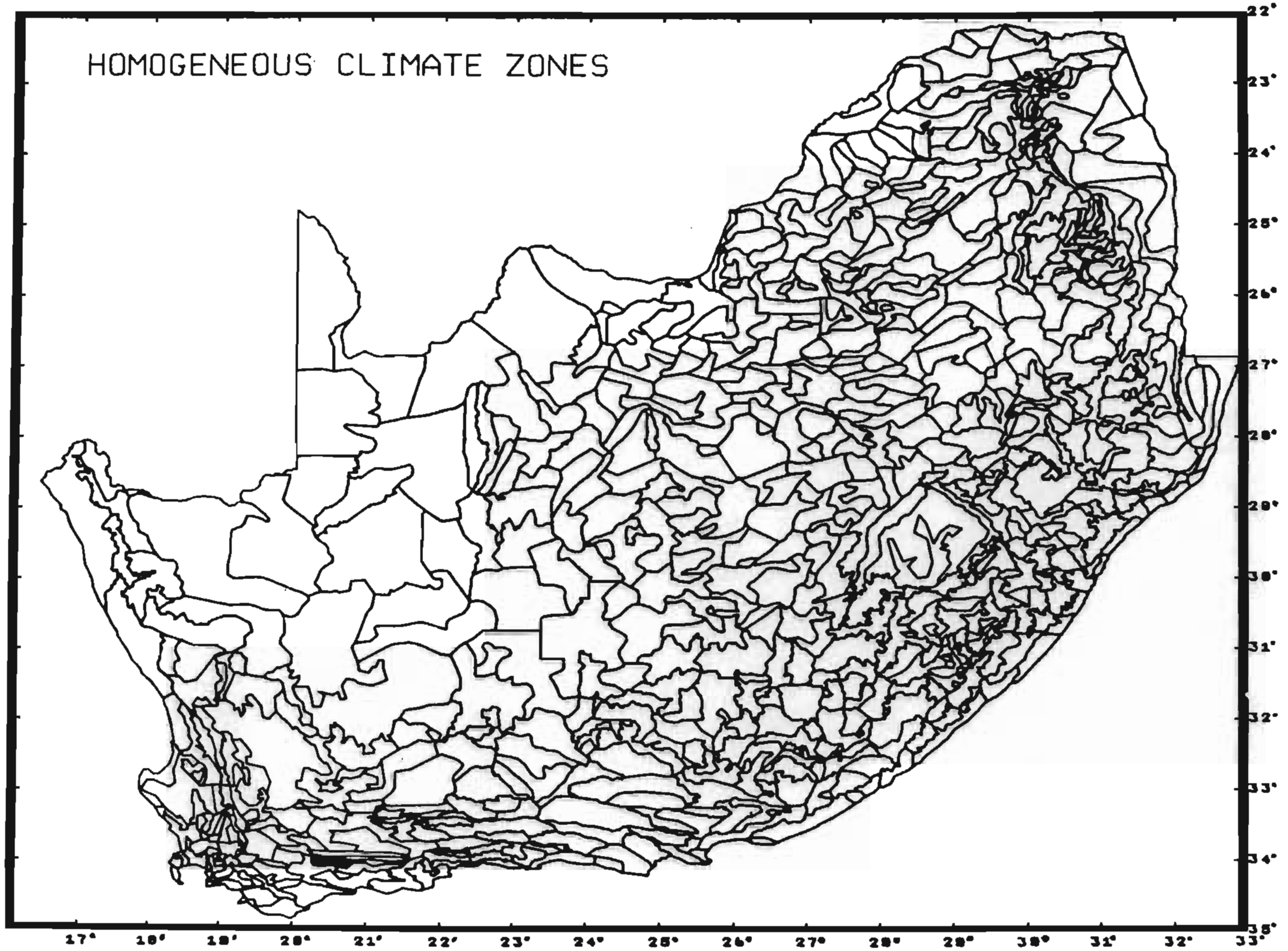


Figure 3.2 The 712 homogeneous climate zones delimited in this study

between monthly precipitation were the sole criterion in the delimitation. The statistics did, however, reveal that the stations whose monthly rainfall is well correlated tend to be clustered in close proximity to one another. This finding is significant since the seasonal distribution and inter-seasonal variability of rainfall is of fundamental importance in agriculture and particularly in a study such as that reported in this thesis.

However, the Welding and Havenga (1974) regions were not adopted for this study, for several reasons. First, the method of Welding and Havenga (1974) did not take cognizance of the mean annual precipitation at stations, since their classification was based purely on interstation monthly rainfall correlation. This was considered a major shortcoming in the light of the intended use of the homogeneous climate zones for this study. Also, the only map found depicting the Welding and Havenga (1974) regions is that which appears in their publication, and it is at a scale of 1:5 000 000 and drawn to an unspecified map projection. A further reason for not adopting the Welding and Havenga (1974) zones was that approximately six times that number of zones were required for this research work. Perusal of Figures 3.1 and 3.2 is sufficient to reinforce this point and illustrate the detail which was achieved in the delimitation described in Section 3.3.

The reasonably homogeneous farming areas (RHFA), defined by Scheepers, Smit and Ludick (1984), for the Highveld region of South Africa were noted with interest but subsequently rejected since their study area covered only a small portion of Southern Africa. The possibility of the timely publication of subsequent studies, by the same authors, and covering the rest of Southern Africa, seemed remote. Indeed this has proved to be the case. It is not possible to compare the RHFA directly with the zones delimited in this study since the latter study employed the major soil types as zonal boundaries in addition to rainfall. The RHFA's are therefore not necessarily contiguous and are fragmented and more intricate as may be seen from Figure 3.3. However, the numbers of RHFA's are considerably less than those delimited subsequently in this study for the Highveld Region shown in Figure 3.4.

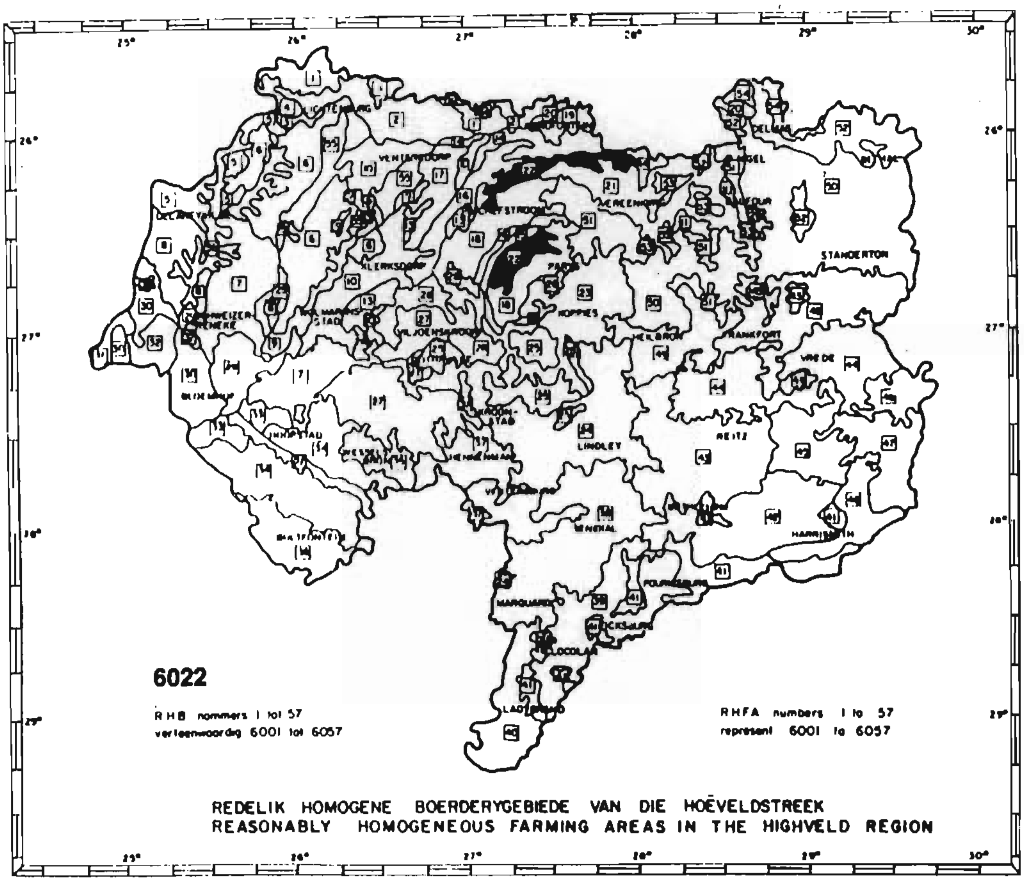


Figure 3.3 Reasonably homogeneous farming areas (RHFA) in the Highveld Region (Scheepers et al. 1984)

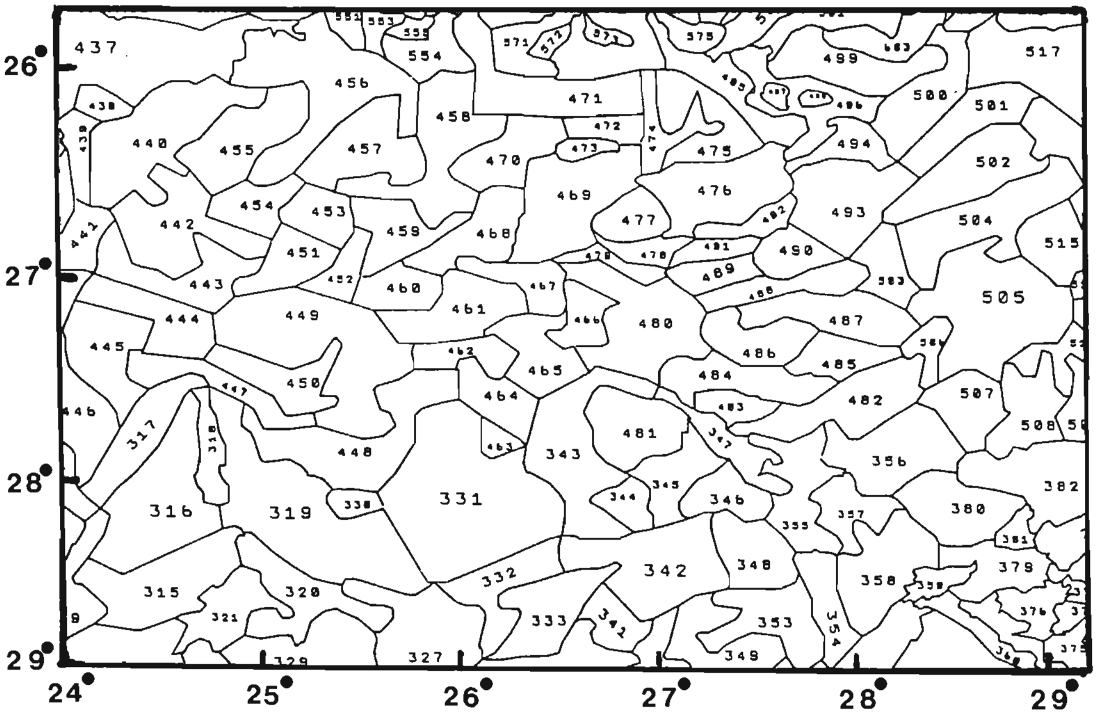


Figure 3.4 Homogeneous climate zones in the Highveld Region, delimited in this study

3.3 Technique of delimiting the homogeneous climate zones

The influence of physiography and in particular altitude on the spatial distribution of long term average rainfall has been well known for a long time. A plethora of studies, inter alia, by Spreen (1947), Schermerhorn (1967), Hutchinson (1968), Whitmore (1968), Hutchinson (1969), Duckstein et al. (1972), Lee (1973), Torrance (1973), Huff et al. (1975), McKay (1976), Schulze (1976), Storebo (1976), Dunne and Leopold (1978), Buys et al. (1979), March et al. (1979), Schulze (1979), Alexander (1980), Dingman (1981), De Villiers and Bond (1982), Hughes (1982), Schulze (1983), London and Emmitt (1986), Dent, Lynch and Schulze (1987a) support this fact.

A number of studies which concern the spatial distribution of temperatures in various parts of Southern Africa, have been conducted in the past. Studies included those undertaken by Whitmore (undated), Talbot and Talbot (1960), de Villiers (1962), South African Weather Bureau (1965), Edwards (1967), Philips (1973), Tyson, Preston-Whyte and Schulze (1976), Schulze and O'Donnell (1976), De Jager and Schulze (1977), Schulze (1979), Schulze (1981) and Dent, Schulze, Lynch and Maharaj (1987b). These studies have shown that temperatures in Southern Africa are influenced to a large extent by altitude, latitude, longitude and continentality.

It was evident on examination of the abovementioned research works that any delimitation of homogeneous climate zones would have to be based on altitude and mean annual precipitation (MAP), primarily. Fortunately, this study was conducted concurrently with a major analysis of the spatial distribution of MAP and other statistics of precipitation in Southern Africa by Dent et al. (1987a). The latter study had established the location and altitude of the rainfall stations in Southern Africa on maps of scale 1:50 000 and had prepared an altitude data set on a grid of size 1 minute by 1 minute of a degree for the entire Southern Africa as defined for this study. The classified digital image of this altitude data set and the location, MAP and length of record of all rainfall stations with more than 10 years of daily rainfall record formed the basis for the selection of "key" long term daily rainfall stations and the delimitation of homogeneous climate zones surrounding these stations.

The methodology pursued in order to effect the delimitation was as follows. A classified image of altitude covering Southern Africa was printed. The locations of all stations with 10 or more years of record were superimposed on this image. The MAP and length of record at each station was noted at the station point, as shown by the example from the south-western Cape in Figure 3.5. Thereafter followed the careful, patience-demanding and very time consuming process of delimiting homogeneous climate zones based, inter alia, on MAP, altitude and aspect, whilst keeping the zones reasonably small and consulting 1:250 000 topographic maps in order to provide a more detailed interpretation of the classified altitude map. Human judgement was used in the delimitation of the zones since such judgement was considered to be more flexible and skillful than delimitation based only upon a set of rigorous, computerised rules. The following criteria were employed as a guide in the delimitation;

(a) Altitude:
Since rainfall and temperature both vary with altitude an effort was made to restrict the range of altitudes covered by any one zone. Consequently, many of the boundary lines were drawn to follow the the classification boundaries of the image of altitude, with refined delimitation from 1:250 000 maps.

(b) MAP at long term daily rainfall stations:
Since rainfall is the primary driving force in the water budget in Southern Africa and certainly the element which is the most erratic or statistically noisy, it was decided to concentrate on rainfall as the main climatic element in the delimitation and allow the more conservative variable, temperature (for which there are also fewer stations than for rainfall), to be estimated from a station within the zone or even from a nearby zone if necessary.

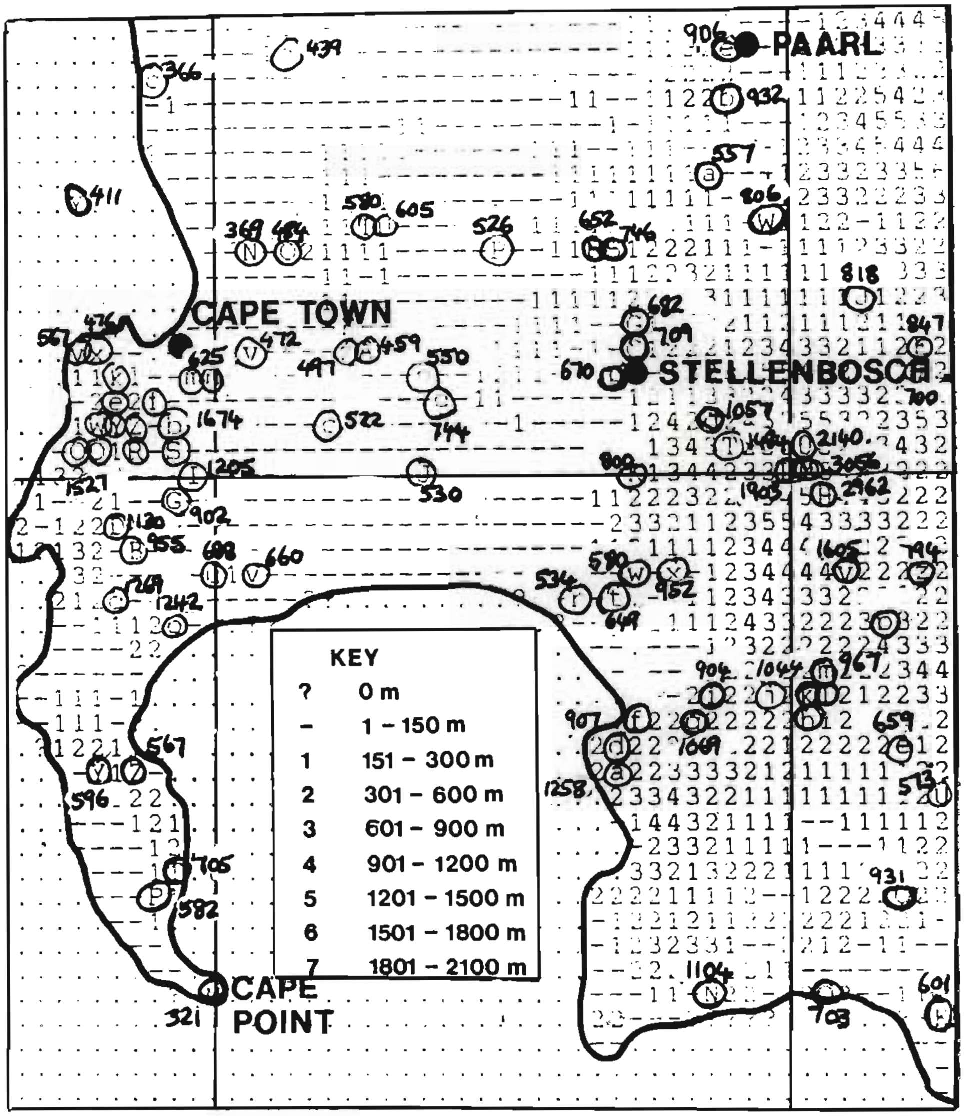


Figure 3.5 Classified image of altitude and the MAP at stations with 10 or more years of rainfall record for part of the south western Cape

The locations of all rainfall stations with 10 years or more of data, were superimposed on the abovementioned image and a key station with at least 20 years and preferably more than 30 years of daily rainfall data was selected from the above in each altitudinal zone. The zones were chosen to reflect a limited range in MAP.

(c) Geographic proximity:
Welding and Havenga (1974) delimited 114 homogeneous rainfall regions in Southern Africa, using interstation correlation techniques and found that stations whose rainfall was highly correlated on a monthly basis, fell into the same geographic area generally. Reasonably small geographic areas i.e. small in relation to the size of the weather systems, are likely to be homogeneous with respect to long term patterns of daily rainfall and temperature, particularly if the designated area has a small range of MAP and altitude. Most of the zones which were delimited in the present study have a range in MAP of less than 100 mm.

The question of the spatial constraints on linear extrapolation of daily raingauge measurements is discussed further in Section 6.1.1.

(d) Aspect:
The direction of movement of weather systems can have a marked influence on rainfall amounts, especially in mountainous areas. An attempt was made therefore to delimit zones according to broad aspect in mountainous areas. Allowances were thus made for rainshadow areas e.g. in the south-western Cape. Meso-scale effects of solar radiation loading due to aspect were thereby also included in the zoning.

(e) Terrain:
In mountainous areas, zones were reduced in size to allow for more rapid spatial variations in altitude and hence rainfall, temperature and aspect. Zones tended to be larger in flat areas.

The lack of rainfall stations in Lesotho made it an exception to this trend.

(f) Agricultural activity:
In areas where the limited amount and spatial variation of rainfall curtails the variety of agricultural activity, larger sized zones were delimited, for example in the northern Cape. The relatively homogeneous farming areas which are being delimited by the Department of Agriculture and Water Supply and which were reported on by Scheepers _et al_. (1984) have only been completed for the Highveld Region and therefore could not be used for this countrywide study. By way of comparison this study yielded 89 homogeneous climate zones in the Highveld Region as compared with 57 by Scheepers _et al_. (1984).

Based on these criteria, 712 zones were delimited and the boundaries of these zones were digitized to a resolution of 1 minute of a degree (±1.6 km) and stored for computerised plotting. An example of this detailed delimitation is presented in Figure 3.6 and the complete map of zones in Southern Africa appears in Appendix A.

It may be argued that 712 zones is too fine a delimitation. However, it was decided to proceed with the process of pattern recognition by humans, based on the above criteria. Zones may always be grouped subsequently by the user for specific tasks.

3.4 Computerisation of climate zone boundaries

It was considered necessary to capture the zonal boundaries in computer compatible form for several reasons. First, it enables the production of the map of the zones, shown in Figure 3.2, at any desired scale and to any map projection for overlay purposes. Secondly, once the co-ordinates of the boundaries are in computer compatible form it is possible to classify each of the nearly half a million grid points in the 1 minute by 1 minute data base of altitudes, MAP, mean monthly rainfall, other statistics of rainfall and several physiographic

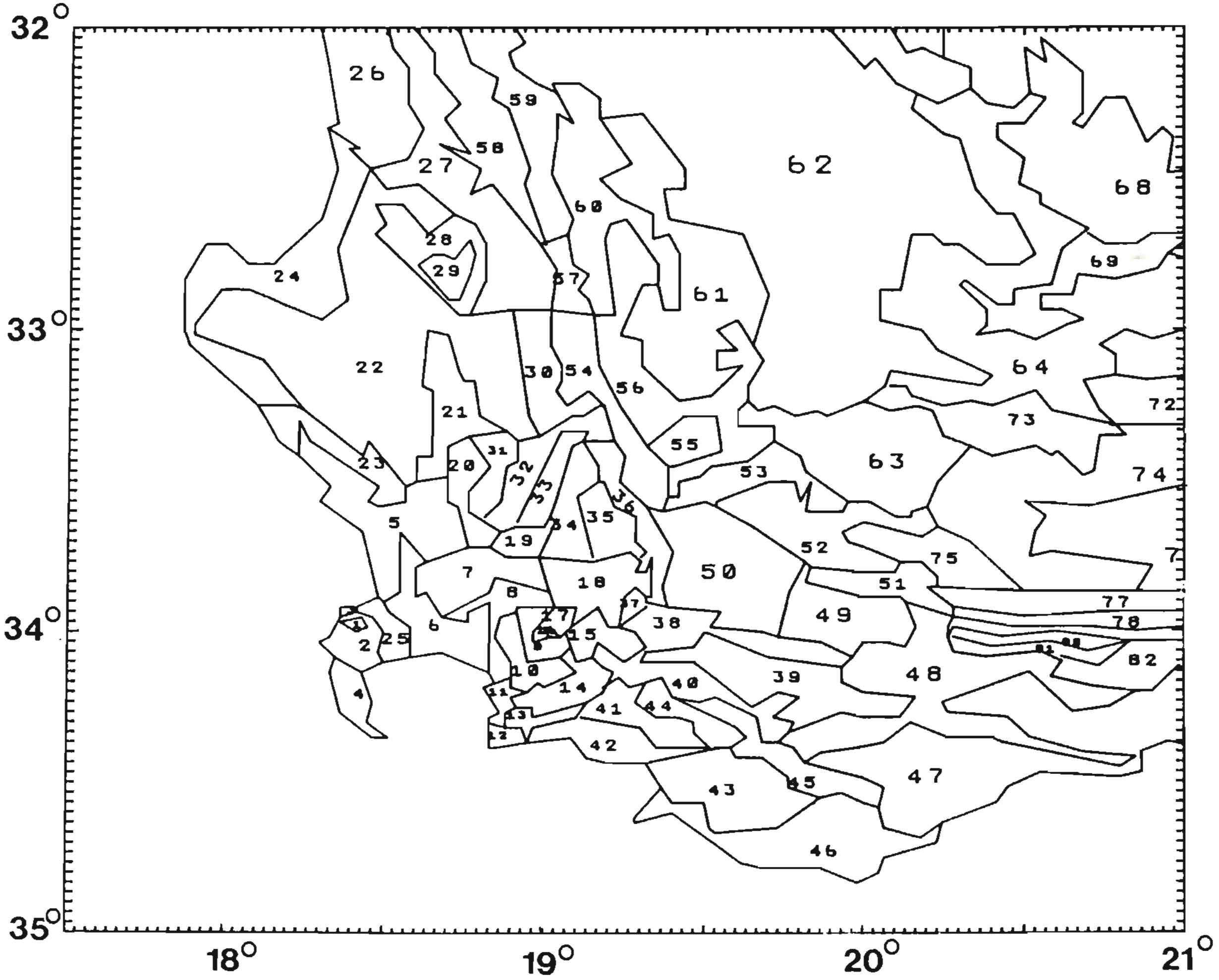


Figure 3.6 Delimitation of homogeneous climate zones in the south western Cape

variables, developed by Dent, et al. (1987a), into one of these climate zones. The potential of this procedure for regional agrohydrology and water resources is truly exciting.

The zone boundaries were drawn on printouts of the classified digital altitude image similar to that shown in Figure 3.5. These zone boundaries were digitised in segments. Each segment was labeled according to the zones which were separated by the segment, for example, segment 031019 separates zones 31 and 19. When all the segments had been digitised a computer program was developed which duplicated each segment and sorted the segments into the correct sequence to form the boundary points for each zone. The duplication was necessary since the boundary segment 031019 which separates zone 31 and zone 19 is also segment 019031, i.e., the separation between zone 19 and zone 31. The segment data were thus manipulated so that each zone boundary was uniquely defined by its own named segments, for example all the 019... segments are boundaries of zone 19 and the 031... segments are boundaries of zone 31. These zones may therefore be plotted individually or in groups. The precision of the plotter at the Computing Centre for Water Research (CCWR) is such that the lines are plotted twice and yet are indistinguishable, one from the other. This technique overcame a major problem which occurs frequently with this type of digitising due to the fact that it is virtually impossible to digitise the same line twice and obtain exactly the same digitised points. Apart from the fact that this looks unacceptable when plotted it poses real problems to the algorithm which classifies the grid points into regions, since errors induced by digitizing a boundary twice would make it possible for a point to fall in two regions or alternatively into no region at all.

4 THE ACRU AND IRRIGATION SOIL MOISTURE BUDGET MODELS

Two soil moisture budget models were used in these analyses. The ACRU model developed by Schulze and others over a number of years and described in detail by Schulze (1984b; 1986) was used for the dryland analyses. A new model which followed most aspects of the ACRU model, with respect to the soil moisture budgeting components, was developed in this study for the analyses under irrigated conditions. The irrigation model and the criteria which determined its structure are discussed in Section 4.2.

The ACRU model was selected for this study since;

(a) the ACRU model has been the subject of continual development for the past 10 years in the Department of Agricultural Engineering at the University of Natal;

(b) the ACRU model has been presented to scientific audiences worldwide and in addition the model has been researched and developed for a year in the U.S.A.;

(c) the ACRU model uses daily rainfall and estimates potential evaporation using temperature; and lastly

(d) the ACRU model has been tested in this and other studies against a range of observed data sets, including lysimeters, neutron probe measurements of soil moisture from field sites and runoff volumes and peaks for a wide range of catchment and climatic conditions.

4.1 Concepts and structure of the ACRU model

The ACRU model is described by Schulze (1986) as a conceptual physical model. It is conceptual in the sense that it conceives of a one-dimensional system in which the important processes are idealised and operate in discrete time units. The ACRU model is physical to the degree that the ability of the soil to store and transmit water is represented explicitly and that water use by vegetation is simulated using variables which, according to Schulze (1986), would be observable if the hydrological system met the idealisations made.

Schulze (1986) states that ACRU is a multipurpose model, outputting, inter alia, runoff elements (stormflow, baseflow, design volumes/ peaks) with associated reservoir yield analysis; irrigation demand/ water supply analysis; seasonal crop yields (e.g. maize or sugarcane, dryland or irrigated). For this study the monthly evapotranspiration deficit i.e. the difference between the potential and actual monthly evapotranspiration and a stress day index were also included in the output.

The model uses daily time steps and thus daily input of climatic data. Monthly models are too coarse for many applications in Southern Africa, where hydrological and agricultural response is highly sensitive to a frequently sporadic rainfall distribution over time (Schulze, 1986). Evaporation and temperature (which is used to estimate evaporation) are more cyclic, conservative and less sensitive variables and may be input at monthly level. These monthly values are discretized to daily values in the ACRU model by Fourier analysis.

4.1.1 Estimation of evapotranspiration in the ACRU model

The ACRU model has been developed into a versatile actual evapotranspiration model (Schulze, 1986) and is capable of conducting daily soil moisture budgeting in the A and B horizons simultaneously. It is therefore sensitive to the effect of land use changes on the soil moisture and runoff regimes and to effects of supplementary watering by irrigation. Budgeting by partitioning of the rainfall and distribution of soil moisture is depicted in Figure 4.1. That rainfall application not abstracted as interception or as stormflow (quickflow or delayed), first enters and resides in the A-horizon. The methods whereby the ACRU model

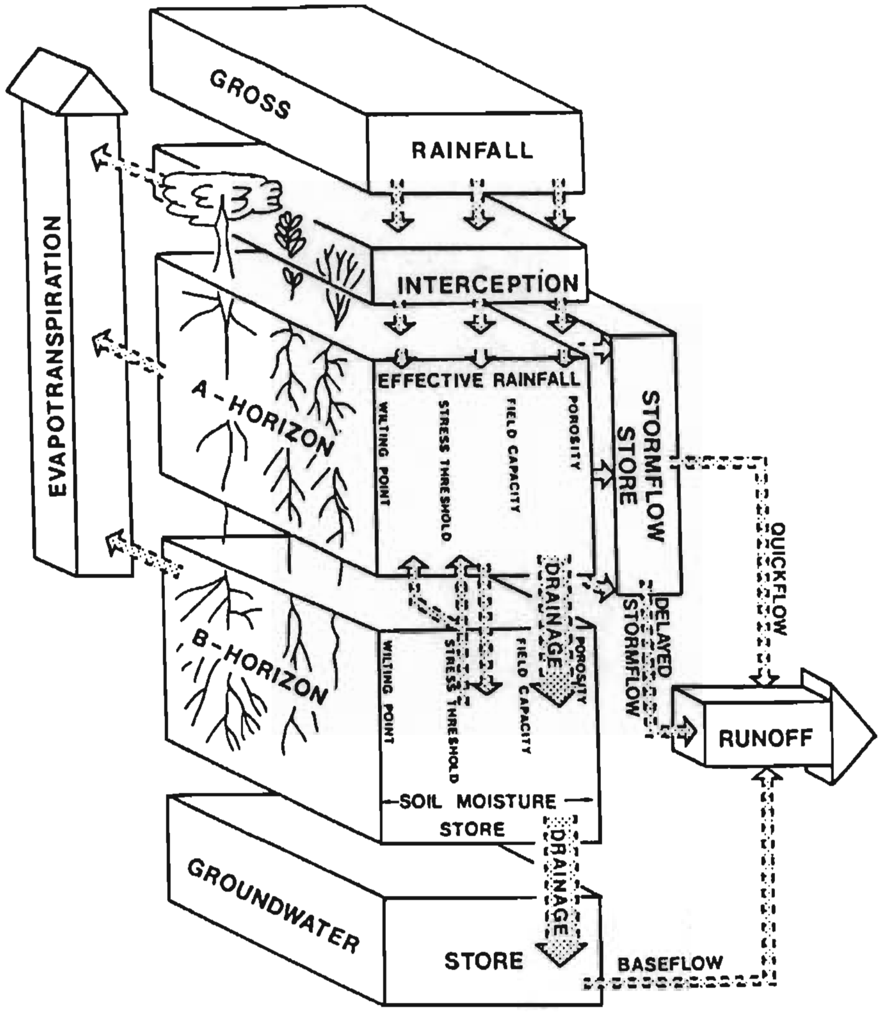


Figure 4.1 The ACRU model structure (Schulze, 1984b)

estimates stormflow and delayed flow are discussed in Section 4.1.2. When the A-horizon is filled, the remaining water percolates into the B-horizon. Vertical drainage into the groundwater store takes place when the soil moisture in the B-horizon exceeds field capacity. Baseflow is then generated from this groundwater store. Evapotranspiration takes place from the A- and the B-horizon and from previously intercepted water. The plant transpiration is estimated according to its stage of growth and the roots absorb water from the soil in proportion to a preselected rooting distribution in the respective horizons.

It is important in soil moisture budget modelling to determine at what point in the depletion of the plant available moisture reservoir, plant stress actually begins since stress indicates the need to irrigate and also if allowed to continue, will reduce crop yield. For the purposes of modelling this point is often expressed as the critical soil moisture content at which actual evapotranspiration (AET), is reduced to below the potential evapotranspiration (PET) for the plant at that particular stage of growth.

Experimental evidence, reported inter alia by Mather (1978) and Slabbers (1980), shows that AET equals PET until a certain fraction (f), of plant available soil moisture (PAM) is exhausted. Beyond this fraction the reduction of AET depends, inter alia, on the remaining water and the PET demand. The literature of the past two decades has frequently attributed differences in (f) to soil textural properties, whilst according to Green (1985), irrigation modellers assume that AET becomes less than PET at a fixed soil moisture content, for example 0,5 PAM. The ACRU model follows Slabbers (1980) by including an option to calculate the critical (f) value daily as a function of inherent plant physiological properties and atmospheric demand. . However, for the purposes of this study it was assumed that the ratio AET:PET drops below unity when soil moisture equals 0,5 PAM. The ratio AET:PET is assumed to decrease linearly with soil moisture from a soil moisture of 0,5 PAM to zero PAM i.e. wilting point.

In this study potential evaporation (PE) was estimated using monthly mean maximum and minimum temperature and other variables through the Linacre (1977) equation as discussed in Section 6.2.3. However, on rain days the PE was reduced to 0,8 PE since it was assumed that on these days the cloudiness associated with a rain day will reduce the PE to below the average daily value. Conversely, on non-rain days the PE was adjusted up by 5 per cent since it was assumed that on such days the PE would be above the mean daily value for the month. This assumption stems from a sub-study in which the daily rainfall and daily Class A-pan evaporation records from all the stations on the Department of Agriculture and Water Supply data files (approximately 740 000 daily values) were used in a comprehensive analysis designed to investigate the approximations of the above assumptions concerning adjustments to the mean PE. The following methodology was adopted in this sub-study.

The mean daily evaporation value was calculated for each month of the record at each station. Thereafter the daily evaporation for each day was divided by the mean daily evaporation value for that month. The abovementioned quotients were stored and a frequency analysis was performed on the rain day (>5 mm rainfall) and non-rain day quotients, separately. The results, which are presented as frequency distributions in Figure 4.2 show that the median value of the quotient on rain days is 0,8 and on non-rain days is 1,05, hence supporting the above assumption. It is also interesting to note from these distributions that 80 per cent of the values of the daily evaporation lie between ± 50 per cent of the mean daily evaporation for that month. The significance of this latter and others findings of the abovementioned sub-study, will be discussed further in Section 6.2 wherein the whole question of temperature based estimation of PE is discussed with particular reference to this study.

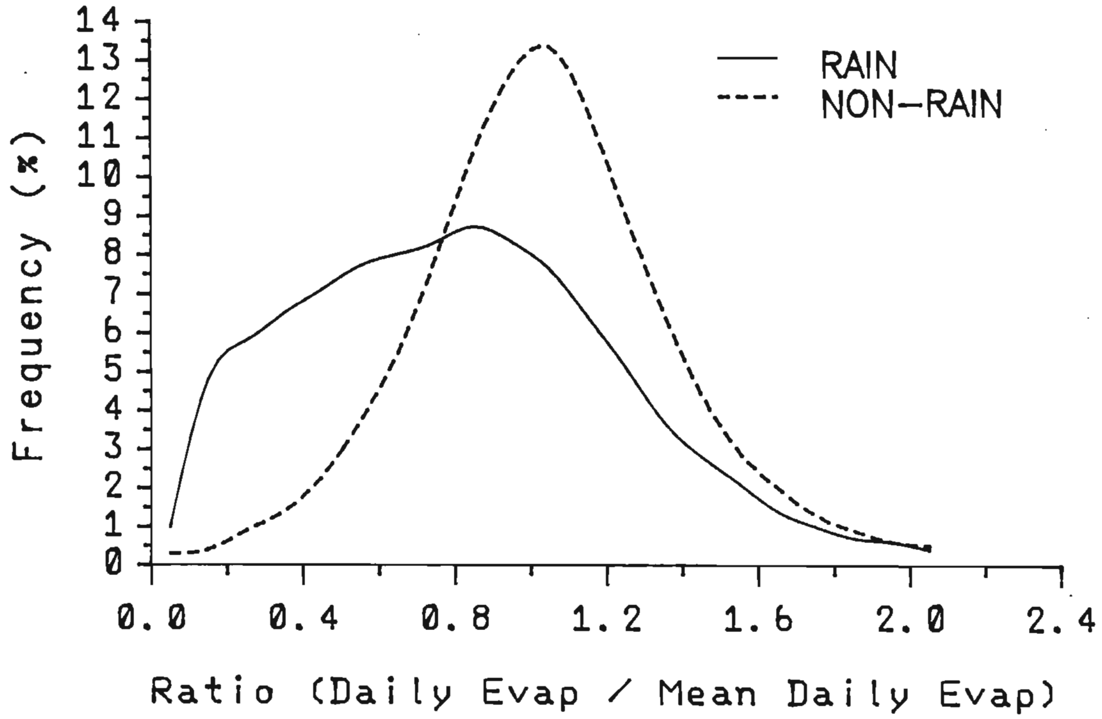


Figure 4.2 Frequency distributions of the ratio daily evaporation to the mean daily evaporation for the month, for rain days and non-rain days

4.1.2 Estimation of runoff in the ACRU model

Schulze (1982) showed that the use of soil moisture budgeting could produce marked improvements to stormflow estimates by the SCS curve number method. This improved SCS method of estimating stormflow was therefore incorporated into the ACRU model as described by Schulze (1984b; 1986). The method considers the variable S, (where S = potential maximum retention of water by the soil) in the SCS equation for stormflow volume, as a soil moisture deficit i.e. the difference between total saturation and the soil moisture content immediately prior to the rainfall event. The variable, S, therefore has a low value when the deficit is small and a high value when the deficit is large. The soil moisture condition of the A-horizon or a lesser but preselected depth is assumed to control the stormflow runoff and therefore S is estimated for this depth. In the dryland analysis reported in this study the depth was selected equal to the A-horizon depth. The assumptions made in this study with regard to the depths of the A- and B-horizons are presented in Appendix C. The coefficient of initial abstraction in the SCS equation was assumed to be 0,2. The stormflow thus estimated, using the modified SCS equation described by Schulze (1982), does not enter the soil and therefore is not considered further in the soil moisture budget.

The moisture which is held in the soil at levels above FC is assumed generally to drain to the B horizon or to groundwater at a rate of 50 per cent of remaining excess water per day, following Ritchie and Otter (1984). However, this A to B response as it has been termed by Schulze (1984b) may be varied depending on the soil type. The A to B response factors used in this study are listed in Appendix C. The stormflow and the abovementioned drainage are combined to form the total runoff. However, whilst this drainage is taking place, evapotranspiration continues to draw from the reservoir of soil moisture above FC, for as long as it is available.

Irrigation water is assumed to be absorbed into the soil completely and no runoff losses therefore occur from this source. It is assumed that the irrigator will apply water at a rate which will not create runoff. It is conceded that such practice is often not the case particularly with regard to the periphery of centre pivot irrigation schemes. However, it is an attainable objective and therefore such an assumption seemed reasonable. A similar assumption regarding the complete absorption of irrigation water was applied to the irrigation model described below.

4.2 The irrigation model

The moisture budgeting component of the irrigation model mimics that of the ACRU model, as far as possible, within the limits imposed by the criteria and design philosophies discussed in the following sections. However, the rest of the routine has a structure which represents a marked departure from the norm for such models. Before describing the structure of the irrigation model it is considered appropriate to present the thoughts, philosophies and criteria which formed the concepts that led to its structure and hence to its ability to provide estimates of crop water requirements for planning in South Africa in accordance with the objectives of this study as presented in Section 1.2.

4.2.1 Design criteria adopted for the irrigation model

The Co-ordinating Committee for Irrigation Research (CCIR) (1986) encapsulates, most aptly, one of the central thoughts underlying the development of the irrigation model and the associated techniques for presenting the results.

"The main requirement of any management model is usefulness in decision making, not sophistication or elegance <u>per se</u>" (p2) Co-ordinating Committee for Irrigation Research (1986).

The question of model complexity and also the distinction between modelling for planning as opposed to scheduling purposes was discussed in some detail in Section 2.3. Arising out of the philosophies expressed in Section 2.3 and also a desire to ensure the usefulness of the results of this study, in planning, several design criteria were determined for the irrigation model as well as the techniques employed to present the output from this model.

These criteria were:

(a) that the soil moisture budgeting aspects of the model should, where possible, mimic the ACRU model described by Schulze (1984b; 1986) for the reasons discussed at the beginning of Chapter 4;

(b) that the estimated irrigation water requirements should be known to be of relevance throughout a small but specified climatic zone and not only of known relevance at a single site and for a specific set of crop and soil conditions;

(c) that the volume of output be condensed to a manageable format whilst maximising the information content thereof;

(d) that the results be simple to use, thus only requiring of the user a local knowledge of the physical properties of the soils, plant rooting depth, crop factor and planting time whilst the climatic data need be of no direct concern to the user;

(e) that the results should accommodate a large range of combinations of the abovementioned land use variables;

(f) that the monthly irrigation requirement be estimated using a demand mode type of analysis, i.e. that irrigation water be applied by the model when the PAM in the root zone of the single layer irrigation model reaches a predetermined level of soil moisture and not at fixed cycle times; and

(g) that the results should assist the user to perform a risk analysis on the estimated irrigation water requirements.

To meet the abovementioned criteria it became apparent that the input variables required by the model would have to be divided into two major categories viz. a category of area-specific or zone-specific variables and one of site-specific variables which relate to a particular site and cropping system. The zone-specific variables were daily rainfall and evaporation. The high spatial variability of daily rainfall is recognised; however, the location of existing long term daily raingauges means that rainfall has, for practical purposes, to be considered specific to or to pertain to a relatively large area. In the context of this study these areas were delimited as the homogeneous climate zones discussed in Chapter 3. With respect to the site-specific variables of crop type, plant population density, planting time, soil type, soil depth and rooting depth, the key to providing for all possible combinations of the above and still fulfilling the criterion which required a condensed volume of output, lay in grouping these variables. As far as the soil moisture budget is concerned the variables of crop type, plant population density, planting time, soil type, soil depth and rooting depth may all be expressed in terms of crop factor and PAM i.e. (FC - WP) in the root zone. Or, in engineering terms, the size of the pump and the depth of the reservoir. The long term daily water budget was therefore modelled using a range of combinations of crop factor and PAM. The irrigation water requirements at the 50, 80 and 90 percentile levels of non-exceedence i.e. that these levels of required monthly irrigation amount will not be exceeded on 50, 80 and 90 per cent of occasions, were extracted for each combination. In this manner the condensed format and flexible usage of the output and also the risk analysis criteria for the model design were accommodated.

4.2.2 Concepts and general structure of the irrigation model

The soil moisture budgeting components of the irrigation model follow, in most respects those of the ACRU model described in Section 4.1. This soil moisture budgeting module which allows for the application of irrigation water when necessary is embodied within an overall controlling program which consists of several major process loops as shown in Figure 4.3. The irrigation model was developed into a quasi two layer model in the sense that the runoff component was controlled by the top 200 - 300 mm of soil only, as described in Section 4.2.3.

It should be stated at the outset that the irrigation water requirements estimated by the method outlined below did not differ significantly from those estimated by the conventional continuous mode soil moisture budgeting methods, employed in the ACRU model, for example. The tests which show this are discussed in Section 5.2.3. In view of this similarity, it was decided to pursue the process outlined in Figure 4.3 and described below since it afforded greater ease of programming and input data manipulation.

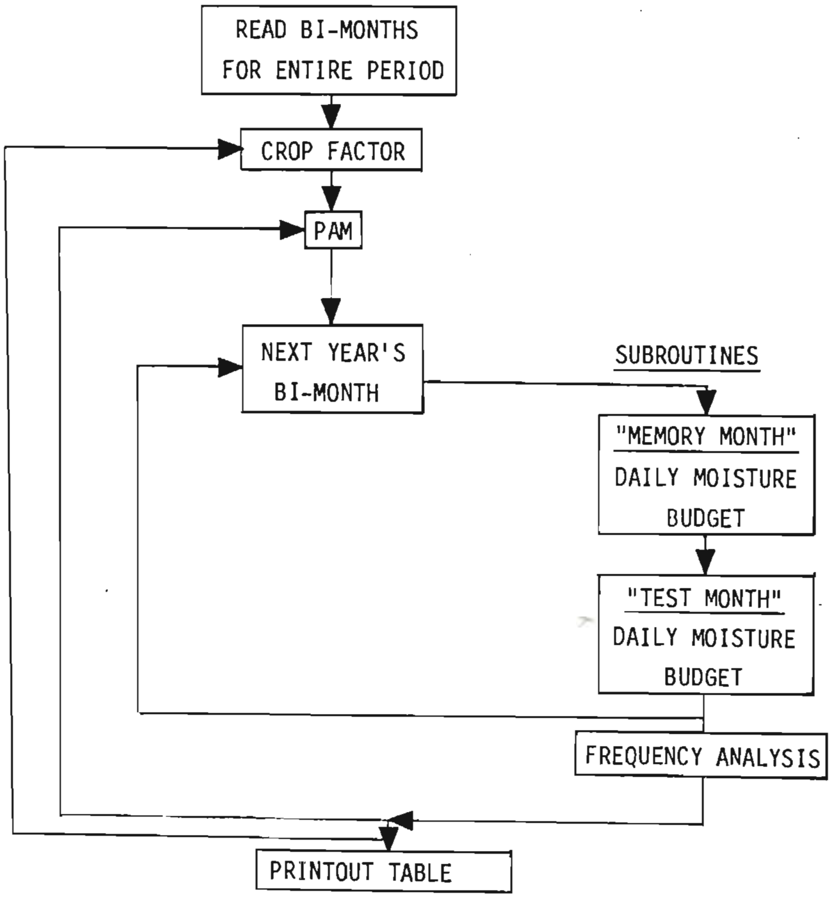


Figure 4.3 Schematic flow chart of the main controlling program for the irrigation model

The controlling program consists of several do-loops and three subroutines. The daily rainfall data are not processed in the monthly sequence, January through to December as is normally the practice in soil moisture budgeting models. Rather the program processes the entire record of rainfall data for January and for a particular crop factor and PAM combination. This procedure is repeated until all the combinations of crop factor and PAM are processed using rainfall data for January. Thereafter the soil moisture budget for February and the remaining months of the year is processed in the same manner. This structure ensures that every combination of crop factor and PAM is processed through the moisture budgeting model for every year of the data record and for all 12 months. A frequency analysis is carried out on the monthly irrigation requirements over the entire record, for each combination of crop factor, PAM and month. A four dimensional array, consisting of the crop factor, PAM, a frequency level of non-exceedance and month of the year is thus generated and the estimated monthly irrigation requirements are contained as the elements in this array. The printout of this array forms the output of the irrigation model, an example of which is presented in Table 7.5.

The selection of a soil moisture content at which to begin the budgeting process is a problem that must be addressed by all exponents of these moisture budgeting models and which is also present here. The assumption adopted in this model, to ensure a random initial soil moisture content in the test month, i.e. the month reported in the analysis, was that the soil moisture had a month long memory. The memory month is taken as the month preceding the month under test. The soil moisture budget is carried out for this memory month and the soil moisture at the end of the memory month is increased to account for the increased rooting depth. This provides an estimate of the starting value of soil moisture in the test month, which includes some recognition of possible deep percolation in the memory month, i.e. recognition that the roots will in all probability be growing into soil which is at a moisture content equal to field capacity. In the moisture budget of the memory month irrigation water is applied when it is required. In addition, the values of the crop factor and PAM for the memory month are reduced to 0,8 of their value in the test month. The growth in crop factor and rooting depth was reflected by this assumption. It is recognised that there are other ways in which a random starting point for soil moisture in the test month could be found, for example by utilizing a random number. However, the chosen method was considered to be realistic. The initial soil moisture in the memory month is assumed to be 75 per cent of the maximum PAM in that month. Figure 4.4 illustrates the memory month and test month moisture budgeting concept employed in this study. Some concern was expressed initially by critics of this approach, that the initial soil moisture in the test month would be unrealistic, in view of the relatively short period of soil moisture budgeting preceding the test month. However, as mentioned earlier, tests discussed in Section 5.2.3, show, that under an irrigation regime, there are virtually no differences between the crop water requirement from irrigation at either the 50, 80 or 90 percentile levels, when using the abovementioned discrete method and when using a continuous soil moisture budgeting approach. These tests proved that the soil moisture memory period of one month is sufficient under an irrigation regime, such as that employed in this study.

4.2.3 Procedures and sequences of soil moisture budgeting in the irrigation model

The moisture inputs are daily rainfall and irrigation water. The rainfall or irrigation amounts are always applied at the end of the day. i.e. after the AET and drainage have taken place and hence depleted the soil moisture content for that day. PE is estimated using the Linacre (1977) equation and, as with the ACRU model, PE is set at 0,8 PE on days on which rainfall is > 5 mm and 1,05 PE on rainless days, as discussed in Section 4.1.1. PE is calculated using mean monthly temperature. Interception loss is set at a value equal to 2 mm multiplied by the crop factor. This was considered a reasonable assumption following interception values presented by de Villiers (1978; 1980). Interception loss thus increases with the stage of growth of the crop. As in the ACRU model the stormflow runoff is estimated using the modified SCS equation, described in Section 4.1.2, and which is assumed to operate only on a top portion of the active root zone as will be described later in Section 4.2.3. The remaining rainfall, i.e. rainfall minus interception loss and minus stormflow then enters the soil as effective rainfall. The irrigation amounts which are applied to the soil by the

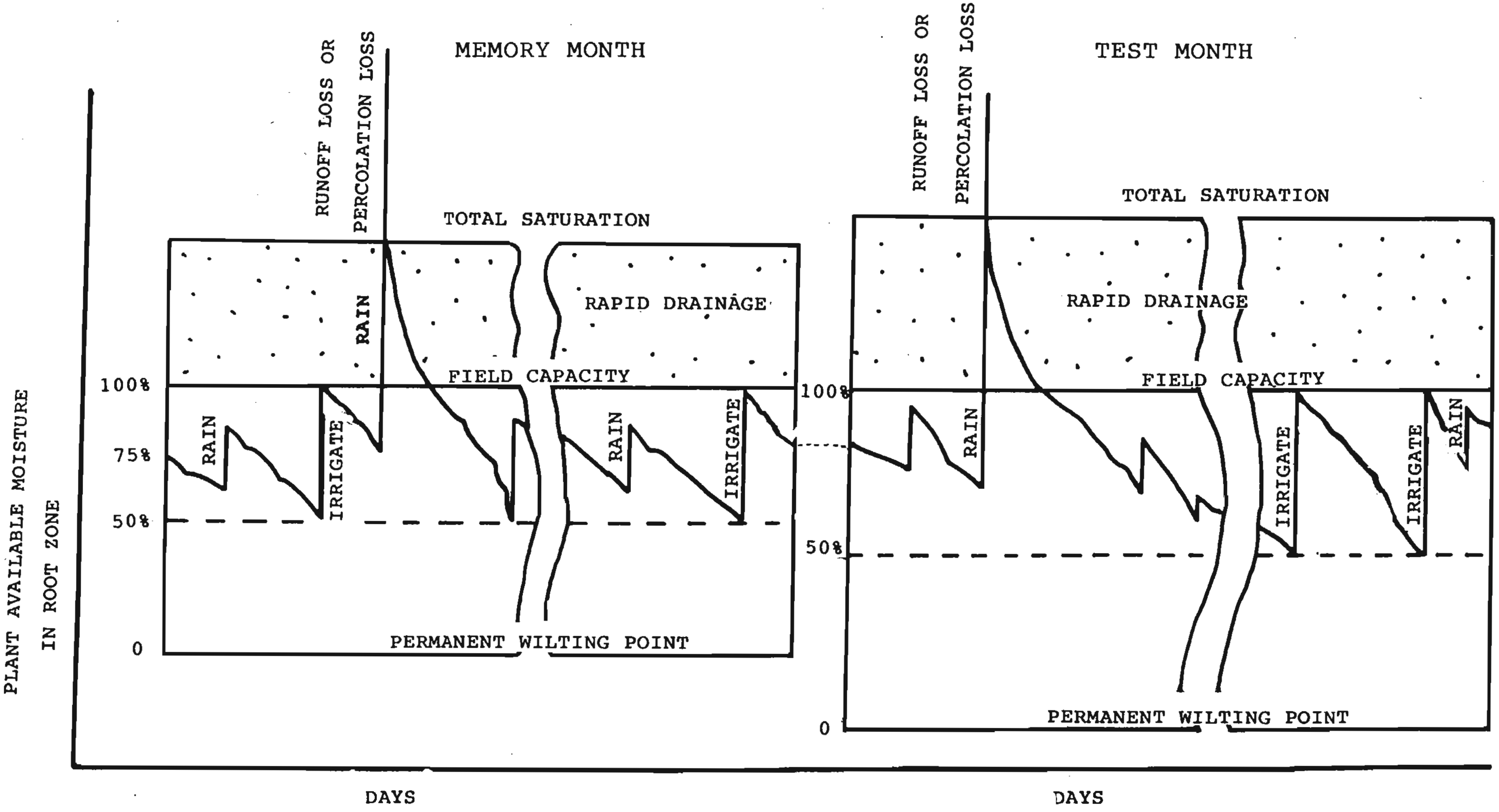


Figure 4.4 Graphical presentation of the procedure for budgeting soil moisture in the irrigation model

model are assumed to include zero runoff loss since the attainment of zero runoff during irrigation is a goal of most irrigators. When applying the results of this study it is therefore necessary to make provision for any expected losses in this respect.

In order to retain the generality of the output and also to fulfill one of the primary objectives of this study, viz. the reduction in the volume of output, it was necessary to make a number of assumptions concerning the input of soils information to the model.

Before describing the assumptions relating to the creation of two layers in the model prior to estimating stormflow runoff it is necessary to provide some background to these assumptions. The soil moisture store is modelled as a single layer in respect of the plant water uptake component. Since the rooting distribution is not specified it would have served no purpose to split the soil into two components for this aspect of the modelling. However, the soil moisture store is split into two distinct conceptual components, viz.:

(a) the plant available moisture (PAM) in the root zone i.e. FC-WP and

(b) the moisture held in the pore space above FC.

The latter has been assumed to have a maximum water holding capacity equal to 1,5 times PAM (where PAM = FC - WP). This value has been assumed since it is approximately the median value of the last column in Table 4.1, i.e. corresponding to silty loam. The sensitivity, to this assumption, of the crop water requirement from irrigation was tested and the results of these tests are discussed in Section 5.2.2. The soil moisture retention values deduced by Schulze, George and Angus (1987) from literature by Dunne and Leopold (1978), Brakensiek, Engleman and Rawls (1981), Rawls and Brakensiek (1982), Hutson and Joubert (1983), and Hutson (1984) and which are presented in Table 4.1 were consulted before making the above assumption. These values of soil moisture retention are also used in the ACRU model for the dryland analyses.

The moisture which is held at levels above FC is assumed to be free to drain to groundwater at a rate of 50 per cent of remaining excess water per day, following Ritchie and Otter (1984). However, whilst this drainage is taking place, it is assumed that evapotranspiration continues to draw from this reservoir of soil moisture (above FC) for as long as it is available. The drainage rate affects this period, however.

Fortunately, if one considers the assumption regarding drainage rate in conjunction with the assumption covering soil moisture storage above FC it is apparent that in terms of days required for drainage that the two assumptions complement each other well. For example the (POR-FC) for clay is less than 1,5 * PAM but the drainage rate is also less than 0,5 of the daily excess water per day. Similarly the (POR-FC) for sand is more than 1,5 * PAM but the drainage rate is more than 0,5 of the daily excess water per day. The net result of these compensating errors in the assumptions is that the number of days during which the plant will be able to make use of such excess water is more or less the same for sand, loam and clay soils. The quantitative effects of these assumptions on the estimated crop water requirement from irrigation are discussed in Section 5.2.2.

Returning to the estimation of stormflow runoff it is only a top portion of the active root zone which is assumed to exercise control. The depth of the active root zone and the soil type are not specified directly to the model. The variable which accounts for these aspects in the model is the PAM and therefore any new term required for the estimation of stormflow runoff would need to be a function of PAM. A term code named SATSCS was introduced for this purpose. SATSCS represents the potential maximum soil moisture retention (i.e. from WP to total saturation) in the portion of the soil profile which is assumed to affect stormflow runoff. SATSCS was set to (2,5 * PAM) mm for values of PAM < 30 mm and equal to (2,5 * 30) mm for values of PAM > 30 mm. The value of 30 mm was chosen since from Table 4.1 a value of 30 mm would represent a soil depth of approximately 300 mm in sand loam and 200 mm in silty loam or silty clay loam. These are similar to the depths chosen for the A-horizon and which affects stormflow runoff in the ACRU model. The desirability of implementing the abovementioned assumptions was evident when the field data sets of soil moisture, discussed in Section 5.2.1, were compared with the daily estimate of soil moisture using the irrigation model. In this manner a differentiation was achieved with respect to the effects on stormflow generation of the various soil textures. The sensitivity of the estimated crop water requirements from irrigation to the factor 2,5 in the above assumption is discussed in Section 5.2.2.

Potential evaporation is estimated according to the Linacre (1977) equation, incorporating regional adjustments and using mean monthly temperature and not daily temperature or pan evaporation. These aspects are discussed in Section 6.2 and test results are presented to illustrate the acceptability of such techniques. The actual evapotranspiration is assumed to proceed at potential rate, i.e. the ratio AET : PET equal to one, until the soil moisture is depleted to 0,5 PAM, whereafter the ratio AET:PET declines linearly to zero at soil moisture equal to wilting point. Irrigation water is applied to the soil when the moisture content (in the root zone) is reduced to 50 per cent of PAM in the root zone. The irrigation amount is dependent on the PAM in the root zone and is set according to the values shown in Table 4.2. and which are calculated to fill the soil to FC. These irrigation amounts are accumulated and contribute to the monthly irrigation requirement as expressed by Eq. 4.1 (p.63).

Table 4.1 Soil moisture retention values (Schulze et al., 1987)

	TOTAL POROSITY (mm/m)	FC (mm/m)	WP (mm/m)	FC-WP (mm/m)	$\frac{\text{POR-FC}}{\text{FC-WP}}$ (mm/m)
Clay	482	416	298	118	0.56
Loam	464	251	128	123	1.73
Sandy	430	112	50	62	5.13
Loam sand	432	143	68	137	2.11
Sand loam	448	189	93	96	2.70
Silty loam	495	272	121	151	1.50
Sandy clay loam	402	254	159	95	1.60
Clay loam	468	312	195	117	1.30
Silt clay loam	473	335	190	145	0.95
Sandy clay	423	323	228	95	1.10
Silty clay	480	390	253	137	0.66

Table 4.2 Irrigation application amounts used in the model

PAM in root zone (mm)	Application amount (mm)
20	10
45	22.5
70	35
100	50
150	75
200	100

The fact that the model is programmed to apply an amount of water to the soil when the PAM reaches 50 per cent of the total PAM (regardless of the rainfall for the following day) is a feature which makes the timing of any rainfall important. Consider two seemingly identical cases, one in which a rainfall amount occurs one day before the irrigation is due and the other case in which that rainfall is just one day too late. In the latter case, the rainfall, if it is substantial, will be largely ineffective as most of it will be accounted to runoff. However, in the former case, that rainfall amount could have saved an irrigation setting. The circumstances described above could well occur under real irrigated conditions and therefore this is not something for which preventative action should be taken in the model. It should be appreciated however that the abovementioned does introduce some uncontrolled noise into the soil moisture budgeting system and this may have an effect on the estimated irrigation requirement in some cases. However, this is a relatively minor problem when compared with the differences which occur between estimates made under a demand mode regime (i.e. application only when required) and a fixed cycle irrigation regime. Furniss (1987) showed that the irrigation requirements in areas which receive approximately 900 mm MAP, are increased markedly when fixed cycle irrigation is applied. Large savings of the order of 30 to 40 per cent can therefore be effected in the humid areas by irrigating in demand mode i.e. only applying irrigation water when the soil moisture reaches a predetermined level of depletion. Such a practice requires more care in scheduling and greater management skills than a fixed cycle practice and it only introduces worthwhile savings in areas of high rainfall (Furniss, 1987). It must be stressed that the irrigation water requirements estimates which are presented in this study are made under demand mode simulated conditions and therefore reflect requirements which may, in areas where supplementary irrigation is practiced, be much lower than irrigation requirements estimated under fixed cycle conditions. In the drier areas where irrigation may be considered to be total, these differences between demand mode and fixed cycle irrigation are negligible (Furniss, 1987).

4.2.4 Irrigation application and the calendar month

It is customary to use some arbitrary time period in which to express the irrigation requirements. Many planners use the monthly time period and this period is very often linked to calendar months, since this allows for synchronization with planting times and stages of crop growth, as well as water supply planning. However, this practice contains elements which inhibit the resolution of the estimate of irrigation requirements. To illustrate this point, consider the following case as presented in Figure 4.5.

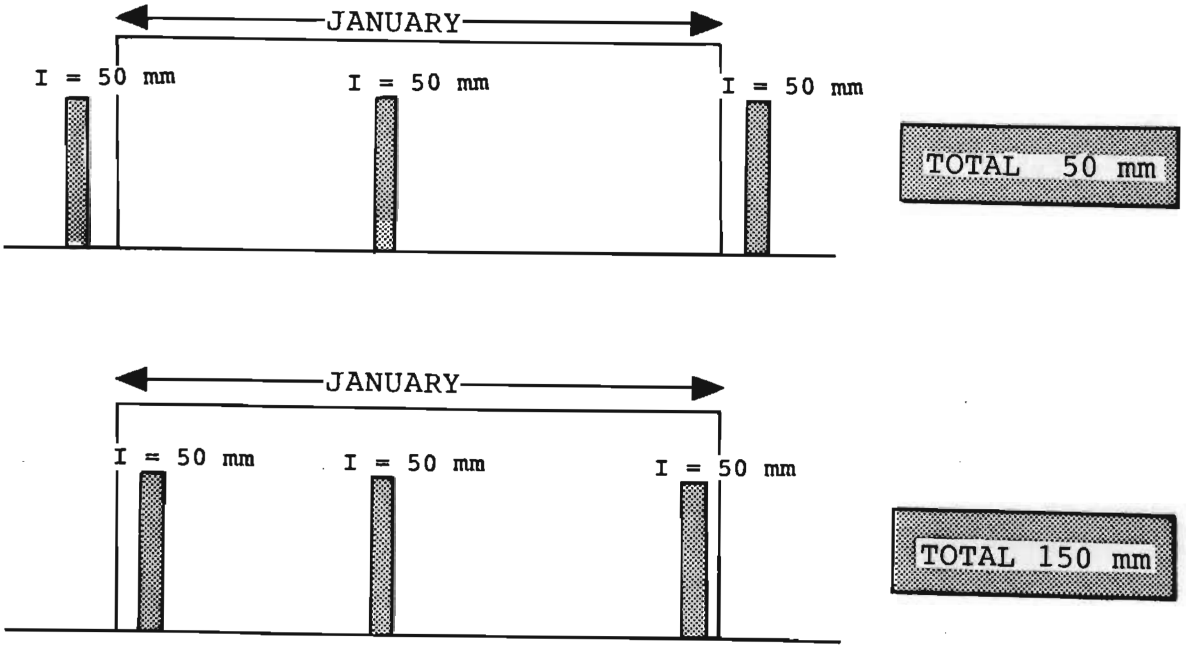


Figure 4.5 Illustration of the irrigation timing problem

An amount of 50 mm is applied on the last day of December, 50 mm is applied in the middle of January and 50 mm is applied on the first day of February. An amount of 50 mm of irrigation for January would clearly not be a good estimate of the real requirement in that month. A possible alternative application mechanism, in these soil moisture budgeting models, would be to apply irrigation up to field capacity at the beginning of the month, then to irrigate as necessary during the month and water to field capacity at the end of the month and in this way calculate the total soil moisture deficit for that month. At first this seemed to be a solution to the aforementioned dilemma. However, consider the case in which the soil moisture is duly watered to field capacity on day one and on day two a substantial rainfall event occurs. The rainfall would be largely ineffective since it would change the soil moisture to above field capacity and then drain away or run off before much of it was used by the plant.

The application of small amounts of water per irrigation setting in order to improve the resolution of the model estimate was considered. However, such shallow, frequent irrigations are not practical since they encourage shallow root growth and in this sense the model would then be unrealistic.

It was decided finally to employ the technique which is presented below in Figure 4.6 and Equ. 4.1.

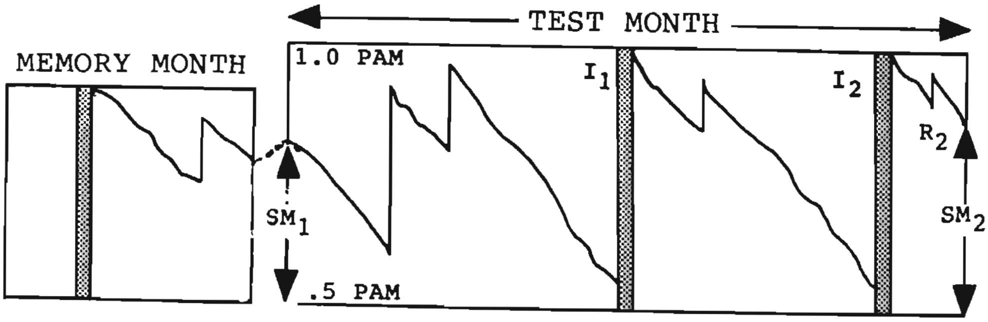


Figure 4.6 Schematic illustration of the solution to the problem of expressing irrigation requirements in monthly time intervals

This requirement is expressed as ;

$$I_{\text{test month}} = (I_1 + I_2) + (SM_1 - SM_2) \qquad \text{Eq. 4.1}$$

where

$I_{\text{test month}}$ = irrigation requirement (mm) in the test month,

I_1, I_2 = irrigation application amounts (mm),

SM_1 = soil moisture content (mm) above 0,5 PAM at beginning of test month,

SM_2 = soil moisture content (mm) above 0,5 PAM at end of test month.

The term ($I_{\text{test month}}$) was bounded by zero at the lower end.

4.2.5 The frequency analysis

One of the objectives of this study is to provide an estimate of the frequency of non-exceedance of the irrigation water requirements which are reported. The selection of an appropriate probability distribution posed a problem, since the frequency of occurrence of zero irrigation requirements for some months meant that any distribution which was fitted to these data would be skewed severely. A possible solution was to remove the zeros and to calculate their probability of occurrence separately. The remaining values could then be used in a 'non-skewed' distribution. To avoid these problems and the difficulty of choosing a suitable probability distribution, Sutter and Corey (1970), cited by Burman et al., (1982) used the distribution free method of non-parametric statistics which involved ranking the irrigation requirements and calculating their frequencies of non-occurrences. The distribution free approach to the frequency analysis procedure was followed in this study. The analysis selects values of irrigation requirements which have 50, 80 and 90 per cent frequency of non-exceedance. The 90 per cent frequency of non-exceedance level is considered to be an adequate upper limit for this type of application. The 95 percentile level was included in preliminary tests. However, there was very little difference between the 90 and 95 percentile levels of non-exceedance at even the stations which have a high rainfall.

The results of the abovementioned frequency analyses for a range of combinations of PAM, cropping factor and calendar months are printed in the tabular form presented in Table 7.5. The numbers which appear in the main body of Table 7.5 are the irrigation requirements which have been estimated at the abovementioned percentile levels and for the assumptions and model mechanisms as presented in the previous sections.

The concepts and structure of the ACRU model and the irrigation model are considered to be sound. However, it remained for the models and in particular the soil moisture estimation aspects thereof to be verified against field observations. Such verification was performed on the ACRU and irrigation models in this study and also on the ACRU model by Schulze (1984b; 1986) and is discussed in some detail in Chapter 5.

5 VERIFICATION OF THE OUTPUT OF THE MODELS

Models need to be verified against observed data and over different climatic regimes before they can be used with a degree of confidence. Several such verifications have been carried out in this study for both the irrigation model and the ACRU model using field plot data of soil moisture measured under irrigated conditions at Roodeplaat near Pretoria and Cedara near Pietermaritzburg. These results are presented in Sections 5.1.3 and 5.2.1. In addition the verifications performed by Schulze (1984b; 1986) on the ACRU model are presented briefly.

Several assumptions, described in Section 4.2.3 were made concerning the soil moisture variables in the irrigation model. The sensitivity of the output of the irrigation model, to these assumptions, was investigated and is discussed in Section 5.2.2.

The relatively short period of soil moisture budgeting prior to the test month described in Sections 4.2.2 and 4.2.3 was viewed with some scepticism by critics of this approach as mentioned in Section 4.2.2. Consequently a series of tests were conducted wherein the crop water requirements estimated using the bi-month approach of the irrigation model were compared with those derived using a continuous soil moisture budgeting approach as described in Section 5.2.3.

5.1 Verification of the output of the ACRU model

Schulze (1984b; 1986) reported the results of tests to verify various of the component output products of the ACRU model. These tests cover the estimation of;

(a) AET under total plant cover and for bare soil using data from a lysimeter,

(b) monthly water yield from catchments in humid, sub-humid and arid regions, and
(c) design stormflow volumes and peaks.

Faced with a scarcity of data sets of observed data from field experiments and from research catchments in South Africa, Schulze (1984; 1986) used data sets from the USA in addition to local data in order to cover a range of hydrological regimes. The results of these tests which contribute towards the verification of the ACRU model, are presented in the sections which follow.

Unfortunately none of the verification tests conducted by Schulze (1984b; 1986) addressed the question of soil moisture specifically. Further verification of the estimation of soil moisture by the ACRU model was therefore conducted in this study using field data sets, which included measurements of soil moisture at Cedara and at Roodeplaat.

5.1.1 Comparison with lysimeter estimates of actual evapotranspiration

Schulze (1986) presented the results of the simulation of AET from two lysimeters by the ACRU model at the University of Natal. A-pan evaporation was used in these simulations by Schulze (1986). AET was simulated under conditions which changed from bare soil for which the leaf area index (LAI) in the model was set at 0,02 to sparse natural grassland cover with LAI of 0,7. The results, of the simulations, presented in Figure 5.1 approximate the line of equality well with the slope of the regression line equal to 0,92, the correlation coefficient equal to 0,93 and the root mean square error (RMSE) for monthly AET was 11 mm . The mean monthly AET for the two lysimeters over an 11 month period was 55 mm . The RMSE expressed as a percentage of the mean was therefore 20 per cent. The month of February was omitted from the above calculations since according to Schulze (1986), excessive spillage took place out of the lysimeters following a rainfall event of 130 mm . Schulze (1986) included soil evaporation, plant transpiration and evaporation of intercepted rainfall in his definition of AET. The lysimeter tests ran from April 1984 to March 1985.

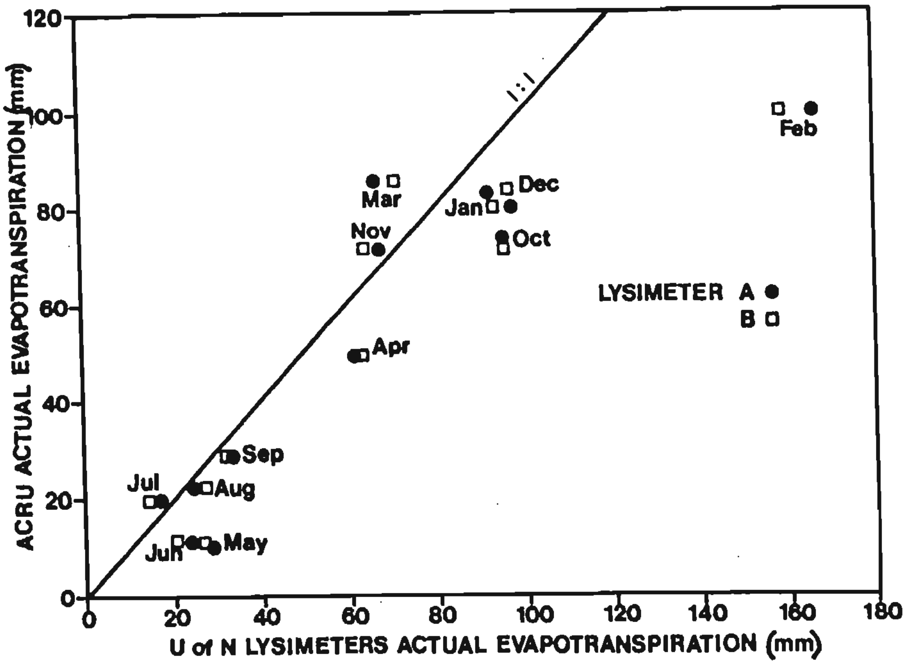


Figure 5.1 Comparison of observed and estimated actual evapotranspiration from bare ground and sparse natural grassland, University of Natal lysimeters (after Schulze, 1986)

5.1.2 Comparison with catchment runoff

The amount of runoff from different agricultural land uses on small catchments is often a key factor in the design of an irrigation scheme which is to be supplied with water from a small farm dam. Estimates of runoff have been included in the dryland analysis and are presented in Chapter 7 along with a discussion on the uses of such output in this study. The performance of the ACRU model in simulating this component of the hydrological cycle is therefore of importance. The statistics of the observed water yield and those estimated through simulation by the ACRU model, at three different locations, are presented in Table 5.1.

The three hydrological regimes are in the USA and South Africa and the MAP ranges from 225 to 1 530 mm and the mean annual runoff from 1 mm at Safford and 70 mm at Hastings to 800 mm at Cathedral Peak. Runoff totals as well as standard deviations are simulated well by the model even under these conditions which differ widely.

Table 5.1 Statistics of water yield simulation from the ACRU model at three different locations (after Schulze, 1986)

Catchment Characteristics	Hastings 4401, Nebraska, USA	Safford 4501 Arizona, USA (July-Oct, ie 97% flow)	Cathedral Peak V1MO3, Natal, SA
Area (km^2)	1,95	2,10	1,95
Latitude (°)	40° 16' N	32° 54' N	29° 00' S
Longitude (°)	98° 16' W	109° 48' W	29° 15' E
Altitude (m)	597	1020	2070
Coefficient of Stormflow Response	0,95	1,00	0,30
Depth of A-horizon (m)	0,22	0,14	0,20
Depth of B-horizon (m)	0,47	0,36	0,58
Wilting point of A-horizon (m/m)	0,21	0,07	0,25
Wilting point of B-horizon (m/m)	0,22	0,10	0,24
Field capacity of A-horizon (m/m)	0,38	0,13	0,37
Field capacity of B-horizon (m/m)	0,34	0,21	0,38
Porosity of A-horizon (m/m)	0,47	0,41	0,48
Porosity of B-horizon (m/m)	0,47	0,41	0,49
Runoff Response Depth (m)	0,30	0,14	0,50
SCS Curve Number II	78	79	61
Mean Annual Precipitation (mm)	600	225	1530
Statistics of Model Performance for Streamflow. (Daily)			
Total observed flow (mm)	2466,8	273,1	4721,7
Total simulated flow (mm)	2331,0	250,2	4920,6
Correlation coefficient	0,914	0,821	0,873
Regression coefficient	0,847	0,706	0,768
Base constant	0,023	0,015	0,592
Std deviation of observed flow (mm)	2,203	0,832	2,692
Std deviation of simulated flow (mm)	2,042	0,715	2,367
Coefficient of Determination	0,835	0,674	0,762
Coefficient of Efficiency	0,835	0,672	0,761

Schulze (1986) also presented the results of a simulated monthly streamflow accumulation for a small (0,41 km^2) well-grassed catchment VIM28 at De Hoek in Natal. Figure 5.2 illustrates the close approximation of simulated monthly streamflow accumulation to the 1:1 line. From the same catchment, which had an MAP of 900 mm, an example of hydrograph simulation by the ACRU model is presented in Figure 5.3. It is acknowledged that the study reported in this thesis did not include estimates of peak runoff rate, however, Figure 5.3 was included to show this aspect of the ACRU model, so that a fuller appreciation of its overall ability to model the soil moisture budget would be gained.

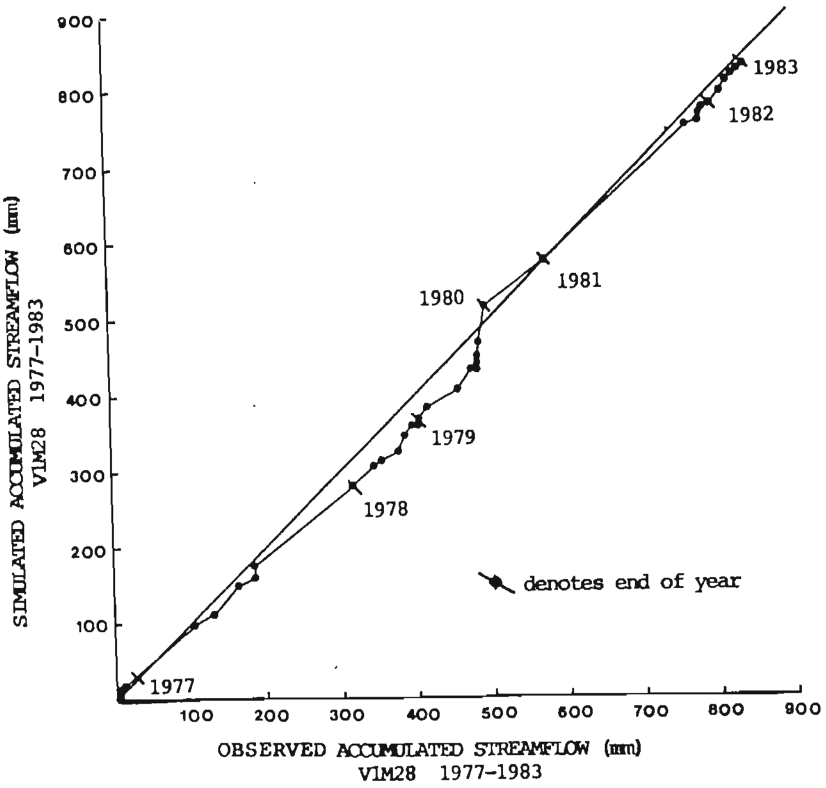


Figure 5.2 Comparison of observed and simulated accumulated monthly streamflow at DeHoek V1M28, Natal for 1977-1983 (after Schulze, 1986)

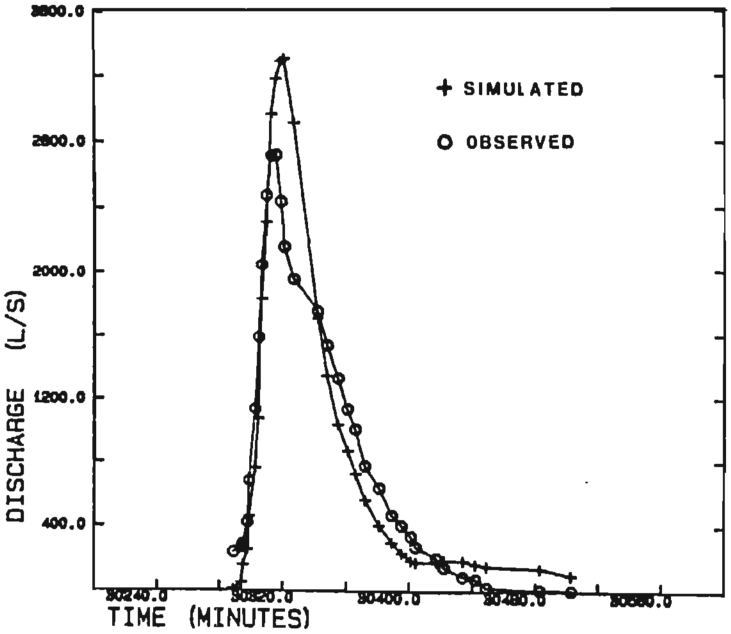


Figure 5.3 Comparison of observed and simulated flood hydrograph at DeHoek V1M28, Natal (Schulze, 1986)

None of the abovementioned tests measured all the outputs, from the ACRU model, simultaneously. This is a shortcoming which is recognised. However, these results do contribute towards an overall assessment of the performance of the ACRU model. Such stepwise or component by component verification is considered acceptable in the case of the ACRU model since it does not contain calibration routines, nor was it conceived as a model which has to be calibrated for good results.

5.1.3 Comparisons with measured soil moisture

The accurate estimation of soil moisture and variables such as AET which relate directly to soil moisture were central to this study. Hence the verification of the ability of the ACRU model to estimate soil moisture was seen as a priority. Therefore data sets of soil moisture, under both irrigated and rainfed conditions, were obtained for sites at Cedara and Roodeplaat and used to verify this aspect of both the ACRU and the irrigation models.

A set of daily climatic and two sets of field plot soil moisture data for wheat growing under irrigated conditions at Roodeplaat near Pretoria were obtained from Nel (1987) of the Soil and Irrigation Research Institute, Department of Agriculture and Water Supply. These data consisted of daily rainfall and irrigation water applications, daily A-pan evaporation, the soil form and series (Hutton/Shorrocks) according to the Binomial System of Soil Classification for Southern Africa (MacVicar et al., 1977), estimates of the crop factor at various growth stages and the root distribution at maturity. Finally and most important, were the measurements of soil moisture which were given in millimeters, for the A-horizon (0 - 90 cm) and the B-horizon (90 - 180 cm). The soil moisture in the profile was modelled in two layers which corresponded with the horizons mentioned above and also as a single layer (0 - 180 cm). The soil moisture holding capacities i.e. FC and WP, were calculated for each horizon using the simplifying assumptions of Schulze, Hutson and Cass (1985) to the soil water retention models of Hutson (1984).

Further soil moisture budget simulations to verify the ACRU model were conducted using daily rainfall and evaporation data and soil moisture data obtained from Mottram (1986), Summer Grain Centre of the Department of Agriculture and Water Supply, Cedara. These data were for soybeans grown under research conditions in field plots, viz. Plot 8 and Plot 17, which were irrigated when necessary and the plots also experienced a good deal of summer rainfall.

Turning back to the Roodeplaat data sets, estimates of crop factors for wheat for approximate monthly growth stages were given by Nel (1987) and were used initially. The monthly crop factors and root distributions were adjusted so as to produce an acceptable simulation on Plot 6. Thereafter these same monthly crop factors and root distributions were used in the simulations on Plot 16 which according to Nel (1987) was a replication of Plot 6 with respect to the crop and the soil. The results of the model performance on Plot 16 are therefore considered a true verification of its ability to estimate soil moisture.

In obtaining the results for the model verifications which are presented in Table 5.2 and 5.3 and discussed in this section it must be emphasised that the crop factors and rooting distributions used were not exactly the same as those presented in Appendix C and used in the dryland analyses. Whilst simulating the soil moisture for the calibration plots viz. Plot 6 at Roodeplaat and Plot 8 at Cedara, some adjustment was necessary at a monthly time step to ensure that the estimated soil moisture related reasonably well to the observed. However, it must be stressed that, in the calibration mentioned above, such adjustments were kept within reasonable limits, that the expected growth and senescence trends in these variables were maintained and that these variables were only altered at the monthly time interval. No finer adjustment of these variables with respect to time was attempted in order to obtain a better relationship between estimated and observed soil moisture on a daily basis.

The crop factors which were selected for the double layer version of the ACRU model simulation on Plot 6 at Roodeplaat were maintained for the single layer version with good results as may be seen in Table 5.2.

Irrigation water was assumed to enter the soil in totality after the subtraction of interception and was not reduced through runoff whereas the rainfall was reduced to effective rainfall through subtraction of estimated runoff and interception. As discussed in Section 4.1.2 a modified version of the SCS equation was used to estimate the runoff from rainfall events. The results of these simulations and those discussed below are presented in Table 5.2.

In the verification of the models at Cedara the soil profile was considered as a single layer for all except the purpose of estimating storm flow runoff from rainfall. It is possible in the ACRU model to specify the depth of the topsoil layer which is used for estimating the maximum soil moisture retention (S) in the SCS stormflow equation. This aspect was discussed in Section 4.1.2. The total depth of the soil profile was 1 m and the depth of the runoff controlling horizon which produced the best estimates of soil moisture was determined to be 300 mm . This was established for the calibration plot viz. Plot 8 and retained at 300 mm for Plot 17.

At Roodeplaat and Cedara the soil moisture was observed at intervals of between two and ten days. The simulated soil moisture was extracted for the days on which observations of soil moisture were available. Time series plots of observed and simulated soil moisture for the sites at Roodeplaat and Cedara are presented in Appendix F. Further analyses of these results are presented in Table 5.2 which shows that the means, standard deviations and ranges of the observed and simulated soil moistures compare reasonably well. In addition the RMSE between the observed and simulated soil moistures is low in relation to the total moisture in the soil profile. The regression intercepts with the exception of that for Plot 17 at Cedara are close to zero, especially when one considers that the plotted points are at most in the range 250 to 400 mm and in some cases much less. The correlation coefficients, with the exception of Plots 8 and 17, are high. The coefficients of efficiency, following Aitken (1973), are reasonably high, again with the

Table 5.2 Comparison of observed and simulated soil moisture from the ACRU model, using field plot data at Roodeplaat and Cedara

STATISTIC	WHEAT AT ROODEPLAAT								SOYBEAN AT CEDARA	
	PLOT 6				PLOT 16				PLOT 8	PLOT 17
	SINGLE HORIZON (1.8m)	DOUBLE HORIZON A (0.9m)	B (0.9m)	TOTAL (A+B) (1.8m)	SINGLE HORIZON (1.8m)	DOUBLE HORIZON A (0.9m)	B (0.9m)	TOTAL (A+B) (1.8m)	SINGLE HORIZON (1m)	SINGLE HORIZON (1m)
Mean observed (mm)	333	163	170	333	336	160	177	336	317	305
Mean simulated (mm)	338	164	179	343	308	160	160	317	315	307
Std. dev. observed (mm)	45	33	16	45	42	34	13	42	9	8
Std. dev. simulated (mm)	46	32	18	48	44	31	17	41	12	13
Regression coefficient	1.01	0.97	1.00	1.06	0.97	0.91	1.05	0.96	1.02	1.18
Regression intercept	3.1	6.2	9.4	-7.8	-19.1	11.8	-25.9	9.9	-8.4	-56.0
Correlation coefficient	0.98	0.98	0.88	0.97	0.93	0.98	0.81	0.91	0.76	0.72
RMSE (mm)	8.8	5.4	8.8	10.3	17.0	6.4	10.1	14.6	8.1	9.3
Maximum observed (mm)	404	207	201	404	388	208	197	388	337	320
Maximum simulated (mm)	402	210	212	417	375	203	192	375	339	329
Minimum observed (mm)	247	106	135	247	248	97	148	248	303	290
Minimum simulated (mm)	249	106	146	254	227	100	135	244	296	284
Coeff. of determination	0.96	0.96	0.77	0.94	0.86	0.96	0.66	0.88	0.58	0.52
Coeff. of efficiency	0.93	0.98	0.30	0.92	0.38	0.95	-1.22	0.67	0.23	-0.38

exception of Plot 8 and Plot 17 at Cedara and the B horizon in both Plots 6 and 16. A comparison of the coefficients of determination and efficiency indicates that systematic bias occurs in all the simulations except the A horizon of Plot 6. The abovementioned shortcomings may be attributed to the following factors. First, the range in the values of observed soil moisture is small, particularly at Cedara and in the B horizon at Roodeplaat. The second reason is one which is valid in all simulation tests of this nature i.e. that one poorly simulated rainfall event displaces the simulated soil moisture for several days or even weeks thereafter. This phenomenon may be seen in the time series plots of observed and simulated soil moisture presented in Appendix F. The rainfall intensity plays a major role in such unpredictable displacements since the amount of runoff and hence effective rainfall is often highly sensitive to the rainfall intensity. This is an aspect which requires attention in future research. Thirdly, there is the question of the accuracy of determination of soil moisture. The inherent variability of soil moisture, texture, bulk density and other properties lead to variability and error in the estimation of soil moisture. The neutron probe method was used by Mottram (1986) to determine soil moisture. Standard errors of between 3 and 10 per cent in the estimation of soil moisture by the neutron probe are reported inter alia by Hewlett et al. (1964), Hills and Reynolds (1969), Rawls and Asmussen (1973), Vachaud et al. (1977) and Mottram (1986). The total range of soil moisture in the Cedara field plot experiment was only 12 per cent of the mean. In the light of the above it may be appreciated that the coefficient of efficiency does not provide a useful objective function in this case and the RMSE is a preferable objective function.

The ACRU model simulations of soil moisture at Roodeplaat are particularly encouraging since they spanned the whole growing season (5 months), during which period the soil moisture in the top 900 mm experienced a range of 100 mm, the nine irrigation applications ranged from 6 mm to 152 mm and the five rainfall events ranged from 9 mm to 80 mm .

The verification of the ACRU model is discussed further in Section 5.3.4.

5.2 Verification of the irrigation model

The verification of the irrigation model embraced more than simply its performance against measured soil moisture. The need to reduce the bulk of information necessitated the introduction of certain assumptions with regard to the soils in particular. Tests of the sensitivity of the model to the most important of these assumptions are presented in Section 5.2.2. In addition the length of the soil moisture budgeting period of one month before the test month was also the subject of testing. Critics of this approach expressed concern that the period of one month was too short and that a continuous soil moisture budgeting approach should be followed. Tests were therefore conducted to establish the difference between the approach described in Section 4.2.2, termed the discrete mode and the more conventional continuous mode. These tests are discussed in Section 5.2.3.

The irrigation model was only tested on four sets of field plot data of soil moisture at two sites. However, the fact that this model followed the ACRU model as well as it did and is structured along very similar lines indicates that it too, like the ACRU model, may be used with confidence under a wide range of conditions.

5.2.1 Comparison with measured soil moisture

The irrigation model has many of the same routines as the ACRU model and therefore it would be expected to perform in a similar fashion and especially to display similar weaknesses. This was in fact the case with the sometimes incorrect estimation of storm runoff providing the major source of error as discussed in Sections 5.1.3 and 5.3.4. and shown in Appendix F. The severity of this unavoidable error was however lessened by the two layer soil moisture budgeting approach with respect to storm runoff estimation, as discussed in Section 4.2.3. Other problem areas which were discussed in Section 5.1.3 and which pertain to this section as well are the small range in soil moisture and large number of small rainfall events on Plots 8 and 17 at Cedara. In addition stomatal closure on very hot days led to the model overestimating the soil moisture removal on these days. The results of these tests in which the crop factors were set at the values deduced for the ACRU model tests described in Section 5.1.3, are shown in Table 5.3. On the positive side, however, all the comments which were made in Section 5.1.3 with respect to Table 5.2 are also pertinent to Table 5.3. In particular the objective function RMSE should be considered as the most relevant one for this type of analysis for the reasons discussed in Section 2.6 and 5.1.3.

Table 5.3 Comparison of observed and simulated soil moisture from the irrigation model using field plot data at Roodeplaat and Cedara

STATISTICS	WHEAT AT ROODEPLAAT PLOT 6	 PLOT 16	SOYBEANS AT CEDARA PLOT 8	 PLOT 17
	SINGLE HORIZON (1.8m)		SINGLE HORIZON (1.0m)	
Mean observed (mm)	339	336	317	305
Mean simulated (mm)	332	304	305	303
Std. dev. observed (mm)	47	42	9	8
Std. dev. simulated (mm)	48	45	16	14
Regression coefficient	1.00	0.89	1.15	1.32
Regression interception	9.0	4.9	-62.2	-98.8
Correlation coefficient	0.98	0.83	0.65	0.75
RMSE (mm)	9.8	25.3	12.8	9.7
Maximum observed (mm)	404	388	337	320
Maximum simulated (mm)	404	380	334	327
Minimum observed (mm)	243	248	303	290
Minimum simulated (mm)	251	225	278	282
Coefficient of determination	0.96	0.70	0.42	0.56
Coefficient of efficiency	0.91	0.06	-2.68	-0.50

5.2.2 Sensitivity tests on the irrigation model

In order to meet the objective, discussed in Section 1.2, of reducing the bulk of information which is generally forthcoming from analyses of crop water requirements for irrigation it was necessary to introduce several simplifying assumptions. These assumptions pertain particularly to the soil moisture holding capacities as discussed in Section 4.2.3. The sensitivity of the estimated irrigation requirement to these assumptions is important and therefore they were the subject of sensitivity tests.

The first tests concerned the value of the ratio (POR-WP)/(FC-WP) i.e. the ratio of soil moisture storage capacity above wilting point to PAM as discussed in Section 4.2.3. This ratio was set at 1,6, 2,5 and 3,7 for successive simulations of estimated irrigation requirements at a number of stations throughout South Africa whose MAP ranged from 129 mm to 1 032 mm . As may be deduced from Table 4.1, the ratios 1,6, 2,5 and 3,7 correspond to clay, silty loam and sand loam respectively.

It is pertinent to recall that the rainfall input to the model is subject to runoff removal as discussed in Section 4.2.3, the estimate of which is provided by the SCS method discussed in Section 4.1.2. The irrigation water however is assumed to be applied in a manner which does not produce runoff. The assumptions regarding runoff in the irrigation model were discussed in Section 4.2.3 and they assume particular significance when considering the sensitivity of the irrigation requirements estimates to the soil moisture storage capacity ratio mentioned above.

The results of the sensitivity tests showed mild sensitivity to the soil moisture holding capacity ratio, when the following three factors coincided;

(a) 50 per cent frequency of non-exceedance,
(b) higher rainfall months and stations, and
(c) lower crop factors.

This may be attributed to the higher incidence of rainfall events, both at the lower levels of non-exceedance and in the wetter months. In the case of lower crop factors, for example 0,5,the soils were likely to be wetter at the time of the rainfall event than if a crop with crop factor of 1.1 was growing at the time. All these factors contribute towards a greater differentiation in effective rainfall and hence the estimated irrigation requirement.

The estimated irrigation requirement was not sensitive to the soil moisture storage capacity ratios, discussed above, under the following conditions;

(a) at the 90 per cent level of non-exceedance,

(b) during the months of low rainfall, and

(c) for the higher crop factors.

A sample of the estimated irrigation requirements which were generated using soil moisture storage capacity ratios of 1,6, 2,5 and 3,7 are presented in Table 5.4. The requirements are for a range of months, frequency levels, crop factors and soil depths.

Table 5.4 Estimated monthly irrigation requirements for a range of locations and soil moisture holding capacity ratios

Soil moisture holding capacity ratios (POR-WP)/(FC-WP)					
1,6	2,5	3,7	1,6	2,5	3,7
Estimated monthly irrigation requirements (mm)					
154	153	153	57	54	52
121	121	121	36	32	23
148	148	148	34	32	33
148	148	148	61	51	48
137	135	135	72	65	64
94	93	91	61	44	41
70	71	71	20	19	20
136	136	136	8	5	3
159	159	159	0	2	0
92	92	92	26	22	24
149	149	149	6	4	5
120	120	120	2	1	2
106	106	106	0	0	0
108	108	108	20	18	18
108	108	108	7	7	6
64	63	64	6	6	4
54	54	54	55	54	55
43	42	41	46	40	43
67	64	64	47	46	45
63	64	64	33	28	27
MAP (129 mm - 438 mm)			MAP (686 mm - 1 032 mm)		

Table 5.4 was divided into dry and wet categories in order to illustrate the differing degrees of sensitivity for these climates. The analysis was not re-produced in a more disaggregated form since the estimated irrigation requirements were so mildly sensitive to this variable that further analyses would have revealed little. This was evident immediately, from a visual inspection of all the outputs.

In concluding this aspect of the sensitivity analysis it must be stressed that such lack of sensitivity would not be present in an analysis of runoff which would of necessity concentrate on the wetter portions of the soil moisture frequency distribution and also on the higher rainfall events. Estimates of runoff would be far more sensitive to the soil moisture storage capacity above FC.

The sensitivity of the estimated irrigation requirement to changes in the drainage rate coefficient which was set such that 50 per cent of the excess water above FC drains per day, was also tested. The coefficient was set at 30 per cent and the results were similar to those presented in Table 5.4. The differences were so small that they do not require mention. This result is not surprising since if the soil moisture storage capacity did not affect the estimated irrigation requirement, then it may be deduced that the rainfall timing and amounts were such that this component of the soil moisture store i.e. that above FC is used very seldom in the drier range of the frequency distribution.

It is pertinent to mention certain trends in the estimated irrigation requirements both between stations and within stations which do indicate increasing or decreasing sensitivity to the estimation of PE. As is discussed in Section 6.2.2 the estimates of irrigation requirements are less sensitive to PE in the more humid areas and particularly at the 50 per cent frequency level of non-exceedance in such areas. At the 80 and 90 percentile levels even in the humid areas it is evident from examining inter alia the output from the irrigation model presented in Appendix E that accurate estimation of PE is important. This may have been deduced since the irrigation requirements vary only slightly with soil depth and between the 80 and 90 percentile levels of non-exceedance, indicating the relative absence of rainfall and hence AET assumes greater importance in the soil moisture budget. The abovementioned is even more pertinent in the arid zones.

5.2.3 Comparison of estimates of irrigation requirements in the discrete and continuous modes

The discrete mode of operating the irrigation model in which a one month warm up or memory month is used, was described in Sections 4.2.2 and 4.2.3. As was mentioned in those sections, some concern was expressed initially by critics of this approach, that the initial soil moisture in the test month would be unrealistic. A set of routines were therefore developed whereby the irrigation model could be operated in continuous mode i.e. calendar months and years of rainfall data were processed through the model in historical sequence. The PAM and crop factors were input according to a fixed monthly sequence. The monthly total estimated irrigation requirements were stored and subsequently arranged into groups according to PAM, crop factor and calendar month. These groups were then subjected to a frequency analysis to establish the 50, 80 and 90 percentile levels of non-exceedance for each set of PAM, crop factor and calendar month. These analyses were conducted at 17 widely distributed rainfall stations in Southern Africa which had MAP's ranging from 129 mm to 1 032 mm . The results obtained from the abovementioned continuous mode were compared with those using the discrete mode approach at the same stations. A plot of the discrete versus continuous mode monthly crop water requirements from irrigation, is presented in Figure 5.4. The locations of the stations used in this analysis are shown in Figure 6.1.

The RMSE was 2,2 mm , the adjusted R^2 equal to 0,99 and the slope of the regression line of continuous or discrete modes was 1,00. It was concluded from Figure 5.4 and the above statistics that for the purposes intended for this irrigation model the discrete approach was acceptable.

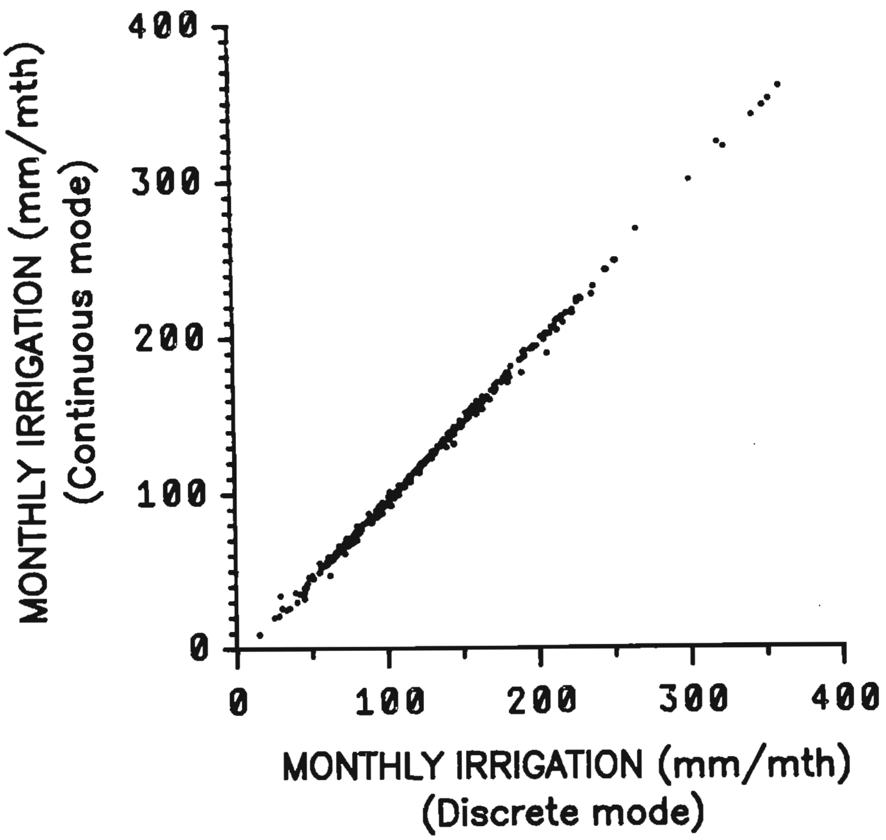


Figure 5.4 Scattergram of the estimated irrigation requirements using the discrete versus the continuous mode of operating the irrigation model at 17 stations, distributed throughout Southern Africa

5.3 Discussion on the verification of the models

The verification tests showed that both the ACRU and the irrigation models estimated soil moisture well and were therefore suitable for use in the analyses described in Chapter 7. However, the models did have some shortcomings which have been discussed in the preceeding sections and are summarised below.

Runoff from rainfall was found to be a primary source of error in the model simulations. The models used daily rainfall and no information with regard to the manner in which the rain fell, was transmitted to the modelling process. The intensity of the rainfall has a marked effect on the amount of runoff generated. The error introduced into the estimated soil moisture by an incorrect estimate of runoff from a large rainfall event provides an offset to all the estimated values of soil moisture thereafter and hence produces poor statistics for observed versus estimated soil moisture. This despite the fact that the model may produce estimates which would mimic the observed soil moisture very well if adjustment was made for the one time stepped offset produced by the single large rainfall event. The abovementioned problem was particularly noticeable with the verifications using data from Cedara in which rainfall accounted for 86 per cent of the 51 water input events and 81 per cent of the water input. Incorrect runoff estimation was less of a problem at Roodeplaat where only 30 per cent of the watering events occurred through rainfall and these events occurred late in the season when the crop offered good protection to the soil and thus judging by the changes in soil moisture, runoff appears to have been reduced. The simulations under conditions consisting largely of deep irrigation watering at Roodeplaat were better than those under largely rainfed conditions at Cedara, as may be seen from Tables 5.2 and 5.3.

Another source of error which was evident when studying the daily estimated soil moisture budget was that during periods of high evaporative demand the measured soil moisture did not reflect the expected reduction. This reduction in expected moisture removal may be ascribed to the stomatal closure discussed in Section 4.1.

In the field data sets of soil moisture the runoff and drainage were not measured and hence the correct estimates of soil moisture could have been obtained through compensating errors in estimating runoff and drainage. Care was taken to observe that the daily soil moisture budget reflected stepped changes, of the correct magnitude, due to rainfall minus runoff and also the steady decrease in soil moisture due to evapotranspiration.

The small range in the values of soil moisture, relative to the magnitude of possible errors in soil moisture measurement was another reason why the models did not, according to the objective functions of correlation coefficient, coefficients of determination and efficiency, perform as well at Cedara as they did at Roodeplaat. However, if one considers the objective function of RMSE which was suggested by Johns and Smith (1975) to be the best objective function for such application then both the ACRU and irrigation models performed as well at Cedara as they did at Roodeplaat. This is particularly encouraging since the frequency and amounts of rainfall at Cedara are typical of much of the Natal midlands where the practice of supplementary irrigation is expanding rapidly. The greater emphasis on large amounts of well controlled irrigation at Roodeplaat produced a wider range of soil moistures and also contributed to less errors due to inaccurate storm flow estimates since 70 per cent of the water application events were deep irrigations.

A final word of caution on the subject of field plot measurements of soil moisture is sounded by Baier and Robertson (1966) when they state:

> "Tests against measured soil moisture assume that the observed values truly reflect the soil moisture variation over time and space. But it is doubtful whether spot readings of soil moisture, even if replicated, represent adequately the distribution of soil moisture in the manner that the time and space integrating estimates from moisture budgets are expected to do." p 311

Although it is recognised that the technology of the neutron probe itself has undoubtedly improved since the above statement was made it is significant to note that very similar thoughts are expressed by Devitt _et al_ (1983) and Calder _et al_ (1983). Therefore although the aforementioned test results for Roodeplaat and Cedara are important in that they indicate that the models simulated the soil moisture budget reasonably well, they should be interpreted in the light of the above.

6 CLIMATIC DATA INPUT TO THE SOIL MOISTURE BUDGET MODELS

Daily rainfall and a temperature based estimate of potential evaporation (PE) were the only climatic inputs to the soil moisture budget models. The above decision was influenced by a combination of the desire to provide a comprehensive spatial and temporal coverage of South Africa in these analyses and the fact that there is a paucity of data for the other climatic or climate related elements viz. pan evaporation, solar radiation, humidity and wind.

6.1 Daily rainfall data

6.1.1 Selection of the rainfall station for each zone

The positions of all the rainfall stations with 10 or more years of daily record were printed on the classified image of altitude described in Section 3.3. The MAP at each of these stations was then transcribed onto this map and used to assist in the delimitation of homogeneous climate zones, as described in Section 3.3. The monthly rainfall data base and rainfall station index system developed by Dent and Wills (1986) was then perused in order to ascertain the completeness as well as the length of record at these stations. The short list of stations from each zone was then subjected to a more thorough investigation with respect to missing daily values. A computer program which presented an analysis of missing daily data in matrix form was developed for this purpose. Cognizance was taken of any temperature stations at or near the shortlisted rainfall stations. Thereafter a key rainfall station was selected in the zone, based on the criteria of record length, amount of missing data, proximity of temperature station and the representativeness of the MAP and altitude at the selected station with respect to the rest of the climate zone. Research by Welding and

Havenga (1974) revealed that stations which are in close proximity to one another have monthly rainfall totals which are well correlated. Studies by Kelbe (1987) in the Orange Free State showed that the spatial constraints on linear extrapolation of daily raingauge measurements are restricted to distances of less than 10 km for isolated, summer, free convective storms, but that this distance may be extended for frontal convective storms. A 10 km radius circle encompasses an area of 314 km^2 and most of the homogeneous climate zones, delimited in this study, are smaller than 314 km^2 in extent. Thus, since the rainfall regions were kept reasonably small and the altitude within a region did not vary much, the chosen rainfall stations were considered to be representative of the climate zone.

The homogeneous climate zones were delimited and their boundaries digitised before it was possible to use the results of a study by Zucchini and Adamson (1984). Their study produced parameters for each of 2 550 daily rainfall stations in Southern Africa, and also the daily rainfall generator model in which these parameters were used. The key rainfall stations in the zones were therefore selected independently of the stations used by Zucchini and Adamson (1984), initially. Later in the study the rainfall stations used by Zucchini and Adamson (1984) were matched with the 712 selected stations. There were 133 stations out of the 712 for which Zucchini and Adamson (1984) did not have model parameters. These stations were predominantly from the Department of Agriculture and Water Supply and the South African Sugar Association. The Zucchini and Adamson (1984) model was used to infill missing data as is described in Section 6.1.2 and therefore these 133 stations posed some difficulties. The approaches used to overcome these difficulties will be described for the following cases:

(a) 50 cases where a suitable station from Zucchini and Adamson (1984) was found within the zone and which could replace the selected station adequately;

(b) 34 cases where the Zucchini and Adamson (1984) station within the zone and with the longest record was considered an unsuitable replacement because the record was at least 10 years shorter than that of the selected station;

(c) 49 cases where no Zucchini and Adamson (1984) station was found to be within the zone.

In the first case the selected station was replaced by the Zucchini and Adamson (1984) station. In the latter two cases the selected stations were retained and missing data record infilled with synthetic data generated using the parameters of a nearby station. The synthesised daily rainfall was multiplied by the ratio of the MAPs at the respective stations.

For zones 1 and 16 it was found that no suitable Zucchini and Adamson (1984) station with a comparable altitude existed in the vicinity. These two zones are at the top of Table Mountain and the Jonkershoek mountains in the south-western Cape respectively. Since these areas are of no significance agriculturally it was decided not to run the analyses on them.

Zones 57 and 394 also presented a problem since it was found that the only suitable stations in these zones had only monthly rainfall totals. A great deal of automation was necessary to complete this study given the manpower and time constraints. It was therefore decided to use the rainfall data from nearby and climatically similar zones, viz. zones 60 and 395 respectively, and retain the zone numbering system and digitized boundaries. Any changes to the above two items would have caused major repercussions for the suite of computer programs and data sets in the system.

The data from the Cathedral Peak stations was infilled manually by Neuwirth and Schmidt (1986) who used rainfall patterns in the area and rainfall from nearby gauges to perform this task.

6.1.2 Synthesising missing daily rainfall

Missing daily rainfall values present a problem to continuous daily moisture budget modelling. It is therefore desirable to have an unbroken record. Fortunately the probabilistic form of the output from the soil moisture budget analyses in this research work was such that it was possible to use a daily rainfall synthesising technique developed by Zucchini and Adamson (1984) which employed a random number generator and individualised model parameters for each station. The soil moisture budget output is reported in the form of either percentile frequency of occurrence or non-exceedance. The soil moisture budgeting models therefore did not require a technique that generated daily rainfall amounts which approached absolute values in the context of real time (i.e. when compared with the records at other stations in the vicinity for the same day).

Adamson (1986) reported that he was in the final stages of developing a technique which involved the use of real concurrent daily data from nearby stations in order to synthesise records which were missing. These synthetic records would preserve the sequence of wet and dry days and also compare realistically with the records at nearby stations for the same day. However, at the time of the analysis for this study the techniques of Adamson (1986) had not been made public and therefore the synthesis of missing rainfall data proceeded as follows :

(a) A complete year of synthetic daily rainfall data was generated using the technique developed by Zucchini and Adamson (1984).

(b) The observed daily rainfall record was then scanned for missing data and the appropriate day of year from the year of synthetic daily data was used to replace any missing daily value.

(c) Once used, the day of year in the synthetic record was labelled as having been used.

(d) If such a "used" day of year was required again at the station under consideration then a complete new year of synthetic daily rainfall data was generated so as not to re-use any particular synthetic rainfall value.

It is conceded that this method does not account for correct probability wet:wet, wet:dry or dry:dry sequences in the case of one day of missing data in an otherwise complete record. However, in replacing missing data by this technique only the record for the first day of the synthetic sequence does not take cognizance of the previous days rainfall. In cases where two or more days were replaced then the probable sequences of wet and dry days within the infilled sequence are maintained by the technique of Zucchini and Adamson (1984). A sub-study was therefore conducted to ascertain what fraction of the total daily rainfall record at the 712 stations was missing and in addition how many of these missing data occurred in sequences of less than four days. The results of this sub- study are presented in Table 6.1 which shows that 95 per cent of the rainfall stations have less than 2 per cent of their missing data, in short sequences. The higher percentage of missing data which occurred in longer sequences (eg. 95 per cent of the stations had less than 14 per cent data missing) did not affect the soil moisture budget appreciably as is shown in Section 6.1.3. In addition the probable sequence of wet and dry days was retained by the Zucchini and Adamson (1984) model in such longer sequences of synthetic data.

Table 6.1 Amount of missing daily rainfall at the 712 stations used in this study

Number of stations (%)	100	95	90	75	50	25	5
Any length sequence of missing data (%)	48	14	10	6	4	3	1
Short sequences (i.e.<4 days) of missing data (%)	41	2	0	0	0	0	0

In the light of the above results, which show the very small portion of missing data at most of the rainfall stations used and after considering the results presented in Section 6.1.3, it was considered appropriate to proceed with the technique described in (a) to (d) above and to accept its minor shortcomings with regard to short sequences. In this manner a complete daily rainfall record was produced and the moisture budgeting model was able to proceed without the intractable problem of dealing with missing data. It remained to assess the effect of these synthetic daily rainfall data on the output from the ACRU soil moisture budget model.

6.1.3 Effect of synthetic rainfall on the soil moisture budget

Tests were conducted at the 17 stations shown in Figure 6.1 to ascertain the effect on the soil moisture budget of employing an entirely synthetic daily rainfall data set versus observed rainfall data in the ACRU model. These stations were chosen since they represented a wide range of climatic regimes throughout Southern Africa and had long records. The results presented in Table 6.2 indicate that there was very little difference in the statistics of the frequency distribution of monthly totals of estimated actual evapotranspiration (AET) and runoff, when using synthetic as opposed to observed daily rainfall data. This applied over a wide range of climatic regimes and for different soils and crop types, the parameters of which are described in Section 4.2.3 and Appendix C respectively. Missing daily rainfall records which were synthesised using the Zucchini and Adamson (1984) techniques were therefore used with confidence. Particularly since the use of such synthetic values was very limited at most stations as shown in Table 6.1.

It is conceded that the tests described above do not offer a direct proof of the acceptability of using rainfall records which have been reconstructed in the manner described in Section 6.1.2. Nevertheless, it is considered a more stringent yet simple test than the markedly more tedious method of removing some rainfall data, then synthesising that missing data using the above method and then comparing the outputs of the ACRU model after using the real and partially synthetic rainfall data sets.

The parameters which are necessary to generate synthetic daily rainfall using the model of Zucchini and Adamson (1984) are available for 2550 stations and are contained in 688 kbytes of disc storage. This entire data set and the techniques to automate its use through the daily rainfall model are therefore suitable for use on micro-computers.

Daily soil moisture budget modelling for planning estimates in Southern Africa is now possible without the need to store and maintain a large and cumbersome daily rainfall data base. The daily rainfall records may be generated as and when they are required. The problem of missing data is also not present when using generated data. This removes two of the largest obstacles in the path of the widespread adoption of daily water budget modelling for a range of applications.

Having indicated the potential for using synthetic rainfall sequences in planning, it is necessary to sound a strong word of caution that this does not imply that the measurement of daily rainfall is no longer necessary. It is necessary, for many reasons, including the monitoring and forecasting of climate related trends, to continue to monitor daily rainfall and even to extend the National network in certain key regions, e.g. mountainous areas. In fact, it is envisaged that the increased usage of models which require daily rainfall input will stimulate a demand for additional daily rainfall measurement. This in itself is a particularly encouraging prospect.

1	Zone	9	Nieweberg
2	Zone	51	Robertson
3	Zone	92	Oudtshoorn
4	Zone	83	Albertina
5	Zone	186	Nqamakwe
6	Zone	208	Diepdrif
7	Zone	217	Lekkervlei
8	Zone	297	Thornlea
9	Zone	367	Richmond
10	Zone	377	Bergville
11	Zone	408	Durban
12	Zone	442	Vryberg
13	Zone	495	Klipspruit
14	Zone	518	Karina
15	Zone	543	Pongola
16	Zone	594	Zaaiplaas
17	Zone	631	Inyoko

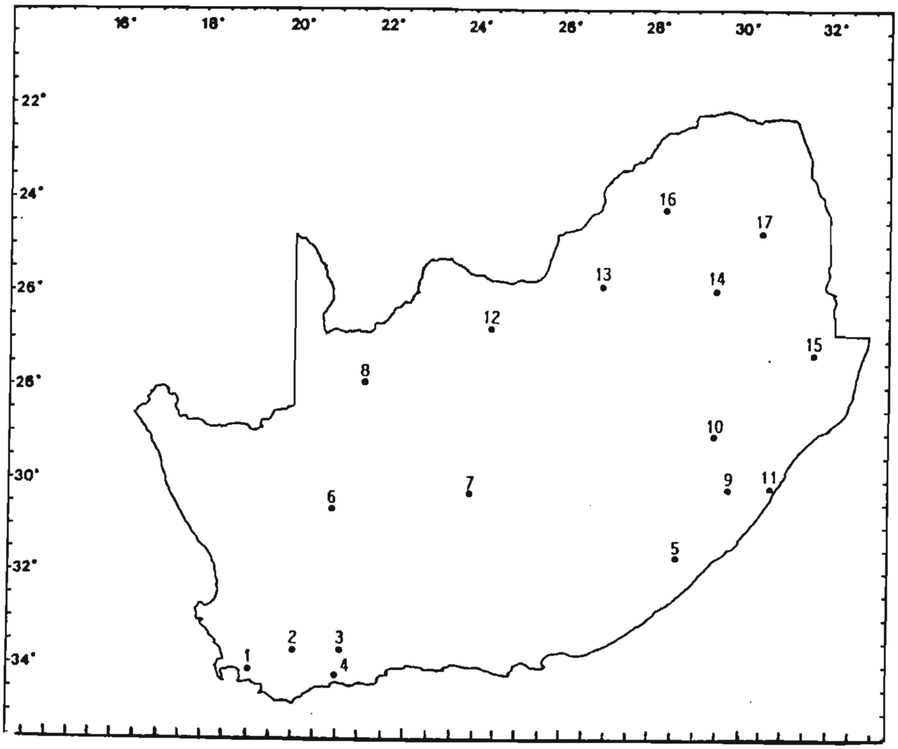


Figure 6.1 Location of the stations used to test the output from the ACRU model when comparing the effect of observed and synthetic daily rainfall data

Table 6.2 Comparison of selected output variables for the ACRU model when using observed and synthetic daily rainfall data

STATION	LENGTH OF RECORD (yrs)	CROP	SOIL	RAIN	MONTHLY ACTUAL EVAPOTRANSPIRATION (mm)							MONTHLY RUNOFF (mm)						
					MEAN	STD DEV	SKEW-NESS	KURT-OSIS	PERCENTILES 95	PERCENTILES 90	PERCENTILES 75	MEAN	STD DEV	SKEW-NESS	KURT-OSIS	PERCENTILES 95	PERCENTILES 90	PERCENTILES 75
1. Nieweberg Zone 9 Lat. Long. 34 04' 19 03' Alt. MAP. 564 m 1605.9 mm	57	Wheat	Clay	obs	23.6	10.1	1.3	1.0	46.0	42.2	25.7	97.8	107.5	2.1	5.1	320.9	233.6	142.1
				syn	23.4	10.1	1.2	0.9	45.0	41.6	25.6	98.3	94.3	1.7	3.8	285.1	234.0	144.9
		Wheat	Sand	obs	22.2	10.3	1.2	0.9	44.6	41.5	24.5	99.1	84.1	1.8	4.5	257.1	207.5	137.2
				syn	22.1	10.2	1.1	0.7	43.9	40.6	24.0	99.5	74.0	1.3	2.7	248.3	198.1	139.4
2. Robertson Zone 51 Lat. Long. 33 48' 19 53' Alt. MAP. 183 m 332.1 mm	104	Wheat	Clay	obs	18.3	11.3	0.9	1.0	43.5	31.7	23.3	3.2	9.1	6.3	54.2	16.4	9.2	2.0
				syn	18.2	10.5	0.7	0.9	38.8	29.8	23.4	2.7	6.2	3.8	17.0	14.6	8.3	2.0
		Wheat	Sand	obs	17.0	11.6	0.9	0.8	43.0	33.7	22.1	4.5	7.6	3.8	22.1	17.7	13.1	5.5
				syn	17.1	11.2	0.9	0.9	41.4	31.0	22.4	3.8	5.7	2.7	10.2	14.9	11.0	5.2
3. Albertinia Zone 83 Lat. Long. 34 12' 21 36' Alt. MAP. 168 m 438.4 mm	54	Wheat	Clay	obs	20.9	11.8	1.4	1.6	48.1	42.6	23.0	8.5	17.0	4.6	29.0	38.2	22.7	8.7
				syn	21.2	12.0	1.3	1.5	48.9	44.4	23.1	9.2	15.2	3.2	13.5	39.5	26.1	11.1
		Wheat	Sand	obs	18.1	10.9	1.2	1.6	43.0	35.2	21.0	11.3	12.6	2.9	15.7	33.7	25.9	16.0
				syn	18.2	11.1	1.2	1.6	43.6	34.4	20.9	12.2	11.5	1.7	3.9	35.9	25.8	17.2
4. Oudtshoorn Zone 92 Lat. Long. 33 35' 22 12' Alt. MAP. 315 m 242.2	101	Veld	Clay	obs	14.6	11.8	1.1	0.8	38.2	31.5	21.4	1.7	5.5	6.4	57.4	10.6	4.4	0.4
				syn	14.6	11.8	1.0	0.8	37.9	31.6	21.4	1.4	3.7	4.8	29.1	7.6	4.2	0.6
		Veld	Sand	obs	15.4	11.5	1.0	0.8	37.2	31.4	22.4	0.9	3.0	7.2	72.8	5.1	2.6	0.2
				syn	15.5	11.7	0.9	0.5	37.8	32.5	22.4	0.5	1.9	7.8	84.2	2.6	1.0	0.0
5. Nquamakwe Zone 186 Lat. Long. 32 12' 27 57' Alt. MAP 1060 m 686.6 mm	94	Maize	Clay	obs	34.4	26.5	1.2	0.5	92.9	75.1	51.0	11.9	20.0	3.0	11.7	52.5	33.7	15.3
				syn	36.4	26.6	1.1	0.3	94.6	76.6	56.1	11.9	17.2	2.5	8.6	45.3	32.8	17.3
		Maize	Sand	obs	31.6	25.9	1.2	0.8	89.9	69.6	47.8	14.7	16.0	2.1	6.0	47.8	35.4	20.5
				syn	33.4	26.2	1.2	0.8	89.6	74.1	50.2	14.9	13.8	1.8	4.9	43.2	32.5	20.9
6. Diepdrif Zone 208 Lat. Long. 31 34' 20 18' Alt. MAP. 1039 m 129.1 mm	49	Sparse Veld	Clay	obs	8.0	10.3	2.0	4.7	30.6	21.9	11.8	1.1	4.5	6.1	43.3	6.4	1.5	0.0
				syn	8.4	10.7	1.9	4.2	30.3	24.9	12.8	1.0	4.5	9.0	100.9	5.1	2.3	0.1
		Sparse Veld	Sand	obs	8.5	10.2	1.8	3.6	30.0	22.2	12.8	0.6	2.4	6.7	52.5	3.0	0.8	0.0
				syn	8.9	10.3	1.7	3.4	30.1	23.9	13.9	0.5	2.6	8.4	76.7	2.2	0.3	0.0
7. Lekkervlei Zone 217 Lat. Long. 31 03' 23 36' Alt. MAP. 1292 m 271.1 mm	61	Sparse Veld	Clay	obs	15.9	16.6	1.5	2.1	51.4	40.0	23.6	2.6	7.7	5.4	40.6	15.3	6.9	1.2
				syn	15.6	14.9	1.4	1.9	46.9	35.9	22.9	2.4	6.2	5.3	41.1	13.0	7.3	1.7
		Sparse Veld	Sand	obs	16.8	16.1	1.4	1.7	50.2	41.1	24.5	1.7	4.9	6.7	69.6	9.8	4.9	1.0
				syn	16.8	14.4	1.2	1.3	46.2	36.8	24.3	1.2	3.3	6.0	49.2	6.1	3.4	0.8
8. Thornlea Zone 297 Lat. Long. 28 39' 21 31' Alt. MAP. 914 m 199.3 mm	67	Sparse Veld	Clay	obs	12.3	15.7	1.8	3.5	47.7	35.9	17.3	2.5	8.2	6.7	69.5	16.3	7.2	0.3
				syn	13.4	15.7	1.5	2.4	47.5	35.8	21.8	2.5	7.0	4.8	32.5	16.1	7.7	0.8
		Sparse Veld	Sand	obs	13.2	15.2	1.7	3.0	45.8	35.3	19.3	1.5	4.8	6.3	51.4	9.4	4.4	0.6
				syn	14.6	15.6	1.4	2.0	46.8	37.2	23.3	1.3	3.5	4.5	26.1	8.0	4.0	0.6
9. Richmond, Natal Zone 367 Lat. Long. 29 52' 30 16' Alt. MAP. 884 m 1032.7 mm	56	Maize	Clay	obs	43.0	35.1	0.9	-0.6	110.8	103.3	60.2	30.6	39.2	3.5	22.3	101.3	76.8	44.5
				syn	43.2	35.0	0.9	-0.6	109.9	104.9	60.2	29.6	33.1	1.6	3.2	95.2	76.6	46.4
		Maize	Sand	obs	39.7	33.5	0.8	-0.6	104.3	96.2	57.5	34.0	28.6	2.6	12.4	79.7	63.9	46.1
				syn	39.9	33.7	0.9	-0.5	104.9	99.5	57.0	32.8	23.8	1.0	1.0	77.7	67.5	46.1

Table 6.2 (continued)

STATION	LENGTH OF RECORD (yrs)	CROP	SOIL	RAIN	MONTHLY ACTUAL EVAPOTRANSPIRATION (mm)							MONTHLY RUNOFF (mm)						
					MEAN	STD DEV	SKEW-NESS	KURT-OSIS	PERCENTILES			MEAN	STD DEV	SKEW-NESS	KURT-OSIS	PERCENTILES		
									95	90	75					95	90	75
10. Bergville Zone 377 Lat. Long. 28 44' 29 21' Alt. MAP. 1130 m 740.9 mm	46	Maize	Clay	obs	39.4	35.2	1.0	0.1	109.7	89.0	63.0	12.3	22.0	2.9	10.6	58.3	37.0	14.2
				syn	38.9	34.9	1.0	0.0	111.0	92.1	62.4	10.7	18.5	2.7	8.8	49.9	33.5	13.9
		Maize	Sand	obs	38.8	38.3	1.1	0.3	120.1	99.4	62.6	12.7	15.9	2.5	7.6	41.8	33.0	16.5
				syn	38.9	38.4	1.1	0.2	121.5	103.6	61.3	10.6	12.1	1.8	3.4	35.9	27.1	15.1
11. Durban Zone 408 Lat. Long. 29 51' 31 00' Alt. MAP. 91 m 1013.5 mm	62	Sugar Cane	Clay	obs	44.4	24.2	0.0	-1.1	81.6	76.3	64.6	23.2	39.4	3.0	11.1	102.6	68.6	29.0
				syn	47.8	24.2	-0.2	-1.0	83.7	77.9	67.7	26.9	37.7	2.3	7.1	106.3	77.3	37.9
		Sugar Cane	Sand	obs	48.0	26.3	-0.1	-1.2	86.1	80.9	71.0	19.5	28.1	3.5	17.7	68.7	50.2	24.1
				syn	52.1	25.9	-0.3	-1.0	87.4	83.2	73.5	22.5	26.9	2.4	9.1	77.5	56.9	30.7
12. Vryburg Zone 442 Lat. Long. 26 58' 24 44' Alt. MAP. 1190 m 463.4 mm	46	Maize	Clay	obs	25.5	25.9	1.3	1.3	75.8	66.5	39.6	6.5	14.9	3.7	17.3	36.2	22.5	5.8
				syn	25.4	25.3	1.2	0.7	80.1	64.6	37.9	7.5	16.6	4.1	21.8	39.7	23.7	7.0
		Maize	Sand	obs	26.3	29.6	1.4	1.8	88.1	70.5	41.2	5.7	8.8	2.9	10.8	23.3	15.6	7.2
				syn	26.4	29.3	1.3	1.1	92.0	70.6	41.0	6.5	11.9	5.3	44.5	26.2	16.3	7.3
13. Klipspruit Zone 495 Lat. Long. 26 16' 27 55' Alt. MAP. 1615 m 688.7	75	Maize	Clay	obs	36.6	34.1	1.0	0.1	105.9	88.9	60.3	10.8	21.3	3.8	19.4	49.9	31.0	12.6
				syn	37.7	33.6	0.9	-0.2	107.3	92.3	63.1	11.0	19.1	3.2	15.9	49.6	33.7	14.5
		Maize	Sand	obs	34.7	34.7	1.0	0.0	108.4	90.9	57.1	12.7	15.9	3.1	16.4	41.3	30.2	17.5
				syn	36.5	35.3	1.0	-0.1	111.5	96.5	59.8	12.1	13.5	2.8	12.8	38.3	27.9	15.5
14. Karina Zone 518 Lat. Long. 26 05' 29 50' Alt. MAP. 1648 m 645.1 mm	67	Maize	Clay	obs	33.5	33.2	1.2	0.3	108.6	91.2	53.5	11.5	21.8	2.9	10.5	60.3	36.4	13.1
				syn	35.5	32.6	1.0	0.0	106.6	88.8	59.1	11.1	18.8	2.8	12.0	51.2	37.1	15.2
		Maize	Sand	obs	31.6	32.7	1.1	0.2	103.1	89.1	50.8	13.3	17.2	2.1	5.7	49.0	36.5	18.6
				syn	33.9	33.0	1.0	0.1	104.2	90.2	55.7	12.7	14.3	1.9	4.4	41.8	31.7	18.6
15. Pongola Zone 543 Lat. Long. 27 25' 31 31' Alt. MAP. 290 m 675.2 mm	27	Maize	Clay	obs	33.1	30.0	1.1	0.3	96.0	80.6	53.7	13.5	31.1	7.8	91.6	53.1	37.0	15.3
				syn	34.0	30.9	1.2	0.4	99.2	84.6	54.4	16.7	28.7	3.2	14.5	71.4	51.2	24.9
		Maize	Sand	obs	31.0	30.5	1.2	0.4	96.4	81.6	47.8	15.6	24.2	8.3	105.9	45.7	35.5	21.6
				syn	32.2	31.8	1.3	0.7	105.0	86.5	50.8	18.4	20.8	2.3	7.6	57.6	43.6	25.8
16. Zaaiplaas Zone 594 Lat. Long. 24 04' 28 42' Alt. MAP. 1204 m 653.4 mm	65	Maize	Clay	obs	33.1	33.1	1.0	0.1	103.1	83.7	54.4	11.5	23.6	3.8	21.6	59.7	36.4	11.6
				syn	34.9	34.0	1.0	0.1	104.7	84.3	58.6	12.2	23.6	3.7	20.4	56.2	41.0	14.1
		Maize	Sand	obs	32.7	35.2	1.1	0.2	108.3	89.8	54.5	11.7	16.0	3.1	15.8	42.6	31.8	16.0
				syn	34.9	36.5	1.1	0.1	113.2	93.2	57.1	12.1	16.7	3.2	15.2	40.4	31.2	16.6
17. Inyoko Zone 631 Lat. Long. 24 08' 30 52' Alt. MAP 390 m 461.1 mm	57	Maize	Clay	obs	23.8	25.9	1.3	1.2	79.0	63.1	36.3	8.8	23.4	6.1	53.8	46.0	27.9	6.5
				syn	25.8	26.8	1.2	0.6	78.8	67.0	42.6	9.3	18.5	2.9	9.6	50.6	31.7	9.9
		Maize	Sand	obs	24.5	28.8	1.4	1.2	88.8	69.7	37.9	8.1	16.1	6.4	65.9	32.4	22.4	10.4
				syn	26.9	30.8	1.3	1.0	91.9	77.7	43.3	8.1	11.6	2.5	8.4	31.8	22.7	10.4

6.2 Estimation of potential evaporation

There were a number of factors which had to be considered before selecting a specific technique for estimating the potential evaporation in this study. These factors are listed below and will be discussed more fully thereafter.

(a) The method of estimating PE for a study of this nature depended primarily on the availability of data for the possible methods.

(b) The availability of such data should be assessed in both terms of the lengths of record and the spatial distribution of the data.

(c) The sensitivity of the soil moisture budget to time units of the variables i.e. whether daily, weekly, monthly or mean monthly values would be acceptable.

(d) Having decided to use a temperature based approach to estimating PE it remained to select the particular method.

6.2.1 Availability of data for estimating potential evaporation

Devitt et al., (1983) conducted a study in which a weighing lysimeter was assumed to provide the most reliable estimate of AET and was thus used as a standard against which were tested the Penman equation, pan evaporation, tensiometers, neutron probe and leafwater potential: Penman correlations. This study by Devitt et al., (1983) revealed that the Penman equation was by far the most accurate method of estimating evapotranspiration and that climatological conditions are usually fairly uniform over large areas of land compared to variations of texture, density and moisture of the soils. Unfortunately the climatic data input required for the Penman equation is not available at most sites in South Africa. The Penman equation was therefore omitted as a possible potential evaporation estimator in this study.

The Class A evaporation pan, whilst not the best, is accepted as a reasonably reliable, inexpensive integrator of the PE process over a period of time and is used commonly as a reference PE (Green, 1985;

Schulze, 1985b). All of the crop factors which were used in the dryland analysis discussed in Chapter 7, are based on A-pan estimates of PE. So whilst it is acknowledged that the A-pan has many disadvantages, there is a substantial body of knowledge (Green, 1985) which uses the Class A-pan evaporation as a reference. However, the spatial distribution of evaporation pans in Southern Africa is such that they are found generally at dams, existing irrigation schemes and at agricultural research stations. These sites are sometimes not representative of the developing areas in which agricultural planning decisions are required. In addition unless these pan data are collected under experimental conditions, they are often subject to error due to one or more of the following;

(a) possible accumulation of dirt/algae,
(b) animals drinking from the pan,
(c) effects of advection and
(d) influences of the local environment.

According to Smith (1975) the extrapolation of evaporation data from a pan to locations where it is not measured is a very hazardous procedure. Green (1985) also discusses the errors which could be incurred when extrapolating A-pan data. Temperature on the other hand is less susceptible to measurement errors or the effects of local anomalies in micro-climate and errors in extrapolation.

Furthermore in an analysis of the soil moisture budget for planning purposes it is desirable to include rainfall stations with as long a record as possible. The record lengths at daily temperature or A-pan evaporation stations are often considerably shorter than those at nearby rainfall stations. Such short record lengths present a problem for studies which involve risk analysis. If daily evaporation or daily temperature data were to be used then short record lengths could not have been avoided since most of the stations have only relatively short concurrent records of daily rainfall and daily temperature and/or daily evaporation.

There are approximately twice as many temperature stations as evaporation stations in South Africa. These temperature stations are of interest in this study since temperature based estimates of potential evaporation are used widely in soil moisture budgeting models.

In view of the abovementioned, and since temperature data are available at twice as many stations as are evaporation data, throughout Southern Africa (in some areas there are several times as many temperature as evaporation stations), it was decided to investigate the use of a temperature based formula to estimate PE. In addition to the numbers of temperature stations the distribution is more even spatially and they cover, generally, a wider range of altitudes and physiographic zones than do the evaporation pans. However, in view of the large body of knowledge in South Africa which presents crop factors in terms of A-pan evaporation (Green, 1985) it is essential to relate temperature based estimates of evaporation to Class A-pan estimates.

6.2.2 Sensitivity of the soil moisture budget to techniques of estimating potential evaporation

A sub-study was conducted to compare the sensitivity of the output from the ACRU soil moisture budgeting model to inputs of PE estimates by daily and monthly mean temperature based equations and estimates based on A-pan evaporation. Monthly totals of actual evapotranspiration and monthly totals of runoff and the soil moisture deficit i.e. (FC - actual soil moisture) on the last day of the month were used as indicators of sensitivity.

Several reported studies and sub-studies conducted during the course of this work lent credibility to the notion that such an exercise might reveal the acceptability of using monthly mean temperature as an estimator of PE in soil moisture budgeting models. These studies are discussed below.

The sub-study described in Section 4.1.1 which included daily A-pan evaporation data from 242 stations throughout South Africa showed that on 80 per cent of occasions the daily evaporation was within ±50 per cent of the daily mean for that month. To demonstrate the low variability of evaporation with time this sub-study was extended to include the frequency distribution of the mean evaporation over four days expressed as a fraction of the mean daily evaporation for the month. The frequency distribution for the abovementioned fraction is presented in Table 6.3. The period of four days was chosen since it was considered to be a common time period between rainfall or irrigation events. It is particularly a time period of approximately four days and not necessarily the one day time period which is of prime interest in the modelling of soil moisture. All the evaporation stations mentioned above were used in this sub-study which included only the summer months for which the mean daily evaporation exceeded 4 mm. More than 100 000 data points are represented in the frequency analysis presented in Table 6.3 and which shows strong evidence of the conservative temporal nature of evaporation.

Table 6.3 Frequency analysis of the ratio of the mean daily Class A-pan evaporation over four days to the mean daily evaporation for that month

Ratio mean daily evaporation 4 days : 1 month	0 - .8	.8 - 1.2	<1.2 -
Frequency (%)	16	67	17

A study by Furniss (1987), some of the results of which are presented in Table 6.4, showed the similarity between estimates of monthly total AET and monthly total irrigation demand when using daily A-pan evaporation and mean monthly A-pan evaporation.

Table 6.4 Outputs from the irrigation version of the ACRU model using mean monthly A-pan evaporation, regressed against outputs using daily A-pan evaporation (after Furniss, 1987)

Station	Monthly Total AET (mm)				Monthly Total Irrigation (mm)			
	b_o	b_1	r^2	RMSE	b_o	b_1	r^2	RMSE
Cedara	-0.16	0.97	0.89	4.0	1.97	0.93	0.61	5.3
Potchefstroom	-3.15	1.02	0.90	4.8	-3.02	1.02	0.82	5.3
Robertson	1.21	0.96	0.98	3.5	5.7	0.94	0.85	5.8
Vaalhartz	1.57	1.01	0.85	6.1	8.1	0.97	0.77	6.6

Johns and Smith (1975) refer to the strong negative feedback influence which exists in the soil water system, thus making it an easy system to simulate numerically. Limits are set by the field capacity and wilting point in the soil profile which determine how wet or dry the soil may become. In addition an overestimation in AET will produce an over-reduction in the soil moisture and hence a decrease in AET in the subsequent period. This effect also works in the reverse direction. The influence of this negative feedback will be less pronounced under an irrigation regime where the soil moisture is replenished to FC when it reached some fraction, usually 0,5 of the PAM as discussed in Section 4.1.1. As a consequence of this negative feedback influence, Johns and Smith (1975) conclude that most of the errors in soil moisture budgeting under dryland conditions are a result of factors such as run-off and run-on under conditions of high rainfall intensity, errors of measurement of soil water, rainfall and evaporation and the influence of defoliation and senescence on the energy exchange of the plant canopy. Linacre and Till (1969) concur with the above findings and cite Hartmann (1960); Penman (1963); Bartels (1965); as well as Rose and Stern (1965) in support of their statement that errors may be incurred in estimating runoff and water draining beneath the root zone. Linacre and Till (1969) go on to say that;

"in view of this and of the appreciable uncertainties in measuring rainfall it is obviously inappropriate to strive for high accuracy in determining the amount of evaporation". p180

In the soil moisture budgeting system there are two distinct groups of variables. There are those which create large stepped changes and those which cause small incremental changes in the soil moisture budget. Rainfall and irrigation timing and amount form the first group and evapotranspiration, crop coefficients, soil depth and drainage characteristics form the latter category of variable. Under conditions of frequent rainfall events this is particularly so. Experiments conducted by Calder, Harding and Rosier (1983) at the Institute of Hydrology in England showed that the inclusion of sophisticated evaporation equations such as those by Priestley-Taylor, Penman or Thom-Oliver, gave no improvement in the estimation of soil moisture deficit, when compared with the monthly mean evaporation and no additional meteorological measurement other than rainfall.

In addition to all the abovementioned evidence from the literature, a study, using the ACRU model in its non-irrigation or dryland mode, was conducted to determine the effect of using mean monthly maximum and minimum temperature in order to estimate PE. Tests were performed at the stations shown in Figure 6.2. Two different soil textures and a variety of crop types were used in simulations. The results presented in Table 6.5 and in Figures 6.3 and 6.4 indicate that there is little difference, at the monthly level, in the various outputs from the ACRU model, viz. AET, runoff and even soil moisture status on the last day of the month, irrespective of whether daily evaporation, daily temperatures or mean monthly temperatures were used to estimate PE.

The systematic error in the estimated AET reflected in Figure 6.4 was due to a systematic error in PE as estimated by the Linacre (1977) equation before applying the regional adjustments discussed in Section 6.2.4. These adjustments for wind and daylength corrected such over or under estimation of PE by the Linacre equation.

It is particularly significant to note that the soil moisture status on the last day of the month showed that even this "point in time" aspect of the soil moisture budget shows no marked difference between the use of daily A-pan evaporation, daily temperature or monthly mean temperature as a means of estimating PE.

Besides the considerable advantages in terms of simplicity of data preparation, other analyses showed that by using monthly mean temperature to estimate PE, the daily rainfall record which then became usable was increased by an average of 400 per cent over that which would have been available had only the daily rainfall which corresponded with the daily A-pan record been used. The resultant increase in the length of record is an important aspect of risk analysis.

Figure 6.2 Location of the climate stations used to test the effect of temperature based estimates of PE on the ACRU model output

1	Calvinia
2	Elgin
3	Robertson
4	Upington
5	Grootfontein
6	Oudtshoorn
7	Vaalharts
8	Potchefstroom
9	Pietersburg
10	Skukuza
11	Piet Retief
12	Cedara
13	Bergville
14	Dohne

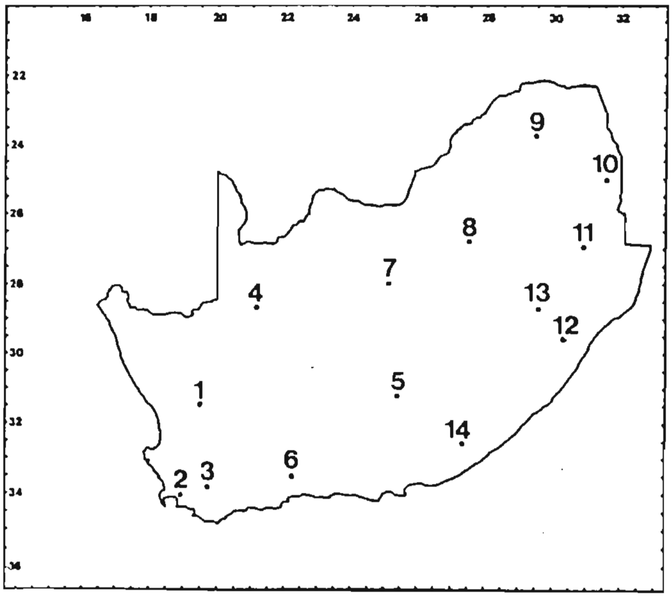


Table 6.5 Sensitivity of the ACRU model to techniques for estimating potential evaporation

<u>Note</u>: Outputs from the ACRU model using daily temperature and monthly mean temperature to estimate PE regressed against outputs using daily A-pan evaporation.

STATION	LENGTH OF RECORD	CROP	SILTY CLAY															
			MONTHLY TOTAL AET (mm)								MONTHLY TOTAL AET (mm)							
			DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE				DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE			
			b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE
1 Calvinia	6 YEARS	WHEAT	0.42	0.96	0.94	3.4	0.61	0.94	0.93	3.6	0.08	1.04	0.99	0.7	0.10	1.05	0.98	1.0
2 Elgin	18 YEARS	WHEAT	1.41	0.84	0.71	11.3	0.39	0.88	0.74	10.5	2.97	1.10	0.98	5.7	2.60	1.08	0.98	5.0
3 Robertson	14 YEARS	WHEAT	0.55	0.95	0.89	4.4	0.58	0.95	0.89	4.2	0.09	1.11	0.98	0.6	0.08	1.11	0.99	0.6
4 Upington	12 YEARS	POOR VELD	0.04	1.00	0.98	1.5	0.14	0.99	0.98	1.8	0.01	1.00	0.99	0.0	0.01	1.00	0.99	0.0
5 Grootfontein	24 YEARS	POOR MAIZE	0.02	0.99	0.98	2.5	0.84	0.95	0.97	3.0	-0.02	1.03	0.99	0.6	0.01	1.07	0.99	0.6
6 Oudtshoorn	9 YEARS	WHEAT	0.03	0.99	0.97	1.9	0.56	0.96	0.95	2.3	0.00	1.01	0.99	0.0	0.00	1.02	0.99	0.0
7 Vaalharts	20 YEARS	MAIZE	1.19	0.96	0.94	6.0	0.95	0.96	0.97	3.9	0.00	0.98	0.98	1.5	0.03	1.02	0.99	1.2
8 Potchefstroom	22 YEARS	MAIZE	0.17	0.99	0.98	4.0	0.53	0.98	0.98	4.7	0.01	0.98	0.99	1.6	0.04	1.01	0.99	1.6
9 Pietersburg	13 YEARS	MAIZE	0.43	1.00	0.98	3.5	0.51	0.99	0.98	3.3	0.09	0.91	0.99	0.9	0.11	0.92	0.99	0.9
10 Skukuza	5 YEARS	TOBACCO	0.26	0.99	0.98	2.7	0.21	0.99	0.97	3.4	-0.02	0.99	0.99	0.3	0.04	1.00	0.99	0.5
11 Piet Retief	17 YEARS	MAIZE	0.51	0.97	0.96	12.6	0.68	0.97	0.94	9.3	0.97	1.00	0.98	3.7	1.03	0.98	0.97	4.1
12 Cedara	23 YEARS	MAIZE	0.45	0.96	0.96	6.4	0.04	0.98	0.96	6.9	0.50	1.07	0.98	2.7	0.43	1.01	0.98	3.0
13 Bergville	7 YEARS	MAIZE	1.02	0.97	0.97	6.3	1.13	0.96	0.97	6.0	0.27	1.02	0.99	3.1	0.26	1.03	0.99	2.4
14 Dohne	7 YEARS	PINEAPPLE	2.58	1.00	0.88	10.6	2.98	1.27	0.82	13.0	-1.19	0.91	0.97	4.2	-1.52	0.88	0.95	5.7

Table 6.5 (contd)

Note: Outputs from the ACRU model using daily temperature and monthly mean temperature to estimate PE regressed against outputs using daily A-pan evaporation.

STATION	LENGTH OF RECORD	CROP	SANDY LOAM															
			MONTHLY TOTAL AET (mm)								MONTHLY TOTAL AET (mm)							
			DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE				DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE			
			b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE
1 Calvinia	6 YEARS	WHEAT	0.36	0.95	0.94	3.3	0.35	0.95	0.94	3.7	0.15	1.16	0.96	0.9	0.16	1.16	0.96	1.0
2 Elgin	18 YEARS	WHEAT	0.99	0.88	0.74	10.4	-1.58	0.91	0.77	9.8	2.76	1.12	0.98	5.4	2.28	1.10	0.98	4.6
3 Robertson	14 YEARS	WHEAT	0.63	0.96	0.89	4.3	0.80	0.95	0.90	4.2	0.08	1.07	0.85	0.5	0.08	1.08	0.85	0.5
4 Upington	12 YEARS	POOR VELD	0.10	0.99	0.98	1.9	0.29	0.98	0.98	2.2	0.00	0.99	1.00	0.0	0.00	0.98	1.00	0.0
5 Grootfontein	24 YEARS	POOR MAIZE	0.06	0.99	0.98	2.9	0.7	0.96	0.97	3.3	0.01	1.06	0.99	0.6	0.01	1.10	0.98	0.8
6 Oudtshoorn	9 YEARS	WHEAT	0.00	0.99	0.96	2.2	0.56	0.96	0.94	2.6	0.00	1.00	1.00	0.0	0.00	1.00	0.99	0.0
7 Vaalharts	20 YEARS	MAIZE	1.06	0.97	0.94	6.8	0.78	0.96	0.97	4.7	-0.01	1.00	0.96	1.2	0.05	1.10	0.96	1.2
8 Potchefstroom	22 YEARS	MAIZE	0.40	0.99	0.98	5.4	0.50	0.98	0.98	5.5	-0.02	0.99	0.97	1.3	0.13	1.05	0.97	1.4
9 Pietersburg	13 YEARS	MAIZE	0.40	1.01	0.97	5.2	0.58	1.00	0.97	4.9	0.08	0.73	0.89	1.6	0.06	0.76	0.92	1.3
10 Skukuza	5 YEARS	TOBACCO	0.32	0.89	0.98	3.3	0.35	0.99	0.97	4.0	0.02	0.96	0.99	0.5	0.13	0.99	0.99	0.0
11 Piet Retief	17 YEARS	MAIZE	0.50	0.95	0.95	9.0	0.33	0.97	0.93	13.3	2.32	0.98	0.91	5.5	1.94	0.94	0.90	6.1
12 Cedara	23 YEARS	MAIZE	1.28	0.92	0.96	8.0	0.04	0.97	0.95	8.9	1.32	1.16	0.93	3.9	0.49	1.03	0.95	3.5
13 Bergville	7 YEARS	MAIZE	1.21	0.97	0.97	8.5	1.09	0.97	0.96	9.1	0.64	1.00	0.97	3.1	0.40	1.03	0.98	2.1
14 Dohne	7 YEARS	PINEAPPLE	1.96	1.04	0.89	11.5	1.98	1.11	0.81	16.5	-1.52	0.80	0.93	3.7	-2.47	0.73	0.85	5.4

Table 6.5 (contd)

Note: Outputs from the ACRU model using daily temperature and monthly mean temperature to estimate PE regressed against outputs using daily A-pan evaporation.

STATION	LENGTH OF RECORD	CROP	SILTY CLAY								SANDY LOAM							
			SOIL MOISTURE DEFICIT LAST DAY (mm)								SOIL MOISTURE DEFICIT LAST DAY (mm)							
			DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE				DAILY TEMPERATURE				MONTHLY MEAN TEMPERATURE			
			b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE	b_0	b_1	r^2	RMSE
1 Calvinia	6 YEARS	WHEAT	20.44	1.18	0.96	43.7	20.53	1.18	0.94	4.2	5.20	1.06	0.99	2.5	6.43	1.07	0.98	3.2
2 Elgin	18 YEARS	WHEAT	10.55	1.04	0.87	12.7	8.67	1.05	0.89	11.7	4.01	1.03	0.96	7.1	2.56	1.04	0.96	7.1
3 Robertson	14 YEARS	WHEAT	21.1	1.19	0.89	4.4	23.1	1.20	0.89	4.4	15.9	1.15	0.91	5.5	14.3	1.13	0.90	5.7
4 Upington	12 YEARS	POOR VELD	4.51	1.04	0.97	1.0	9.48	1.09	0.96	1.2	3.39	1.04	0.97	1.9	9.57	11.11	0.96	2.2
5 Grootfontein	24 YEARS	POOR MAIZE	4.03	1.03	0.96	2.6	14.71	1.13	0.94	3.5	0.72	1.01	0.98	2.9	8.05	1.08	0.97	3.9
6 Oudtshoorn	9 YEARS	WHEAT	5.40	0.95	0.94	1.6	0.12	0.99	0.91	2.0	3.74	0.95	0.97	1.7	1.10	1.00	0.95	2.4
7 Vaalharts	20 YEARS	MAIZE	1.12	1.00	0.91	4.7	14.45	1.12	0.93	4.2	4.77	0.93	0.90	7.7	2.79	1.00	0.91	7.3
8 Potchefstroom	22 YEARS	MAIZE	8.78	1.08	0.94	4.2	13.81	1.12	0.90	5.5	0.40	1.01	0.95	5.3	3.77	1.04	0.94	6.2
9 Pietersburg	13 YEARS	MAIZE	14.7	0.86	0.96	2.0	11.9	0.89	0.96	2.0	14.5	0.83	0.97	3.1	13.5	0.84	0.97	3.2
10 Skukuza	5 YEARS	TOBACCO	0.79	0.99	0.97	2.6	3.49	1.02	0.95	3.2	0.79	0.99	0.98	3.6	3.24	1.03	0.97	4.7
11 Piet Retief	17 YEARS	MAIZE	8.09	0.02	0.85	10.2	3.69	0.97	0.83	11.0	2.56	0.90	0.83	12.9	0.17	0.89	0.81	13.5
12 Cedara	23 YEARS	MAIZE	18.3	1.11	0.88	8.4	11.7	1.06	0.89	8.2	2.71	0.90	0.86	10.3	0.29	0.92	0.90	8.7
13 Bergville	7 YEARS	MAIZE	5.50	1.03	0.91	6.1	8.14	1.05	0.94	4.7	0.26	0.94	0.95	6.0	0.54	0.94	0.94	6.8
14 Dohne	7 YEARS	PINEAPPLE	31.44	0.70	0.91	6.3	38.6	0.64	0.87	7.8	21.3	0.80	0.80	14.2	27.0	0.77	0.72	16.7

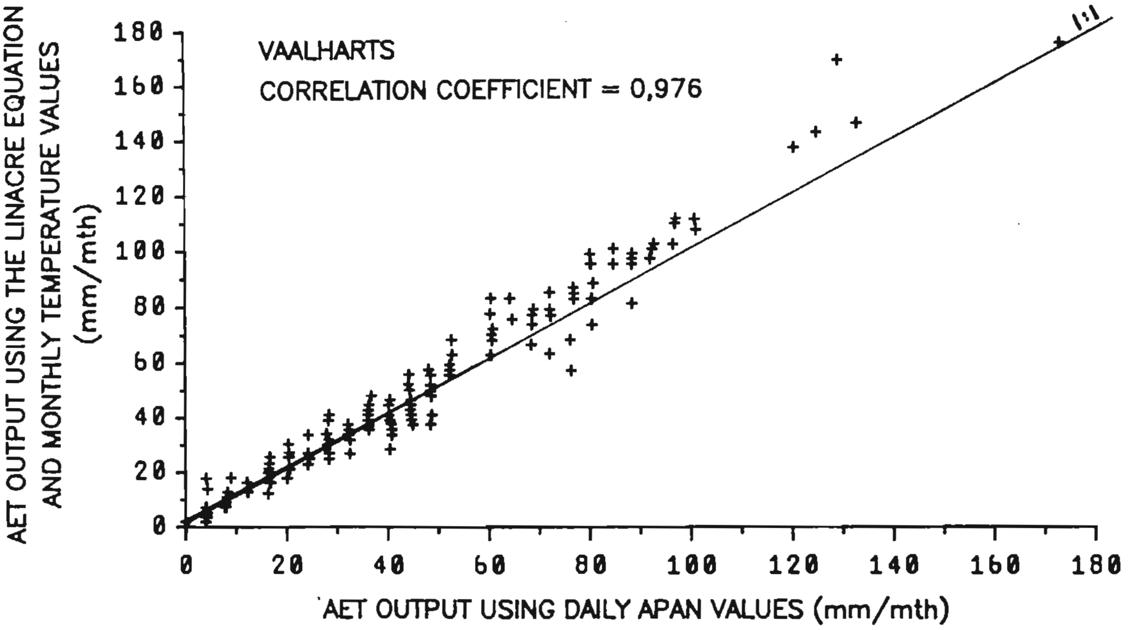


Figure 6.3 Monthly AET estimated using the Linacre (1977) equation vs. monthly AET estimated using daily A-pan values at Vaalharts under dryland conditions

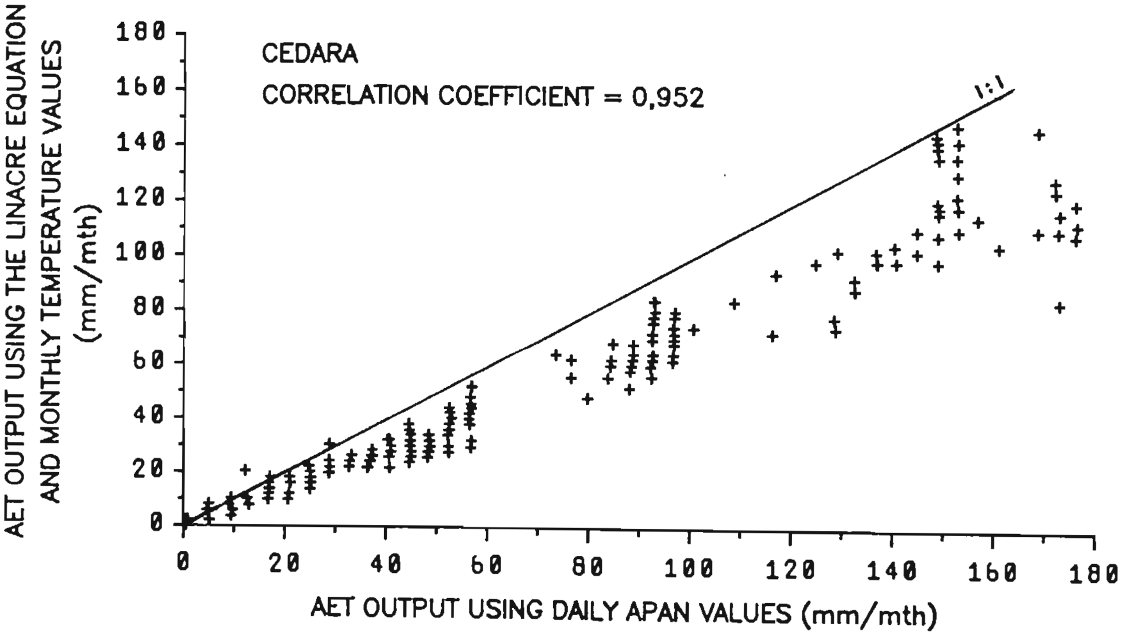


Figure 6.4 Monthly AET estimated using the Linacre (1977) equation vs monthly AET estimated using daily A-pan values at Cedara under dryland conditions

The aforementioned has merit in areas where rainfall supplies a significant proportion of the crop water requirements, however, in areas where the crop water requirements are supplied primarily by irrigation then the accurate determination of evaporation assumes greater importance. This is especially so when one is considering the dry portion of the frequency distribution of estimated irrigation water requirements. It is evident from the results of the irrigation model analyses presented in Section 7.5 and in Appendix E, that even in supplementary irrigation areas PE estimates play an increasingly important role at high levels of non-exceedance of irrigation requirement.

6.2.3 Estimating potential evaporation by the Linacre equation

Clemence and Schulze (1982) compared six commonly used temperature based equations for the estimation of PE, including the Thornthwaite and Blaney-Criddle equations, and found from lysimeter studies undertaken under diverse climatic conditions that for maize, wheat, sugarcane and soyabeans, the equation proposed by Linacre (1977) proved to be superior to the others. The Linacre (1977) equation was therefore chosen to provide the temperature based estimates of PE. This equation is a function of temperature, locational variables and parameters, yet it contains, according to Linacre (1977), much of the generality and universality of the Penman (1948) equation. Linacre (1977) approximated the Penman (1948) equation by "disaggregating" it and relating its components to temperature variables or replacing them with equivalent expressions or approximations involving temperature values alone. The outcome is an empirical formula, simple to use, but with a basis which is physical enough to be of general use, according to Linacre (1977) "with sufficient accuracy for many practical problems and unusually modest demands as regards input data" p410.

For lake evaporation Linacre's equation gives the potential evaporation rate as

$$PE = \frac{700T_m/(100 - ALAT) + LINWIN(T_a - T_d)}{(80 - T_a)} \text{ mm day}^{-1} \quad \text{Eq. 6.1}$$

where

LINWIN = wind factor (with a default value of 15, adjustments to this wind factor are discussed in Section 6.2.4),

T_m = T_a + 0,006 ELEV, with

T_a = mean air temperature (^{o}C),

T_d = mean dew point temperature (^{o}C),

ELEV = elevation above sea level (m),

ALAT = latitude in degrees, and

$(T_a - T_d)$ = difference between air and dew point temperature,

= $0{,}0023ELEV + 0{,}37T_a + 0{,}53R + 0{,}35\ R_{an} - 10{,}9$ in ^{o}C

in which

R = the mean daily or monthly range of temperature (^{o}C) and

R_{an} = the difference between the mean temperature of the hottest and coldest months of the year (^{o}C).

Apart from the elevation and latitude of a location, all the variables in the equation are obtained from maximum and minimum temperatures. The equation has been tested with temperature and pan evaporation data from 24 widely scattered stations in Natal by Schulze (1983) and was found to yield markedly more reliable simulations of A-pan values in all months of the year when compared with other temperature based equations commonly in use viz. Thornthwaite and Blaney-Criddle. However, despite being the best, these estimates of evaporation using the standard Linacre (1977) equation (Equ 6.1), were not considered to be sufficiently accurate when compared with Class A-pan evaporation at a number of stations throughout South Africa. A daylength factor was thus introduced and in addition a sub-study was conducted to regionalize the wind correction factor and also to vary this factor by month.

6.2.4 Regionalization of adjustments to the Linacre equation

The need for local adjustment to, in particular, temperature based empirical methods of estimating PE has been recognised for a long time and has been reported inter alia by, Baier (1963), Linacre and Till (1969) and Doorenbos and Pruitt (1977). More recently, this need for local adjustment has again been stressed by Cuenca (1982); Hill, Johns and Frevert (1983) and Cuenca and Amegee (1987).

Ritchie (1981) states:

"It is important to understand that PE cannot be calculated exactly and that all equations are empirical and therefore need some calibration". p82

Cuenca (1982) states:

"Poor prediction is expected from a temperature based method in certain climatic zones if local calibration is not made. This holds true for every commonly used method". p13.

Cuenca (1982) then cites Jensen (1974) who stated that no methods based on limited data have been found to work extremely well in all climatic regions without some local climatic calibration. Hill, Johns and Frevert (1983) in a study to compare equations used for estimating agricultural crop evapotranspiration, concluded inter alia, that the calibration or adjustment, to local conditions, of equations which estimate ET is essential.

In an analysis of evapotranspiration as a regionalized variable Cuenca and Amegee (1987) concluded that in many instances the fiscal realities will dictate that regional evapotranspiration estimates will have to be made using empirical methods which require local calibration and adjustment. The abovementioned was precisely the case in this study.

It is acknowledged that what follows in this Section 6.2.4 cannot be termed local adjustment, it is rather regional adjustment. Due to time, budget and quality of evaporation data constraints it was not possible to perform more detailed local adjustments to the Linacre (1977) equation on the basis of individual stations. The approach which was adopted relied on an assessment of the frequency distribution of the residuals between the observed mean monthly A-pan evaporation and the adjusted Linacre (1977) estimate, of that value, using mean monthly temperature. This method was considered to be more robust and safer than making sweeping assumptions as to the regional applicability of an adjustment based on results from one or two stations. The number of stations per region varied between 13 and 83 and therefore the effect of any adjustment could be assessed for the region as a whole.

Once it had been accepted that some manner of regionalized adjustment to the Linacre (1977) equation was necessary, attention turned to the form of that adjustment.

It was decided to adjust the equation using two variables which are meaningful physically viz. daylength and wind. This decision was motivated in part by the findings of a sensitivity analysis by Waggoner (1968) cited by Schulze (1984a) in which net radiation, vapour pressure deficit and wind, were the most influential factors effecting PE. A daylength correction was applied to the radiation related term as indicated in Eq. 6.2.

$$DL(700\ T_m/(100-\ ALAT)) \qquad \text{Eq. 6.2}$$

where

DL = (daylight hours according to latitude)/12.

T_m, ALAT defined for Eq. 6.1.

The wind factor (LINWIN) which was given a default value of 15 by Linacre (1977) was adjusted initially according to the monthly mean wind velocities for each month at stations within or near the major wind regions depicted in Figure 6.5. These regions were delimited by considering proximity to the coast and major topographic features.

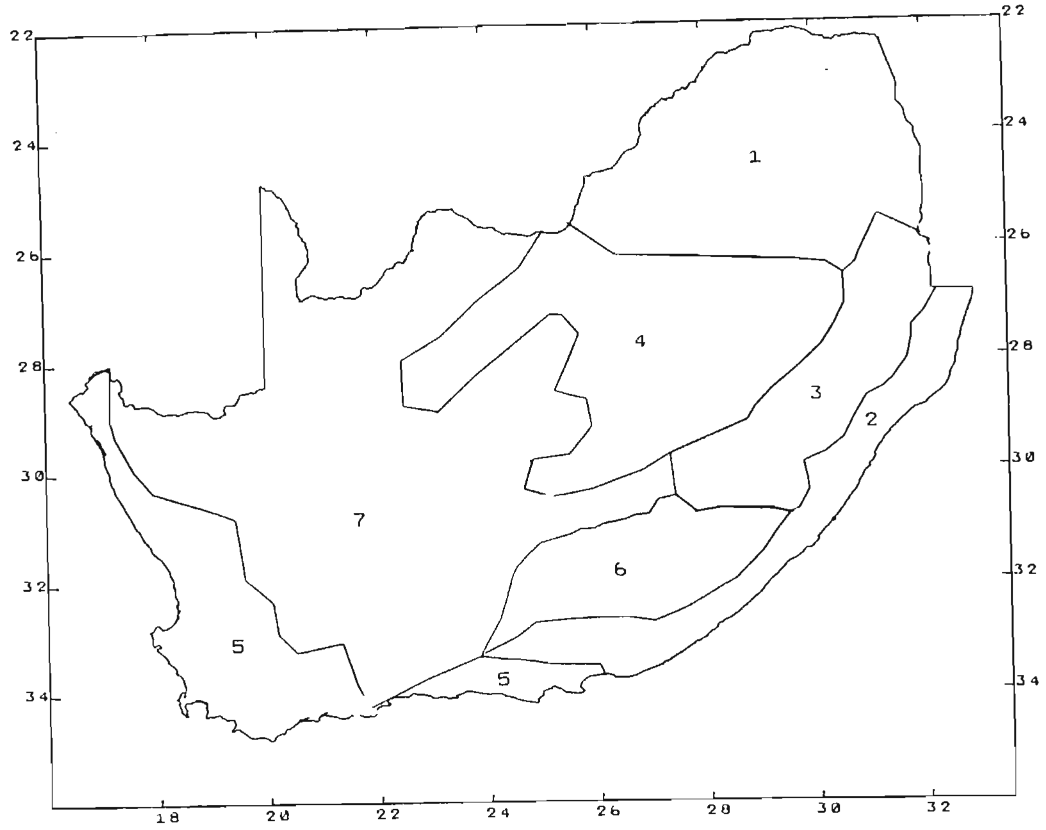


Figure 6.5 Delimitation of major wind regions

The monthly mean wind velocities for Cape Town, Durban, Kimberley, Middelburg (Cape Province), Germiston, Pretoria and Piet Retief obtained from SAWB (1965) were used initially. Thereafter small adjustments were made to these values until the frequency distribution of the residuals i.e. (obs-est) monthly mean evaporation, were acceptable. In all regions and months the adjustment to LINWIN improved the estimates of PE. The monthly wind velocities in each region were adjusted, within reasonable limits, until the mean and median of the residuals (obs-est) as well as the kurtosis of the frequency distributions of residuals in each month and for each region were considered acceptable. In most instances, the general seasonal wind patterns present in SAWB (1965) remained largely unaltered, however, the scale of the adjustment from these patterns did vary from region to region. Table 6.6 shows the values of LINWIN which were estimated by the above process.

Table 6.6 Monthly values of LINWIN for the 7 regions

WIND FACTORS FOR THE WIND REGIONS												
WIND REGION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	10.2	9.7	9.5	9.0	8.9	8.7	9.0	11.4	13.4	13.8	12.8	10.8
2	17.0	13.7	13.1	12.4	12.2	12.1	15.0	19.4	20.8	21.1	21.0	19.2
3	10.9	9.7	9.5	9.2	8.9	8.9	10.2	11.6	14.1	14.3	13.1	11.6
4	12.4	11.2	10.5	9.7	9.7	10.2	11.2	13.5	15.6	15.7	15.3	15.0
5	27.0	26.5	21.9	20.0	18.9	18.2	17.6	19.7	22.6	25.8	27.3	27.0
6	17.3	16.0	14.3	13.4	14.6	16.8	18.2	19.0	18.9	18.5	18.5	18.8
7	16.0	14.6	14.4	13.8	13.8	14.3	14.6	16.0	18.5	20.0	20.4	17.5

The application of these wind factors resulted in the residuals from more than 70 per cent of the stations lying between ± 1 mm/day for almost all of the 84 region months contained in the analyses.

PE is sensitive to vapour pressure deficit as mentioned above. The term (T_a-T_d) provides an index of vapour pressure deficit and hence any adjustment to this term eg. by the LINWIN factor may be considered as an adjustment to the vapour pressure deficit. Hence the LINWIN factor provides a pseudo wind function adjustment.

It is recognised that the regions are rather broad and that further refinement of these boundaries and the consequent further adjustment to the wind factor both temporally and spatially is possible. The possibilities in this direction for future more detailed research are interesting. One of the reasons for not pursuing the investigation during this study, was the thought that some of the stations produced a poor fit because the Class A-pan evaporation data were not good or that local anomalies existed. Hence, it would be undesirable for finer adjustment to take place until the evaporation data had been investigated further. The fact that the stations at which the adjusted Linacre (1977) equation's performance was poor, were scattered and formed no clear pattern, lent credibility to the above hypothesis.

6.2.5 Selection of temperature stations for each zone

The temperature stations used in each zone were selected on the basis of the following criteria:

(a) Proximity to the zone: In a number of cases there was no temperature station within a zone. However, a suitable temperature station was found nearby.

(b) Altitude: Since temperature and evaporation are related to altitude, the altitudes of the selected stations were as representative of the average zonal altitude as possible.

(c) Regression relationships: Regression relationships were generated to yield temperature as a function of location, altitude and continentality for 7 zones viz. 9, 11, 29, 52, 201, 202 and 204.

7 APPLICATION OF THE MODELS AND THEIR OUTPUT

The primary objective of this study was to determine crop water requirements for use in irrigation planning. However, as was stressed in Section 1.2, irrigation should not be considered in isolation but rather as one of a range of options facing the agriculturalist. The dryland farming option should also be considered in the preliminary stages of a feasibility study on irrigation. Consequently such an analysis was conducted using the ACRU model with a range of crops, soil types, soil depths and planting times in each of the 712 zones, in addition to the analyses conducted for irrigated conditions. The discussion on the application of the dryland model and its output is longer than that on the irrigation model. This should not be interpreted as an indication of its relative importance, rather it is a consequence of the mode of analysis and presentation chosen for the irrigation model which lends itself to a more concise format and description.

7.1 Purpose and value of the dryland analysis

By way of introduction it is considered appropriate to recall the following point which was presented in Section 1.1. In Southern Africa the areas in which the major dryland crops are being grown, have in the past been determined by a number of factors among which the economic factor plays a dominant role. Climatological disadvantages have often been masked by economics which has enabled crops to be grown profitably under dryland conditions in regions where the rainfall is too low or unreliable. Profitability, although understandably a dominant factor in decision-making, is also an unreliable factor which can alter very suddenly and a change in the pricing structure of inputs, transport or the produce itself, may result in the need to seek alternative crops or to provide for irrigation to boost and secure yields. The 1986/87 market oriented approach to the maize price was a particularly dramatic example of the above point.

Scientific research such as that conducted in this study is particularly valuable at times like these, when the need to find alternative dryland crops is most pressing.

The purpose of the dryland analysis is to provide the agricultural planner with information on the following three important aspects of agrohydrology, for a range of sites, crops, soils and risk management options, in a concise and usable form. First, the degree to which rainfall fails to supply the evapotranspiration needs of the crop. Secondly, the number of days of plant water stress which result from such a shortfall. Both the ratio between the actual and potential evapotranspiration as well as the number of days of crop water stress play an important role in crop yield functions. Thirdly, the water yield from a cropped land provides valuable information for use in water resources assessment of irrigation dams, for example.

7.2 Procedure for analysis of soil moisture under dryland conditions

As may be appreciated with 712 homogeneous climate zones and the large number of combinations of crop and soil type, soil depth and planting time to be processed for each zone, some form of automatic generation of the input file to the ACRU model was necessary.

The broad boundaries of regions in which the various crops may possibly be grown were delimited and digitized. A program was then developed whereby all the zones enclosed in these defined boundaries could be identified. These broad crop regions are presented in Appendix B. If a key rainfall station was located within the boundary of a crop region then that crop type was incorporated in the data file for that station. In this way a data set was generated in which each of the 712 stations was allocated a number of crop types to be processed. Each of these crops had a data set which included, planting date, monthly root distribution and monthly crop factors throughout the year. These data sets are presented in Appendix C. The three soil textures and depths which were used for each crop type and planting date were also linked to data sets which contained these soil variables in the form required by the ACRU model.

A program was developed which proceeded through the zone file and produced an input data file for the ACRU model from the crop type and planting date. The relevant information was obtained from the library of look-up tables and data sets which contained the aforementioned information.

The ACRU model was then modified to operate inside a continuous looping program which processed all 712 stations for all the combinations of crop type, soil texture, soil depth and planting times, in several large computer runs.

7.3 Analysis of soil moisture under dryland conditions: output

The three output variables which are presented in Tables 7.1, 7.2 and 7.3 are; actual evapotranspiration deficit, an index of stress days and water yield. Some discussion is necessary to clarify the definition of these three variables in the context in which they were used.

7.3.1 Terminology used to describe the output

The water yield includes surface flow, interflow and deep percolation. Unfortunately space does not permit these variables to be printed out separately. A close inspection of the water yield amounts reveals in some instances that sand yields more runoff than clay and it may thus appear at first that there is an error in the model. However, it should be appreciated that the deep percolation component of water yield in sand would be considerably more than for clay at the same location so although runoff from the surface may not be visible, subsurface runoff is still taking place and it is the sum total of runoff that is reported. In clay and loam more of the water which enters the soil is retained in the soil matrix and these soils are therefore more likely to be in a wetter state than sand in the rainy season. Sand on the other hand has a very limited moisture holding capacity and therefore allows more water to percolate and that which remains is depleted in a shorter time than is the case with clay and loam. Sandy soils are therefore more likely to be found in a dry state and consequently the chances of surface runoff are reduced.

An important point to note in the presentation of the levels of non-exceedance for water yield in Table 7.3 is that the wetter half of the frequency distribution is presented. Irrigation is more likely to take place when runoff levels are low and hence the reasons for presenting the higher levels in the water yield tables may not be apparent immediately. The reasons are several. First the water yield is bounded at the lower end by zero in almost all cases and therefore extrapolation on the lower side is made easier. Secondly, this study is designed to assess the water resources available in small farm dams and consequently high flows into the dam are important and irrigation is most unlikely to take place from the run of river in times of low or no flow. Thirdly, the columnar nature of the output dictated a uniform format throughout and in most of the dry months the water yield even at the 50 percentile level is already zero.

The evapotranspiration deficit was defined mathematically as:

$$\sum_{n=1}^{n=30,31} (PET_n - AET_n)$$

AET is assumed equal to PET until the soil moisture content reaches 0,5 PAM, thereafter the ratio AET:PET declines linearly to zero at a soil moisture content equal to wilting point (WP).

Evapotranspiration deficit was output since AET is an important driving force for growth in plants. Therefore the difference between the ET which the plant requires for unhindered growth and the AET which it achieves, is a crucial element in the estimation of growth and yield potential. It should be noted however that although the ACRU Model does contain the mechanism for estimating the reduction in ET due to stomatal closure in times of adequate soil moisture but excessive atmospheric demand, as discussed in Section 4.1.1, the mechanism was not used in this study since only monthly mean PET was input to the model. The midday peaks of excessive atmospheric demand were thus not seen by the model. Therefore, only the reduction in ET caused by a deficiency of soil moisture was modelled in this analysis.

Models which estimate crop yield and which are based primarily on AET or an index of moisture stress are found commonly in the agronomic literature eg. Rosenzweig (1968); Mallett et al. (1974); Hellman

(1975); Thompson (1976); du Pisani (1977; 1978); de Jager (1982); Hill et al (1984). An index of stress was therefore considered to be a useful output from the dryland analysis in order to complement the evapotranspiration deficit and thus provide the agricultural planner with additional useful information which could serve as input to crop yield models proposed by the abovementioned. The onset of moisture stress in plants is a complex function controlled inter alia by the plant's critical leaf water potential, the atmospheric demand, soil moisture status and the soil texture, as discussed in Section 4.1.1. In a broad analysis for planning purposes it is not possible to consider all these factors and it was thus decided to proceed on the assumption that a stress day is one on which the ratio AET:PET <0,5. In view of the assumed relationship between AET:PET and soil moisture discussed in Section 4.1.1, this meant that the soil moisture was assumed to be equal to 0,25 PAM before stress sets in. The index of stress recorded was the number of days that the soil moisture was at or below this level. Whilst making the above assumption with regard to the definition of a stress day it is recognised that in some cases a stress day could be considered to have occurred at a higher ratio of AET:PET than 0,5.

7.3.2 Application of the output

Each line of output as presented in the body of Tables 7.1 to 7.3 represents selected results generated by a daily soil moisture budget analysis using the ACRU model for the complete period of record at the relevant station. The planting date, crop type, soil depth and soil texture for each output line are given in the tables. Further numeric descriptions of these variables are presented in Appendix C i.e. the crop factor and root distribution for each month as well as the soil depths of each horizon.

The ET deficit, index of stress days and water yield are reported at the frequency level of 50 and 90 per cent non-exceedance and in time steps of one month after planting. It is important to note that the column headings of Month 1, Month 2 etc. in Table 7.1 to 7.3 do not refer to January, February, March etc, but to the monthly time period after planting. Therefore, these headings should be read in conjunction with the planting date in order to establish the ET deficit, water yield or index of stress days for a particular calendar month.

Table 7.1 Evapotranspiration deficit output from the dryland analysis (Zone 377, Bergville)

```
   ZONE NO.377

   RAINFALL STATION 0299614  BERGVILLE (MAG)      LAT 28 44 LONG 29 21 ALTITUDE 1130m  55 YEARS OF DATA

 TEMPERATURE STATION ATS0288  AVONDALE, BERGVILLE  LAT 28 45 LONG 29 19 ALTITUDE 1121m  WIND REGION :  3

                         JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC ANNUAL

RAINFALL (mm)       MEAN 132.5 117.9  95.2  44.0  19.2   9.7  10.4  19.0  31.2  59.8  87.7 104.4  740.0
 M.A.P.  740.9mm    MEDN 119.9 104.3  82.1  38.7   8.5   0.0   1.0   4.4  18.8  51.6  88.7 100.4  719.0
                    SDEV  65.2  62.8  56.2  33.3  28.2  17.1  17.6  27.4  37.2  45.7  48.9  55.9  195.0
                    C.V.  49.2  53.2  59.1  75.8 146.9 176.7 170.1 144.6 119.2  76.5  55.7  53.6   26.0
                    SKEW   0.7   1.0   1.2   1.4   2.2   2.6   1.9   1.6   2.3   1.0   0.8   1.3    0.0

    MONTHLY
MEAN TEMPERATURES   MAX   30.6  31.2  30.3  28.9  26.7  24.8  25.2  26.8  27.9  29.8  30.4  31.4
(DEGREES CELSIUS)   MIN   14.9  15.4  13.4   9.3   3.3   0.6   0.4   3.1   7.2  10.7  12.4  14.1
----------------------------------------------------------------------------------------------------------------------

CROP AND SOIL INFORMATION                              EVAPOTRANSPIRATION DEFICIT (mm)

PLANT  CROP  SOIL  SOIL  MONTH 1 MONTH 2 MONTH 3 MONTH 4 MONTH 5 MONTH 6 MONTH 7 MONTH 8 MONTH 9 MONTH10 MONTH11 MONTH12
DATE   TYPE  DEPTH TEXT  50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90%

 1 NV MAIZE DEEP  CLAY    57  95 153 202 180 228 144 193  54  88   6  24  13  24  17  23  22  28  28  33  31  44  19  41
 1 NV MAIZE DEEP  LOAM    52  92 136 183 165 223 129 189  49  86   5  24  13  24  17  22  22  28  28  33  31  44  19  42
 1 NV MAIZE DEEP  SAND    64  97 127 184 173 223 131 188  51  84  10  25  19  27  19  24  26  28  30  33  30  45  23  41
 1 NV MAIZE MEDM  CLAY    61  95 157 201 184 229 150 196  56  88   7  25  15  25  18  23  24  28  29  33  30  44  20  41
 1 NV MAIZE MEDM  LOAM    57  92 133 185 171 223 135 191  50  87   7  24  14  24  18  23  24  28  28  33  30  44  20  41
 1 NV MAIZE MEDM  SAND    66  98 142 198 176 229 136 191  53  85  12  26  21  27  19  24  26  28  31  33  31  45  25  41
 1 NV MAIZE SHALW CLAY    68 100 171 217 196 237 162 203  63  88  12  27  20  27  19  24  26  28  31  33  31  45  24  41
 1 NV MAIZE SHALW LOAM    67  97 156 212 186 233 147 195  56  86  11  26  20  27  19  24  26  28  30  33  31  45  24  41
 1 NV MAIZE SHALW SAND    76 104 159 217 182 230 148 195  60  86  16  30  24  30  21  24  27  28  31  33  33  45  30  42
 1 DC MAIZE DEEP  CLAY    33  82 111 169 154 207 142 180  54  79  24  31  19  24  23  28  28  33  30  44  17  38   7  26
 1 DC MAIZE DEEP  LOAM    31  77  79 156 135 195 130 175  52  77  24  31  18  24  23  28  27  33  30  44  17  38   7  27
 1 DC MAIZE DEEP  SAND    47  88  94 145 145 203 133 176  53  78  27  32  19  24  25  28  30  33  30  44  20  38  14  32
 1 DC MAIZE MEDM  CLAY    37  83 112 170 163 214 146 182  56  79  24  31  19  24  23  28  28  33  29  44  19  38   9  27
 1 DC MAIZE MEDM  LOAM    36  80  89 153 147 202 134 177  52  78  24  31  19  24  23  28  28  33  30  44  18  38   9  28
 1 DC MAIZE MEDM  SAND    51  91 105 153 152 209 138 179  56  79  27  33  19  24  25  28  30  33  30  44  22  38  16  33
 1 DC MAIZE SHALW CLAY    53  90 133 175 181 226 152 185  61  82  27  33  19  24  25  28  30  33  30  44  22  38  16  32
 1 DC MAIZE SHALW LOAM    50  90 121 165 166 216 145 182  57  79  27  32  19  24  25  28  30  33  30  44  22  38  16  33
 1 DC MAIZE SHALW SAND    61  96 127 171 167 217 143 180  60  81  28  34  21  24  26  28  31  33  32  44  27  38  23  37
15 DC SUNFL DEEP  CLAY     3  24  43 104  96 146  99 138  74 101  49  55  22  27  22  27  30  35  29  42  19  42   9  25
15 DC SUNFL DEEP  LOAM     2  22  22  91  72 132  81 128  69  93  46  55  22  27  22  27  29  35  29  42  19  42   9  25
15 DC SUNFL DEEP  SAND     7  31  39  83  89 145  87 133  72 100  47  56  22  27  24  27  32  35  29  43  23  41  12  29
15 DC SUNFL MEDM  CLAY     4  26  46 106 108 155 104 140  76 103  50  56  22  27  23  27  30  35  28  42  21  41  10  25
15 DC SUNFL MEDM  LOAM     3  24  34  92  84 142  87 133  71  99  48  56  22  27  23  27  30  35  28  42  20  41   9  26
15 DC SUNFL MEDM  SAND     9  34  51  94  95 154  93 139  75 102  48  57  22  27  25  27  32  35  29  43  25  41  14  31
15 DC SUNFL SHALW CLAY     9  34  75 112 130 171 113 144  82 105  52  58  22  27  24  27  32  35  29  43  24  42  13  30
15 DC SUNFL SHALW LOAM     9  33  64 105 111 162 105 142  79 102  50  58  22  27  24  27  32  35  29  43  24  42  13  30
15 DC SUNFL SHALW SAND    15  40  77 113 119 166 106 141  80 104  51  58  24  27  25  27  32  35  31  43  30  42  19  35

NOTE:  "MONTH X" REFERS TO MONTHS AFTER PLANTING, BUT VELD AND TIMBER ASSUMED TO BE MATURE THROUGHOUT THE YEAR
```

NV = November
DC = December

MEDM = medium
SHALW = shallow

SUNFL = sunflowers

Table 7.2 Index of stress days output from the dryland analysis (Zone 377, Bergville)

INDEX OF STRESS DAYS

PLANT DATE		CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
					50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1	NV	MAIZE	DEEP	CLAY	14	22	22	28	23	28	19	25	15	26	4	24	15	31	28	30	31	31	31	31	22	30	14	28
1	NV	MAIZE	DEEP	LOAM	11	21	18	26	21	28	18	24	13	25	3	23	14	31	28	30	31	31	31	31	23	30	14	28
1	NV	MAIZE	DEEP	SAND	15	22	16	23	20	26	18	23	15	24	10	22	23	31	27	30	31	31	31	31	22	30	15	27
1	NV	MAIZE	MEDM	CLAY	13	22	21	28	23	28	20	24	15	24	6	23	17	31	29	30	31	31	30	31	23	30	14	28
1	NV	MAIZE	MEDM	LOAM	12	22	19	25	22	28	19	24	14	24	5	24	17	31	28	30	31	31	30	31	23	30	13	28
1	NV	MAIZE	MEDM	SAND	16	23	18	24	20	26	17	23	15	24	11	22	24	31	26	30	31	31	31	31	23	30	16	26
1	NV	MAIZE	SHALW	CLAY	16	22	22	27	22	27	20	24	17	25	11	23	24	31	27	30	31	31	31	31	22	30	16	27
1	NV	MAIZE	SHALW	LOAM	16	22	20	27	21	27	19	23	16	25	10	22	23	31	27	30	31	31	31	31	22	30	16	27
1	NV	MAIZE	SHALW	SAND	17	23	20	27	20	25	18	23	18	24	14	26	25	31	27	30	31	31	30	31	23	30	18	25
1	DC	MAIZE	DEEP	CLAY	7	21	16	26	20	25	23	29	21	30	28	31	30	30	31	31	31	31	22	30	14	28	3	14
1	DC	MAIZE	DEEP	LOAM	7	20	11	23	18	24	22	29	20	29	27	31	30	30	31	31	31	31	22	30	14	28	3	14
1	DC	MAIZE	DEEP	SAND	11	22	12	20	18	23	22	28	21	29	26	31	28	30	31	31	31	31	22	30	15	27	8	16
1	DC	MAIZE	MEDM	CLAY	9	22	17	25	20	25	23	29	21	29	27	31	30	30	31	31	30	31	22	30	13	27	4	14
1	DC	MAIZE	MEDM	LOAM	8	21	12	24	19	24	22	29	21	29	27	31	30	30	31	31	30	31	23	30	13	27	4	14
1	DC	MAIZE	MEDM	SAND	13	23	15	21	18	23	22	27	21	29	26	31	26	30	31	31	31	31	22	30	16	26	9	18
1	DC	MAIZE	SHALW	CLAY	12	24	19	25	21	24	24	28	22	29	28	31	27	30	31	31	31	31	22	30	15	26	8	16
1	DC	MAIZE	SHALW	LOAM	12	23	17	23	19	24	23	28	21	29	26	31	28	30	31	31	31	31	22	30	15	26	8	17
1	DC	MAIZE	SHALW	SAND	16	24	17	22	18	23	21	26	22	28	27	31	27	30	31	31	30	31	23	30	18	25	11	20
15	DC	SUNFL	DEEP	CLAY	0	12	7	21	14	22	21	27	22	29	31	31	30	30	31	31	31	31	23	30	14	28	4	14
15	DC	SUNFL	DEEP	LOAM	0	10	1	16	11	22	16	27	21	29	31	31	30	30	31	31	31	31	22	30	13	29	4	14
15	DC	SUNFL	DEEP	SAND	3	16	6	15	12	22	18	27	21	29	29	31	28	30	31	31	31	31	22	30	15	27	8	18
15	DC	SUNFL	MEDM	CLAY	0	13	8	22	16	23	21	28	23	29	31	31	30	30	31	31	30	31	22	30	14	28	4	16
15	DC	SUNFL	MEDM	LOAM	0	12	4	17	13	23	18	28	21	29	31	31	30	30	31	31	30	31	22	30	14	28	4	15
15	DC	SUNFL	MEDM	SAND	4	17	8	16	14	22	19	27	22	29	29	31	28	30	31	31	31	31	22	30	16	26	9	19
15	DC	SUNFL	SHALW	CLAY	4	17	14	22	19	23	22	27	23	29	30	31	29	30	31	31	31	31	22	30	16	27	8	18
15	DC	SUNFL	SHALW	LOAM	4	17	11	19	17	22	20	27	22	29	30	31	28	30	31	31	31	31	22	30	16	27	8	18
15	DC	SUNFL	SHALW	SAND	8	19	13	20	16	22	19	25	22	28	28	31	28	30	31	31	30	31	23	30	19	25	11	20
1	JA	SVELD	DEEP	CLAY	11	23	8	20	13	26	19	29	31	31	30	30	31	31	31	31	30	30	21	31	15	26	16	27
1	JA	SVELD	DEEP	LOAM	9	22	3	19	7	26	11	26	23	31	30	30	31	31	31	31	30	30	21	31	14	27	15	25
1	JA	SVELD	DEEP	SAND	10	20	6	18	11	23	15	26	24	31	30	30	31	31	31	31	27	30	20	30	13	24	14	23
1	JA	SVELD	MEDM	CLAY	12	23	10	21	14	26	19	29	31	31	30	30	31	31	31	31	29	30	21	31	15	26	16	26
1	JA	SVELD	MEDM	LOAM	10	22	6	19	10	26	14	27	26	31	30	30	31	31	31	31	29	30	21	31	14	26	15	24
1	JA	SVELD	MEDM	SAND	10	21	8	18	12	24	18	27	28	31	30	30	31	31	31	31	26	30	20	30	14	24	14	23
1	JA	SVELD	SHALW	CLAY	15	24	14	22	18	25	22	28	31	31	30	30	31	31	31	31	28	30	22	30	18	25	18	27
1	JA	SVELD	SHALW	LOAM	13	21	11	20	15	24	19	28	30	31	30	30	31	31	31	31	27	30	21	30	15	25	15	26
1	JA	SVELD	SHALW	SAND	13	21	12	20	16	24	20	27	28	31	30	30	31	31	31	31	25	30	21	28	16	24	16	26
1	JA	GVELD	DEEP	CLAY	18	26	15	23	20	27	25	30	31	31	30	30	31	31	31	31	30	30	25	31	20	28	19	28
1	JA	GVELD	DEEP	LOAM	15	25	13	23	16	27	22	30	31	31	30	30	31	31	31	31	30	30	25	31	19	28	18	27
1	JA	GVELD	DEEP	SAND	16	23	13	22	17	26	21	28	31	31	30	30	31	31	31	31	28	30	23	30	18	26	17	26
1	JA	GVELD	MEDM	CLAY	18	26	16	23	21	27	24	30	31	31	30	30	31	31	31	31	30	30	24	31	20	27	21	28
1	JA	GVELD	MEDM	LOAM	16	25	13	22	17	27	22	29	31	31	30	30	31	31	31	31	30	30	24	31	19	28	18	27
1	JA	GVELD	MEDM	SAND	16	24	13	21	18	26	22	28	31	31	30	30	31	31	31	31	27	30	23	30	18	26	17	26
1	JA	GVELD	SHALW	CLAY	19	25	18	23	22	27	24	30	31	31	30	30	31	31	31	31	28	30	25	30	20	27	21	28
1	JA	GVELD	SHALW	LOAM	17	24	16	22	19	27	23	29	31	31	30	30	31	31	31	31	28	30	24	30	19	26	19	27
1	JA	GVELD	SHALW	SAND	17	23	15	22	19	25	22	29	30	31	30	30	31	31	31	31	26	30	23	29	19	26	18	27

NOTE: "MONTH X" REFERS TO MONTHS AFTER PLANTING, BUT VELD AND TIMBER ASSUMED TO BE MATURE THROUGHOUT THE YEAR

NV = November
DC = December
JA = January
MEDM = medium
SHALW = shallow
SUNFL = sunflowers
SVELD = sparse veld
GVELD = good veld

Table 7.3 Water yield output from the dryland analysis (Zone 377, Bergville)

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1 50%	MONTH 1 90%	MONTH 2 50%	MONTH 2 90%	MONTH 3 50%	MONTH 3 90%	MONTH 4 50%	MONTH 4 90%	MONTH 5 50%	MONTH 5 90%	MONTH 6 50%	MONTH 6 90%	MONTH 7 50%	MONTH 7 90%	MONTH 8 50%	MONTH 8 90%	MONTH 9 50%	MONTH 9 90%	MONTH10 50%	MONTH10 90%	MONTH11 50%	MONTH11 90%	MONTH12 50%	MONTH12 90%
1 NV	MAIZE	DEEP	CLAY	3	30	5	33	11	41	7	38	7	49	2	22	0	6	0	0	0	1	0	1	0	12	0	32
1 NV	MAIZE	DEEP	LOAM	0	15	1	23	4	20	2	17	3	26	0	8	0	1	0	0	0	0	0	0	0	2	0	8
1 NV	MAIZE	DEEP	SAND	7	29	7	32	6	23	3	14	2	26	1	17	1	15	0	8	0	8	0	7	0	9	2	21
1 NV	MAIZE	MEDM	CLAY	5	37	7	40	14	49	10	46	9	55	3	26	0	8	0	0	0	3	0	3	0	16	1	38
1 NV	MAIZE	MEDM	LOAM	0	23	4	32	6	26	5	22	3	33	1	11	0	4	0	2	0	1	0	1	0	6	0	13
1 NV	MAIZE	MEDM	SAND	9	31	10	38	9	27	6	21	5	34	5	25	5	18	4	10	2	12	1	8	1	12	4	27
1 NV	MAIZE	SHALW	CLAY	13	57	17	60	28	75	20	65	20	71	6	36	0	16	0	3	0	7	0	10	0	28	5	52
1 NV	MAIZE	SHALW	LOAM	13	40	13	48	16	46	10	43	10	52	5	30	3	14	2	9	1	10	1	6	1	18	4	34
1 NV	MAIZE	SHALW	SAND	15	42	18	52	18	50	12	45	15	55	14	37	12	22	7	16	4	16	3	10	3	20	7	36
1 DC	MAIZE	DEEP	CLAY	5	41	13	50	7	39	6	44	1	18	0	7	0	0	0	1	0	1	0	12	0	33	4	39
1 DC	MAIZE	DEEP	LOAM	0	27	4	27	3	19	2	24	0	8	0	3	0	1	0	0	0	0	0	2	0	8	0	15
1 DC	MAIZE	DEEP	SAND	10	47	13	45	9	26	5	27	2	10	1	8	0	4	0	2	0	2	0	4	0	16	3	35
1 DC	MAIZE	MEDM	CLAY	8	50	16	58	10	47	8	50	1	22	0	9	0	0	0	2	0	3	0	16	1	39	7	44
1 DC	MAIZE	MEDM	LOAM	4	40	10	36	5	23	5	29	1	11	0	6	0	1	0	0	0	0	0	5	0	12	1	29
1 DC	MAIZE	MEDM	SAND	17	52	18	49	11	29	7	31	3	15	2	8	0	6	0	7	0	5	0	9	1	25	11	37
1 DC	MAIZE	SHALW	CLAY	19	71	31	83	19	65	16	64	5	32	0	18	0	2	0	7	0	10	0	28	6	53	17	65
1 DC	MAIZE	SHALW	LOAM	19	56	25	61	14	44	12	47	4	22	1	12	0	6	0	6	0	4	0	16	2	32	14	47
1 DC	MAIZE	SHALW	SAND	25	61	30	66	18	49	16	50	9	30	6	18	3	13	2	13	1	9	2	19	6	34	19	47
15 DC	SUNFL	DEEP	CLAY	9	55	17	68	9	46	8	48	1	18	0	6	0	0	0	1	0	1	0	12	0	32	4	40
15 DC	SUNFL	DEEP	LOAM	1	35	8	41	5	31	4	30	0	9	0	5	0	2	0	1	0	0	0	3	0	8	0	13
15 DC	SUNFL	DEEP	SAND	12	53	19	56	12	32	9	31	3	14	2	11	1	4	0	3	0	1	0	2	0	15	1	31
15 DC	SUNFL	MEDM	CLAY	13	63	22	76	12	54	10	54	1	21	0	9	0	0	0	2	0	3	0	16	1	38	7	44
15 DC	SUNFL	MEDM	LOAM	5	48	16	50	10	37	8	36	2	14	1	7	0	2	0	1	0	1	0	5	0	12	1	26
15 DC	SUNFL	MEDM	SAND	19	57	25	61	16	37	12	39	5	18	2	12	1	6	0	4	0	3	0	7	0	24	8	37
15 DC	SUNFL	SHALW	CLAY	25	86	37	97	24	70	18	68	5	32	0	18	0	2	0	7	0	10	0	28	5	51	17	64
15 DC	SUNFL	SHALW	LOAM	21	67	33	71	19	49	15	50	5	25	2	13	1	3	0	5	0	3	0	16	2	31	13	47
15 DC	SUNFL	SHALW	SAND	27	67	38	76	24	58	20	55	10	30	6	19	3	10	2	12	1	8	1	19	5	34	18	47
1 JA	SVELD	DEEP	CLAY	19	68	14	50	8	50	1	19	0	7	0	0	0	3	0	3	0	16	1	33	5	36	8	46
1 JA	SVELD	DEEP	LOAM	3	21	3	20	3	30	0	8	0	5	0	1	0	0	0	0	0	5	0	12	0	14	1	15
1 JA	SVELD	DEEP	SAND	4	25	5	31	6	32	3	18	1	15	0	6	0	3	0	2	0	3	0	7	0	13	0	20
1 JA	SVELD	MEDM	CLAY	23	74	16	56	11	57	2	22	0	9	0	1	0	4	0	5	0	19	2	39	8	42	11	53
1 JA	SVELD	MEDM	LOAM	7	32	6	26	6	38	1	13	0	8	0	3	0	1	0	1	0	7	0	17	1	18	2	20
1 JA	SVELD	MEDM	SAND	6	34	11	39	12	43	6	24	3	16	1	8	1	5	0	3	0	5	0	11	1	19	3	27
1 JA	SVELD	SHALW	CLAY	37	97	25	76	20	74	5	33	0	18	0	4	0	9	0	12	0	29	5	53	14	58	20	72
1 JA	SVELD	SHALW	LOAM	15	60	17	52	15	53	6	26	2	13	1	4	0	4	0	4	0	16	2	30	7	35	9	44
1 JA	SVELD	SHALW	SAND	20	61	22	56	23	61	12	34	8	21	4	11	2	10	1	6	1	16	3	30	9	36	12	48
1 JA	GVELD	DEEP	CLAY	14	56	9	43	7	47	0	18	0	6	0	0	0	3	0	3	0	15	1	28	5	33	7	41
1 JA	GVELD	DEEP	LOAM	3	17	1	17	1	24	0	7	0	2	0	0	0	0	0	0	0	4	0	10	0	13	0	12
1 JA	GVELD	DEEP	SAND	2	17	2	15	3	25	0	10	0	9	0	3	0	2	0	1	0	3	0	7	0	10	0	13
1 JA	GVELD	MEDM	CLAY	18	64	12	51	9	53	1	21	0	9	0	1	0	4	0	5	0	18	2	34	7	37	10	47
1 JA	GVELD	MEDM	LOAM	5	23	3	23	2	31	0	10	0	4	0	0	0	0	0	0	0	7	0	14	1	17	2	17
1 JA	GVELD	MEDM	SAND	5	25	5	24	6	33	2	14	1	10	0	5	0	3	0	1	0	5	0	10	1	16	1	19
1 JA	GVELD	SHALW	CLAY	32	86	23	71	18	69	4	31	0	17	0	4	0	8	0	12	0	28	5	49	13	54	20	66
1 JA	GVELD	SHALW	LOAM	13	52	11	47	9	48	2	21	1	11	0	2	0	3	0	3	0	15	2	28	6	32	7	38
1 JA	GVELD	SHALW	SAND	16	52	16	49	15	53	8	27	5	16	2	7	1	9	1	5	0	15	2	27	6	32	9	41
1 DC	SOYAS	DEEP	CLAY	8	49	16	61	8	43	7	49	2	22	0	6	0	0	0	1	0	1	0	12	0	33	5	40
1 DC	SOYAS	DEEP	LOAM	2	35	9	42	4	28	5	29	0	10	0	5	0	2	0	1	0	0	0	3	0	8	0	23
1 DC	SOYAS	DEEP	SAND	15	54	20	57	12	31	8	32	3	18	2	13	1	7	0	7	0	5	0	7	1	18	8	35
1 DC	SOYAS	MEDM	CLAY	12	60	20	68	11	51	10	55	3	25	0	8	0	0	0	3	0	3	0	16	1	39	8	45

NOTE: "MONTH X" REFERS TO MONTHS AFTER PLANTING, BUT VELD AND TIMBER ASSUMED TO BE MATURE THROUGHOUT THE YEAR

NV = November	MEDM = medium	SVELD = sparse veld
DC = December	SHALW = shallow	GVELD = good veld
JA = January	SUNFL = sunflowers	SOYAS = soybeans

The 80 per cent frequency level of non-exceedance was produced in the analysis but has not been presented in Tables 7.1 to 7.3 and in Appendix D in the interest of the appearance of these Tables. The 80 per cent level is available on the computer compatible form of this output.

The monthly ET deficit provides a rough estimate of the supplementary irrigation requirement. However, it should be noted that under irrigated conditions the soil is generally kept more wet and hence there is more ineffective rainfall and water yield from irrigated lands. Thus an estimate of supplementary irrigation requirement based on the ET deficit is likely to be an underestimate in the more humid areas and for the lower levels of non-exceedance.

The purpose of the dryland analysis is illustrated by the following example which uses the output displayed in Tables 7.1 and 7.2.

<u>Problem</u>: A farmer in the Bergville area of Natal wishes to investigate the feasibility, from a climatic viewpoint, of growing sunflowers in shallow loam soil in the area.

<u>Analysis</u>: From the map of homogeneous climate zones (Appendix A) it is established that Bergville lies within Zone 377. It is confirmed that the station used in this zone is the most appropriate station, of those processed, for the farm in question. Information on evapotranspiration deficit in millimeters and index of stress for sunflowers planted in shallow loam soil on 15 December are extracted from Tables 7.1 and 7.2 and presented in Table 7.4.

These two sets of figures will enable a knowledgeable person to make an informed decision as to the advisability, in terms of climatic risk, of growing sunflowers under dryland conditions and in the above soils, in the Bergville area. The appropriate row of values from Table 7.3 would provide probable levels of water yield for the abovementioned set of conditions in the Bergville area.

Table 7.4 Extracts of evapotranspiration deficit and index of stress days from Tables 7.1 and 7.2

Period	16/12 - 15/01		16/01 - 15/02		16/02 - 15/03		16/03 - 15/04	
Frequency (%)	50	90	50	90	50	90	50	90
ET deficit (mm)	9	33	$\boxed{64}$	105	111	162	105	142

$\boxed{64}$ indicates that for the month 16 January to 15 February the evapotranspiration deficit of 64 mm was not exceeded for 50 per cent of the years which were analysed.

Period	16/12 - 15/01		16/01 - 15/02		16/02 - 15/03		16/03 - 15/04	
Frequency (%)	50	90	50	90	50	90	50	90
Index stress (days)	4	17	$\boxed{11}$	19	17	22	20	27

$\boxed{11}$ indicates that for the month 16 January to 15 February the number of days for which AET<0.5 PET did not exceed 11 for 50 per cent of the years which were analysed.

An essential element of any irrigation analysis is an assessment of the available water resources in the vicinity of the scheme. An estimation of water yield was therefore included in the study. In addition amongst the land use options sparse veld, good veld and commercial timber were incorporated in the analysis as crops. These latter land uses are very common and it was felt that the information necessary to estimate runoff into farm dams would have been incomplete without these elements.

To obtain an estimate of the probable runoff into a small farm dam from Table 7.3 it would first be necessary to classify the land use and soils in each section of the catchment. The sum of the runoff volumes from each land use unit and for a predetermined frequency of non-exceedance could then be calculated. If the catchment is fairly small say 100 km^2 it may be assumed, reasonably, that the water yields reported for different landuses but for the same frequency level of non-exceedance, will occur in the same year. If this latter assumption regarding the timing is reasonable then the estimates of frequency levels of non-exceedance of water yield so provided would be very similar to those given by the ACRU model operating in a distributed mode. In instances where no alternative exists, this technique may be extended to much larger catchments. Such a statement is based on the assumption that the rainfall and temperature stations are representative of the climate zone. The care with which such zones and stations were selected, as discussed in Chapter 3, indicates that this is a reasonable assumption.

Given the soils and land use information there is potential for mapping probable AET, irrigation requirements and runoff on a scale hitherto not attempted in South Africa.

7.4 Discussion on some aspects of the soil moisture analysis under dryland conditions

The inclusion of the dryland soil moisture analysis has increased the relevance of this work by encompassing a wider base of potential users. The all combinations approach was adopted since the increase in the output volume and computer time was considered to be minimal relative to the logistical problems and time which would be required to select and prepare the data sets for these analyses if they were to be conducted on an individual and ad hoc basis at future dates.

The crop factors used are with respect to the Class A-pan evaporation and were obtained from Green (1985), Schulze and George (1986) and Mallett (1987). The crop factors reported by Green (1985) are for irrigated conditions. Unfortunately the literature revealed a dearth of crop factors for crops grown under dryland conditions. In the case of winter wheat in the Orange Free State this provided a problem in that dryland winter wheat lies dormant until sufficient moisture is present. Downward adjustment was therefore made to the crop factors in the early season to accommodate this phenomenon. The extent of this adjustment is a matter for further research. However, some discussion on this aspect is considered appropriate since the central and eastern Orange Free State (OFS) is one of South Africa's major wheat growing regions. Wheat in this area is planted in mid-June and harvested in December. The wheat plants depend initially on the moisture stored in the soil during the fallow months i.e. January to June. Germination takes about 10 days and after emergence, growth is very slow until the spring rains in September (Purchase, 1987). Root growth is rapid during this early spring period. This phenomenon has been reflected in the rooting distribution input to the ACRU model. The crop factors for the bare fallow period have been set at 0,2 for bare soil. Green (1985) cites 0,30 but this higher value reflects largely the evaporation from an irrigated soil surface during the crop establishment period. The crop factor for such surfaces often goes as high as unity (Burgers, 1982). The crop factor is held low until the third month when the spring rains accelerate growth and canopy cover. Until this time the land is almost in a bare fallow situation with respect to canopy cover and consequently a crop factor of 0,2 is used. The crop factor of wheat rises rapidly to a maximum of unity. However, this is for an irrigated situation in which yields of 5 to 6 tons per hectare may be expected. In the OFS dryland spring wheat regions yields are commonly between 1 and 2 tons per hectare (Purchase 1987). The cropping coefficient for wheat which is planted at 460 mm row spacing because of the limited moisture situation, has been set at 0,6 at maturity, in consultation with Purchase (1987).

The number of stress days (by the definition discussed in Section 7.3.1) revealed for spring wheat in the OFS may at first seem to be exceptionally high. However, discussions with Purchase (1987) confirmed that this is very often the case and in particular at the start of the season when, after emergence, the wheat plants remain dormant as they await the spring rains.

In this study the crop factor for all crops was assumed to return to pre-stress levels immediately the soil moisture returned. This is a shortcoming of the present analysis which is recognised since in most vegetation the crop factor does not return to its pre-stressed level when soil moisture ceases to be limiting.

7.5 Purpose and value of the irrigation analysis

Irrigation schemes on individual farms are sometimes conceived of from the point of view of the availability of funds for the purchase of pumps and piping only and with little regard to the demands which the scheme will place on the water resources of the catchment. The exercise of modelling, whilst undoubtedly being very useful, is time consuming, requires computing and hydrological expertise and is therefore considered costly by many farmers. This is especially so in the preliminary and necessarily wide ranging initial phases of such analyses.

The purpose of the irrigation analysis presented in this study was to provide information on irrigation requirements for a wide range of crops, all over Southern Africa in a concise, accurate and usable form. The value of the irrigation analysis lies in the fact that it fulfills precisely this purpose, since:

(a) a quick and concise reference to determine irrigation requirements has been provided,

(b) Southern Africa, has for this purpose, been delimited into 712 zones which indicates the degree of detail given in this analysis;

(c) the analysis provides, through the concept of PAM and crop factor, for an unrestricted choice of combinations of soils, crop types, plant population densities, rooting depths and planting dates;

(d) the estimation of risk is addressed by the analysis; and

(e) the whole analysis is based on the moisture budget at a daily time step.

The abovementioned implies that the design criteria outlined in Section 4.2.1 were achieved and the irrigation analysis procedure discussed in Section 4.2 was followed for each of the 712 climate zones discussed in Chapter 3. The final output from the irrigation analysis is a table similar to Table 7.5 for each of the climatic zones. The application of the output presented in these tables is discussed in Section 7.6.

Table 7.5 Estimates of irrigation water requirements for each month: example of output (Zone 377, Bergville)

```
    ZONE NO.377

    RAINFALL STATION  299614  BERGVILLE (MAG)    LAT 28 44 LONG 29 21 ALTITUDE 1130m  45 YEARS OF DATA

TEMPERATURE STATION ATS0288  AVONDALE, BERGVILLE  LAT 28 45 LONG 29 19 ALTITUDE 1121m  WIND REGION :  3

                            JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEP    OCT    NOV    DEC ANNUAL

RAINFALL (mm)        MEAN  132.5  117.9   95.2   44.0   19.2    9.7   10.4   19.0   31.2   59.8   87.7  104.4  740.0
 M.A.P.  740.9mm     MEDN  119.9  104.3   82.1   38.7    8.5    0.0    1.0    4.4   18.8   51.6   88.7  100.4  719.0
                     SDEV   65.2   62.8   56.2   33.3   28.2   17.1   17.6   27.4   37.2   45.7   48.9   55.9  195.0
                     C.V.   49.2   53.2   59.1   75.8  146.9  176.7  170.1  144.6  119.2   76.5   55.7   53.6   26.0
                     SKEW    0.7    1.0    1.2    1.4    2.2    2.6    1.9    1.6    2.3    1.0    0.8    1.3    0.0

      MONTHLY
MEAN TEMPERATURES    MAX    30.6   31.2   30.3   28.9   26.7   24.8   25.2   26.8   27.9   29.8   30.4   31.4
(DEGREES CELSIUS)    MIN    14.9   15.4   13.4    9.3    3.3    0.6    0.4    3.1    7.2   10.7   12.4   14.1

                                       ESTIMATED IRRIGATION REQUIREMENT
                                       --------------------------------

-----------------------------------------------------------------------------------------------

***********************************************************************************************
*P.A.M.*       50 TH PERCENTILE       **      80 TH PERCENTILE       **      90 TH PERCENTILE    ** *
***********************************************************************************************
*      *          CROP FACTOR         *          CROP FACTOR         *          CROP FACTOR    * MTH*
* (mm) *   0.5   0.7    0.9    1.1    *   0.5   0.7    0.9    1.1    *   0.5   0.7    0.9    1.1 *    *
***********************************************************************************************
                                       ESTIMATED IRRIGATION REQUIREMENT                       *
*                                                                                             *
*      *  (mm)  (mm)  (mm)  (mm)  *  (mm)  (mm)  (mm)  (mm)  *  (mm)  (mm)  (mm)  (mm)  *      *
***********************************************************************************************
*   20  *    56    90   140   184  *    75   122   167   217  *    83   131   181   231  *  1 *
*   45  *    48    87   134   179  *    71   122   166   219  *    86   128   178   231  *  1 *
*   70  *    44    83   130   175  *    63   115   162   212  *    75   129   178   232  *  1 *
*  100  *    36    79   127   172  *    63   108   160   212  *    78   128   178   231  *  1 *
*  150  *    27    76   121   174  *    63   111   160   213  *    75   125   179   232  *  1 *
*  200  *    27    81   124   173  *    59   114   160   210  *    76   126   181   231  *  1 *
*   20  *    47    81   115   155  *    72   109   150   193  *    89   128   170   211  *  2 *
*   45  *    41    72   108   147  *    66   106   150   194  *    83   121   166   212  *  2 *
*   70  *    39    72   110   150  *    65   105   149   189  *    79   123   166   211  *  2 *
*  100  *    31    67   101   152  *    62   104   148   195  *    80   121   167   213  *  2 *
*  150  *    32    72   101   151  *    61   103   149   194  *    76   120   166   210  *  2 *
*  200  *    31    58   104   148  *    61   104   149   194  *    76   124   163   211  *  2 *
*   20  *    55    90   126   166  *    71   111   149   195  *    85   124   165   209  *  3 *
*   45  *    51    82   122   164  *    67   101   148   189  *    79   126   165   209  *  3 *
*   70  *    48    80   120   163  *    66   100   142   184  *    78   122   165   209  *  3 *
*  100  *    46    78   121   163  *    61    98   139   187  *    76   120   169   209  *  3 *
*  150  *    41    79   120   163  *    63   102   142   184  *    77   120   165   209  *  3 *
*  200  *    35    78   120   163  *    55    97   140   188  *    75   120   165   209  *  3 *
*   20  *    62    97   131   165  *    77   113   150   186  *    86   122   159   196  *  4 *
*   45  *    58    92   125   163  *    77   113   149   186  *    86   122   159   196  *  4 *
*   70  *    56    91   128   160  *    78   113   150   186  *    86   122   159   195  *  4 *
*  100  *    56    90   124   161  *    78   113   149   186  *    85   122   159   194  *  4 *
*  150  *    52    90   124   161  *    79   112   150   186  *    85   122   157   196  *  4 *
*  200  *    53    86   127   161  *    77   113   150   186  *    84   122   157   194  *  4 *
*   20  *    67    96   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*   45  *    65    96   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*   70  *    65    95   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*  100  *    65    95   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*  150  *    65    96   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*  200  *    66    95   125   155  *    75   105   135   165  *    75   105   135   165  *  5 *
*   20  *    62    87   112   137  *    62    87   112   137  *    62    87   112   137  *  6 *
*   45  *    62    87   112   137  *    62    87   112   137  *    62    87   112   137  *  6 *
*   70  *    62    87   112   137  *    62    89   112   137  *    62    89   112   137  *  6 *
*  100  *    62    87   112   137  *    62    87   112   137  *    62    87   112   137  *  6 *
*  150  *    62    87   112   137  *    62    87   113   137  *    62    87   113   137  *  6 *
*  200  *    62    87   112   137  *    62    87   112   137  *    62    87   112   137  *  6 *
*   20  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*   45  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*   70  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*  100  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*  150  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*  200  *    70    98   126   154  *    70    98   126   154  *    70    98   126   154  *  7 *
*   20  *    82   117   151   186  *    87   122   157   192  *    87   122   157   192  *  8 *
*   45  *    82   117   151   186  *    87   122   157   192  *    87   122   157   192  *  8 *
*   70  *    82   117   151   186  *    87   122   157   192  *    87   122   157   192  *  8 *
*  100  *    82   117   151   186  *    87   122   157   192  *    87   122   157   192  *  8 *
*  150  *    82   117   155   186  *    87   122   161   192  *    87   122   161   192  *  8 *
*  200  *    82   117   151   186  *    87   122   157   192  *    87   122   157   192  *  8 *
*   20  *    87   128   169   211  *   104   146   188   230  *   105   147   189   231  *  9 *
*   45  *    86   128   170   211  *   104   146   188   230  *   105   147   189   231  *  9 *
*   70  *    87   128   169   211  *   104   146   188   230  *   105   147   189   231  *  9 *
*  100  *    86   128   169   211  *   105   146   188   230  *   107   147   189   231  *  9 *
*  150  *    86   128   169   211  *   104   146   188   230  *   105   147   189   231  *  9 *
*  200  *    86   128   170   212  *   104   146   188   230  *   105   147   189   231  *  9 *
*   20  *    86   134   182   232  *   112   162   214   265  *   119   170   222   273  * 10 *
*   45  *    83   132   180   231  *   111   162   214   265  *   119   170   221   273  * 10 *
*   70  *    85   133   182   232  *   111   162   214   265  *   119   170   221   273  * 10 *
*  100  *    82   132   181   230  *   111   162   214   265  *   118   170   221   273  * 10 *
*  150  *    77   132   180   229  *   111   162   214   265  *   119   170   221   273  * 10 *
*  200  *    83   132   182   232  *   111   162   214   265  *   119   170   221   273  * 10 *
*   20  *    72   115   159   203  *    96   148   201   250  *   109   163   216   268  * 11 *
*   45  *    64   113   156   206  *    95   148   201   250  *   110   160   214   268  * 11 *
*   70  *    61   106   159   203  *    95   148   201   250  *   111   160   214   265  * 11 *
*  100  *    60   105   156   203  *    95   148   201   251  *   108   160   216   265  * 11 *
*  150  *    60   104   154   204  *    95   148   197   246  *   109   160   212   265  * 11 *
*  200  *    59   104   154   203  *    95   141   201   248  *   108   160   213   266  * 11 *
*   20  *    73   116   166   212  *    92   141   194   249  *   103   158   211   266  * 12 *
*   45  *    63   112   160   210  *    89   138   195   248  *   102   157   212   267  * 12 *
*   70  *    59   112   159   212  *    88   144   195   249  *   101   156   211   267  * 12 *
*  100  *    60   105   160   213  *    89   140   193   249  *   101   156   211   267  * 12 *
*  150  *    54   104   160   211  *    88   139   194   249  *   101   157   212   267  * 12 *
*  200  *    49   107   158   212  *    83   139   194   250  *   101   156   212   266  * 12 *
***********************************************************************************************
```

7.6 Application of the output from the irrigation analysis

Before proceeding with an example of the use of the output from the irrigation analysis it is necessary to address briefly the following:

(a) the crop factors used;
(b) the estimation of peak irrigation demand;
(c) the irrigation water application efficiency;
(d) the frequency of application and the question of interception.

It must be stressed again that the crop factors referred to in this study are for the plant ET relative to Class A-pan evaporation. Therefore the use of this information would need to convert any crop factors accordingly.

It is common practice to plan an irrigation scheme to meet peak demand. Such demand is often confused with the maximum rate of evaporation as measured by the Class A-pan for example. In this analysis the estimated mean monthly evaporation was used and as such the peak evaporation demand was never applied to the water budget. Furthermore the frequency analysis stops at the 90 percentile level. The question then is how does one estimate the peak irrigation demand from the results presented in Table 7.5, for example? To answer this, consider first the question of rainfall. In most cases particularly in the drier areas it was noticed that the 90 and 95 percentile levels of irrigation water requirement were very similar, indicating that rainfall was not affecting the requirement at these frequency levels. With regard to the peak evaporation demand, such demand could very often cause stomatal closure resulting in the AET being markedly less than PET. This was indeed the case in the test results from Roodeplaat and Cedara and which were discussed in Chapter 5. Similar findings have been reported _inter alia_ by Slabbers (1980), Calder _et al_. (1983) and Hill _et al_. (1983). In view of the abovementioned and also considering that the irrigation requirement as reported is the integral over a month, the 90 percentile level of irrigation is considered, in most cases, to be fairly close to the monthly peak demand. However, should this assumption not satisfy the potential user then the 90 percentile level of irrigation water requirement could be increased by an amount equal to the difference between the maximum and the mean monthly Class A-pan evaporation.

The irrigation water requirements as presented in Table 7.5 and Appendix E do not contain any allowance for irrigation application efficiency. The amounts presented in Table 7.5 are simply the additional water requirements of the plants themselves. Interception loss during irrigation is also not taken into account in the figures presented in Table 7.5. Calculation of gross amounts of water for irrigation must therefore consider these losses. The depth of irrigation per setting and the timing of such irrigations in relation to soil moisture are discussed in Section 4.2.3. The irrigation requirements such as those presented in Table 7.5 will be most meaningful if the operating rules for the planned irrigation scheme follow the irrigation depths and timing assumptions of the irrigation model, as discussed in Section 4.2.3.

Having clarified the above aspects concerning the use of the irrigation analysis output it remains to consider a worked example of the use of such output. The example which has been chosen, incorporates the use of the output shown in Table 7.5 to produce an estimated monthly irrigation demand curve for an irrigation scheme in which three crops are grown.

The problem of matching irrigation requirements to the long term water supply is one of fundamental importance to the agricultural planner. An important component of a yield analysis, on a reservoir, dam or stream, for irrigation purposes is the construction of a monthly irrigation demand curve for the scheme. The results presented in Table 7.5 are suited to such an application, which would result in the preparation of a curve such as that shown in Figure 7.1

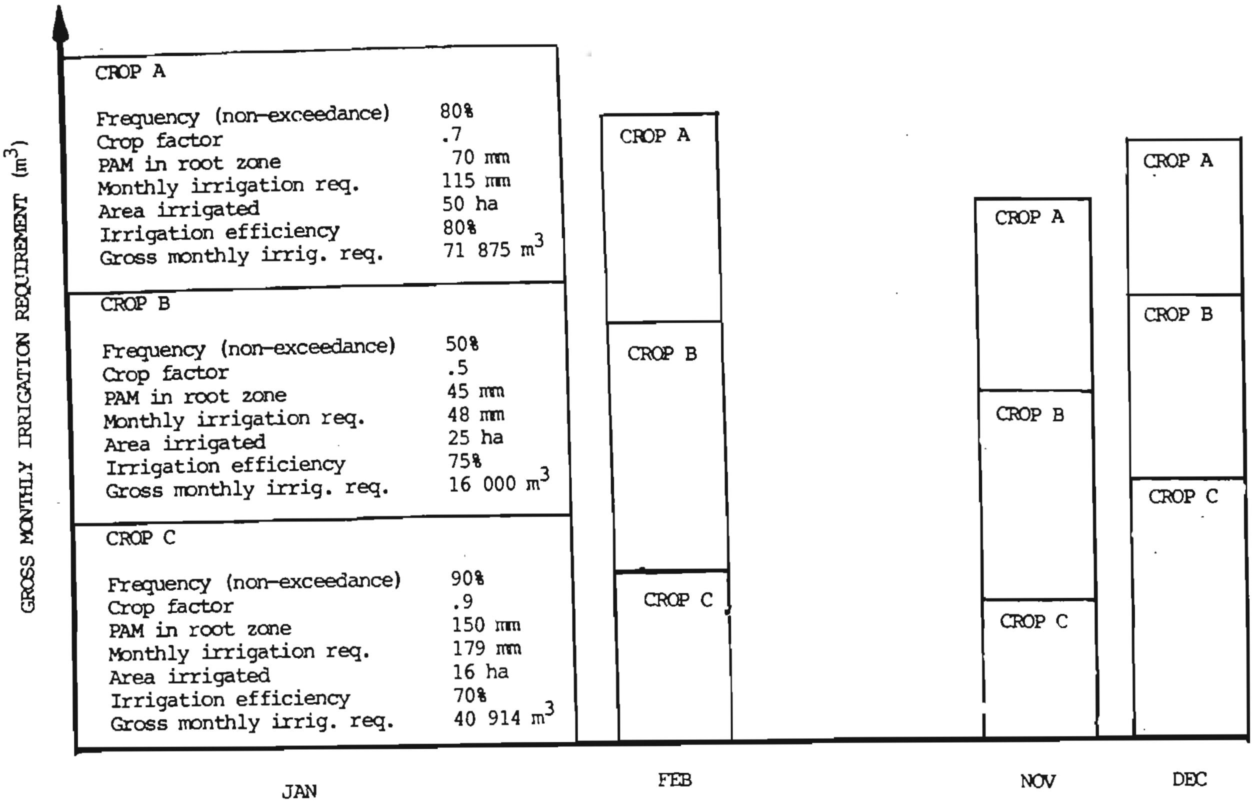


Figure 7.1 Estimation of monthly irrigation demand curve for planning: example using selected values from Zone 377, Bergville

The values of PAM (mm/m) for most South African soil series may be obtained, <u>inter alia</u>, from Schulze (1984b); Schulze (1985a); Schulze, Hutson and Cass (1985). This value of PAM multiplied by the rooting depth of the particular crop, expressed in meters, yields the PAM in the root zone. These values are shown for crops A, B and C in Figure 7.1

The crop factor and the desired risk, i.e. frequency of non-exceedance would be assessed for each crop in the scheme and for each month. The irrigation requirement corresponding to these variables would then be obtained from Table 7.5 which in this case is the output for Zone 377, Bergville in Natal. Adjustment must then be made for irrigation efficiency. These requirements for each crop are superimposed as shown in Figure 7.1 to produce the total monthly demand. The demand curve is then available for use in a reservoir yield analysis for example. In such an analysis the monthly irrigation demands as reflected by the curve are extracted from the reservoir or stream in a monthly water budget simulation. The analysis described above is certainly no substitute for a long term daily water budget of the system which includes the water resources and irrigation requirements of the area. It is meant simply as quick first approximating which may be performed manually and used as input to a computerised continuous monthly water balance of the proposed reservoir and irrigation scheme. In addition it illustrates one of the uses of the output from the irrigation analysis.

There are some general trends which are repeated and are noticeable in many of the outputs from the irrigation analyses. For example, in the dry season it is evident that the soil depth does not affect the irrigation requirement. This is to be expected since the manner in which the model applies water ensures that no runoff occurs from irrigation. In the wetter months the deeper soils require less irrigation water since more of the rainfall is effective. This trend reduces at the 80 and 90 percentile levels, due to the drier conditions which would have prevailed at these times. In addition the trend towards lower irrigation requirements for deeper soils becomes less noticeable as the crop factor increases. This is caused by the soil moisture being depleted more rapidly and hence the rainfall is more likely to be effective.

In the dry months the difference in irrigation water requirements at the 50, 80 and 90 percentile levels are negligible. This trend is evident throughout the range of crop factors in these dry months. Again this is to be expected when irrigation provides the only water input to the system.

8 DISCUSSION AND CONCLUSIONS

The final discussion and conclusions on a subject as wide as that covered by this study will of necessity embrace a broad spectrum of thoughts. Consequently it is considered helpful to classify and discuss the conclusions under four headings viz.;

(a) the contribution made by this study to the state of knowledge with regard to estimating crop water requirements for planning in South Africa, in particular, and to local and regional aspects of the soil moisture budgeting, in general:

(b) the extent to which the objectives of the study as presented in Section 1.2 have been achieved;

(c) recommendations for future research needs in relation to aspects of this study; and

(d) the future challenge.

8.1 Contribution to the state of knowledge

Perceptions of the extent to which this study has contributed to the state of knowledge on the subject of estimating crop water requirements for irrigation and other soil moisture budget related variables in Southern Africa, may vary. However, this study is certainly unique in many respects and judging by the reactions from planners of irrigation schemes the results of this study will contribute significantly to their state of knowledge in the abovementioned areas and will be most useful in practice.

The delimitation of homogeneous climate zones in Southern Africa was an essential foundation to this study and it provided a considerably larger amount of detail than that contained in previous studies of this nature. The delimitation of 712 homogeneous rainfall regions provides six times more detail than that contained in the study by Welding and Havenga (1974) which until the completion of this study had been the most comprehensive delimitation of homogeneous rainfall zones in Southern Africa. In addition to the extra detail, the regions delimited in this study were based on altitude and MAP and not only on interstation monthly rainfall correlation as were those of Welding and Havenga (1974). This latter point in addition to the detail of the delimitation makes this sub-study unique in Southern Africa.

The delimitation of homogeneous climate zones surrounding long term daily rainfall stations produced a systematic mechanism for selecting representative rainfall stations covering Southern Africa. The resultant set of 712 rainfall stations which are carefully distributed with respect to MAP and altitude as well as in space have been a popular by product of this study. The high degree of interest shown by the planning and research community leads to the conclusion that a large set of stations covering Southern Africa and which have been selected so systematically, represents a new contribution to the state of knowledge in this regard.

The decision to digitise the boundaries of these zones and to store these co-ordinates in terms of latitude and longitude, enables these boundaries to be reproduced at any scale or projection. The usefulness of these data for overlay purposes has been recognised as may be judged by the number of requests from researchers and planners for these data. Again this leads to the conclusion that such a sub-study is indeed unique in South Africa and the products of the sub-study make a contribution to knowledge in this field. The abovementioned products of this study are used in a number of applications, the majority of which embrace soil moisture budgeting either directly or by implication.

The generally bulky form of the information on irrigation requirements and dryland soil moisture analyses has in the past limited the advancement and propogation of such potentially useful information. This study has demonstrated that a marked reduction in this bulk is achievable and that the usefulness and accuracy of the estimates so generated, are not affected detrimentally. The wide range of combinations of crops and soils which were accommodated, make this study unique in Southern Africa. It has been shown that under an irrigation regime the technique to perform the moisture budget in discrete bi-monthly stages did not impair the quality of the estimate of irrigation requirements. The adoption of this technique and the subsequent format of the presentation of the irrigation requirements wherein the soil and crop type are not specified directly will enable these results to retain their relevance despite the fact that estimates of crop factors, soil moisture variables or crop planting dates may be modified in the future.

The concepts of area specific and site specific variables and the opportunities which such an approach offers is thought to be unique. With the ever increasing power of computers and increasing costs of field acquisition of soils and land use data it is more cost effective to produce all combinations of soil and crop whilst the computer run is set up than to keep returning to perform computer runs for each new combination. The concept could be extended to provide much more detailed coverage both in terms of climatic and also soil/crop combinations in limited areas.

The results of this study have provided the potential for mapping estimates of runoff, AET and crop water requirements from irrigation to a detail which is dependent only on the detail to which the classification of soils and land use is produced. The procedure to achieve this was discussed in Section 7.4. In this sense the potential for further increasing the state of knowledge in terms of geographic information systems containing the abovementioned estimates is truly exciting.

The extensive detailed coverage of Southern Africa afforded by this study has increased knowledge with respect to moisture requirements and shortfalls for a range of crops in areas which may be considered marginal in terms of soil moisture for crop production. The study was not restricted to analysing the soil moisture regime for conventional crops in existing production areas only. The results may therefore be used to provide an indication of potential crop water requirements for crop/zone combinations where no knowledge, based on experience, exists. The fluid situation with respect to changing markets, prices and transport costs make the results of this study, most useful for scenario planning.

This study has contributed to the state of knowledge on the ACRU model in that for the first time the model has been tested against observed soil moisture data from field plots. The performance of the ACRU model in these tests has led to increased confidence in the use of the model for soil moisture estimation in particular.

Since only long term daily rainfall records were used, the risk analysis incorporated in this study goes beyond that accomplished by previous studies on this topic in Southern Africa. Therefore it may be presumed that the state of knowledge with regard to the frequency of occurrence of levels of crop water requirements from irrigation, runoff and AET has been enhanced by this study, particularly in the humid areas.

The study has also contributed to an increase in knowledge on several issues of fundamental importance to the furtherance of soil moisture budget modelling on the scale and detail of this study, in Southern Africa. Here specific reference should be made to the regionalisation of wind factor in the Linacre (1977) equation for estimating PE. In addition tests showed that for the South African data set of evaporation and daily rainfall, the median value of the frequency distribution of daily A-pan evaporation measurements is reduced by 20 per cent on raindays and increased by 5 per cent on non-raindays when compared to the median value for all days, irrespective of the rainfall. It has been demonstrated that it is possible to use mean monthly values of PE in models such as the ACRU model for the purposes outlined in this study without introducing unacceptable changes to the soil moisture budget. Finally, the use of synthetic rainfall data as generated by the Zucchini and Adamson (1984) model has been shown to be acceptable in the estimation of probabilistic values of AET and runoff. The Zucchini and Adamson (1984) technique of rainfall data generation was also shown to be acceptable when used to infill rainfall data for use in this study.

8.2 Achievement of objectives

The study had several primary objectives relating to the estimation of crop water requirements from irrigation. The objectives were broad in the sense that even the soil moisture and runoff implications of dryland farming as an alternative to irrigation were considered by making a dryland analysis a secondary objective.

The extent to which the objectives stated in Section 1.2, were achieved will be discussed in the order stated in that section. Since the achievement of most of the objectives entailed increasing the state of knowledge in these areas in Southern Africa it is possible to cover these achievements very briefly in this section as they were discussed in more detail in Section 8.1. In summary therefore the achievement of objectives may be discussed as follows:

(a) A delimitation of homogeneous climatic zones throughout Southern Africa was achieved at a detail of approximately six times that of the previously most comprehensive study of this kind in the region. In addition estimates of crop water requirements under irrigated conditions were provided in each zone.

(b) The bulk of information which is normally forthcoming from such analyses was reduced markedly whilst retaining the essential information content for a wide range of possible crop, soil and planting date options, for irrigated and dryland farming conditions.

(c) An estimate of the frequency of non-exceedance of certain levels of irrigation requirement, based on analyses of soil moisture budgets using long daily rainfall records was established. A similar frequency analysis was achieved for the dryland analysis variables of evapotranspiration deficit, runoff and index of stress days.

(d) The form of the irrigation analysis ensures that within the limitations of the assumptions made, the results will not become redundant in time due to improved estimates of crop factors, soil moisture variables and changes in farming practice with respect to planting dates.

(e) The above information has been provided in a form which is easy and quick to consult whilst remaining flexible and relevant in a facet of agriculture, viz. irrigation which is expanding rapidly in Southern Africa.

(f) The soil moisture budgeting models which were used in this analysis have undergone verification as discussed in Chapter 5, particularly with regard to their ability to estimate soil moisture. The models were verified against four sets of field plot data of soil moisture measurement which each covered a season. This verification led inter alia to the irrigation model being developed into a quasi two layer model in the sense that the runoff component was controlled by the top 200 to 300 mm of soil only as described in Section 4.2.3. Considering the limitations of daily models, especially with respect to their inability to account for rainfall intensity, both the ACRU and the irrigation models performed well. A more detailed discussion of these and other limitations of the models was presented in Section 5.3.4.

Finally the objective of automation which embraced almost every facet of the above and the pursuance of which was essential to the successful completion of this study, was achieved. The systems developed in this study are already finding a number of other uses in addition to ensuring the possible rapid revision of the analyses in the light of better data, for example.

8.3 Recommendation for future research

Further research to improve the estimates provided by this study and to achieve this within the format of this analysis is important. The specific aspects which could be improved by further research are discussed below. The format of this study will probably be superceded in 10 to 15 years time when it is foreseen that it will be common practice for computer networks, data bases and computer models to provide readily available and more individualised analyses of soil moisture budgeting for a host of possible uses including those discussed in this study.

One immediately apparent task for future research could be to further subdivide and refine the homogeneous climate zones and to conduct similar analyses for these smaller zones.

The climatic data input could be more refined by future research. Of particular importance here is researching ways of estimating rainfall intensity inter alia by analysing regional patterns of daily rainfall, estimating rainfall intensity from synoptic information or extrapolating measured rainfall intensity to design sites. It is recognised that progress on the above aspects may be extremely difficult to achieve, however the improvements to soil moisture budget modelling which would emanate from success in such work are considerable.

The estimation of PE and hence PET and AET is another aspect which requires further research. The analyses in this study revealed that it is not important to have precise daily estimates of the above in humid areas and in particular for runoff estimation. However, it is evident from this study and from the literature that in drier areas and even in drier periods in wet areas, the estimation of PE assumes increasing importance. The interpolation and extrapolation of estimates of PE onto maps is a natural progression from the abovementioned and is also an aspect of future research to which attention is recommended.

The extent to which the estimates of crop water requirements for irrigation planning as presented in this study match those being used by designers and planners of irrigation schemes around the country would no doubt reveal some interesting facts.

With regard to runoff it may be recommended that the results of this analysis be combined with actual crop and soil information in a small agricultural catchment. The purpose of this would be to investigate whether it is possible to estimate the 50, 80 and 90 percentile levels of monthly runoff total from the results presented in the dryland analysis of this study.

The estimation of crop factors is a topic which requires continuing research. It must be stressed again that the crop factors used in these analyses, both irrigation and dryland, relate to class A-pan estimates of PE. In addition, owing to the absence of dryland crop factors in the literature the crop factors used are for irrigated conditions. Estimates of crop factor are being revised continually by researchers and are also affected by such factors as management practices, hybrids, soil nutrition, plant population density and moisture stress history of the plant. Therefore where dryland conditions deviate substantially from those which would be the norm on a well managed irrigation field then the results of the dryland analysis must be treated with caution. Typical third world management, soil, nutritional and plant hybrid conditions are particularly clear examples of the above. The effect of all these factors on the crop factor are topics which deserve attention in future research.

Some irrigation planners prefer to structure the equipment and water needs such that they will meet the peak demand albeit for short periods. In the calculation of such peak demands it may be assumed that no rain occurs and that the local PE remains at its maximum for several days. The question of peak irrigation demand is one which could be the subject of further research. Based on the results of the present study, however, it is possible to speculate as to what one may find in such research. For example, the estimated level of irrigation generally remained constant or varied very little between the 90 and 95 percentile levels and hence the latter estimate was not presented in the irrigation requirements tables. This phenomenon indicated that at these levels of non exceedance, rainfall generally made no contribution to the water budget. The two factors which remain unknown and would therefore require future research are;

(a) the difference between the mean monthly PE and the maximum PE, and

(b) the extent to which stomatal closure would reduce the AET in the abovementioned cases. The stomatal closure effect will vary according to the crop and the peak demand.

Finally it must be emphasised again that the estimated crop water requirements presented in this study reflect the plant needs as determined by demand mode irrigation. Therefore, no account has been taken of interception of irrigation water, irrigation efficiency or the increase in irrigation requirements under a fixed cycle regime in humid areas.

8.4 The future challenge

The following quotation from van Robbroeck (1983) provides an insight into the challenges which the future holds. The results of this study offer a contribution towards meeting these challenges.

> "Advantages of scale make it possible and economic to transport an easily handled commodity such as water over long distances and against high heads. This introduces competition for water even in remote areas.
>
> At the same time, the spread of the electricity network, new irrigation techniques and new kinds of crops have made irrigation in previously inconceivable areas a proposition.

In addition, the phenomenal growth of the timber industry and land conservation practices have reduced the amount of water available from runoff.

Water resources planning for irrigation use is impossible to divorce from planning for other uses. As a country's resources approach full utilization, competition for the remaining slice of the cake becomes increasingly fierce and the allocation becomes more difficult. Conflict will be almost inevitable and the decision maker will have to gear himself for handling it."

9 REFERENCES

ADAMSON, P.T. 1986. Personal communication. Dept. Water Affairs. Durban.

AITKEN, A.P. 1973. Assessing systematic errors in rainfall-runoff models. J.Hydrol., 20: 121-136.

ALEXANDER, W.J.R. 1980. Precipitation. 1980 Pretoria Hydrology Course, Dept. Civil Engineering, University of Pretoria, Pretoria. Ch 1: 1-2.

BAIER, W. 1963. Studies on estimating potential evapotranspiration from empirical relationships. S.Afr.J.Agric.Sci., 6: 455-474.

BAIER, W. and ROBERTSON, G.W. 1966. A new versatile soil moisture budget. Can. J. Plant Sci., 46: 299-315.

BAKER, J.M. and VAN BAVEL, C.H.M. 1986. Resistance of plant roots to water loss. Agron. J., 78: 641-644.

BALIGAR, V.C., WRIGHT, R.J. and SMEDLEY, M.D. 1988. Acid phosphate activity in soils of the Appalachian region. Soil Sci. Soc. Am. J. 52: 1612-1616.

BARTELS, L.F. 1965. Estimation of soil drainage losses following irrigation. Aust. J. Exp. Agric. Anim. Husb., 5: 59-64.

BLOODWORTH, M.E., BURLESON, C.A. and COWLEY, W.R. 1958. Root distribution of some irrigated crops using undisrupted soil cores. Agron. J., 50: 317-320.

BRAKENSIEK, D.L., ENGLEMAN, R.L. and RAWLS, W.J. 1981. Variation within texture classes of soil water parameters. Trans. ASAE., 24: 335 - 339.

BURGERS, M.S. 1982. Besproeiingsprogrammering met behulp van panverdamping by koring, aartappels en stambone. Unpublished D.Sc.Agric. Thesis. University of Pretoria, Pretoria.

BURMAN, R.D., CUENCA, R.H. and WEISS, A. 1983. Techniques for estimating irrigation water requirements. Adv. Irrig., 3: 335-394.

BURMAN, R.D., POCHOP, L.Q., KOSTRZEWSKI, M.A. and YONTS, C.D. 1982. Statistical and numerical representation of irrigation water requirements. Trans. ASAE., 25: 165-168.

BUYS, M.E.L., FABRICIUS, A.F., VAN DEN BERGH, P. and KLOPPER, A.P.J. 1979. Analysis of rainfall in South Africa. Expectancy of monthly rainfall. Dept. Agric. Tech. Services, Pretoria. Tech. Comm. No. 148, pp 33.

CALDER, I.R., HARDING, R.J. and ROSIER, P.T.W. 1983. An objective assessment of soil moisture deficit models. J.Hydrol., 60: 329-355.

CLEMENCE, B.S.E. and SCHULZE, R.E. 1982. An assessment of temperature-based equations for estimating daily crop water loss to the atmosphere in South Africa. Crop Prod., 11: 21-25.

CO-ORDINATING COMMITTEE FOR IRRIGATION RESEARCH (CCIR) 1986. Recommendations of the workshop on research requirements relating to economic, sociological and ecological aspects of irrigation development. Co-ord. Comm. Irrig. Res., Water Research Commission, Pretoria.

CUENCA, R.H. 1982. Reliable techniques for estimating evapotranspiration with limited data. Proc. Irrig. Assoc. Agri-Turf Tech. Conf., Portland, Oregon. 140-154.

CUENCA, R.H. and AMEGEE, K.Y. 1987. Analysis of evapotranspiration as a regionalized variable. Adv. Irrig., 4: 181-220.

DENMEAD, O.T. and SHAW, R.H. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J., 54: 385-390.

DENT, M.C. and FURNISS, P.W. 1987. Unpublished research results. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg.

DENT, M.C., LYNCH, S.D. and SCHULZE, R.E. 1987a. Mapping mean annual and other rainfall statistics over Southern Africa. Dept. Agricultural Engineering, University of Natal. ACRU Report 27.

DENT, M.C., SCHULZE, R.E., LYNCH, S.D. and MAHARAJ, M. 1987b. Unpublished research results pertaining to average monthly temperatures over Southern Africa. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg.

DENT, M.C. and WILLS, H.M.M. 1986. On-line data base management system for monthly rainfall in Southern Africa. Integrated Design of Hydrological Network, Proc. Budapest Symp. IAHS Publication, 158: 381-387.

DEPARTMENT OF AGRICULTURAL TECHNICAL SERVICES. 1973. Beraamde besproeiingsbehoeftes van gewasse in Suid-Afrika. Pretoria.

DEPARTMENT OF WATER AFFAIRS. 1986. Management of water resources of the Republic of South Africa. ISBN 0 621 11004 3. Dept. Water Affairs, Pretoria.

DE JAGER, J.M. 1982. Personal communication. Dept. Agrometeorology, University of the Orange Free State, Bloemfontein.

DE JAGER, J.M. and SCHULZE, R.E. 1977. The broad geographic distribution in Natal of climatological factors important to agricultural planning. Agrochemophysica, 9: 81-91.

DE VILLIERS, J.M. 1962. A study of soil formation in Natal. Ph.D. thesis, University of Natal, Pietermaritzburg.

DE VILLIERS, G. du T. 1978. Grondreënval en onderskeppingsverliese by landbougewasse. Crop Prod., 7: 153-157.

DE VILLIERS, G. du T. 1980. Rainfall interception by grass. J. Univ. Durban-Westville, 3: 237-239.

DE VILLIERS, G. du T. and BOND, R. 1982. Enkele kenmerke van die reenval van Durban en omgewing. J. Univ. Durban-Westville, 4: 163-173.

DEVITT, D., JURY, W.A., STERNBERG, P. and STOLZY, L.H. 1983. Comparison of methods used to estimate evapotranspiration for leaching control. Irrig. Sci., 4: 59-69.

DINGMAN, S.L. 1981. Elevation: a major influence on the hydrology of New Hampshire and Vermont, USA. Hydrol. Sci. Bull., 26: 399-413.

DOORENBOS, J. and PRUITT, W.O. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Rome. pp 144.

DUCKSTEIN, L., FOGEL, M.M. and THAMES, J.L. 1972. Elevation effects on rainfall: a stochastic model. J.Hydrol., 18: 21-35.

DUNNE, T. and LEOPOLD, L.B. 1978. Water in Environmental Planning. Freeman, San Francisco, 71-72; 138.

DU PISANI, A.L. 1977. A simple versatile moisture budget model for maize. Crop Prod., 6: 87-90.

DU PISANI, A.L. 1978. The application of a moisture budget in determining maize yield potential. Proc. Eighth National Congress Soil Sci. Soc. S. Afr., Pietermaritzburg. Dept. Agric. Tech. Services, Pretoria. Tech.Comm. 165: 211-215.

DU PISANI, A.L. 1987. The CERES-MAIZE model as a potential tool for drought assessment in South Africa. Water SA, 13: 159-164.

EAGLEMAN, J.R. 1971. An experimentally derived model for actual evapotranspiration. Agric. Meteorol. 8: 385-394.

EAGLEMAN, J.R. and DECKER, W.L. 1965. The role of soil moisture in evapotranspiration. Agron. J., 57: 626-629.

EDWARDS, D. 1967. A plant ecology survey of the Tugela Basin. Memoirs Botanical Survey of South Africa. BRI, Pretoria. 36: pp 285.

ENGLISH, M., TAYLOR, A. and JOHN, P. 1986. Evaluating sprinkler system performance. New Zealand Agric. Sci., 20: 32-38.

ENGMAN, E.T. 1986. Hydrologic research before and after AgRISTARS. IEEE Trans. Geosci. Remote Sensing, GE24(1): 5-11.

FACI, J.M. and FERERES, E. 1980. Responses of grain sorghum to variable water supply under two irrigation frequencies. Irrig. Sci., 1: 149-159.

FURNISS, P.W. 1987. Planning for effective irrigation water utilization. Unpublished M.Sc. Eng. Thesis, Dept. Agricultural Engineering, University of Natal, Pietermaritzburg.

GARDNER, W.R. 1964. Relation of root distribution to water uptake and availability. Agron. J., 56: 41-45.

GREEN, G.C. 1984. A green look at irrigation. S.A. Water Bulletin, May: 31-33.

GUNTON, J.L. and EVENSON, J.P. 1980. Moisture stress in navy beans. Irrig. Sci., 2: 49-58.

HANKS, R.J. and MALICK, M.A. 1989. Interfacial contribution to two-electrode soil moisture senson readings. Irrig. Sci. 10: 41-54.

HARMSE, H.J. von M., VAN DER WATT, H. v H., VAN ROOYEN, T.H. and BURGER, R.D.U.T. 1984. Glossary of soil science terms. Soil Sci. Soc. of SA, Pretoria.

GREEN, G.C. 1985. (ed.) Estimated irrigation requirements of crops in South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 2. Soil and Irrigation Research Institute, Dept. Agriculture and Water Supply, Pretoria. pp 857.

GREEN, G.C. 1986. Report on a visit to the USA to attend the National Conference on advances in evapotranspiration in Chicago. December 1985. Water Research Commission, Pretoria.

HARTMANN, M.A. 1960. Soil moisture recounting under a permanent grass cover. J. Geophys. Res., 65: 355-357.

HELLMANN, D.B. 1975. The effect of soil moisture stress on wheat grain yields and the determination of E_t/E_o ratios for estimating water use by wheat. Crop Prod., 4: 119-124.

HERSHFIELD, D.M. 1964. Effective rainfall and irrigation water requirements. J.Irrig.Drain.Div.Am.Soc.Civ.Eng., IR-2, 33-47.

HEWLETT, J.D., DOUGLASS, J.E. and CLUTTER, J.L. 1964. Instrumental and soil moisture variance using the neutron-scattering method. Soil Sci., 97: 19-24.

HILL, R.W., HANKS, R.J. and WRIGHT, J.L. 1984. Crop yield models adapted to irrigation scheduling programs. Final report USDA-SEA/AR Co-operative Research No. 58-9AHZ-9-440. Utah Agricultural Experiment Station Res. Report No. 99. Utah State University, Logan, Utah.

HILLEL, D. 1980. Applications of soil physics. Academic Press, New York.

HILLEL, D. 1980a. Fundamentals of soil physics. Academic Press, New York.

HILLS, R.C. and REYNOLDS, S.G. 1969. Illustrations of soil moisture variability in selected areas and plots of different sizes. J. Hydrol., 8: 27-47.

HUFF, F.A., CHANGNON, S.A. and JONES, M.A. 1975. Precipitation increases in the low hills of Southern Illinois. Part I. Climatic and network studies. Mon.Wea.Rev., 103: 823-836.

HUGHES, D.A. 1982. The relationship between mean annual rainfall and physiographic variables applied to a coastal region of Southern Africa. S.Afr.Geogr.J., 64: 41-50.

HUGHES, D.A. and MOOLMAN, J.H. 1987. Soluble salt content of the alluvial banks of a semi-arid tributary catchment of the Great Fish River. Water SA, 13: 81-86.

HUTCHINSON, P. 1968. An analysis of the effect of topography on rainfall in the Taieri Catchment Area, Otago. Earth Sci., 2: 51-68.

HUTCHINSON, P. 1969. Estimation of rainfall in sparsely gauged areas. Bull. Int. Assoc. Sci. Hydrol., 14: 101-119.

HUTSON, J.L. 1984. Estimation of hydrological properties of South African soils. Dept. Soil Science and Agrometeorology, University of Natal, Pietermaritzburg, Unpubl. Ph.D. dissertation. pp 232.

HUTSON, J.L. and JOUBERT B.J. 1983. Movement and behaviour of water in soil. Development of field and laboratory methods. Part 1: Estimating and describing water retentivity of South African soils. Soil and Irrigation Research Institute. Final Report, Project (A) S-Pr 51/1. Mimeographed. pp 28 and Appendix.

ISTOK, J.D. and BOERSMA, L. 1986. Effect of antecedent rainfall on runoff during low-intensity rainfall. J. Hydrol., 88: 329-342.

JENSEN, M.E. (ed.) 1974. Consumptive use of water and irrigation water requirements. American Society of Civil Engineers, New York. pp 216.

JOHNS, G.G. and SMITH, R.C.G. 1975. Accuracy of soil water budgets based on a range of relationships for the influence of soil water availability on actual water use. Aust. J. Agric. Res., 26: 871-873.

KELBE, B. 1987. Spatial constraints in extrapolating daily rainfall in the semi-arid interior of Southern Africa. Agric. and Forest Meteor., 40: 51-59.

KIRKHAM, M.B. 1983. Physical model of water in a split root system. Plant and Soil, 75: 153-168.

KRISTENSEN, K.J. 1974. Actual evapotranspiration in relation to leaf area. Nordic Hydrol., 5: 173-182.

LEDIEU, J., DE RIDDER, P., DE CLERCK, P. and DAUTREBAUDE, S. 1988. A method of measuring soil moisture by time-domain reflectometry. J. Hydrol., 88: 319-328.

LEE, R. 1973. An optographic technique for evaluating the exposure of precipitation gauge sites in mountainous areas. Proc. Symp. Distr. Precip. Mtns. Areas, World Meteorological Organization, Geneva, W.M.O. No. 326, 2: 67-72.

LINACRE, E.T. 1963. Determining evapotranspiration rates. J. Aust. Inst. Agric.Sci., 29: 165-177.

LINACRE, E.T. and TILL, M.R. 1969. Irrigation timing and amounts. J. Aust. Inst. Agric. Sci., Sept., 175-196.

LINACRE, E.T. 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. Agric. Meteor., 18: 409-424.

LOAGUE, K.M. and FREEZE, R.A. 1981. A comparison of rainfall-runoff modelling techniques on small upland catchments. Wat. Resour. Res., 21: 229-248.

LONDON, W. and EMMITT, G.D. 1986. Topographical influences on radar echo properties - implications to weather modification projects in mountainous terrain. 2nd Conference on Planned and Inadvertent Weather Modification, Baltimore.

MAC VICAR, C.N., De VILLIERS, J.M., LOXTON, R.F., VERSTER, E., LAMBRECHTS, J.J.N., MERRYWEATHER, F.R., LE ROUX, J., VAN ROOYEN, T.H and HARMSE, H.J. VON M. 1977. Soil classification - a binomial system for South Africa. Soil and Irrigation Research Institute, Pretoria. Department of Agricultural Technical Services. pp 150.

MALLETT, J.B., DE JAGER, J.M. and FARINA, M.P.W. 1974. An explanation for the seasonal yield variation of maize grown at Dundee. Crop Prod., 3: 43-45.

MALLETT, J.B. 1987. Personal communication. Summer Grain Research Centre, Dept. Agriculture and Water Supply, Cedara.

MARCH, W.J., WALLACE, J.R. and SWIFT, L.W. 1979. An investigation into the effect of storm type on precipitation in a small mountain watershed. Wat.Resour.Res., 15: 298-304.

MATHER, J.R. 1978. The climatic water budget in environmental analysis. Lexington Books. Toronto. Ch. 2. pp 239.

McKAY, G.A. 1976. Hydrological mapping. In: Rodda, J.C. (Ed.) Facets of Hydrology. John Wiley and Sons, London: 1-35.

MEYER, W.S., OOSTERHUIS, D.M., BERLINER, P.R., GREEN, G.C. and VAN DER MERWE, A.J. 1987. Evapotranspiration and water use studies in wheat and soybeans with the help of the weighing lysimeter technique. Water Research Commission, Pretoria.

McQUITTY, L.L. 1960. Hierarchical syndrome analysis. Educ. Psychol. Measur., 20: 293-304.

MIDGLEY, D.C. 1983. Water Resources of South Africa. Paper presented at workshop on hydrological and water supply aspects of irrigation research. Co-ord. Comm. Irrig. Res. (CCIR), Water Research Commission, Pretoria. pp 6.

MOTTRAM, R. 1986. Unpublished research results. Summer Grain Centre, Dept. Agriculture and Water Supply, Pretoria.

NAEF, F. 1985. Can we model the rainfall-runoff process today?

Hydrol. Sci. Bull., 26: 281-289.

NEL, A. 1987. Personal communication. Soil and Irrigation Research Institute, Dept. Agriculture and Water Supply, Pretoria.

NEUWIRTH, S.D. and SCHMIDT, E.J. 1986. Unpublished research results. Dept. Agricultural Engineering, University of Natal Pietermaritzburg.

OGATA, G., RICHARDS, L.A. and GARDNER, W.R. 1960. Transpiration of alfalfa determined from soil water content changes. Soil Sci., 89: 179-182.

PENMAN, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Royal Soc., London, A193, 120-146.

PENMAN, H.L. 1963. Vegetation and hydrology. Tech. Comm. Commonw. Bur. Soils. Harpenden No. 53. (Cited by Linacre and Till, 1969).

PHILIPS, J. 1973. The agricultural and related development of the Tugela basin and its influent surrounds. Natal Town and Regional Planning Commission, Pietermaritzburg. pp 299 and maps.

PURCHASE, J.P. 1987. Personal communication. Small Grain Centre, Dept. Agriculture and Water Supply, Bethlehem.

RAWLS, W.J. and ASMUSSEN, L.E. 1973. Neutron probe field calibration for soils in the Georgia coastal plain. Soil Sci., 116; 262-265.

RAWLS, W.J. and BRAKENSIEK, D.L. 1982. Estimating soil water retention from soil properties. J. Irrig. Drain. Div., Proc. ASAE 108 (IR2): 166 - 171.

RITCHIE, J.T. 1981. Water dynamics in the soil-plant-atmosphere system. Plant and Soil, 58: 81-96.

RITCHIE, J.T., BURNETT, E. and HENDERSON, R.C. 1972. Dryland evaporative flux in a subhumid climate. III. Soil water influence. Agron. J., 64: 168-173.

RITCHIE, J.T. and OTTER, S. 1984. CERES - wheat: A user-oriented wheat yield model preliminary documentation. AGRISTARS. Publ. No YM-U3-04442-JSC-18892.

ROSE, C.W. and STERN, W.R. 1965. The drainage component of the water balance equation. Aust. J. Soil Res., 3: 95-100.

ROSE, C.W. and STERN, W.R. 1967. Determination of withdrawal of water from soil by crop roots as a function of depth and time. Aust. J. Soil Res., 5: 11-19.

ROSENZWEIG, M.L. 1968. Net primary productivity of terrestrial communities: prediction from climatological data. American Naturalist, 102: 67-74.

SCHEEPERS, J.J., SMIT, J.A. and LUDICK, B.P. 1984. An evaluation of the agricultural potential of the Highveld Region in terms of dryland cropping and livestock production. Dept. Agriculture, Pretoria. Tech. Comm. 185. pp 258.

SCHERMERHORN, V.P. 1967. Topography and annual precipitation. Wat. Resour. Res., 3: 707-711.

SCHMIDT, E.J. and SCHULZE, R.E. 1987. SCS-based design runoff. Department of Agricultural Engineering, University of Natal, Pietermaritzburg. ACRU Report 24. Water Research Commission Report T31/87. pp 164 and Appendixes.

SCHULZE, R.E. 1976. On the application of trend surfaces of precipitation to mountainous areas. Water SA, 2: 110-118.

SCHULZE, R.E. 1979. Hydrology and water resources of the Drakensberg. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg, ACRU Report 6. Natal Town and Regional Planning Commission, Pietermaritzburg. pp 179.

SCHULZE, R.E. 1981. Mean monthly temperature distributions for Natal. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg, ACRU Report 11. pp 27.

SCHULZE, R.E. 1982. The use of soil moisture budgeting to improve stormflow estimates by the SCS curve number method. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg, ACRU Report 15. pp 63.

SCHULZE, R.E. 1983. Agrohydrology and climatology of Natal. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg, ACRU Report 14, Water Research Commission, Pretoria: pp 138.

SCHULZE, R.E. 1984a. Hydrological processes: Concepts and thoughts, with reference to Southern Africa. Proc. S. Afr. National Hydrol. Symp. Ed. Maaren, H., Dept. Environment Affairs and Water Research Commission Tech. Report 119; 18-67.

SCHULZE, R.E. 1984b. Hydrological models for application to small rural catchments in Southern Africa: refinements and development. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg, ACRU Report 19, pp 248 and Appendix.

SCHULZE, R.E. 1985a. Hydrological characteristics and properties of soils in Southern Africa 1: Runoff response. Water SA, 11: 121-128.

SCHULZE, R.E. 1985b. Regional potential evaporation mapping in areas of sparse climatic data. Beitrage zur Hydrologie, Freiburg Sonderheft 5.1, 373-386.

SCHULZE, R.E. 1986. The 'ACRU' model for agrohydrological decision making: structure, options and applications. Proc. Second S. Afr. National Hydrol. Symp. Ed. Schulze, R. E., Dept. Agricultural Engineering, University of Natal, Pietermaritzburg. ACRU Report 22: 345-362.

SCHULZE, R.E. 1987. Personal communication, Dept. Agricultural Engineering, University of Natal, Pietermaritzburg.

SCHULZE, R.E. and GEORGE, W.J. 1986. The 'ACRU' model as a dynamic simulator of afforestation effects on water yield: Concepts and first results. Proc. Second S.Afr. National Hydrol. Symp. Ed. Schulze, R.E. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg. ACRU Report 22: 345-362.

SCHULZE, R.E., GEORGE, W.J. and ANGUS, G.R. 1987. Unpublished recommended values of soil moisture retention for use in the ACRU model. Dept. Agricultural Engineering, University of Natal, Pietermaritzburg.

SCHULZE, R.E., HUTSON, J.L. and CASS, A. 1985. Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models. Water SA, 11: 129-136.

SCHULZE, R.E. and O'DONNELL, J. 1976. Temperature mapping in Natal by multivariate analysis. University of Natal, Pietermaritzburg, Dept. Geography. Unpubl. manuscript. pp 10.

SHAW, R.H. 1964. Prediction of soil moisture under meadow. Agron. J., 56: 320-324.

SLABBERS, P.J. 1980. Practical prediction of actual evapotranspiration. Irrig. Sci., 1: 185-196.

SMITH, L.P. 1975. Methods in agricultural meteorology. Dev. in Atmos. Sci., 3. Elsevier, Amsterdam.

SOIL SCIENCE SOCIETY OF AMERICA. 1979. Glossary of soil science terms. Soil Science Society of America. Madison.

SOUTH AFRICAN WEATHER BUREAU (SAWB). 1960. Climate of South Africa. Part 5. District Rainfall. Dept. Transport, Pretoria.

SOUTH AFRICAN WEATHER BUREAU (SAWB). 1965. Climate of South Africa. Part 8 General Survey. Dept. Transport, Pretoria. WB 28.

SOUTH AFRICAN WEATHER BUREAU (SAWB). 1972. Climate of South Africa. Part 10. District Rainfall. Dept. Transport, Pretoria. WB 35.

SPREEN, W.C. 1947. A determination of the effect of topography upon precipitation. Trans. Am. Geophys. Union, 28: 285-290.

STAFFORD, J.V. 1988. Remote, non-contact and in-situ measurement of soil moisture content. J. Ag. Eng. Res. 41: 151-172.

STEGMAN, E.C. 1982. Corn grain yield as influenced by timing of evapotranspiration deficits. Irrig. Sci., 3: 75-87.

STONE, L.R., HORTON, M.L. and OLSON, T.C. 1973. Water loss from an irrigated sorghum field. I. Water flux within and below the root zone. Agron. J., 65: 492-495.

STOREBO, P.B. 1976. Small scale topographical influences on precipitation. TELLUS 28: 1.

SUTTER, R.J. and COREY, G.L. 1970. Consumptive irrigation requirements for crops grown in Idaho. Bulletin 516, University of Idaho, College of Agriculture. Cited in Burman et al., 1982.

TALBOT, A.M. and TALBOT, W.J. 1960. Atlas of the Union of South Africa. Govt. Printer, Pretoria.

TAYLOR, H.M. and KLEPPER, B. 1978. The role of rooting characteristics in the supply of water to plants. Adv. Agron., 30: 99-128.

THOMPSON, G.D. 1976. Water use by sugarcane. S. Afr. Sugar Jour., 60: 593-600 and 627-635.

TORRANCE, J.D. 1973. The variation of meteorological elements with increasing altitude in the eastern border mountains of Rhodesia. Rhod. J. Agric. Res., 11: 181-189.

TYSON, P.D., PRESTON-WHYTE, R.A. and SCHULZE, R.E. 1976. The climate of the Drakensberg. Natal Town and Regional Planning Commission, Pietermaritzburg. pp 79.

VACHAUD, G., ROYER, J.M. and COOPER, J.D. 1977. Comparison of methods of calibration of a neutron probe by gravimetry or neutron capture model. J. Hydrol, 34: 343-356.

VAN ROBBROECK, T.P.C. 1983. Irrigation water resources planning for the 90's and beyond. Paper presented at workshop on hydrological and water supply aspects of irrigation research. Co-ord. Comm. Irrig. Res. (CCIR), Water Research Commission, Pretoria.

VON HOYNINGEN-HUENE, J. 1983. Die Interzeption des Niederschlages in Landwirtschaftlichen Pflanzenbestanden. Deutscher Verband fur Wasserwirtschaft und Kulturbau, Verlag Paul Parey-Hamburg. Schriften 57: 1-66.

WAGGONER, P.E. 1968. Meteorological data and the agricultural problem. In: Agroclimatological Methods. Proc. Reading Symp. UNESCO, Paris. 25-38.

WATSON, H.K. and DE VILLIERS, G. 1986. Surface and subsurface flow from a Natal coastal catchment. Water SA, 2: 185-190.

WELDING, M.C. and HAVENGA, C.M. 1974. The statistical classification of rainfall stations in the Republic of South Africa. Agrochemophysica, 6: 5-24.

WILCOX, J.C. 1960. Rate of soil drainage following an irrigation. II Effects on determination of rate of consumptive use. Can. J. Soil Sci., 40: 15-25.

WHITMORE, J.S. 1968. The relationship between mean annual rainfall and locality and site factors. S.Afr.Jour.Sci. 64: Vol. 423-427.

WHITMORE, J.S. Undated. Mean monthly temperature. Agro-Climatology, Series I: Temperature. Division of Agricultural Education and Research, Pretoria.

WU, A.Y.K. 1967. The relationship between soil moisture content and the rate of evapotranspiration. J. Aust. Inst. Agric. Sci. March: 41-42.

ZISKA, L.H. and HALL, A.E. 1983. Soil and plant measurements for determining when to irrigate cowpeas (Vigna unguiculata [L.] Walp.) grown under planned-water deficits. Irrig. Sci., 3: 247-257.

ZUCCHINI, W. and ADAMSON, P.T. 1984. The occurrence and severity of droughts in South Africa. Dept. Civil Engineering, University of Stellenbosch and Dept. Water Affairs. Water Research Commission Report No. 91/1/84 and Appendix.

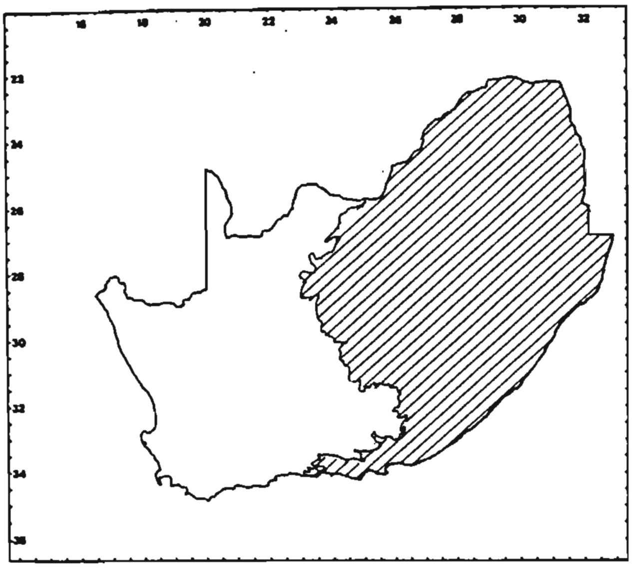
APPENDIX A

Homogeneous climatic zones in Southern Africa

(Map supplied)

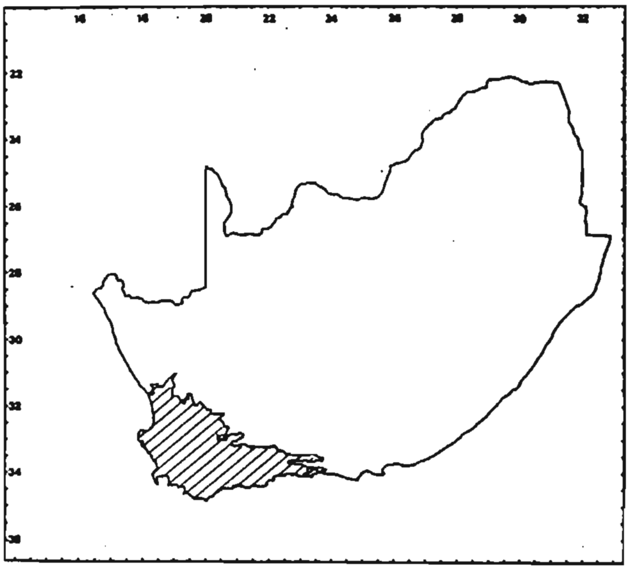
APPENDIX B

Assumed spatial distribution of the crops used in the dryland analyses

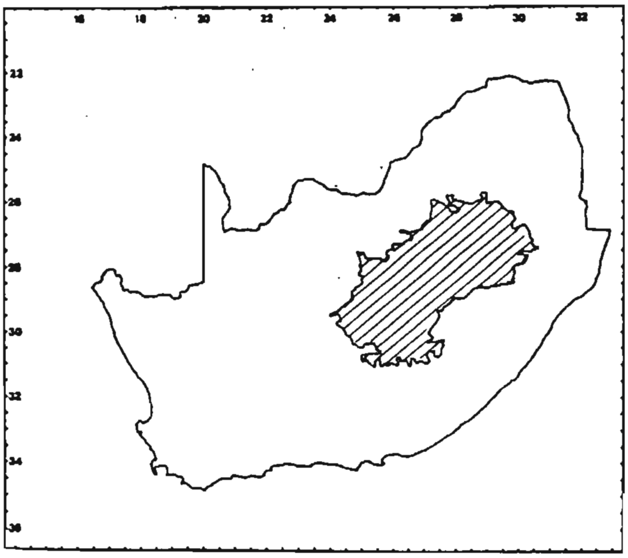


MAIZE SOYBEANS

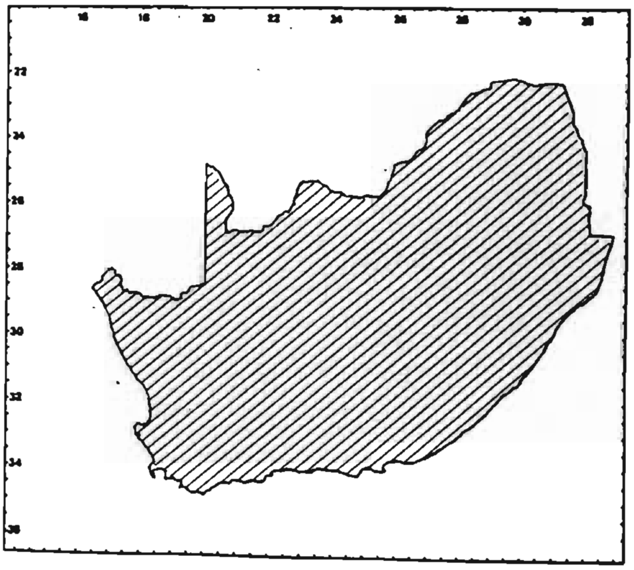
SUNFLOWER SORGHUM



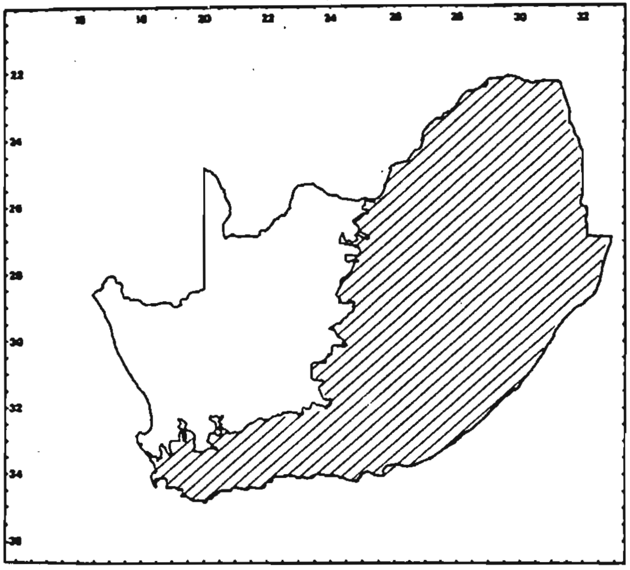
WHEAT (WINTER)



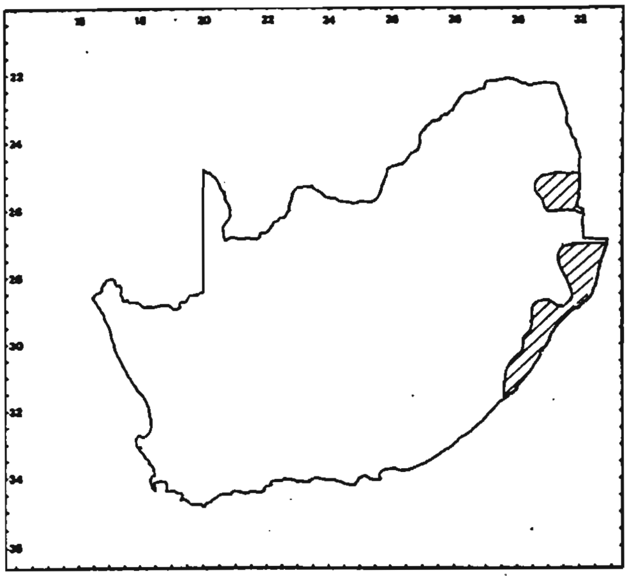
WHEAT (SPRING)



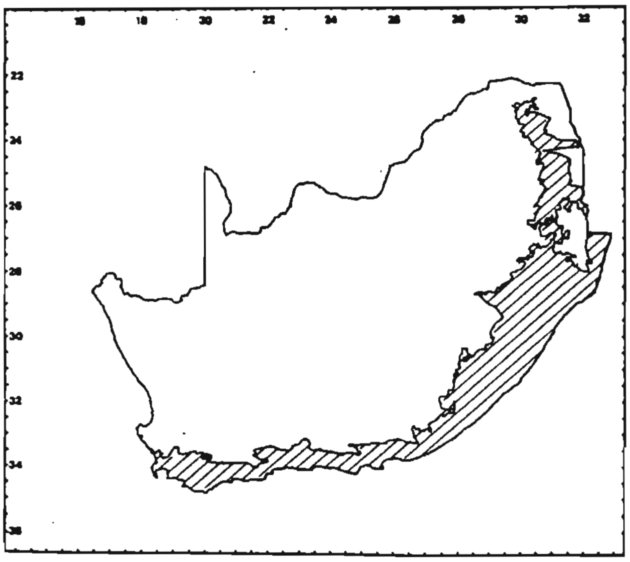
SPARSE VELD



GOOD VELD



SUGARCANE



TIMBER

APPENDIX C

Tables of variable values including crop factors and rooting depths for crops used in the analyses of soil moisture under dryland conditions

CROP FACTORS USED IN THE DRYLAND ANALYSIS

CROP	PLANTING DATE	J	F	M	A	M	J	J	A	S	O	N	D
MAIZE	1 NOV.	1.10	0.95	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.98
MAIZE	1 DEC.	0.89	1.10	0.96	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.50
WHEAT(W.CAPE)	15 MAY	0.20	0.20	0.20	0.20	0.30	0.79	1.00	0.52	0.20	0.20	0.20	0.20
WHEAT(O.F.S.)	15 JUNE	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.50	0.60	0.40	0.20
SUNFLOWER	15 DEC.	0.70	0.80	0.80	0.60	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20
GOOD VELD	-	0.55	0.55	0.55	0.45	0.35	0.35	0.35	0.35	0.35	0.40	0.50	0.55
SPARSE VELD	-	0.75	0.75	0.75	0.65	0.50	0.45	0.45	0.45	0.50	0.60	0.65	0.70
SUGARCANE	-	0.81	0.84	0.85	0.86	0.87	0.85	0.82	0.78	0.77	0.78	0.81	0.82
SOYBEANS	1 DEC.	0.73	0.94	0.55	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.33
TIMBER	-	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
SORGHUM		(same as Maize)											

ROOTING DISTRIBUTION
(fraction of roots in A horizon)

CROP	PLANTING DATE	J	F	M	A	M	J	J	A	S	O	N	D
MAIZE	1 NOV.	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
MAIZE	1 DEC.	0.79	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
WHEAT(W.CAPE)	15 MAY	1.00	1.00	1.00	1.00	0.92	0.75	0.65	0.55	1.00	1.00	1.00	1.00
WHEAT(O.F.S.)	15 JUNE	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.65	0.50	0.40	0.40	1.00
SUNFLOWER	15 DEC.	0.70	0.70	0.70	0.70	0.80	0.85	1.00	1.00	1.00	1.00	1.00	0.90
GOOD VELD	-	0.75	0.75	0.75	0.65	0.50	0.45	0.45	0.45	0.50	0.60	0.65	0.70
SPARSE VELD	-	0.75	0.75	0.75	0.65	0.50	0.45	0.45	0.45	0.50	0.60	0.65	0.70
SUGARCANE	-	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
SOYBEANS	1 DEC.	0.79	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
TIMBER	-	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
SORGHUM		(same as Maize)											

COEFFICIENT OF INITIAL ABSTRACTION

CROP	PLANTING DATE	J	F	M	A	M	J	J	A	S	O	N	D
MAIZE	1 NOV.	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
MAIZE	1 DEC.	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
WHEAT(W.CAPE)	15 MAY	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
WHEAT(O.F.S.)	15 JUNE	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
SUNFLOWER	15 DEC.	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
GOOD VELD	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SPARSE VELD	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SUGARCANE	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SOYBEANS	1 DEC.	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
TIMBER	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SORGHUM		(same as Maize)											

SOIL DEPTHS (m): CONVENTIONS USED

	A	B	TOTAL
Deep	0.30	0.80	1.10
Medium	0.25	0.50	0.75
Shallow	0.15	0.15	0.30

RESPONSE FACTORS FOR MOVEMENT OF SOIL MOISTURE BETWEEN HORIZONS

FACTOR	CLAY	LOAM	SAND
Base flow response factor	0.3	0.6	0.5
A to B horizon response factor	0.4	0.7	0.5

APPENDIX D

Tabular output from 5 stations used in the dryland analyses

The tabular output for each zone may be obtained from the Department of Agricultural Engineering, University of Natal, through the Computing Centre for Water Research.

ZONE NO. 9

RAINFALL STATION 0006065 NIEWEBERG (BOS) LAT 34 04 LONG 19 03 ALTITUDE 564m 58 YEARS OF DATA

TEMPERATURE STATION ESTIMATE NIEWEBERG LAT 34 04 LONG 19 03 ALTITUDE 564m WIND REGION : 5

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 1605.9mm	MEAN	42.2	41.2	51.4	103.5	210.1	266.3	250.8	255.5	150.1	101.3	67.7	46.1	1605.0
	MEDN	31.1	33.4	53.1	86.5	183.7	217.4	227.8	231.4	130.8	92.5	47.8	34.3	1490.0
	SDEV	44.5	32.8	31.2	75.7	140.4	173.8	138.7	136.5	93.5	64.1	67.3	42.6	442.0
	C.V.	105.5	79.6	60.7	73.1	66.8	65.3	55.3	53.4	62.3	63.2	99.5	92.4	27.0
	SKEW	3.3	1.4	0.5	1.2	1.4	0.8	0.7	1.7	0.9	0.9	2.6	2.0	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	23.9	25.7	24.3	19.7	16.5	14.5	13.6	13.6	15.4	17.6	21.0	24.0	
	MIN	12.3	12.5	11.3	10.3	7.3	6.1	5.0	5.2	5.6	8.6	9.6	9.6	

CROP AND SOIL INFORMATION

EVAPOTRANSPIRATION DEFICIT (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
15 MY	WHEAT	DEEP	CLAY	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	27	22	40	21	40	13	28	0	7
15 MY	WHEAT	DEEP	LOAM	0	0	0	0	0	0	0	0	0	0	0	0	0	8	13	27	22	40	21	40	13	28	0	7
15 MY	WHEAT	DEEP	SAND	0	2	0	4	0	3	0	0	0	0	0	2	7	19	20	36	24	43	26	43	14	30	0	10
15 MY	WHEAT	MEDM	CLAY	0	0	0	1	0	1	0	0	0	0	0	0	2	11	16	31	23	41	23	41	13	29	0	7
15 MY	WHEAT	MEDM	LOAM	0	0	0	1	0	1	0	0	0	0	0	0	2	11	16	31	23	41	23	41	13	28	0	7
15 MY	WHEAT	MEDM	SAND	0	3	0	5	0	6	0	1	0	0	0	3	9	22	23	37	24	43	27	43	15	30	1	11
15 MY	WHEAT	SHALW	CLAY	0	3	0	7	0	16	0	5	0	0	0	2	8	21	22	36	25	43	27	43	15	30	0	11
15 MY	WHEAT	SHALW	LOAM	0	3	0	7	0	12	0	4	0	0	0	3	8	21	21	36	24	43	27	43	15	30	0	11
15 MY	WHEAT	SHALW	SAND	1	6	3	17	4	21	0	5	0	2	1	8	15	26	27	39	30	45	30	44	18	33	3	13
1 JA	SVELD	DEEP	CLAY	93	115	107	128	73	98	18	41	3	11	0	1	0	0	0	0	0	0	0	0	7	18	61	90
1 JA	SVELD	DEEP	LOAM	89	114	103	127	72	98	17	40	0	9	0	0	0	0	0	0	0	0	0	0	6	16	57	88
1 JA	SVELD	DEEP	SAND	101	124	109	132	72	101	15	42	0	9	0	0	0	0	0	0	0	0	0	2	26	45	82	108
1 JA	SVELD	MEDM	CLAY	100	123	113	133	76	101	19	42	3	11	0	1	0	0	0	0	0	0	0	0	18	35	80	102
1 JA	SVELD	MEDM	LOAM	97	121	108	131	73	100	17	41	0	10	0	0	0	0	0	0	0	0	0	0	16	32	76	101
1 JA	SVELD	MEDM	SAND	106	126	111	133	75	101	17	42	0	9	0	0	0	0	0	0	0	0	0	5	39	59	87	114
1 JA	SVELD	SHALW	CLAY	108	128	116	137	79	103	22	46	2	10	0	0	0	0	0	0	0	0	2	13	52	72	101	118
1 JA	SVELD	SHALW	LOAM	106	128	114	135	75	102	18	43	0	9	0	0	0	0	0	0	0	0	0	10	47	69	97	117
1 JA	SVELD	SHALW	SAND	106	128	114	137	74	104	19	46	1	10	0	1	0	0	0	0	0	2	5	22	57	78	100	120
1 JA	GVELD	DEEP	CLAY	141	169	162	185	113	142	36	67	9	20	0	4	0	0	0	0	0	0	0	2	29	56	108	132
1 JA	GVELD	DEEP	LOAM	139	165	160	184	110	141	34	64	4	18	0	1	0	0	0	0	0	0	0	2	26	55	100	129
1 JA	GVELD	DEEP	SAND	150	175	162	188	108	143	33	66	2	16	0	0	0	0	0	0	0	0	2	15	57	87	121	148
1 JA	GVELD	MEDM	CLAY	148	175	166	188	113	143	36	69	8	19	0	3	0	0	0	0	0	0	0	10	51	79	123	146
1 JA	GVELD	MEDM	LOAM	145	172	163	188	110	143	34	65	2	17	0	0	0	0	0	0	0	0	0	6	45	77	118	142
1 JA	GVELD	MEDM	SAND	154	176	164	189	110	143	32	66	2	16	0	0	0	0	0	0	0	0	5	25	72	99	127	151
1 JA	GVELD	SHALW	CLAY	156	177	166	189	115	145	40	72	8	22	0	3	0	0	0	0	0	5	19	44	90	108	137	155
1 JA	GVELD	SHALW	LOAM	154	176	165	189	112	144	33	71	4	18	0	0	0	0	0	0	0	4	9	36	84	106	134	154
1 JA	GVELD	SHALW	SAND	155	177	165	189	110	145	36	71	5	21	0	3	0	0	0	0	2	12	21	48	87	111	136	156
1 JA	TIMBR	DEEP	CLAY	180	201	191	213	137	165	60	92	23	43	3	15	0	5	0	1	0	3	7	40	89	125	164	184
1 JA	TIMBR	DEEP	LOAM	180	200	190	213	133	165	57	92	14	38	0	9	0	0	0	0	0	0	1	27	75	118	158	182
1 JA	TIMBR	DEEP	SAND	180	203	193	214	133	167	55	93	12	36	0	8	0	0	0	0	0	10	15	63	110	145	167	191
1 JA	TIMBR	MEDM	CLAY	180	202	192	213	139	166	60	95	22	44	2	15	0	5	0	2	0	10	26	61	112	142	170	190
1 JA	TIMBR	MEDM	LOAM	180	202	192	213	134	166	55	91	11	38	0	7	0	0	0	0	0	5	11	51	101	141	164	188
1 JA	TIMBR	MEDM	SAND	181	204	193	216	133	167	55	97	12	36	0	8	0	1	0	3	3	23	25	75	117	149	169	192
1 JA	TIMBR	SHALW	CLAY	183	204	196	216	139	168	62	98	26	50	4	23	2	16	0	12	21	42	54	87	133	153	176	192
1 JA	TIMBR	SHALW	LOAM	182	203	195	216	137	168	57	98	20	41	2	15	0	7	0	9	12	39	40	82	124	152	173	192
1 JA	TIMBR	SHALW	SAND	184	205	194	216	135	169	57	98	22	49	6	22	2	15	2	14	20	48	51	86	130	154	172	193

INDEX OF STRESS DAYS

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
15 MY	WHEAT	DEEP	CLAY	0	0	0	0	0	0	0	0	0	0	0	0	0	5	8	21	15	30	13	28	9	26	0	8
15 MY	WHEAT	DEEP	LOAM	0	0	0	0	0	0	0	0	0	0	0	0	0	6	8	21	15	30	12	28	9	26	0	8
15 MY	WHEAT	DEEP	SAND	0	1	0	0	0	0	0	0	0	0	0	1	6	16	16	26	17	29	17	27	11	26	0	15
15 MY	WHEAT	MEDM	CLAY	0	0	0	0	0	0	0	0	0	0	0	0	0	9	11	24	16	30	15	28	12	24	0	8
15 MY	WHEAT	MEDM	LOAM	0	0	0	0	0	0	0	0	0	0	0	0	0	9	11	24	16	30	14	28	10	24	0	8
15 MY	WHEAT	MEDM	SAND	0	3	0	0	0	1	0	0	0	0	0	4	8	18	17	27	17	30	17	27	13	26	0	16
15 MY	WHEAT	SHALW	CLAY	0	2	0	3	0	6	0	2	0	0	0	2	6	17	17	27	18	29	17	27	13	26	0	16
15 MY	WHEAT	SHALW	LOAM	0	2	0	3	0	5	0	1	0	0	0	2	6	17	17	27	17	30	17	27	13	26	0	16
15 MY	WHEAT	SHALW	SAND	1	7	0	8	2	11	0	4	0	3	1	10	12	21	20	27	20	30	18	25	15	26	4	17
1 JA	SVELD	DEEP	CLAY	25	31	25	28	23	31	10	28	0	8	0	0	0	0	0	0	0	0	0	0	0	3	18	29
1 JA	SVELD	DEEP	LOAM	24	31	24	28	22	31	8	27	0	7	0	0	0	0	0	0	0	0	0	0	0	2	16	28
1 JA	SVELD	DEEP	SAND	26	31	24	28	21	31	8	26	0	6	0	0	0	0	0	0	0	0	0	0	7	15	22	30
1 JA	SVELD	MEDM	CLAY	26	31	25	28	22	31	10	30	0	8	0	0	0	0	0	0	0	0	0	0	4	11	22	31
1 JA	SVELD	MEDM	LOAM	26	31	25	28	22	31	8	26	0	8	0	0	0	0	0	0	0	0	0	0	2	10	21	31
1 JA	SVELD	MEDM	SAND	26	31	24	28	21	31	8	24	0	8	0	0	0	0	0	0	0	0	0	1	2	20	23	30
1 JA	SVELD	SHALW	CLAY	27	31	25	28	23	31	10	27	0	11	0	0	0	0	0	0	0	0	0	7	17	24	26	31
1 JA	SVELD	SHALW	LOAM	27	31	25	28	22	31	8	26	0	8	0	0	0	0	0	0	0	0	0	3	14	22	24	31
1 JA	SVELD	SHALW	SAND	26	31	24	28	21	30	10	25	0	10	0	0	0	0	0	0	0	1	2	13	18	25	25	30
1 JA	GVELD	DEEP	CLAY	28	31	26	28	26	31	15	30	0	10	0	0	0	0	0	0	0	0	0	0	5	15	24	31
1 JA	GVELD	DEEP	LOAM	28	31	26	28	26	31	13	30	0	10	0	0	0	0	0	0	0	0	0	0	5	13	22	31
1 JA	GVELD	DEEP	SAND	28	31	25	28	24	31	12	28	0	10	0	0	0	0	0	0	0	0	0	5	14	23	25	31
1 JA	GVELD	MEDM	CLAY	28	31	26	28	26	31	14	30	0	12	0	0	0	0	0	0	0	0	0	0	13	21	26	31
1 JA	GVELD	MEDM	LOAM	28	31	26	28	25	31	13	30	0	10	0	0	0	0	0	0	0	0	0	0	10	21	25	31
1 JA	GVELD	MEDM	SAND	27	31	25	28	23	31	12	28	0	10	0	0	0	0	0	0	0	0	1	11	17	25	26	30
1 JA	GVELD	SHALW	CLAY	28	31	26	28	25	31	15	29	3	14	0	0	0	0	0	0	0	2	6	18	23	28	28	31
1 JA	GVELD	SHALW	LOAM	28	31	25	28	24	31	13	29	0	13	0	0	0	0	0	0	0	0	4	14	20	28	27	31
1 JA	GVELD	SHALW	SAND	27	31	25	28	23	30	14	26	2	14	0	3	0	0	0	0	1	7	8	20	21	27	26	30
1 JA	TIMBR	DEEP	CLAY	31	31	28	29	30	31	21	30	7	16	0	4	0	0	0	0	0	0	0	9	18	29	30	31
1 JA	TIMBR	DEEP	LOAM	31	31	27	29	30	31	21	30	2	16	0	0	0	0	0	0	0	0	0	4	14	27	29	31
1 JA	TIMBR	DEEP	SAND	29	31	26	28	27	31	19	30	3	15	0	2	0	0	0	0	0	2	3	20	21	28	28	31
1 JA	TIMBR	MEDM	CLAY	30	31	27	29	29	31	21	30	7	18	0	6	0	0	0	0	0	0	4	20	23	30	30	31
1 JA	TIMBR	MEDM	LOAM	30	31	27	29	29	31	21	30	3	16	0	1	0	0	0	0	0	0	0	15	21	29	30	31
1 JA	TIMBR	MEDM	SAND	29	31	26	28	27	31	19	30	4	15	0	3	0	0	0	0	0	8	7	23	22	28	28	31
1 JA	TIMBR	SHALW	CLAY	29	31	26	28	28	31	20	30	10	22	1	12	0	7	0	5	6	15	15	27	25	30	28	31
1 JA	TIMBR	SHALW	LOAM	29	31	26	28	28	31	19	30	7	18	0	8	0	4	0	5	3	14	11	26	24	30	28	31
1 JA	TIMBR	SHALW	SAND	28	31	25	28	25	31	17	30	10	20	3	12	1	9	1	10	8	16	14	26	24	29	27	31

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
15 MY	WHEAT	DEEP	CLAY	106	256	144	419	153	366	157	326	88	190	61	148	40	77	23	43	13	39	7	22	6	30	30	104
15 MY	WHEAT	DEEP	LOAM	72	170	142	342	147	283	151	297	129	203	101	170	67	106	44	73	26	44	14	26	11	26	22	70
15 MY	WHEAT	DEEP	SAND	63	150	130	305	145	260	152	286	136	216	111	173	74	118	49	81	30	51	18	32	15	33	28	69
15 MY	WHEAT	MEDM	CLAY	115	266	148	425	160	372	158	335	87	190	59	145	35	79	20	40	12	40	7	25	6	34	37	111
15 MY	WHEAT	MEDM	LOAM	80	181	145	363	149	300	153	300	127	199	94	165	65	100	42	69	25	44	13	27	12	28	26	75
15 MY	WHEAT	MEDM	SAND	72	163	138	330	145	273	151	295	131	203	107	173	71	112	48	79	30	50	18	34	15	35	30	71
15 MY	WHEAT	SHALW	CLAY	122	289	163	443	167	381	166	355	91	198	53	139	28	85	16	45	10	40	7	31	9	47	43	135
15 MY	WHEAT	SHALW	LOAM	103	217	145	389	140	341	152	314	105	192	78	157	55	89	34	61	21	47	14	30	12	36	35	98
15 MY	WHEAT	SHALW	SAND	93	201	153	377	147	325	154	305	119	199	88	164	65	102	43	71	27	51	19	37	17	39	34	93
1 JA	SVELD	DEEP	CLAY	7	23	4	16	2	21	21	83	98	234	150	403	162	369	164	328	93	191	55	143	28	59	14	28
1 JA	SVELD	DEEP	LOAM	17	28	9	15	6	10	6	42	43	130	114	323	142	293	166	311	136	209	99	171	57	92	32	52
1 JA	SVELD	DEEP	SAND	21	32	10	17	6	11	6	43	44	132	118	296	155	276	169	308	143	223	109	177	66	106	36	59
1 JA	SVELD	MEDM	CLAY	6	25	3	19	3	25	25	94	104	251	157	423	176	386	171	346	96	195	54	141	25	62	12	30
1 JA	SVELD	MEDM	LOAM	16	28	8	15	6	12	7	52	61	151	127	351	157	319	170	317	134	206	93	168	55	86	30	49
1 JA	SVELD	MEDM	SAND	19	30	10	17	6	15	9	55	57	149	129	324	155	294	169	315	140	212	105	177	63	99	35	57
1 JA	SVELD	SHALW	CLAY	5	31	3	27	4	37	34	122	116	283	172	458	187	410	181	367	98	201	50	134	18	71	9	35
1 JA	SVELD	SHALW	LOAM	13	33	7	21	5	23	19	77	90	209	139	387	161	366	173	333	113	198	77	159	46	78	25	42
1 JA	SVELD	SHALW	SAND	17	37	11	22	8	27	20	81	86	194	141	375	162	349	173	328	125	205	88	165	57	90	32	53
1 JA	GVELD	DEEP	CLAY	5	18	2	13	2	17	16	76	92	227	145	396	152	361	155	319	81	179	43	129	21	47	9	23
1 JA	GVELD	DEEP	LOAM	14	24	7	12	5	8	5	37	38	119	103	309	133	278	157	302	125	199	87	157	49	83	26	45
1 JA	GVELD	DEEP	SAND	17	29	8	14	5	10	4	37	38	117	105	284	147	267	162	300	134	214	95	162	56	96	31	53
1 JA	GVELD	MEDM	CLAY	5	21	2	17	2	22	20	87	97	243	153	415	168	378	163	334	85	184	42	126	20	51	9	25
1 JA	GVELD	MEDM	LOAM	13	22	6	14	5	9	7	44	52	144	117	339	151	308	163	308	125	197	83	153	45	76	25	42
1 JA	GVELD	MEDM	SAND	16	27	8	14	5	14	7	50	51	137	118	314	149	285	162	307	131	203	93	163	54	90	30	50
1 JA	GVELD	SHALW	CLAY	3	29	3	25	4	36	31	113	111	275	168	449	179	404	174	361	87	191	40	119	14	61	6	30
1 JA	GVELD	SHALW	LOAM	11	29	6	20	4	21	16	70	84	203	131	377	153	357	166	326	103	189	65	144	39	67	21	38
1 JA	GVELD	SHALW	SAND	15	32	9	21	6	24	16	76	81	188	133	365	154	342	167	320	119	196	79	152	50	80	27	46
1 JA	TIMBR	DEEP	CLAY	2	15	1	11	1	15	12	67	75	204	127	368	125	338	120	289	49	139	26	96	9	29	3	16
1 JA	TIMBR	DEEP	LOAM	9	16	4	9	3	6	4	33	32	102	82	275	102	241	119	264	90	169	54	119	30	57	15	32
1 JA	TIMBR	DEEP	SAND	11	20	6	11	3	7	3	29	26	96	86	252	119	232	130	261	105	177	66	132	37	65	19	37
1 JA	TIMBR	MEDM	CLAY	2	18	1	14	1	20	16	75	83	218	135	385	135	353	129	304	53	147	26	99	9	35	3	19
1 JA	TIMBR	MEDM	LOAM	9	15	4	9	3	7	5	41	40	125	94	303	118	264	125	271	90	162	52	118	29	54	15	32
1 JA	TIMBR	MEDM	SAND	11	21	5	10	3	11	5	41	38	116	94	283	125	249	129	270	101	176	62	127	35	66	20	36
1 JA	TIMBR	SHALW	CLAY	1	25	2	21	3	33	25	99	98	249	154	413	154	377	145	331	62	158	27	98	8	49	3	25
1 JA	TIMBR	SHALW	LOAM	7	23	4	16	3	18	13	63	70	179	117	344	123	326	134	288	81	160	46	115	26	49	14	31
1 JA	TIMBR	SHALW	SAND	11	24	6	17	5	20	11	68	65	166	117	334	126	310	140	282	95	167	60	124	36	63	20	39

```
ZONE NO. 51

RAINFALL STATION 0023678  ROBERTSON (TNK)      LAT 33 48 LONG 19 53 ALTITUDE  183m 108 YEARS OF DATA

TEMPERATURE STATION ATS0004  ROBERTSON (NIVV)   LAT 33 50 LONG 19 54 ALTITUDE  170m  WIND REGION :  5

                               JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEP    OCT    NOV    DEC ANNUAL

RAINFALL (mm)          MEAN   14.7   18.2   21.5   29.9   34.3   37.6   32.6   37.6   30.7   26.3   22.8   15.1  322.0
 M.A.P.  322.1mm       MEDN    7.9    8.1   18.0   22.5   27.3   33.1   28.6   30.5   24.9   21.6   16.1    5.3  313.0
                       SDEV   22.8   24.6   17.6   26.0   25.7   24.2   20.4   27.0   22.0   22.5   22.6   25.2   86.0
                       C.V.  154.9  135.4   81.7   87.0   74.9   64.5   62.7   72.0   71.6   85.3   99.3  166.7   26.0
                       SKEW    3.9    2.5    1.1    1.9    1.3    0.8    0.8    1.4    1.0    2.1    1.4    3.8    1.0

      MONTHLY
MEAN TEMPERATURES      MAX    30.5   30.3   28.5   25.3   21.7   19.2   18.8   19.1   21.6   24.5   26.9   29.4
(DEGREES CELSIUS)      MIN    15.5   15.8   14.4   11.3    8.0    5.8    5.0    6.0    7.9   10.3   12.6   14.4
-------------------------------------------------------------------------------------------------------------------------

CROP AND SOIL INFORMATION                                    EVAPOTRANSPIRATION DEFICIT (mm)

PLANT CROP  SOIL  SOIL   MONTH 1 MONTH 2 MONTH 3 MONTH 4 MONTH 5 MONTH 6 MONTH 7 MONTH 8 MONTH 9 MONTH10 MONTH11 MONTH12
DATE  TYPE  DEPTH TEXT   50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90%

15 MY WHEAT DEEP  CLAY    15  25  29  53  55  74  30  40   8  20  17  31  37  51  54  63  62  69  58  63  38  47  18  29
15 MY WHEAT DEEP  LOAM    14  24  24  47  48  71  27  38   7  20  17  31  37  50  54  63  61  69  58  63  38  48  18  29
15 MY WHEAT DEEP  SAND    14  25  20  46  46  68  25  39  10  23  21  37  41  53  59  64  62  69  59  64  37  47  19  29
15 MY WHEAT MEDM  CLAY    15  25  28  52  55  74  29  41   8  21  19  33  38  52  55  64  62  69  58  64  38  47  18  29
15 MY WHEAT MEDM  LOAM    14  24  21  47  48  70  27  38   8  20  18  32  38  51  55  63  62  69  58  64  38  47  18  29
15 MY WHEAT MEDM  SAND    15  26  22  45  52  71  26  42  11  23  23  38  42  53  60  64  62  69  58  64  38  47  20  29
15 MY WHEAT SHALW CLAY    16  26  32  51  62  77  31  43  12  23  23  38  42  53  59  64  62  69  59  64  38  47  20  29
15 MY WHEAT SHALW LOAM    15  25  26  48  57  76  28  43  11  23  22  37  42  53  59  64  62  69  59  64  38  47  19  29
15 MY WHEAT SHALW SAND    16  27  33  52  61  78  29  43  15  24  26  39  44  54  61  64  62  69  59  64  38  48  21  30
 1 JA SVELD DEEP  CLAY   179 187 173 181 121 134  63  74  29  38  11  21   9  20   8  16  19  34  51  67 117 133 165 170
 1 JA SVELD DEEP  LOAM   179 186 173 181 121 133  62  74  29  37  10  21   8  19   7  15  16  32  45  66 113 131 162 170
 1 JA SVELD DEEP  SAND   179 187 173 180 120 134  60  74  26  37   8  21   6  19   5  15  17  34  52  69 117 135 166 171
 1 JA SVELD MEDM  CLAY   179 187 173 180 121 134  63  74  29  38  10  21   9  19   8  16  21  35  54  69 121 134 166 171
 1 JA SVELD MEDM  LOAM   179 187 173 180 120 134  61  74  29  38  10  21   7  19   6  15  17  33  49  67 116 133 166 171
 1 JA SVELD MEDM  SAND   179 187 174 180 120 134  60  74  26  37   7  22   5  19   4  15  19  36  56  72 121 136 167 172
 1 JA SVELD SHALW CLAY   179 188 174 181 122 134  63  74  29  39  11  22  10  20   9  19  26  40  62  78 125 137 167 172
 1 JA SVELD SHALW LOAM   179 188 174 180 121 134  61  74  27  38   9  21   8  19   5  17  21  37  59  76 124 137 167 172
 1 JA SVELD SHALW SAND   179 188 174 181 121 134  61  73  25  39   8  21   9  21   8  19  28  43  62  79 125 138 167 172
 1 JA GVELD DEEP  CLAY   246 255 239 247 170 184  96 108  48  58  18  31  16  29  15  26  40  57  96 113 165 179 214 220
 1 JA GVELD DEEP  LOAM   246 254 239 247 169 184  96 108  47  57  18  31  15  29  13  26  38  57  93 110 163 178 213 219
 1 JA GVELD DEEP  SAND   246 255 239 248 169 184  94 108  45  57  16  31  13  29  12  27  39  61  97 115 166 179 214 220
 1 JA GVELD MEDM  CLAY   246 255 239 248 170 184  97 108  47  58  18  31  17  29  15  27  42  60  98 116 166 180 215 220
 1 JA GVELD MEDM  LOAM   246 255 239 248 169 184  95 108  46  57  17  31  15  29  13  26  39  58  95 113 165 179 214 220
 1 JA GVELD MEDM  SAND   246 255 240 248 170 184  94 107  45  57  15  30  13  29  12  28  41  63 100 118 167 180 215 220
 1 JA GVELD SHALW CLAY   246 255 240 248 170 184  96 108  47  58  19  31  17  30  19  31  50  64 103 119 168 181 215 220
 1 JA GVELD SHALW LOAM   246 255 240 248 170 184  95 108  46  58  16  31  14  29  15  29  45  63 101 119 167 180 215 220
 1 JA GVELD SHALW SAND   244 255 238 247 170 184  94 107  45  60  16  31  17  31  18  32  51  67 103 120 168 181 215 220
 1 JA TIMBR DEEP  CLAY   282 290 273 283 197 210 131 142  87  99  53  68  54  67  60  73 103 119 156 171 224 236 262 267
 1 JA TIMBR DEEP  LOAM   282 290 273 283 197 210 130 142  87  99  53  68  53  67  59  72 102 118 155 171 224 236 262 267
 1 JA TIMBR DEEP  SAND   282 290 274 283 197 210 129 143  87 100  50  67  53  68  59  75 104 122 157 172 225 237 263 267
 1 JA TIMBR MEDM  CLAY   282 290 273 283 197 210 131 142  87  99  53  67  53  67  60  74 103 120 156 172 225 237 262 267
 1 JA TIMBR MEDM  LOAM   282 290 273 283 197 210 131 142  87  99  52  67  53  67  58  73 103 120 156 171 224 237 262 267
 1 JA TIMBR MEDM  SAND   282 290 274 283 198 210 131 143  86 101  50  68  53  68  60  76 105 122 157 173 225 237 263 267
 1 JA TIMBR SHALW CLAY   282 290 274 283 198 210 132 143  87 101  53  68  56  69  64  77 108 122 159 173 225 237 263 267
 1 JA TIMBR SHALW LOAM   282 290 274 283 198 210 131 143  87 101  51  68  54  69  62  76 106 122 157 172 225 237 263 267
 1 JA TIMBR SHALW SAND   282 290 274 283 198 210 130 142  87 102  51  68  54  71  62  78 107 124 158 173 226 238 263 267

                                                        INDEX OF STRESS DAYS

PLANT CROP  SOIL  SOIL   MONTH 1 MONTH 2 MONTH 3 MONTH 4 MONTH 5 MONTH 6 MONTH 7 MONTH 8 MONTH 9 MONTH10 MONTH11 MONTH12
DATE  TYPE  DEPTH TEXT   50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90% 50% 90%

15 MY WHEAT DEEP  CLAY    13  29  13  30  25  31  23  31   5  24  14  31  23  30  31  31  31  31  28  29  27  31  19  30
15 MY WHEAT DEEP  LOAM    12  29  10  29  22  31  21  31   4  24  13  31  22  30  31  31  31  31  28  29  28  31  19  30
15 MY WHEAT DEEP  SAND    14  28   4  24  20  31  19  31  11  25  18  31  23  30  30  31  30  31  28  29  25  31  19  29
15 MY WHEAT MEDM  CLAY    14  28  14  29  25  31  23  31   7  25  16  30  23  30  30  31  31  31  28  29  27  31  18  30
15 MY WHEAT MEDM  LOAM    13  28   9  26  21  31  21  31   5  25  16  30  23  30  30  31  31  31  28  29  27  31  19  30
15 MY WHEAT MEDM  SAND    14  27   8  23  22  31  19  30  12  25  19  31  24  30  30  31  30  31  27  29  25  31  19  29
15 MY WHEAT SHALW CLAY    14  28  14  26  26  31  23  31  12  26  19  31  24  30  31  31  30  31  28  29  25  31  19  29
15 MY WHEAT SHALW LOAM    13  28  11  24  24  31  22  31  11  25  18  31  24  30  31  31  30  31  28  29  25  31  19  29
15 MY WHEAT SHALW SAND    16  28  15  24  24  30  19  29  16  25  21  31  24  30  30  31  29  31  27  28  25  31  20  28
 1 JA SVELD DEEP  CLAY    31  31  28  29  31  31  29  30  28  31   8  30   5  29   0  17  10  28  22  31  30  30  31  31
 1 JA SVELD DEEP  LOAM    31  31  28  29  31  31  29  30  28  31   8  30   1  29   0  16   6  26  19  31  29  30  31  31
 1 JA SVELD DEEP  SAND    31  31  28  29  29  31  26  30  23  31   5  27   1  26   0  14   8  26  22  31  28  30  31  31
 1 JA SVELD MEDM  CLAY    31  31  28  29  31  31  28  30  27  31   8  30   6  29   0  17  12  28  24  31  29  30  31  31
 1 JA SVELD MEDM  LOAM    31  31  28  29  31  31  28  30  26  31   8  30   2  28   0  16   7  26  20  31  29  30  31  31
 1 JA SVELD MEDM  SAND    31  31  28  29  29  31  25  30  22  31   5  25   1  25   0  15  10  26  23  31  28  30  31  31
 1 JA SVELD SHALW CLAY    31  31  28  29  30  31  27  30  24  31   9  28   8  27   5  22  17  29  26  31  29  30  31  31
 1 JA SVELD SHALW LOAM    31  31  28  29  29  31  26  30  23  31   6  27   5  26   1  19  14  28  24  31  28  30  31  31
 1 JA SVELD SHALW SAND    30  31  28  29  28  31  25  29  21  31   8  25  10  25   6  19  17  28  24  31  27  30  31  31
 1 JA GVELD DEEP  CLAY    31  31  28  29  31  31  29  30  31  31  17  30  13  31   9  28  20  30  29  31  30  30  31  31
 1 JA GVELD DEEP  LOAM    31  31  28  29  31  31  30  30  31  31  16  30  12  31   6  26  17  30  28  31  30  30  31  31
 1 JA GVELD DEEP  SAND    31  31  28  29  30  31  27  30  27  31  11  29  10  29   6  24  18  30  28  31  29  30  31  31
 1 JA GVELD MEDM  CLAY    31  31  28  29  31  31  29  30  29  31  17  30  13  31   9  28  20  30  29  31  30  30  31  31
 1 JA GVELD MEDM  LOAM    31  31  28  29  31  31  29  30  29  31  15  30  11  31   6  26  19  30  28  31  30  30  31  31
 1 JA GVELD MEDM  SAND    31  31  28  29  30  31  27  30  26  31  11  29  10  29   6  24  18  30  27  31  28  30  31  31
 1 JA GVELD SHALW CLAY    31  31  28  29  30  31  27  30  27  31  16  30  15  29  14  27  22  30  29  31  29  30  31  31
 1 JA GVELD SHALW LOAM    31  31  28  29  30  31  27  30  27  31  13  30  12  30   9  27  20  30  28  31  29  30  31  31
 1 JA GVELD SHALW SAND    30  31  28  29  29  31  26  30  24  31  13  27  15  27  13  25  21  29  27  31  28  30  31  31
 1 JA TIMBR DEEP  CLAY    31  31  28  29  31  31  30  30  31  31  28  30  29  31  29  31  30  30  31  31  30  30  31  31
 1 JA TIMBR DEEP  LOAM    31  31  28  29  31  31  30  30  31  31  28  30  30  31  28  31  30  30  31  31  30  30  31  31
 1 JA TIMBR DEEP  SAND    31  31  28  29  31  31  29  30  29  31  24  30  26  31  25  31  27  30  31  31  30  30  31  31
 1 JA TIMBR MEDM  CLAY    31  31  28  29  31  31  30  30  31  31  27  30  29  31  28  31  29  30  31  31  30  30  31  31
 1 JA TIMBR MEDM  LOAM    31  31  28  29  31  31  30  30  31  31  27  30  29  31  28  31  29  30  31  31  30  30  31  31
 1 JA TIMBR MEDM  SAND    31  31  28  29  31  31  29  30  29  31  23  30  26  31  25  31  27  30  31  31  30  30  31  31
 1 JA TIMBR SHALW CLAY    31  31  28  29  31  31  30  30  30  31  25  30  27  31  27  31  28  30  31  31  30  30  31  31
 1 JA TIMBR SHALW LOAM    31  31  28  29  31  31  29  30  29  31  24  30  26  31  26  31  27  30  31  31  30  30  31  31
 1 JA TIMBR SHALW SAND    31  31  28  29  30  31  28  30  28  31  22  30  25  31  24  31  26  30  29  31  29  30  31  31
```

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
15 MY	WHEAT	DEEP	CLAY	0	7	0	5	0	4	0	8	0	9	0	3	0	3	0	1	0	1	0	4	0	1	0	4
15 MY	WHEAT	DEEP	LOAM	0	1	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 MY	WHEAT	DEEP	SAND	0	10	0	8	0	4	0	4	0	3	0	1	0	2	0	1	0	3	0	3	0	3	0	8
15 MY	WHEAT	MEDM	CLAY	0	10	0	8	0	6	0	10	0	11	0	5	0	4	0	3	0	2	0	6	0	3	0	6
15 MY	WHEAT	MEDM	LOAM	0	3	0	1	0	1	0	3	0	3	0	1	0	0	0	0	0	0	0	1	0	1	0	1
15 MY	WHEAT	MEDM	SAND	1	14	1	12	1	8	1	5	0	4	0	5	0	6	0	8	0	7	0	5	0	7	0	10
15 MY	WHEAT	SHALW	CLAY	0	17	3	15	1	13	2	20	1	16	0	13	0	11	0	7	0	6	0	14	0	7	0	15
15 MY	WHEAT	SHALW	LOAM	1	13	2	12	1	8	1	8	1	10	0	6	0	8	0	8	0	7	0	7	0	10	0	9
15 MY	WHEAT	SHALW	SAND	4	18	5	16	3	12	3	11	2	14	3	12	3	14	3	15	2	14	1	11	1	16	3	15
1 JA	SVELD	DEEP	CLAY	0	2	0	6	0	3	0	6	0	9	0	10	0	11	0	14	0	11	0	5	0	5	0	3
1 JA	SVELD	DEEP	LOAM	0	0	0	0	0	0	0	1	0	2	0	0	0	1	0	2	0	3	0	1	0	1	0	0
1 JA	SVELD	DEEP	SAND	0	1	0	1	0	1	0	0	0	1	0	0	0	3	0	8	0	7	0	4	0	3	0	1
1 JA	SVELD	MEDM	CLAY	0	3	0	8	0	4	0	8	0	12	1	13	1	13	1	17	0	13	0	7	0	6	0	4
1 JA	SVELD	MEDM	LOAM	0	1	0	1	0	0	0	2	0	3	0	1	0	3	0	5	0	6	0	4	0	2	0	1
1 JA	SVELD	MEDM	SAND	0	1	0	2	0	1	0	1	0	3	0	4	0	9	0	14	0	11	0	7	0	4	0	2
1 JA	SVELD	SHALW	CLAY	0	7	0	15	0	9	0	14	1	19	4	21	2	21	3	24	2	17	0	14	0	13	0	9
1 JA	SVELD	SHALW	LOAM	0	4	0	7	0	4	0	7	0	8	0	10	1	13	2	16	1	14	1	9	0	8	0	4
1 JA	SVELD	SHALW	SAND	0	5	0	7	0	5	0	7	0	10	2	13	3	15	4	19	4	17	2	12	1	10	1	7
1 JA	GVELD	DEEP	CLAY	0	2	0	5	0	3	0	5	0	8	0	9	0	9	0	12	0	9	0	4	0	4	0	3
1 JA	GVELD	DEEP	LOAM	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0	0	0	0	0	0
1 JA	GVELD	DEEP	SAND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	3	0	2	0	2	0	0
1 JA	GVELD	MEDM	CLAY	0	3	0	7	0	4	0	7	0	10	0	12	0	11	0	15	0	11	0	6	0	6	0	4
1 JA	GVELD	MEDM	LOAM	0	0	0	1	0	0	0	1	0	3	0	1	0	2	0	3	0	4	0	2	0	1	0	1
1 JA	GVELD	MEDM	SAND	0	1	0	1	0	1	0	1	0	2	0	2	0	4	0	8	0	5	0	4	0	4	0	1
1 JA	GVELD	SHALW	CLAY	0	7	0	14	0	8	0	13	1	17	3	19	2	19	2	22	1	16	0	12	0	12	0	9
1 JA	GVELD	SHALW	LOAM	0	3	0	6	0	3	0	6	0	7	0	8	0	9	1	11	0	10	0	7	0	6	0	4
1 JA	GVELD	SHALW	SAND	0	4	0	6	0	4	0	6	0	9	1	11	2	13	3	17	2	14	1	9	1	7	0	6
1 JA	TIMBR	DEEP	CLAY	0	1	0	4	0	2	0	4	0	5	0	3	0	4	0	4	0	4	0	2	0	4	0	2
1 JA	TIMBR	DEEP	LOAM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 JA	TIMBR	DEEP	SAND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 JA	TIMBR	MEDM	CLAY	0	2	0	6	0	3	0	6	0	7	0	5	0	5	0	7	0	6	0	3	0	5	0	3
1 JA	TIMBR	MEDM	LOAM	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
1 JA	TIMBR	MEDM	SAND	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0
1 JA	TIMBR	SHALW	CLAY	0	6	0	13	0	7	0	11	0	13	1	10	0	12	0	14	0	12	0	9	0	10	0	7
1 JA	TIMBR	SHALW	LOAM	0	2	0	5	0	2	0	4	0	5	0	3	0	3	0	5	0	6	0	2	0	4	0	3
1 JA	TIMBR	SHALW	SAND	0	3	0	4	0	3	0	4	0	7	0	5	0	6	0	6	0	7	0	5	0	4	0	4

ZONE NO.442

RAINFALL STATION 0432387 VRYBURG (POL) LAT 26 58 LONG 24 44 ALTITUDE 1190m 99 YEARS OF DATA

TEMPERATURE STATION 0432387 VRYBURG (POL) LAT 26 57 LONG 24 43 ALTITUDE 1190m WIND REGION : 4

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm)	MEAN	92.0	76.6	75.8	39.9	15.0	7.2	4.8	6.7	8.5	26.5	41.3	67.1	463.0
M.A.P. 463.4mm	MEDN	77.9	71.3	62.8	31.0	6.5	0.5	0.0	0.0	0.9	16.8	33.0	66.8	460.0
	SDEV	65.7	43.9	53.9	38.1	21.9	13.5	13.4	13.2	14.1	25.5	31.8	45.2	136.0
	C.V.	71.4	57.3	71.2	95.5	146.4	188.0	278.3	196.1	166.5	96.3	77.0	67.3	29.0
	SKEW	1.2	0.4	1.0	1.2	2.3	2.4	4.5	2.6	2.0	1.3	1.1	0.5	0.0
MONTHLY MEAN TEMPERATURES	MAX	32.6	30.7	28.4	25.7	22.4	19.6	19.2	22.6	25.9	29.7	30.5	31.8	
(DEGREES CELSIUS)	MIN	17.2	16.2	14.2	9.7	4.2	0.1	-0.6	2.3	6.7	12.2	14.4	16.4	

CROP AND SOIL INFORMATION

EVAPOTRANSPIRATION DEFICIT (mm)

PLANT DATE	CROP TYPE		SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
					50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1	NV	MAIZE	DEEP	CLAY	119	151	232	284	275	312	196	243	70	103	10	30	14	26	16	21	21	24	30	32	43	46	48	58
1	NV	MAIZE	DEEP	LOAM	118	147	222	278	266	308	191	241	68	101	8	29	14	26	15	20	21	24	30	32	43	46	48	58
1	NV	MAIZE	DEEP	SAND	119	144	209	268	267	314	192	242	68	101	13	31	19	29	19	22	23	24	31	32	44	46	46	59
1	NV	MAIZE	MEDM	CLAY	121	149	235	285	277	317	198	243	71	102	12	30	16	27	17	21	22	24	30	32	43	46	47	58
1	NV	MAIZE	MEDM	LOAM	118	147	220	276	270	313	191	242	68	102	10	30	16	27	16	21	22	24	30	32	43	46	48	58
1	NV	MAIZE	MEDM	SAND	118	144	222	276	268	316	192	242	69	102	15	32	20	29	20	22	24	24	31	32	44	46	46	60
1	NV	MAIZE	SHALW	CLAY	124	148	247	289	283	319	206	244	73	104	14	32	20	29	19	22	24	24	31	32	44	46	47	60
1	NV	MAIZE	SHALW	LOAM	119	145	236	284	276	318	198	243	70	102	14	32	20	29	19	22	23	24	31	32	44	46	46	59
1	NV	MAIZE	SHALW	SAND	121	146	237	288	268	312	192	242	73	102	17	33	22	29	20	22	24	24	32	32	45	46	47	60
1	DC	MAIZE	DEEP	CLAY	92	138	206	242	215	261	159	202	58	82	23	32	17	21	22	24	30	31	42	46	44	53	38	64
1	DC	MAIZE	DEEP	LOAM	89	135	192	235	204	259	152	198	56	81	23	32	17	21	21	24	29	31	42	46	44	53	38	63
1	DC	MAIZE	DEEP	SAND	94	133	184	226	207	261	155	201	58	82	24	32	19	22	23	24	31	32	43	46	42	54	42	64
1	DC	MAIZE	MEDM	CLAY	94	140	208	243	219	262	161	204	59	82	24	32	18	21	22	24	30	31	43	46	44	53	39	64
1	DC	MAIZE	MEDM	LOAM	91	134	188	235	207	260	155	201	56	82	24	32	17	21	22	24	30	31	42	46	44	53	39	64
1	DC	MAIZE	MEDM	SAND	97	134	193	233	211	264	157	203	59	82	24	32	20	22	23	24	31	32	44	46	43	55	44	65
1	DC	MAIZE	SHALW	CLAY	102	137	216	252	227	267	167	204	62	82	25	32	19	22	23	24	31	32	44	46	43	55	44	64
1	DC	MAIZE	SHALW	LOAM	99	134	203	245	219	265	160	204	60	82	24	32	19	22	23	24	31	32	43	46	43	54	43	64
1	DC	MAIZE	SHALW	SAND	105	137	206	248	213	262	158	203	61	83	26	32	20	22	24	24	31	32	44	46	43	55	48	65
15	DC	SUNFL	DEEP	CLAY	30	66	131	174	157	203	118	158	79	105	46	55	21	24	22	23	32	33	41	44	48	58	37	58
15	DC	SUNFL	DEEP	LOAM	28	64	112	164	147	199	111	157	75	105	44	54	21	24	21	23	31	33	41	44	48	58	37	58
15	DC	SUNFL	DEEP	SAND	33	64	113	158	150	201	111	158	76	106	45	55	23	24	22	23	33	33	42	44	47	59	39	59
15	DC	SUNFL	MEDM	CLAY	31	65	131	176	161	205	120	161	80	105	46	55	22	24	22	23	32	33	41	44	48	58	38	59
15	DC	SUNFL	MEDM	LOAM	29	63	113	164	150	202	113	158	77	105	45	55	22	24	22	23	32	33	41	44	48	58	36	59
15	DC	SUNFL	MEDM	SAND	36	64	120	166	154	203	115	160	78	106	45	55	23	24	23	23	33	33	42	44	47	60	41	60
15	DC	SUNFL	SHALW	CLAY	37	66	145	180	171	208	127	163	85	107	48	55	23	24	22	23	33	33	42	44	47	59	41	60
15	DC	SUNFL	SHALW	LOAM	35	65	133	177	161	206	119	162	80	107	47	55	23	24	22	23	33	33	42	44	47	59	40	60
15	DC	SUNFL	SHALW	SAND	43	67	140	179	161	205	121	162	83	107	47	55	23	24	23	23	33	33	43	44	48	60	44	60
1	JA	SVELD	DEEP	CLAY	116	149	91	132	67	103	48	74	38	48	31	37	37	40	50	53	74	78	96	107	123	150	117	160
1	JA	SVELD	DEEP	LOAM	110	149	83	132	61	101	40	70	33	48	29	36	35	39	49	53	73	77	95	107	119	149	112	160
1	JA	SVELD	DEEP	SAND	109	149	82	130	62	101	42	71	34	48	31	37	38	40	52	54	75	78	94	107	120	150	112	159
1	JA	SVELD	MEDM	CLAY	118	149	93	132	68	105	50	75	39	49	33	37	38	40	52	54	74	78	96	107	124	151	119	161
1	JA	SVELD	MEDM	LOAM	111	149	83	131	63	101	42	72	35	48	31	37	36	40	50	53	74	78	96	107	120	151	112	160
1	JA	SVELD	MEDM	SAND	108	149	85	131	64	103	46	72	37	49	33	37	39	40	53	54	76	78	94	108	121	149	112	159
1	JA	SVELD	SHALW	CLAY	123	151	100	136	76	109	56	76	41	49	35	38	39	40	53	54	76	78	96	109	126	151	127	162

INDEX OF STRESS DAYS

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 NV	MAIZE	DEEP	CLAY	25	30	27	31	28	31	24	28	19	31	8	30	18	31	30	30	31	31	31	31	30	30	27	31
1 NV	MAIZE	DEEP	LOAM	25	30	26	31	27	31	23	28	18	31	6	30	18	31	30	30	31	31	31	31	30	30	27	31
1 NV	MAIZE	DEEP	SAND	24	29	24	29	26	30	22	27	18	30	13	30	24	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	MEDM	CLAY	25	30	27	31	27	31	24	28	19	31	11	30	20	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	MEDM	LOAM	24	30	25	31	27	31	23	28	18	30	10	30	20	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	MEDM	SAND	24	29	24	29	26	30	22	27	19	29	14	30	24	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	SHALW	CLAY	25	30	27	30	27	30	23	27	19	30	15	30	25	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	SHALW	LOAM	25	30	25	30	26	30	23	27	19	30	14	30	24	31	30	30	31	31	31	31	30	30	26	31
1 NV	MAIZE	SHALW	SAND	25	29	24	30	26	29	22	26	19	29	16	30	26	31	30	30	31	31	31	31	30	30	25	31
1 DC	MAIZE	DEEP	CLAY	21	30	26	31	24	28	26	31	23	30	27	31	30	30	31	31	31	31	30	30	27	31	20	30
1 DC	MAIZE	DEEP	LOAM	21	30	25	31	23	28	25	31	22	30	27	31	30	30	31	31	31	31	30	30	27	31	20	30
1 DC	MAIZE	DEEP	SAND	21	29	22	28	22	27	24	31	22	30	27	31	30	30	31	31	31	31	30	30	26	31	20	29
1 DC	MAIZE	MEDM	CLAY	21	30	26	30	24	28	26	31	23	30	27	31	30	30	31	31	31	31	30	30	26	31	20	30
1 DC	MAIZE	MEDM	LOAM	21	30	24	30	23	28	25	31	23	30	27	31	30	30	31	31	31	31	30	30	26	31	19	30
1 DC	MAIZE	MEDM	SAND	21	29	23	28	22	27	24	31	23	30	27	31	30	30	31	31	31	31	30	30	26	31	21	28
1 DC	MAIZE	SHALW	CLAY	23	29	26	30	24	27	25	31	23	30	27	31	30	30	31	31	31	31	30	30	26	31	21	29
1 DC	MAIZE	SHALW	LOAM	22	29	25	30	23	27	24	31	23	30	27	31	30	30	31	31	31	31	30	30	26	31	21	29
1 DC	MAIZE	SHALW	SAND	22	29	24	28	22	26	23	30	24	30	27	31	30	30	31	31	31	31	30	30	25	31	21	29
15 DC	SUNFL	DEEP	CLAY	13	30	23	31	23	28	24	31	24	30	31	31	30	30	31	31	31	31	30	30	27	31	20	30
15 DC	SUNFL	DEEP	LOAM	13	29	20	31	21	28	23	31	24	30	30	31	30	30	31	31	31	31	30	30	27	31	20	30
15 DC	SUNFL	DEEP	SAND	14	27	17	25	20	27	22	30	23	30	29	31	30	30	31	31	31	31	30	30	26	31	20	29
15 DC	SUNFL	MEDM	CLAY	14	29	24	31	23	27	24	31	24	30	30	31	30	30	31	31	31	31	30	30	27	31	20	30
15 DC	SUNFL	MEDM	LOAM	13	29	19	30	22	27	23	31	23	30	30	31	30	30	31	31	31	31	30	30	27	31	19	30
15 DC	SUNFL	MEDM	SAND	15	27	19	26	21	26	22	30	24	30	29	31	30	30	31	31	31	31	30	30	26	31	21	29
15 DC	SUNFL	SHALW	CLAY	15	28	24	29	23	27	24	31	25	30	30	31	30	30	31	31	31	31	30	30	26	31	21	29
15 DC	SUNFL	SHALW	LOAM	15	27	22	29	22	27	23	31	24	30	29	31	30	30	31	31	31	31	30	30	26	31	21	29
15 DC	SUNFL	SHALW	SAND	17	27	22	28	21	26	22	30	24	30	28	31	30	30	31	31	31	31	30	30	26	31	22	29
1 JA	SVELD	DEEP	CLAY	23	31	19	27	18	30	22	30	31	31	30	30	31	31	31	31	30	30	31	31	27	30	24	31
1 JA	SVELD	DEEP	LOAM	23	31	17	27	17	30	18	30	28	31	30	30	31	31	31	31	30	30	31	31	27	30	23	31
1 JA	SVELD	DEEP	SAND	22	28	17	26	18	29	19	30	27	31	30	30	31	31	31	31	30	30	29	31	25	30	22	30
1 JA	SVELD	MEDM	CLAY	23	30	20	27	20	29	22	30	31	31	30	30	31	31	31	31	30	30	30	31	27	30	24	31
1 JA	SVELD	MEDM	LOAM	23	31	18	27	18	29	19	30	29	31	30	30	31	31	31	31	30	30	30	31	27	30	23	31
1 JA	SVELD	MEDM	SAND	22	28	17	25	18	29	20	30	27	31	30	30	31	31	31	31	30	30	29	31	25	30	22	30
1 JA	SVELD	SHALW	CLAY	24	28	20	26	21	30	23	30	31	31	30	30	31	31	31	31	30	30	30	31	26	30	24	30
1 JA	SVELD	SHALW	LOAM	23	28	19	26	19	29	21	30	30	31	30	30	31	31	31	31	30	30	29	31	25	30	23	30
1 JA	SVELD	SHALW	SAND	22	28	18	25	19	28	22	30	28	31	30	30	31	31	31	31	30	30	28	31	25	29	22	29
1 DC	SOYAS	DEEP	CLAY	17	30	24	30	23	28	21	31	11	30	17	31	30	30	31	31	31	31	30	30	27	31	20	30
1 DC	SOYAS	DEEP	LOAM	16	30	20	29	22	28	20	31	8	30	17	31	30	30	31	31	31	31	30	30	27	31	20	30
1 DC	SOYAS	DEEP	SAND	17	28	18	25	21	27	19	30	14	30	22	31	30	30	31	31	31	31	30	30	26	31	20	29
1 DC	SOYAS	MEDM	CLAY	17	29	24	29	23	28	21	31	12	30	18	31	30	30	31	31	31	31	30	30	26	31	20	30
1 DC	SOYAS	MEDM	LOAM	17	29	19	27	22	27	21	31	11	30	18	31	30	30	31	31	31	31	30	30	26	31	19	30
1 DC	SOYAS	MEDM	SAND	18	28	19	25	21	26	19	30	15	30	23	31	30	30	31	31	31	31	30	30	26	31	21	28
1 DC	SOYAS	SHALW	CLAY	19	28	24	28	23	27	22	30	16	30	23	31	30	30	31	31	31	31	30	30	26	31	21	29
1 DC	SOYAS	SHALW	LOAM	18	28	23	28	22	27	20	30	14	30	23	31	30	30	31	31	31	31	30	30	26	31	21	29
1 DC	SOYAS	SHALW	SAND	20	28	23	28	21	26	19	29	16	30	25	31	30	30	31	31	31	31	30	30	25	31	21	29

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 NV	MAIZE	DEEP	CLAY	0	6	3	24	3	29	3	28	4	38	0	21	0	4	0	0	0	0	0	0	0	0	0	4
1 NV	MAIZE	DEEP	LOAM	0	0	0	9	0	11	0	11	0	14	0	3	0	0	0	0	0	0	0	0	0	0	0	0
1 NV	MAIZE	DEEP	SAND	0	6	1	10	1	7	0	9	0	14	0	10	0	12	0	6	0	4	0	2	0	2	0	3
1 NV	MAIZE	MEDM	CLAY	0	9	4	29	4	35	5	33	6	44	0	25	0	5	0	0	0	0	0	0	0	1	0	7
1 NV	MAIZE	MEDM	LOAM	0	1	0	12	0	15	0	15	0	19	0	8	0	5	0	1	0	0	0	0	0	1	0	1
1 NV	MAIZE	MEDM	SAND	0	8	3	15	3	12	1	14	1	23	1	18	1	17	1	9	1	7	0	4	0	4	0	5
1 NV	MAIZE	SHALW	CLAY	1	21	9	44	11	55	12	50	13	60	3	37	0	12	0	3	0	1	0	1	0	4	0	14
1 NV	MAIZE	SHALW	LOAM	0	10	6	26	4	30	5	31	5	41	2	24	1	16	0	8	0	5	0	4	0	3	0	10
1 NV	MAIZE	SHALW	SAND	3	16	7	27	6	29	7	31	7	44	9	30	8	24	5	14	3	9	2	7	1	8	1	11
1 DC	MAIZE	DEEP	CLAY	2	26	3	31	3	27	3	31	0	14	0	5	0	0	0	0	0	0	0	0	0	4	0	8
1 DC	MAIZE	DEEP	LOAM	0	9	0	12	0	12	0	11	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1 DC	MAIZE	DEEP	SAND	0	15	2	15	1	10	1	12	0	4	0	4	0	1	0	1	0	0	0	0	0	1	0	5
1 DC	MAIZE	MEDM	CLAY	3	32	5	38	5	32	4	37	0	17	0	7	0	0	0	0	0	0	0	0	0	7	0	13
1 DC	MAIZE	MEDM	LOAM	0	13	2	17	1	15	0	15	0	5	0	2	0	0	0	0	0	0	0	0	0	1	0	2
1 DC	MAIZE	MEDM	SAND	3	20	7	21	4	19	2	20	1	9	0	8	0	3	0	2	0	2	0	2	0	4	0	9
1 DC	MAIZE	SHALW	CLAY	9	49	12	58	11	47	11	53	2	29	0	13	0	2	0	0	0	0	0	3	0	14	2	28
1 DC	MAIZE	SHALW	LOAM	7	31	10	33	6	32	4	35	2	17	0	8	0	3	0	2	0	1	0	3	0	8	0	13
1 DC	MAIZE	SHALW	SAND	12	33	14	38	9	34	7	38	5	21	4	18	2	9	1	6	0	5	0	8	1	10	3	18
15 DC	SUNFL	DEEP	CLAY	3	33	4	42	4	29	3	37	0	14	0	4	0	0	0	0	0	0	0	0	0	4	0	10
15 DC	SUNFL	DEEP	LOAM	0	9	0	15	0	12	0	12	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0
15 DC	SUNFL	DEEP	SAND	0	15	4	19	2	18	1	16	0	6	0	4	0	1	0	0	0	0	0	0	0	0	0	2
15 DC	SUNFL	MEDM	CLAY	5	40	6	49	5	35	5	42	0	17	0	6	0	0	0	0	0	0	0	0	0	7	0	15
15 DC	SUNFL	MEDM	LOAM	0	14	3	20	1	16	0	17	0	5	0	2	0	0	0	0	0	0	0	0	0	1	0	2
15 DC	SUNFL	MEDM	SAND	3	23	9	28	5	22	3	24	2	11	1	7	0	3	0	2	0	1	0	1	0	2	0	6
15 DC	SUNFL	SHALW	CLAY	12	54	14	67	12	51	12	56	2	26	0	13	0	2	0	0	0	0	0	3	0	14	2	29
15 DC	SUNFL	SHALW	LOAM	8	35	12	41	7	35	5	39	2	15	1	7	0	2	0	1	0	1	0	2	0	6	0	13
15 DC	SUNFL	SHALW	SAND	14	35	18	45	11	40	9	42	6	19	4	15	2	7	1	4	0	4	0	7	0	8	2	17
1 JA	SVELD	DEEP	CLAY	5	44	4	32	4	42	0	16	0	5	0	0	0	0	0	0	0	1	0	7	0	10	4	31
1 JA	SVELD	DEEP	LOAM	0	13	0	13	0	14	0	3	0	1	0	0	0	0	0	0	0	0	0	1	0	2	0	10
1 JA	SVELD	DEEP	SAND	0	10	0	14	0	18	0	11	0	6	0	3	0	2	0	1	0	0	0	1	0	1	0	8
1 JA	SVELD	MEDM	CLAY	7	51	6	37	6	46	0	21	0	8	0	1	0	0	0	0	0	1	0	9	0	13	5	37
1 JA	SVELD	MEDM	LOAM	1	13	1	17	1	19	0	6	0	3	0	0	0	0	0	0	0	0	0	2	0	4	1	14
1 JA	SVELD	MEDM	SAND	1	18	1	20	2	25	1	16	0	9	0	5	0	3	0	2	0	1	0	2	0	3	0	11
1 JA	SVELD	SHALW	CLAY	14	70	14	55	13	59	2	33	0	13	0	4	0	0	0	1	0	4	0	16	3	28	11	50
1 JA	SVELD	SHALW	LOAM	5	41	7	37	6	42	3	18	1	10	0	4	0	2	0	1	0	2	0	8	0	11	4	29
1 JA	SVELD	SHALW	SAND	7	39	10	37	10	43	7	25	4	18	2	9	1	5	0	3	0	3	0	7	1	9	6	28
1 DC	SOYAS	DEEP	CLAY	3	30	4	38	3	28	4	37	0	21	0	4	0	0	0	0	0	0	0	0	0	4	0	9
1 DC	SOYAS	DEEP	LOAM	0	10	0	14	0	12	0	13	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0
1 DC	SOYAS	DEEP	SAND	2	19	5	20	3	16	2	17	1	9	0	9	0	4	0	3	0	1	0	2	0	3	0	8
1 DC	SOYAS	MEDM	CLAY	4	37	6	45	5	33	6	43	0	25	0	6	0	0	0	0	0	0	0	1	0	7	0	14
1 DC	SOYAS	MEDM	LOAM	0	16	4	20	1	17	1	18	0	8	0	5	0	1	0	0	0	0	0	0	0	1	0	2
1 DC	SOYAS	MEDM	SAND	5	24	10	27	5	22	4	27	2	15	1	14	1	9	0	5	0	3	0	3	0	5	0	10
1 DC	SOYAS	SHALW	CLAY	11	53	14	64	12	50	13	59	2	36	0	12	0	3	0	0	0	1	0	4	0	14	2	30
1 DC	SOYAS	SHALW	LOAM	8	35	12	38	7	35	6	42	3	23	1	15	0	7	0	4	0	4	0	3	0	10	1	15
1 DC	SOYAS	SHALW	SAND	14	36	17	43	11	39	9	46	8	29	7	23	4	13	3	9	1	6	1	8	1	11	3	18

ZONE NO.297

RAINFALL STATION 0284008 THORNLEA LAT 28 39 LONG 21 31 ALTITUDE 914m 85 YEARS OF DATA

TEMPERATURE STATION 0317474 UPINGTON LAT 28 24 LONG 21 16 ALTITUDE 825m WIND REGION : 7

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm)	MEAN	26.0	32.5	44.2	26.2	12.6	3.4	3.6	4.4	3.6	10.5	16.1	15.8	199.0
M.A.P. 199.3mm	MEDN	9.6	21.6	31.5	16.0	5.8	0.0	0.0	0.0	0.0	5.3	6.4	8.3	193.0
	SDEV	41.3	35.2	38.5	29.9	16.2	6.8	9.6	9.0	8.1	13.4	20.1	20.0	99.0
	C.V.	158.6	108.3	87.0	113.9	128.7	198.2	268.3	204.7	226.3	127.4	125.5	126.8	49.0
	SKEW	3.2	1.8	1.1	1.9	1.5	2.8	4.0	2.2	3.8	1.5	1.5	1.9	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	34.9	33.9	31.5	28.2	23.6	21.2	21.1	22.1	26.4	29.8	32.6	34.0	
	MIN	19.4	19.7	17.5	13.5	7.9	6.0	5.3	5.3	8.8	12.3	15.4	18.0	

CROP AND SOIL INFORMATION

EVAPOTRANSPIRATION DEFICIT (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 JA	SVELD	DEEP	CLAY	194	204	171	191	121	148	80	95	48	55	39	44	42	45	51	52	77	79	113	118	175	184	189	200
1 JA	SVELD	DEEP	LOAM	194	204	170	191	121	147	78	95	46	55	39	44	41	44	50	52	77	79	113	118	175	184	189	200
1 JA	SVELD	DEEP	SAND	193	204	169	191	119	147	78	96	45	55	40	44	42	45	51	53	78	79	113	118	176	184	190	200
1 JA	SVELD	MEDM	CLAY	194	204	170	191	122	149	80	96	48	55	39	44	43	45	51	53	78	79	113	118	176	184	190	200
1 JA	SVELD	MEDM	LOAM	194	204	170	191	121	148	79	95	47	55	39	44	42	45	51	53	77	79	113	118	175	184	189	200
1 JA	SVELD	MEDM	SAND	194	204	169	191	120	148	78	95	45	55	41	44	44	45	52	53	78	79	113	118	176	184	190	200
1 JA	SVELD	SHALW	CLAY	194	204	171	191	124	149	82	97	49	55	41	44	44	45	52	53	78	79	113	118	178	184	191	200
1 JA	SVELD	SHALW	LOAM	194	204	169	191	121	149	81	96	47	55	41	44	44	45	52	53	78	79	113	118	177	184	191	200
1 JA	SVELD	SHALW	SAND	194	204	169	191	121	149	81	97	48	55	42	44	45	45	53	53	79	79	113	118	177	184	191	200

INDEX OF STRESS DAYS

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 JA	SVELD	DEEP	CLAY	31	31	27	29	28	31	28	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	DEEP	LOAM	31	31	27	29	28	31	28	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	DEEP	SAND	31	31	26	28	26	31	27	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	MEDM	CLAY	31	31	27	29	27	31	28	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	MEDM	LOAM	31	31	27	29	27	31	28	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	MEDM	SAND	31	31	26	28	26	31	27	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	30	31
1 JA	SVELD	SHALW	CLAY	31	31	26	28	27	31	27	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	SHALW	LOAM	31	31	26	28	26	31	27	30	31	31	30	30	31	31	31	31	30	30	31	31	30	30	31	31
1 JA	SVELD	SHALW	SAND	30	31	25	28	25	31	26	30	29	31	30	30	31	31	31	31	30	30	31	31	29	30	30	31

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 JA	SVELD	DEEP	CLAY	0	6	0	12	0	14	0	12	0	2	0	0	0	0	0	0	0	0	0	1	0	5	0	2
1 JA	SVELD	DEEP	LOAM	0	1	0	3	0	4	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1 JA	SVELD	DEEP	SAND	0	0	0	1	0	3	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 JA	SVELD	MEDM	CLAY	0	8	0	15	1	19	0	15	0	4	0	0	0	0	0	0	0	0	0	2	0	7	0	3
1 JA	SVELD	MEDM	LOAM	0	2	0	6	0	7	0	5	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0
1 JA	SVELD	MEDM	SAND	0	1	0	4	0	5	0	6	0	3	0	1	0	0	0	0	0	0	0	0	0	1	0	0
1 JA	SVELD	SHALW	CLAY	0	14	0	24	3	30	0	23	0	8	0	0	0	0	0	0	0	0	0	4	0	14	0	8
1 JA	SVELD	SHALW	LOAM	0	7	0	13	0	15	0	13	0	5	0	1	0	0	0	0	0	0	0	1	0	6	0	2
1 JA	SVELD	SHALW	SAND	0	6	0	12	1	17	1	15	1	9	0	4	0	2	0	2	0	1	0	2	0	6	0	2

ZONE NO.518

RAINFALL STATION 0479545 KARINA LAT 26 05 LONG 29 50 ALTITUDE 1648m 70 YEARS OF DATA

TEMPERATURE STATION 0480184A CAROLINA (TNK) LAT 26 04 LONG 30 07 ALTITUDE 1692m WIND REGION : 1

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 645.1mm	MEAN	118.2	81.3	67.8	41.5	15.7	7.1	7.9	8.2	23.7	64.5	111.8	107.6	645.0
	MEDN	115.9	69.0	59.3	32.0	10.9	0.1	1.0	0.4	14.6	49.6	112.6	109.0	706.0
	SDEV	64.0	54.3	42.2	33.7	19.0	16.3	14.5	14.0	26.7	47.7	62.7	57.0	233.0
	C.V.	54.2	66.9	62.3	81.2	121.6	229.5	184.0	172.0	112.2	73.9	56.1	52.9	36.0
	SKEW	0.8	0.8	0.7	0.9	2.1	3.7	2.5	2.6	1.4	1.2	0.4	0.6	0.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	24.3	23.7	23.0	20.5	18.9	16.5	16.6	19.0	22.1	23.2	22.8	24.0	
	MIN	13.5	13.0	12.1	8.7	5.2	2.7	2.4	5.1	8.0	10.1	11.6	12.6	

CROP AND SOIL INFORMATION EVAPOTRANSPIRATION DEFICIT (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 NV	MAIZE	DEEP	CLAY	18	68	73	154	117	184	124	169	49	77	3	20	7	19	12	18	17	20	23	27	26	36	11	34
1 NV	MAIZE	DEEP	LOAM	18	68	50	150	102	177	113	168	47	76	3	20	6	19	12	18	17	20	23	26	26	36	11	34
1 NV	MAIZE	DEEP	SAND	28	68	66	146	115	183	121	173	49	76	5	22	13	22	16	19	19	21	25	27	28	37	15	33
1 NV	MAIZE	MEDM	CLAY	22	70	75	152	125	185	128	173	50	77	4	21	9	20	14	18	18	21	24	27	27	37	12	34
1 NV	MAIZE	MEDM	LOAM	20	69	59	148	113	184	121	172	48	76	3	21	9	20	13	18	18	21	24	27	27	37	12	34
1 NV	MAIZE	MEDM	SAND	31	65	77	152	121	184	123	174	51	76	6	23	14	23	17	20	19	21	25	27	28	37	15	33
1 NV	MAIZE	SHALW	CLAY	31	71	101	159	144	194	137	176	56	78	7	22	14	22	16	20	19	21	25	27	28	37	15	33
1 NV	MAIZE	SHALW	LOAM	31	67	89	157	129	192	129	175	51	77	6	22	14	22	16	20	19	21	25	27	28	37	15	33
1 NV	MAIZE	SHALW	SAND	40	71	97	157	131	192	128	176	55	77	10	25	16	24	18	20	20	21	26	27	29	37	17	33
1 DC	MAIZE	DEEP	CLAY	8	60	48	137	125	181	114	151	40	64	16	25	15	19	17	21	23	26	26	36	11	32	0	17
1 DC	MAIZE	DEEP	LOAM	9	60	32	128	109	167	106	151	39	63	16	25	15	19	17	20	23	26	26	36	11	32	0	17
1 DC	MAIZE	DEEP	SAND	21	61	51	120	124	184	113	149	40	64	19	26	16	20	19	21	25	27	27	37	14	31	1	15
1 DC	MAIZE	MEDM	CLAY	12	60	59	136	134	183	119	151	40	65	18	26	15	19	18	21	24	27	27	36	11	32	0	16
1 DC	MAIZE	MEDM	LOAM	12	60	45	117	122	182	113	150	40	64	18	25	15	19	18	21	24	27	27	36	11	32	0	16
1 DC	MAIZE	MEDM	SAND	25	62	65	129	135	187	118	149	41	65	19	27	17	20	19	21	25	27	27	37	15	32	1	16
1 DC	MAIZE	SHALW	CLAY	24	63	89	142	148	192	124	155	45	65	20	27	17	20	19	21	25	27	28	37	15	31	1	16
1 DC	MAIZE	SHALW	LOAM	24	61	77	138	143	191	122	154	42	65	19	26	17	20	19	21	25	27	27	37	15	31	1	15
1 DC	MAIZE	SHALW	SAND	35	64	87	145	143	192	122	155	46	65	20	27	18	20	20	21	26	27	28	37	16	31	5	20
15 DC	SUNFL	DEEP	CLAY	0	18	6	77	68	125	76	118	55	80	37	45	18	22	17	20	25	28	25	35	11	34	0	15
15 DC	SUNFL	DEEP	LOAM	0	18	5	74	53	124	65	117	51	78	35	44	18	22	17	20	25	28	25	35	11	35	0	15
15 DC	SUNFL	DEEP	SAND	1	21	16	71	78	138	75	118	54	82	36	46	20	22	18	20	26	28	26	35	15	33	2	15
15 DC	SUNFL	MEDM	CLAY	0	18	13	78	83	132	85	118	58	83	38	46	19	22	18	20	26	28	26	35	12	34	0	15
15 DC	SUNFL	MEDM	LOAM	0	18	8	73	74	129	76	118	54	81	37	45	19	22	18	20	26	28	26	35	12	34	1	15
15 DC	SUNFL	MEDM	SAND	3	21	25	75	88	143	83	118	57	83	38	46	20	22	18	20	27	28	26	35	15	33	2	16
15 DC	SUNFL	SHALW	CLAY	2	22	43	90	110	149	94	123	65	85	40	46	20	22	18	20	26	28	26	35	15	33	2	16
15 DC	SUNFL	SHALW	LOAM	2	19	37	85	96	147	88	119	59	84	39	46	20	22	18	20	26	28	26	35	15	33	2	15
15 DC	SUNFL	SHALW	SAND	7	22	47	94	103	150	90	121	61	84	40	47	21	22	19	20	27	28	27	35	17	34	5	18
1 JA	SVELD	DEEP	CLAY	22	79	40	83	41	77	30	53	27	38	27	32	29	34	38	45	50	62	37	69	25	70	29	79
1 JA	SVELD	DEEP	LOAM	12	76	27	76	27	76	20	49	21	38	23	31	27	33	36	44	48	61	36	69	17	70	18	78
1 JA	SVELD	DEEP	SAND	16	77	31	84	33	74	25	52	24	39	26	33	30	35	40	45	51	62	35	66	13	69	18	77
1 JA	SVELD	MEDM	CLAY	26	79	45	87	45	77	32	55	29	39	28	33	31	35	41	45	51	62	38	69	28	69	29	79
1 JA	SVELD	MEDM	LOAM	13	78	28	80	33	76	26	50	25	38	25	32	29	34	39	45	50	62	35	68	16	69	19	78
1 JA	SVELD	MEDM	SAND	20	79	38	88	39	77	28	53	28	40	30	34	32	35	41	46	52	62	34	68	16	69	21	77
1 JA	SVELD	SHALW	CLAY	41	79	57	93	55	80	38	60	34	41	31	34	33	35	43	46	54	63	42	68	38	70	39	80

INDEX OF STRESS DAYS

PLANT	CROP	SOIL	SOIL	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
DATE	TYPE	DEPTH	TEXT	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 NV	MAIZE	DEEP	CLAY	3	25	13	29	19	30	20	28	17	29	1	27	7	31	26	30	31	31	31	31	25	30	9	26
1 NV	MAIZE	DEEP	LOAM	3	25	7	29	17	29	19	27	16	29	1	27	6	31	23	30	31	31	31	31	26	30	9	27
1 NV	MAIZE	DEEP	SAND	8	21	10	26	18	27	20	26	17	28	5	26	20	31	30	30	31	31	31	31	25	30	12	26
1 NV	MAIZE	MEDM	CLAY	5	24	14	28	21	28	21	27	17	29	2	27	13	31	29	30	31	31	31	31	25	30	10	27
1 NV	MAIZE	MEDM	LOAM	5	24	9	28	18	28	20	27	16	28	2	27	11	31	27	30	31	31	31	31	25	30	10	27
1 NV	MAIZE	MEDM	SAND	10	20	12	26	18	28	20	26	18	28	7	26	21	31	30	30	31	31	31	31	24	30	13	26
1 NV	MAIZE	SHALW	CLAY	9	21	17	27	21	28	22	26	19	29	8	27	20	31	30	30	31	31	31	31	25	30	13	26
1 NV	MAIZE	SHALW	LOAM	9	21	16	27	20	28	20	26	18	29	6	27	20	31	30	30	31	31	31	31	25	30	13	26
1 NV	MAIZE	SHALW	SAND	12	22	16	26	18	27	19	26	19	26	12	26	23	31	30	30	31	31	31	31	24	30	14	26
1 DC	MAIZE	DEEP	CLAY	1	19	6	27	20	28	24	31	20	30	23	31	30	30	31	31	31	31	25	30	9	26	0	11
1 DC	MAIZE	DEEP	LOAM	1	19	2	26	16	26	22	31	20	30	22	31	30	30	31	31	31	31	25	30	9	27	0	12
1 DC	MAIZE	DEEP	SAND	7	22	7	22	19	26	23	29	19	30	25	31	30	30	31	31	31	31	25	30	12	25	0	11
1 DC	MAIZE	MEDM	CLAY	3	19	9	27	21	28	23	31	21	30	25	31	30	30	31	31	31	31	25	30	10	26	0	12
1 DC	MAIZE	MEDM	LOAM	3	20	6	25	20	27	23	30	20	30	24	31	30	30	31	31	31	31	25	30	10	27	0	12
1 DC	MAIZE	MEDM	SAND	8	22	10	23	19	26	22	29	20	29	25	31	30	30	31	31	31	31	24	30	13	25	0	13
1 DC	MAIZE	SHALW	CLAY	7	22	16	26	22	26	25	30	21	30	26	31	30	30	31	31	31	31	25	30	13	25	0	12
1 DC	MAIZE	SHALW	LOAM	7	22	14	25	20	27	23	30	20	30	25	31	30	30	31	31	31	31	25	30	13	25	0	12
1 DC	MAIZE	SHALW	SAND	12	22	15	25	20	26	23	29	21	28	25	31	30	30	31	31	31	31	24	30	14	25	5	14
15 DC	SUNFL	DEEP	CLAY	0	6	0	20	13	25	20	31	22	30	30	31	30	30	31	31	31	31	26	30	9	27	0	11
15 DC	SUNFL	DEEP	LOAM	0	6	0	19	8	25	17	31	21	30	29	31	30	30	31	31	31	31	26	30	9	27	0	11
15 DC	SUNFL	DEEP	SAND	0	11	1	17	16	25	20	28	21	30	28	31	30	30	31	31	31	31	25	30	13	26	0	12
15 DC	SUNFL	MEDM	CLAY	0	6	1	21	15	25	21	30	22	30	30	31	30	30	31	31	31	31	26	30	9	27	0	12
15 DC	SUNFL	MEDM	LOAM	0	6	0	19	14	25	19	31	22	30	30	31	30	30	31	31	31	31	26	30	10	27	0	12
15 DC	SUNFL	MEDM	SAND	1	12	5	18	17	25	20	28	21	30	28	31	30	30	31	31	31	31	24	30	13	26	1	13
15 DC	SUNFL	SHALW	CLAY	0	12	9	22	20	26	23	30	24	30	29	31	30	30	31	31	31	31	25	30	13	26	0	12
15 DC	SUNFL	SHALW	LOAM	0	11	7	21	18	26	21	29	22	30	28	31	30	30	31	31	31	31	25	30	13	26	0	12
15 DC	SUNFL	SHALW	SAND	4	15	11	23	18	25	22	28	22	29	28	31	30	30	31	31	31	31	24	30	14	25	4	14
1 JA	SVELD	DEEP	CLAY	4	25	11	23	14	29	15	30	28	31	30	30	31	31	31	31	30	30	16	31	4	26	5	25
1 JA	SVELD	DEEP	LOAM	0	25	5	21	8	30	7	29	18	31	30	30	31	31	31	31	29	30	15	31	4	26	2	25
1 JA	SVELD	DEEP	SAND	3	23	8	22	11	27	13	29	22	31	30	30	31	31	31	31	28	30	15	29	4	23	4	23
1 JA	SVELD	MEDM	CLAY	6	24	12	24	15	29	17	30	30	31	30	30	31	31	31	31	30	30	16	31	6	25	6	26
1 JA	SVELD	MEDM	LOAM	2	24	7	22	12	29	12	29	24	31	30	30	31	31	31	31	30	30	16	31	3	25	2	25
1 JA	SVELD	MEDM	SAND	5	23	10	23	14	27	16	29	25	31	30	30	31	31	31	31	28	30	14	28	5	22	5	24
1 JA	SVELD	SHALW	CLAY	11	24	15	25	18	28	20	30	30	31	30	30	31	31	31	31	28	30	18	29	11	24	11	25
1 JA	SVELD	SHALW	LOAM	7	23	13	24	16	27	17	30	29	31	30	30	31	31	31	31	28	30	15	29	7	23	8	24
1 JA	SVELD	SHALW	SAND	10	23	14	25	18	26	18	29	28	31	30	30	31	31	31	31	27	30	16	28	10	21	10	23
1 JA	GVELD	DEEP	CLAY	13	28	17	27	20	31	24	30	31	31	30	30	31	31	31	31	30	30	24	31	12	28	11	28
1 JA	GVELD	DEEP	LOAM	8	28	15	25	18	31	21	30	31	31	30	30	31	31	31	31	30	30	23	31	9	29	9	27
1 JA	GVELD	DEEP	SAND	10	26	16	26	18	28	21	30	30	31	30	30	31	31	31	31	28	30	20	31	9	26	9	25
1 JA	GVELD	MEDM	CLAY	13	27	18	27	20	30	24	30	31	31	30	30	31	31	31	31	30	30	23	31	14	28	12	27
1 JA	GVELD	MEDM	LOAM	10	27	15	26	19	30	22	30	31	31	30	30	31	31	31	31	30	30	22	31	9	28	10	27
1 JA	GVELD	MEDM	SAND	12	25	16	25	19	28	21	30	30	31	30	30	31	31	31	31	28	30	20	30	10	25	10	25
1 JA	GVELD	SHALW	CLAY	17	27	19	26	23	30	24	30	31	31	30	30	31	31	31	31	28	30	23	31	16	26	16	26
1 JA	GVELD	SHALW	LOAM	14	26	18	26	20	28	22	30	31	31	30	30	31	31	31	31	28	30	21	31	13	26	12	
1 JA	GVELD	SHALW	SAND	14	25	18	25	21	28	22	29	29	31	30	30	31	31	31	31	27	30	21	29	14	24	14	
1 DC	SOYAS	DEEP	CLAY	0	13	0	22	15	26	18	29	3	29	5	31	25	30	31	31	30	31	25	30	9	26	0	
1 DC	SOYAS	DEEP	LOAM	0	12	0	20	12	25	16	29	2	28	4	31	23	30	31	31	31	31	25	30	9	27	0	
1 DC	SOYAS	DEEP	SAND	2	16	2	20	18	26	17	28	6	27	18	31	29	30	31	31	31	31	25	30	12	25	0	
1 DC	SOYAS	MEDM	CLAY	0	13	3	20	18	27	19	29	4	28	10	31	27	30	31	31	31	31	25	30	10	26	0	
1 DC	SOYAS	MEDM	LOAM	0	13	1	18	17	26	17	29	2	28	8	31	26	30	31	31	31	31	25	30	10	27	0	
1 DC	SOYAS	MEDM	SAND	3	18	6	20	18	26	17	28	7	27	20	31	30	30	31	31	31	31	24	30	13	25	0	
1 DC	SOYAS	SHALW	CLAY	3	17	11	23	21	26	20	30	8	27	20	31	30	30	31	31	31	31	25	30	13	25	0	
1 DC	SOYAS	SHALW	LOAM	3	17	9	23	20	26	18	29	7	27	19	31	30	30	31	31	31	31	25	30	13	25	0	
1 DC	SOYAS	SHALW	SAND	6	19	11	23	19	26	18	28	12	27	22	31	30	30	31	31	31	31	24	30	14	25	4	

WATER YIELD (mm)

PLANT DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1		MONTH 2		MONTH 3		MONTH 4		MONTH 5		MONTH 6		MONTH 7		MONTH 8		MONTH 9		MONTH10		MONTH11		MONTH12	
				50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1 NV	MAIZE	DEEP	CLAY	8	40	6	43	6	45	4	37	3	28	1	23	0	3	0	0	0	0	0	0	0	9	0	27
1 NV	MAIZE	DEEP	LOAM	1	32	3	33	4	20	2	15	1	11	0	7	0	1	0	0	0	0	0	0	0	1	0	8
1 NV	MAIZE	DEEP	SAND	12	42	13	42	11	30	6	23	4	18	2	18	1	19	0	11	0	8	0	5	0	7	1	17
1 NV	MAIZE	MEDM	CLAY	13	46	9	49	8	52	6	42	5	34	1	27	0	4	0	0	0	0	0	0	0	12	1	34
1 NV	MAIZE	MEDM	LOAM	8	43	9	36	10	32	4	21	3	16	1	12	0	6	0	3	0	3	0	1	0	3	0	16
1 NV	MAIZE	MEDM	SAND	16	49	16	48	14	35	8	32	5	25	4	24	2	22	2	14	1	10	1	6	1	9	5	24
1 NV	MAIZE	SHALW	CLAY	26	66	19	65	19	78	14	58	12	47	4	40	0	10	0	3	0	3	0	2	0	21	7	54
1 NV	MAIZE	SHALW	LOAM	21	57	22	61	16	49	9	44	8	34	4	32	2	19	1	11	0	8	0	6	1	16	5	29
1 NV	MAIZE	SHALW	SAND	26	59	27	64	21	57	13	49	14	42	10	39	9	27	5	17	3	12	2	12	2	17	9	32
1 DC	MAIZE	DEEP	CLAY	9	58	8	58	4	37	2	24	0	16	0	3	0	0	0	0	0	0	0	9	0	27	19	53
1 DC	MAIZE	DEEP	LOAM	6	49	11	44	5	31	3	17	2	8	0	4	0	2	0	1	0	0	0	0	0	5	3	29
1 DC	MAIZE	DEEP	SAND	28	64	23	57	12	40	8	23	4	13	2	7	1	4	0	3	0	1	0	2	0	14	10	47
1 DC	MAIZE	MEDM	CLAY	14	71	12	65	7	44	5	30	1	20	0	5	0	0	0	0	0	0	0	12	1	34	24	63
1 DC	MAIZE	MEDM	LOAM	19	60	19	55	10	36	6	22	3	11	1	4	0	2	0	1	0	0	0	1	0	12	10	46
1 DC	MAIZE	MEDM	SAND	32	68	28	61	15	47	9	27	5	16	3	10	1	7	1	6	0	3	0	7	3	20	18	55
1 DC	MAIZE	SHALW	CLAY	30	86	22	90	14	60	10	43	4	32	0	10	0	3	0	2	0	2	0	21	6	54	36	86
1 DC	MAIZE	SHALW	LOAM	33	83	30	73	15	50	10	34	5	24	2	10	1	5	0	4	0	3	0	14	4	28	26	63
1 DC	MAIZE	SHALW	SAND	37	82	36	82	19	56	15	42	8	31	6	20	3	11	2	10	1	9	1	17	9	28	31	66
15 DC	SUNFL	DEEP	CLAY	18	72	17	72	8	46	5	29	1	15	0	3	0	0	0	0	0	0	0	9	0	27	19	54
15 DC	SUNFL	DEEP	LOAM	12	56	22	58	13	47	7	24	4	14	2	5	1	2	0	1	0	0	0	0	0	5	3	27
15 DC	SUNFL	DEEP	SAND	30	69	35	69	19	49	12	29	6	16	3	8	1	5	1	3	0	1	0	1	0	10	9	43
15 DC	SUNFL	MEDM	CLAY	22	87	22	79	11	55	6	34	2	19	0	4	0	1	0	0	0	0	0	12	1	34	24	61
15 DC	SUNFL	MEDM	LOAM	21	69	30	73	17	50	10	27	5	15	2	6	1	3	0	1	0	0	0	1	0	10	9	41
15 DC	SUNFL	MEDM	SAND	35	75	39	75	21	58	13	34	7	19	4	10	2	6	1	3	0	2	0	4	0	18	14	51
15 DC	SUNFL	SHALW	CLAY	41	104	30	102	19	66	11	47	4	30	1	9	0	3	0	2	0	1	0	21	6	53	36	83
15 DC	SUNFL	SHALW	LOAM	36	93	38	89	20	61	15	37	6	25	3	9	1	4	1	3	0	2	0	11	2	27	26	62
15 DC	SUNFL	SHALW	SAND	42	90	44	92	25	68	20	48	11	32	7	17	4	10	2	7	1	9	1	16	7	28	30	65
1 JA	SVELD	DEEP	CLAY	11	67	6	49	4	31	0	19	0	4	0	0	0	0	0	0	0	13	1	30	15	46	11	59
1 JA	SVELD	DEEP	LOAM	2	28	1	34	0	17	0	9	0	4	0	2	0	1	0	0	0	3	0	9	2	17	1	25
1 JA	SVELD	DEEP	SAND	7	35	5	48	4	30	2	18	1	9	0	5	0	3	0	1	0	1	0	5	2	22	2	34
1 JA	SVELD	MEDM	CLAY	14	75	8	53	6	36	1	22	0	6	0	1	0	1	0	0	0	16	2	37	19	52	14	64
1 JA	SVELD	MEDM	LOAM	6	42	4	41	2	22	1	13	0	5	0	2	0	2	0	0	0	4	0	13	5	24	3	33
1 JA	SVELD	MEDM	SAND	12	46	9	54	8	36	4	21	3	12	2	7	1	4	0	2	0	3	0	10	7	33	8	42
1 JA	SVELD	SHALW	CLAY	25	95	14	65	12	46	3	35	0	10	0	5	0	3	0	2	0	23	6	54	30	68	24	76
1 JA	SVELD	SHALW	LOAM	16	66	11	60	8	38	4	29	3	11	1	5	0	4	0	2	0	10	1	27	18	43	15	58
1 JA	SVELD	SHALW	SAND	21	70	17	66	17	49	12	35	7	21	4	11	2	7	1	7	1	10	3	26	21	46	20	61
1 JA	GVELD	DEEP	CLAY	8	58	5	41	3	26	0	15	0	3	0	0	0	0	0	0	0	10	1	26	12	39	9	50
1 JA	GVELD	DEEP	LOAM	1	19	0	18	0	9	0	5	0	0	0	0	0	0	0	0	0	2	0	8	1	14	1	18
1 JA	GVELD	DEEP	SAND	2	24	1	29	1	18	0	10	0	5	0	2	0	1	0	0	0	1	0	5	1	15	0	19
1 JA	GVELD	MEDM	CLAY	11	65	7	46	5	32	0	18	0	4	0	1	0	0	0	0	0	14	1	31	15	43	12	55
1 JA	GVELD	MEDM	LOAM	3	31	2	26	1	13	0	9	0	2	0	1	0	0	0	0	0	4	0	12	3	18	2	26
1 JA	GVELD	MEDM	SAND	5	33	4	39	3	25	2	14	1	8	0	4	0	2	0	1	0	3	0	8	3	27	4	29
1 JA	GVELD	SHALW	CLAY	21	88	13	60	11	45	3	30	0	9	0	4	0	3	0	2	0	23	5	47	28	63	21	69
1 JA	GVELD	SHALW	LOAM	12	53	8	49	6	32	2	22	1	7	0	2	0	2	0	1	0	10	1	25	14	36	10	48
1 JA	GVELD	SHALW	SAND	16	60	13	56	11	41	7	28	4	14	2	8	1	6	0	6	1	9	2	23	16	41	15	49
1 DC	SOYAS	DEEP	CLAY	14	74	14	69	6	43	5	30	2	24	0	4	0	0	0	0	0	0	0	9	0	27	19	56
1 DC	SOYAS	DEEP	LOAM	19	63	22	60	12	43	7	24	4	14	2	6	1	3	0	1	0	1	0	1	0	10	6	39
1 DC	SOYAS	DEEP	SAND	34	70	32	68	18	48	11	30	6	20	3	17	2	11	1	7	0	4	0	7	1	17	15	50
1 DC	SOYAS	MEDM	CLAY	21	83	19	77	10	51	7	36	3	28	0	5	0	1	0	0	0	0	0	12	1	34	25	69
1 DC	SOYAS	MEDM	LOAM	27	67	29	69	15	48	9	27	5	16	2	8	1	4	0	3	0	1	0	3	0	15	16	51
1 DC	SOYAS	MEDM	SAND	37	76	36	73	19	55	12	34	7	24	4	21	2	14	2	10	1	6	0	9	3	21	22	55
1 DC	SOYAS	SHALW	CLAY	37	98	28	97	17	64	12	49	5	40	0	11	0	3	0	3	0	2	0	21	6	54	39	89
1 DC	SOYAS	SHALW	LOAM	36	89	35	85	18	57	14	38	7	32	4	18	2	10	1	7	0	5	1	15	4	29	28	66
1 DC	SOYAS	SHALW	SAND	41	87	40	89	23	64	20	49	12	39	9	27	5	16	3	12	1	11	2	17	10	31	31	67

APPENDIX E

Tabular output from 10 stations used in the irrigation analyses

The tabular output for each zone may be obtained from the Department of Agricultural Engineering, University of Natal, through the Computing Centre for Water Research.

ZONE NO. 9

RAINFALL STATION 006065 NIEWEBERG (BOS) LAT 34 04 LONG 19 03 ALTITUDE 564m 47 YEARS OF DATA

TEMPERATURE STATION ESTIMATE NIEWEBERG LAT 34 04 LONG 19 03 ALTITUDE 564m WIND REGION : 5

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 1605.9mm	MEAN	42.2	41.2	51.4	103.5	210.1	266.3	250.8	255.5	150.1	101.3	67.7	46.1	1605.0
	MEDN	31.1	33.4	53.1	86.5	183.7	217.4	227.8	231.4	130.8	92.5	47.8	34.3	1490.0
	SDEV	44.5	32.8	31.2	75.7	140.4	173.8	138.7	136.5	93.5	64.1	67.3	42.6	442.0
	C.V.	105.5	79.6	60.7	73.1	66.8	65.3	55.3	53.4	62.3	63.2	99.5	92.4	27.0
	SKEW	3.3	1.4	0.5	1.2	1.4	0.8	0.7	1.7	0.9	0.9	2.6	2.0	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	23.9	25.7	24.3	19.7	16.5	14.5	13.6	13.6	15.4	17.6	21.0	24.0	
	MIN	12.3	12.5	11.3	10.3	7.3	6.1	5.0	5.2	5.6	8.6	9.6	9.6	

ESTIMATED IRRIGATION REQUIREMENT

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	94	137	184	231	104	151	199	248	112	160	208	257	1
45	92	137	184	232	103	152	200	248	112	160	208	257	1
70	89	137	184	231	103	152	199	248	112	160	208	257	1
100	90	137	184	231	103	153	200	248	112	161	208	257	1
150	89	137	184	232	105	151	199	248	112	160	208	257	1
200	89	136	184	231	103	151	199	248	112	160	208	257	1
20	89	134	180	225	103	150	197	243	109	157	205	249	2
45	88	133	178	224	103	150	197	243	109	157	205	250	2
70	85	132	176	221	104	150	197	243	110	157	205	250	2
100	90	131	174	221	103	150	197	243	109	157	206	253	2
150	81	133	177	223	103	151	195	243	109	157	202	252	2
200	81	127	178	222	103	150	198	241	108	157	202	249	2
20	63	100	137	175	82	122	162	202	87	127	167	207	3
45	60	96	135	171	82	122	162	202	86	128	167	207	3
70	58	96	131	171	82	122	162	202	86	127	167	207	3
100	54	92	132	170	82	122	162	202	86	127	167	207	3
150	53	95	131	170	82	122	162	202	86	127	167	207	3
200	52	93	135	170	82	122	162	202	86	127	168	207	3
20	22	40	62	81	37	58	78	100	46	70	96	122	4
45	13	36	56	79	34	55	75	97	47	69	96	122	4
70	12	33	54	79	26	54	72	101	47	69	96	122	4
100	8	29	50	69	26	53	74	97	47	69	96	122	4
150	3	25	50	70	26	47	72	96	47	69	96	122	4
200	3	22	50	72	26	46	71	96	43	69	96	122	4
20	5	11	22	35	15	25	37	53	22	37	42	56	5
45	0	0	12	26	10	15	30	45	16	35	41	56	5
70	0	0	6	14	6	16	19	40	12	25	29	51	5
100	0	0	0	10	6	12	20	33	12	21	33	47	5
150	0	0	0	2	6	11	18	33	12	19	30	40	5
200	0	0	0	0	6	5	21	34	12	17	30	44	5
20	0	7	11	17	12	20	26	33	13	25	33	46	6
45	0	1	4	8	13	16	24	33	21	23	27	38	6
70	0	0	4	5	13	16	21	26	22	23	27	31	6
100	0	0	0	3	13	15	18	22	21	20	27	29	6
150	0	0	0	0	13	15	17	18	20	21	22	29	6
200	0	0	0	0	13	15	17	16	20	21	22	28	6
20	2	5	11	17	12	17	22	29	16	22	31	37	7
45	1	1	5	8	15	19	21	28	25	27	28	37	7
70	0	0	1	3	15	16	22	29	26	28	31	34	7
100	0	0	0	1	15	15	17	24	26	28	30	30	7
150	0	0	0	0	15	12	17	23	26	28	30	30	7
200	0	0	0	0	15	12	13	22	26	28	29	29	7
20	1	1	8	10	10	17	22	31	18	21	31	37	8
45	0	1	1	7	13	15	17	25	18	19	23	31	8
70	0	0	0	2	13	16	19	22	18	19	23	25	8
100	0	0	0	1	13	16	16	19	18	19	21	25	8
150	0	0	0	0	13	16	16	19	18	19	21	25	8
200	0	0	0	0	13	15	16	19	16	19	22	25	8
20	10	20	32	41	21	34	46	60	26	38	52	67	9
45	7	14	24	38	22	31	43	54	27	35	46	65	9
70	4	9	22	33	21	30	40	51	28	34	46	62	9
100	4	9	13	33	21	29	40	53	28	34	46	62	9
150	4	9	12	24	21	29	38	47	29	34	45	58	9
200	4	8	12	24	21	29	38	47	29	34	45	58	9
20	27	47	63	83	45	70	86	109	56	76	98	121	10
45	23	44	56	76	42	66	84	105	49	73	94	115	10
70	24	34	50	73	39	58	80	104	48	68	92	109	10
100	20	34	50	68	37	58	78	104	43	67	86	114	10
150	20	31	49	68	37	57	76	101	43	67	85	109	10
200	19	34	48	68	37	56	75	103	43	66	85	109	10
20	59	93	126	161	71	106	142	180	83	119	157	194	11
45	55	85	125	155	73	105	142	179	81	120	157	194	11
70	52	84	119	157	68	105	142	179	81	119	157	194	11
100	53	83	119	155	67	105	142	179	81	119	157	194	11
150	53	82	119	155	68	105	142	179	81	119	157	194	11
200	46	82	119	154	67	105	142	180	81	119	157	194	11
20	93	139	187	234	112	162	210	258	116	165	214	264	12
45	92	139	185	234	112	160	209	258	115	165	214	264	12
70	90	139	185	233	111	160	209	258	115	163	213	263	12
100	90	136	186	233	111	159	209	258	114	163	213	262	12
150	91	139	185	234	111	160	204	258	114	163	213	262	12
200	87	136	185	235	106	160	204	253	113	[illegible]	[illegible]	[illegible]	12

ZONE NO. 51

RAINFALL STATION 023678 ROBERTSON (TNK) LAT 33 48 LONG 19 53 ALTITUDE 183m 95 YEARS OF DATA

TEMPERATURE STATION ATS0004 ROBERTSON (NIVV) LAT 33 50 LONG 19 54 ALTITUDE 170m WIND REGION : 5

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 322.1mm	MEAN	14.7	18.2	21.5	29.9	34.3	37.6	32.6	37.6	30.7	26.3	22.8	15.1	322.0
	MEDN	7.9	8.1	18.0	22.5	27.3	33.1	28.6	30.5	24.9	21.6	16.1	5.3	313.0
	SDEV	22.8	24.6	17.6	26.0	25.7	24.2	20.4	27.0	22.0	22.5	22.6	25.2	86.0
	C.V.	154.9	135.4	81.7	87.0	74.9	64.5	62.7	72.0	71.6	85.3	99.3	166.7	26.0
	SKEW	3.9	2.5	1.1	1.9	1.3	0.8	0.8	1.4	1.0	2.1	1.4	3.8	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	30.5	30.3	28.5	25.3	21.7	19.2	18.8	19.1	21.6	24.5	26.9	29.4	
	MIN	15.5	15.8	14.4	11.3	8.0	5.8	5.0	6.0	7.9	10.3	12.6	14.4	

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	ESTIMATED IRRIGATION REQUIREMENT												
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	163	231	300	315	171	240	308	320	172	241	310	321	1
45	163	231	300	368	170	239	308	376	172	241	310	379	1
70	163	231	300	368	171	239	308	376	172	241	310	379	1
100	163	231	300	368	171	239	308	376	172	241	310	379	1
150	163	232	300	368	171	240	308	376	172	241	310	379	1
200	163	231	301	368	170	239	310	376	172	241	311	379	1
20	139	197	255	283	145	203	263	288	146	204	263	293	2
45	139	197	255	313	145	203	263	321	146	204	263	323	2
70	139	197	255	313	145	204	263	321	146	204	263	323	2
100	139	197	255	313	145	203	263	321	146	204	263	323	2
150	139	197	255	313	145	204	263	321	146	207	263	323	2
200	139	197	255	313	145	203	263	321	146	204	263	323	2
20	104	152	200	248	116	165	214	263	121	170	219	268	3
45	103	151	200	248	116	165	214	263	121	170	219	268	3
70	105	151	200	248	116	165	214	263	121	170	219	268	3
100	103	151	200	249	117	165	214	263	121	170	219	268	3
150	103	152	200	248	117	167	214	263	121	170	219	268	3
200	102	151	200	249	116	165	214	263	121	170	219	268	3
20	67	100	133	167	77	111	145	180	79	113	148	183	4
45	67	99	133	165	76	110	145	180	79	113	148	183	4
70	64	98	133	165	76	111	145	180	79	113	148	183	4
100	63	98	132	166	76	111	145	180	79	114	148	183	4
150	62	97	131	167	76	111	145	180	79	114	148	183	4
200	64	98	133	166	76	111	145	180	79	114	149	183	4
20	40	62	87	112	50	76	99	124	58	83	109	134	5
45	39	62	86	111	49	74	98	124	58	83	109	134	5
70	37	62	86	111	50	74	98	124	58	83	109	134	5
100	37	61	86	111	48	74	99	124	59	83	109	134	5
150	36	61	87	111	48	73	101	124	58	83	109	134	5
200	38	61	86	112	48	74	99	125	59	83	109	134	5
20	25	39	56	72	33	51	69	87	38	56	75	92	6
45	21	35	54	70	31	50	68	87	38	56	73	92	6
70	16	35	50	69	31	50	68	87	36	56	74	93	6
100	16	31	53	69	31	49	68	86	37	54	75	92	6
150	16	32	50	69	32	50	68	86	38	55	73	93	6
200	13	33	50	68	30	50	67	86	37	56	73	92	6
20	26	43	61	79	35	52	70	89	38	56	74	93	7
45	23	41	59	78	33	51	69	88	39	55	74	94	7
70	22	39	59	76	32	50	68	88	37	56	74	94	7
100	21	40	57	76	31	50	68	88	37	55	74	93	7
150	21	39	56	76	31	49	68	87	38	55	74	93	7
200	20	38	56	75	30	49	68	87	37	56	74	94	7
20	31	49	70	91	42	63	84	106	46	66	88	109	8
45	27	48	69	89	42	62	84	106	45	67	88	110	8
70	26	48	68	89	41	62	84	106	44	66	87	109	8
100	25	46	67	89	42	62	84	106	45	65	88	109	8
150	25	45	67	88	41	62	84	106	45	66	88	109	8
200	24	45	67	88	40	62	84	106	44	67	88	111	8
20	50	78	105	133	60	90	119	148	65	94	124	153	9
45	47	75	104	133	61	90	119	148	65	94	124	153	9
70	47	75	104	131	60	90	119	148	65	94	124	153	9
100	45	75	104	133	60	90	119	148	65	94	124	153	9
150	46	75	103	132	60	90	119	148	65	94	124	153	9
200	45	74	104	132	60	89	119	148	65	94	124	153	9
20	86	128	167	209	96	137	180	222	102	145	188	230	10
45	85	125	167	209	95	137	180	222	102	145	188	230	10
70	83	125	167	209	95	137	180	222	102	145	188	230	10
100	83	125	167	209	95	137	180	222	102	145	188	230	10
150	83	125	167	209	95	137	180	222	102	145	188	230	10
200	83	125	167	209	95	138	180	222	102	145	188	230	10
20	115	167	219	272	127	180	233	286	131	184	238	291	11
45	115	167	219	272	127	180	233	286	131	184	238	291	11
70	115	167	220	272	127	180	233	286	131	184	238	291	11
100	115	167	220	272	127	180	233	286	131	184	238	291	11
150	114	167	220	272	127	180	233	286	131	184	238	291	11
200	114	167	220	272	127	180	233	286	131	184	238	291	11
20	157	222	287	314	163	228	293	318	163	228	293	319	12
45	157	222	287	352	163	228	293	359	163	228	293	359	12
70	157	221	287	352	163	228	293	359	163	228	293	359	12
100	156	221	287	352	163	228	293	359	163	228	293	359	12
150	157	221	287	352	163	228	293	359	163	228	293	359	12
200	156	222	287	352	163	228	293	359	163	228	293	359	12

ZONE NO. 83

RAINFALL STATION 011132 ALBERTINIA (POL) LAT 34 12 LONG 21 36 ALTITUDE 168m 52 YEARS OF DATA

TEMPERATURE STATION ATS0099 WITTEKLIP LAT 34 12 LONG 21 50 ALTITUDE 167m WIND REGION : 7

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 438.4mm	MEAN	24.2	32.0	34.0	39.0	44.4	35.4	38.6	43.4	38.9	41.0	41.2	19.0	438.0
	MEDN	15.6	22.9	29.5	27.0	37.7	31.7	32.5	32.4	30.0	33.8	33.8	10.7	415.0
	SDEV	29.1	30.5	27.7	41.7	37.6	26.9	28.6	38.7	33.4	32.2	38.8	22.4	119.0
	C.V.	120.4	95.2	81.6	106.8	84.7	76.0	74.0	89.3	85.9	78.5	94.1	117.9	27.0
	SKEW	2.0	1.6	0.8	2.8	1.3	0.9	1.0	2.7	2.8	1.4	1.5	1.6	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	24.5	24.9	24.0	22.1	20.5	18.2	18.3	17.9	19.1	20.6	22.4	24.4	
	MIN	15.7	16.3	14.9	12.7	10.6	8.1	7.8	8.2	8.5	10.8	12.6	14.5	

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				
	CROP FACTOR				CROP FACTOR				CROP FACTOR				MTH
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	ESTIMATED IRRIGATION REQUIREMENT												
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	77	113	148	183	91	127	164	200	91	127	164	200	1
45	78	111	147	183	91	127	164	200	91	127	164	200	1
70	75	111	147	183	91	127	164	200	91	127	164	200	1
100	77	111	147	183	91	127	164	200	91	127	164	200	1
150	77	114	147	183	91	127	164	200	91	128	164	200	1
200	77	111	150	183	91	127	164	200	91	127	164	200	1
20	59	91	121	152	72	103	135	166	78	110	142	174	2
45	59	90	120	152	72	103	135	166	78	110	142	174	2
70	58	90	122	152	72	103	135	166	78	110	142	174	2
100	58	90	121	152	72	103	135	166	78	110	142	174	2
150	57	89	120	152	72	103	136	166	78	110	142	174	2
200	58	89	120	153	72	104	135	167	78	110	142	174	2
20	52	79	106	138	67	96	126	156	73	103	133	164	3
45	49	77	107	135	65	95	125	156	73	103	133	164	3
70	47	78	105	136	65	95	125	156	73	103	133	164	3
100	48	74	105	136	65	95	126	156	74	103	133	164	3
150	48	74	104	135	65	95	126	156	73	103	137	167	3
200	44	75	104	135	65	96	125	156	73	103	133	165	3
20	37	58	81	103	45	66	89	112	52	74	97	121	4
45	34	55	80	102	46	68	90	113	52	74	97	121	4
70	33	57	80	103	43	68	89	111	51	74	97	121	4
100	32	55	80	101	44	65	88	112	51	74	97	121	4
150	32	55	80	101	43	64	88	112	51	74	97	121	4
200	32	55	78	102	42	65	88	112	51	74	98	121	4
20	26	39	57	75	35	55	75	93	44	64	83	103	5
45	23	38	55	73	36	54	74	93	44	64	83	103	5
70	18	38	53	71	37	54	74	94	46	64	83	103	5
100	19	34	52	72	40	54	74	93	46	66	83	103	5
150	17	37	49	71	35	54	74	93	47	64	83	105	5
200	13	33	52	68	35	57	75	93	46	67	83	103	5
20	17	31	43	57	29	42	56	70	35	50	64	78	6
45	17	28	41	54	31	40	56	69	35	50	64	78	6
70	15	27	41	52	27	44	53	67	33	49	62	80	6
100	13	27	37	53	27	41	56	70	33	49	65	76	6
150	13	26	41	51	27	39	53	67	33	47	64	76	6
200	8	25	41	51	24	41	52	69	33	47	62	78	6
20	20	33	46	61	28	43	58	73	32	46	60	74	7
45	17	29	45	58	27	42	57	72	30	45	59	74	7
70	15	29	44	58	27	42	58	72	32	44	60	74	7
100	14	29	40	54	27	42	57	72	29	43	59	74	7
150	9	29	44	54	27	42	57	72	33	44	59	76	7
200	6	28	41	54	27	42	57	72	28	47	59	74	7
20	22	34	48	61	29	44	58	75	33	47	65	79	8
45	16	31	43	59	26	42	58	75	31	48	62	80	8
70	13	29	43	57	25	40	58	71	31	47	63	75	8
100	12	27	44	57	25	39	56	71	31	43	59	75	8
150	13	25	41	59	23	39	54	71	27	42	58	75	8
200	9	25	40	57	22	39	54	71	26	42	58	75	8
20	28	44	63	80	37	55	75	94	39	57	77	96	9
45	22	42	60	77	33	53	74	92	38	59	77	96	9
70	24	39	60	76	33	52	72	92	38	57	77	96	9
100	22	40	57	76	34	53	72	92	37	57	77	96	9
150	19	38	57	77	33	53	72	92	37	57	77	96	9
200	18	38	58	76	33	53	72	92	37	57	77	96	9
20	40	64	88	110	53	75	102	125	60	85	109	135	10
45	38	62	84	110	50	75	100	125	60	86	108	134	10
70	37	58	85	108	49	75	102	125	60	85	105	130	10
100	34	60	85	108	49	74	100	125	59	82	105	130	10
150	33	60	83	108	49	75	100	125	56	79	105	130	10
200	33	57	83	109	49	74	100	125	55	79	105	130	10
20	54	81	110	139	66	95	125	156	77	108	140	171	11
45	49	77	106	136	64	95	125	156	77	108	140	171	11
70	47	78	105	134	64	95	125	156	77	108	140	171	11
100	45	73	106	137	64	95	125	156	77	108	140	171	11
150	47	75	103	134	64	95	125	156	77	108	140	171	11
200	47	77	104	134	64	96	126	156	77	108	140	171	11
20	80	117	154	191	92	129	166	203	92	129	166	203	12
45	80	117	154	191	92	129	166	203	92	129	166	203	12
70	80	117	154	191	92	129	166	203	92	129	166	203	12
100	80	117	154	191	92	129	166	203	92	129	166	203	12
150	80	115	150	191	92	129	166	203	92	129	166	203	12
200	80	117	153	191	92	129	166	203	92	129	166	203	12

```
    ZONE NO. 92

    RAINFALL STATION  028335  OUDTSHOORN (TNK)     LAT 33 35 LONG 22 12 ALTITUDE  315m  94 YEARS OF DATA

 TEMPERATURE STATION 0028335A OUDTSHOORN            LAT 33 35 LONG 22 12 ALTITUDE  335m  WIND REGION :  7

                               JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC ANNUAL

RAINFALL (mm)          MEAN   15.0  18.1  28.0  23.8  23.6  18.0  16.8  21.1  21.8  21.3  22.4  15.1  242.0
 M.A.P.  242.2mm       MEDN    8.7  11.6  22.9  16.5  18.8  13.7  11.6  14.2  15.5  17.6  17.7   7.8  238.0
                       SDEV   18.0  20.1  23.6  21.6  23.2  16.2  14.6  18.9  23.5  15.3  20.8  18.2   68.0
                       C.V.  119.6 110.8  84.2  90.9  98.3  89.7  87.1  89.6 107.8  71.8  93.1 121.0   28.0
                       SKEW    2.5   1.7   1.0   1.6   2.0   2.1   1.6   1.6   2.8   0.7   1.5   1.8    0.0

      MONTHLY
MEAN TEMPERATURES      MAX    32.2  32.3  30.0  26.7  22.5  19.9  18.9  21.3  23.2  25.9  28.2  30.4
(DEGREES CELSIUS)      MIN    15.3  15.4  14.0  10.7   6.7   3.3   3.4   4.8   7.3   9.9  12.4  13.6

                                      ESTIMATED IRRIGATION REQUIREMENT
                                      --------------------------------

-------------------------------------------------------------------------------------------------------

*******************************************************************************************************
*P.A.M.*      50 TH PERCENTILE       **      80 TH PERCENTILE       **      90 TH PERCENTILE      **  *
*******************************************************************************************************
*      *          CROP FACTOR         *          CROP FACTOR         *          CROP FACTOR         * MTH*
* (mm) *  0.5     0.7     0.9    1.1  *  0.5     0.7     0.9    1.1  *  0.5     0.7     0.9    1.1  *    *
*******************************************************************************************************
                                      ESTIMATED IRRIGATION REQUIREMENT
*                                                                                                     *
*      *  (mm)    (mm)    (mm)   (mm) *  (mm)    (mm)    (mm)   (mm) *  (mm)    (mm)    (mm)   (mm) *    *
*******************************************************************************************************
*  20  *   144     206     267    311 *   153     215     277    317 *   155     217     279    318 *  1 *
*  45  *   144     206     267    329 *   153     215     277    339 *   155     217     279    341 *  1 *
*  70  *   145     206     267    329 *   153     215     277    339 *   155     217     279    341 *  1 *
* 100  *   144     206     267    329 *   153     215     277    339 *   155     217     279    341 *  1 *
* 150  *   144     206     267    329 *   153     215     277    339 *   155     217     279    341 *  1 *
* 200  *   144     206     267    329 *   153     215     277    339 *   155     217     279    341 *  1 *
*  20  *   117     169     220    272 *   126     178     230    281 *   129     181     233    283 *  2 *
*  45  *   117     169     220    273 *   126     178     230    282 *   129     181     233    285 *  2 *
*  70  *   117     169     220    273 *   126     178     230    282 *   129     181     233    285 *  2 *
* 100  *   117     169     220    273 *   126     178     230    282 *   129     181     233    285 *  2 *
* 150  *   117     169     220    273 *   127     178     230    282 *   129     181     233    285 *  2 *
* 200  *   117     169     220    273 *   126     178     230    282 *   129     181     233    285 *  2 *
*  20  *    95     140     185    231 *   109     156     203    250 *   114     161     208    255 *  3 *
*  45  *    94     139     184    231 *   109     156     203    250 *   114     161     208    255 *  3 *
*  70  *    92     138     185    231 *   109     156     203    250 *   114     161     208    255 *  3 *
* 100  *    93     138     184    231 *   109     156     203    250 *   114     161     208    255 *  3 *
* 150  *    92     138     184    232 *   110     156     203    250 *   114     161     209    256 *  3 *
* 200  *    91     139     185    231 *   109     156     203    251 *   114     161     208    255 *  3 *
*  20  *    69     103     136    170 *    78     112     146    181 *    82     117     151    185 *  4 *
*  45  *    69     103     136    171 *    78     112     146    181 *    82     117     151    185 *  4 *
*  70  *    69     102     137    171 *    78     112     146    181 *    82     117     151    185 *  4 *
* 100  *    68     102     136    171 *    78     112     146    181 *    82     117     151    185 *  4 *
* 150  *    68     102     136    171 *    78     112     146    181 *    82     117     151    186 *  4 *
* 200  *    68     102     137    171 *    78     112     146    181 *    83     116     151    185 *  4 *
*  20  *    47      70      95    119 *    56      81     107    132 *    60      86     111    136 *  5 *
*  45  *    44      70      93    118 *    56      81     106    132 *    60      86     111    136 *  5 *
*  70  *    44      69      94    118 *    56      82     106    132 *    60      86     111    136 *  5 *
* 100  *    47      70      94    119 *    56      81     107    132 *    61      86     111    136 *  5 *
* 150  *    44      68      93    119 *    56      81     107    132 *    60      86     111    136 *  5 *
* 200  *    44      68      93    119 *    56      81     106    133 *    60      86     111    137 *  5 *
*  20  *    35      54      73     92 *    41      60      79     98 *    45      64      83    103 *  6 *
*  45  *    35      54      73     92 *    41      60      79     98 *    45      64      83    102 *  6 *
*  70  *    35      54      73     92 *    41      60      79     98 *    45      64      83    102 *  6 *
* 100  *    35      54      73     92 *    41      60      79     98 *    45      64      83    103 *  6 *
* 150  *    34      54      73     92 *    41      60      79     99 *    45      64      83    103 *  6 *
* 200  *    35      54      73     92 *    41      60      79     98 *    46      65      83    103 *  6 *
*  20  *    36      54      73     93 *    41      60      79     99 *    43      62      82    100 *  7 *
*  45  *    35      55      73     92 *    41      60      79     99 *    43      62      81    101 *  7 *
*  70  *    35      54      73     92 *    41      61      79     99 *    42      62      81    101 *  7 *
* 100  *    35      54      73     93 *    41      60      79     99 *    42      62      82    101 *  7 *
* 150  *    36      54      73     92 *    41      60      79     98 *    43      62      81    100 *  7 *
* 200  *    35      55      73     92 *    41      61      79     98 *    42      64      82    100 *  7 *
*  20  *    50      74      99    125 *    56      81     107    132 *    60      86     111    137 *  8 *
*  45  *    50      74      99    125 *    56      81     107    132 *    60      86     111    137 *  8 *
*  70  *    49      74      99    125 *    56      81     107    132 *    60      86     111    137 *  8 *
* 100  *    49      74      99    125 *    56      81     107    132 *    61      86     111    137 *  8 *
* 150  *    50      75      99    125 *    56      81     107    132 *    61      86     111    137 *  8 *
* 200  *    49      74      99    125 *    56      82     107    132 *    60      86     111    137 *  8 *
*  20  *    66      97     129    162 *    75     107     139    172 *    79     111     143    176 *  9 *
*  45  *    65      97     129    162 *    75     107     139    172 *    78     111     143    176 *  9 *
*  70  *    65      97     129    162 *    75     107     139    172 *    78     111     143    176 *  9 *
* 100  *    65      98     129    162 *    75     107     139    172 *    78     111     144    176 *  9 *
* 150  *    65      97     129    162 *    75     107     139    173 *    80     111     143    177 *  9 *
* 200  *    66      97     129    162 *    75     107     139    172 *    80     111     143    176 *  9 *
*  20  *    92     136     178    222 *   103     146     190    234 *   109     153     198    242 * 10 *
*  45  *    92     135     178    222 *   103     146     190    234 *   109     153     198    242 * 10 *
*  70  *    92     135     179    222 *   103     146     190    234 *   109     153     198    242 * 10 *
* 100  *    91     136     179    223 *   102     146     190    234 *   109     153     198    242 * 10 *
* 150  *    91     135     181    223 *   102     145     191    234 *   109     153     198    242 * 10 *
* 200  *    91     135     179    225 *   102     145     189    236 *   109     153     198    242 * 10 *
*  20  *   116     167     219    271 *   126     179     231    284 *   129     182     235    287 * 11 *
*  45  *   114     168     219    271 *   126     179     231    284 *   129     182     235    287 * 11 *
*  70  *   114     167     219    271 *   126     179     231    284 *   129     182     235    287 * 11 *
* 100  *   114     166     219    271 *   126     179     231    284 *   129     182     235    287 * 11 *
* 150  *   114     166     219    271 *   126     179     231    284 *   131     182     235    287 * 11 *
* 200  *   114     167     219    271 *   126     179     231    284 *   129     182     235    287 * 11 *
*  20  *   137     196     254    308 *   146     205     263    314 *   147     206     265    316 * 12 *
*  45  *   137     196     254    313 *   146     205     263    322 *   147     206     265    324 * 12 *
*  70  *   137     196     254    313 *   146     205     263    322 *   147     206     265    324 * 12 *
* 100  *   137     196     254    313 *   146     205     263    322 *   147     206     265    324 * 12 *
* 150  *   137     196     254    313 *   146     205     263    322 *   147     206     265    324 * 12 *
* 200  *   137     196     254    313 *   146     205     263    322 *   147     206     265    324 * 12 *
*******************************************************************************************************
```

ZONE NO.297

RAINFALL STATION 284008 THORNLEA LAT 28 39 LONG 21 31 ALTITUDE 914m 77 YEARS OF DATA

TEMPERATURE STATION 0317474 UPINGTON LAT 28 24 LONG 21 16 ALTITUDE 825m WIND REGION : 7

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 199.3mm	MEAN	26.0	32.5	44.2	26.2	12.6	3.4	3.6	4.4	3.6	10.5	16.1	15.8	199.0
	MEDN	9.6	21.6	31.5	16.0	5.8	0.0	0.0	0.0	0.0	5.3	6.4	8.3	193.0
	SDEV	41.3	35.2	38.5	29.9	16.2	6.8	9.6	9.0	8.1	13.4	20.1	20.0	99.0
	C.V.	158.6	108.3	87.0	113.9	128.7	198.2	268.3	204.7	226.3	127.4	125.5	126.8	49.0
	SKEW	3.2	1.8	1.1	1.9	1.5	2.8	4.0	2.2	3.8	1.5	1.5	1.9	1.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	34.9	33.9	31.5	28.2	23.6	21.2	21.1	22.1	26.4	29.8	32.6	34.0	
	MIN	19.4	19.7	17.5	13.5	7.9	6.0	5.3	5.3	8.8	12.3	15.4	18.0	

ESTIMATED IRRIGATION REQUIREMENT

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	179	256	309	313	191	267	317	314	191	267	320	314	1
45	179	256	332	408	191	267	344	421	191	267	344	421	1
70	179	256	332	408	191	267	344	421	191	267	344	421	1
100	179	256	332	408	191	267	344	421	191	267	344	421	1
150	179	256	332	408	191	267	344	421	191	267	344	421	1
200	179	256	332	408	191	267	344	421	191	267	344	421	1
20	132	191	252	273	149	211	275	283	154	216	278	292	2
45	128	191	252	313	149	211	275	336	154	216	278	340	2
70	130	191	252	313	149	211	275	336	154	216	278	340	2
100	131	191	252	313	149	211	275	336	154	216	278	340	2
150	130	192	252	313	149	211	275	336	154	216	278	340	2
200	130	191	253	313	151	211	275	336	158	216	278	340	2
20	112	165	220	276	128	184	241	296	137	194	251	307	3
45	111	167	219	276	128	184	241	297	137	194	251	308	3
70	108	166	218	276	128	184	241	297	137	194	251	308	3
100	109	164	219	274	128	184	241	297	138	195	251	308	3
150	107	166	222	274	128	185	241	297	137	194	251	308	3
200	111	162	222	275	128	185	241	297	137	194	251	308	3
20	91	132	174	216	104	148	191	234	108	151	194	237	4
45	91	132	174	217	104	148	191	234	108	151	194	237	4
70	89	131	174	216	104	148	191	234	108	151	194	237	4
100	91	132	174	216	105	148	191	234	108	151	194	237	4
150	89	131	174	216	105	148	192	234	108	151	194	237	4
200	89	131	174	216	104	149	191	234	108	151	194	237	4
20	74	103	135	167	80	112	145	177	80	112	145	177	5
45	74	106	136	167	80	112	145	177	80	112	145	177	5
70	71	106	135	167	80	112	145	177	80	112	145	177	5
100	74	103	136	167	80	112	145	177	80	112	145	177	5
150	71	106	135	169	80	112	145	177	80	112	145	177	5
200	74	103	138	167	80	112	145	177	80	112	145	177	5
20	66	92	119	146	66	92	119	146	66	92	119	146	6
45	66	92	119	146	66	92	119	146	66	92	119	146	6
70	66	92	119	146	66	92	119	146	66	92	119	146	6
100	66	92	119	146	66	92	119	146	66	92	119	146	6
150	66	92	119	146	66	92	119	146	66	92	119	146	6
200	66	92	119	146	66	92	119	147	66	92	119	147	6
20	69	96	124	152	69	96	124	152	69	96	124	152	7
45	69	96	124	152	69	96	124	152	69	96	124	152	7
70	69	96	124	152	69	96	124	152	69	96	124	152	7
100	69	96	124	152	69	96	124	152	69	96	124	153	7
150	69	96	124	152	69	96	124	152	69	96	124	152	7
200	69	96	124	152	69	96	124	152	69	96	124	152	7
20	81	114	146	179	81	114	146	179	81	114	146	179	8
45	81	114	146	179	81	114	146	179	81	114	146	179	8
70	81	114	146	179	81	114	146	179	81	114	146	179	8
100	81	114	146	179	81	114	146	179	81	114	146	179	8
150	81	114	146	179	81	114	151	179	81	114	151	179	8
200	81	114	146	179	81	114	146	179	81	114	146	179	8
20	112	158	203	248	112	158	203	248	112	158	203	248	9
45	112	158	203	248	112	158	203	248	112	158	203	248	9
70	112	158	203	248	112	158	203	248	112	158	203	248	9
100	112	158	203	248	112	158	203	248	112	158	203	248	9
150	112	158	203	248	112	158	203	248	112	158	203	248	9
200	112	158	203	248	112	158	203	248	112	158	203	248	9
20	148	209	270	314	153	214	275	321	153	214	275	321	10
45	148	209	270	331	153	214	275	336	153	214	275	336	10
70	148	209	270	331	153	214	275	336	153	214	275	336	10
100	148	209	270	331	153	214	275	336	153	214	275	336	10
150	148	209	270	331	153	214	275	336	153	214	275	336	10
200	148	209	270	331	153	214	275	336	153	214	275	336	10
20	172	244	302	307	181	254	305	309	181	254	308	311	11
45	172	244	316	389	181	254	326	399	181	254	326	399	11
70	172	244	316	389	181	254	326	399	181	254	326	399	11
100	172	244	316	389	181	254	326	399	181	254	326	399	11
150	172	244	316	389	181	254	326	399	181	254	326	399	11
200	172	244	316	389	181	254	326	399	181	254	326	399	11
20	181	257	311	314	191	267	316	314	191	267	320	317	12
45	181	257	333	409	191	267	344	420	191	267	344	420	12
70	181	257	333	409	191	267	344	420	191	267	344	420	12
100	181	257	333	409	191	267	344	420	191	267	344	420	12
150	181	257	333	409	191	267	344	420	191	267	344	420	12
200	181	257	333	410	191	267	344	420	191	267	344	420	12

```
   ZONE NO.442

   RAINFALL STATION   432387   VRYBURG (POL)        LAT 26 58 LONG 24 44 ALTITUDE 1190m  65 YEARS OF DATA

TEMPERATURE STATION 0432387   VRYBURG (POL)         LAT 26 57 LONG 24 43 ALTITUDE 1190m  WIND REGION :  4
                                 JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC ANNUAL

RAINFALL (mm)            MEAN   92.0  76.6  75.8  39.9  15.0   7.2   4.8   6.7   8.5  26.5  41.3  67.1  463.0
 M.A.P. . 463.4mm        MEDN   77.9  71.3  62.8  31.0   6.5   0.5   0.0   0.0   0.9  16.8  33.0  66.8  460.0
                         SDEV   65.7  43.9  53.9  38.1  21.9  13.5  13.4  13.2  14.1  25.5  31.8  45.2  136.0
                         C.V.   71.4  57.3  71.2  95.5 146.4 188.0 278.3 196.1 166.5  96.3  77.0  67.3   29.0
                         SKEW    1.2   0.4   1.0   1.2   2.3   2.4   4.5   2.6   2.0   1.3   1.1   0.5    0.0

     MONTHLY
MEAN TEMPERATURES        MAX    32.6  30.7  28.4  25.7  22.4  19.6  19.2  22.6  25.9  29.7  30.5  31.8
(DEGREES CELSIUS)        MIN    17.2  16.2  14.2   9.7   4.2   0.1  -0.6   2.3   6.7  12.2  14.4  16.4
                                       ESTIMATED IRRIGATION REQUIREMENT
                                       --------------------------------

-------------------------------------------------------------------------------------------------------

*******************************************************************************************************
*P.A.M.*      50 TH PERCENTILE       **       80 TH PERCENTILE       **       90 TH PERCENTILE      **    *
*******************************************************************************************************
*      *          CROP FACTOR           *          CROP FACTOR           *          CROP FACTOR         * MTH*
* (mm) *   0.5    0.7    0.9    1.1     *   0.5    0.7    0.9    1.1     *   0.5    0.7    0.9    1.1   *    *
*******************************************************************************************************
                                       ESTIMATED IRRIGATION REQUIREMENT
*                                                                                                      *
*      *  (mm)   (mm)   (mm)   (mm)     *  (mm)   (mm)   (mm)   (mm)     *  (mm)   (mm)   (mm)   (mm)   *    *
*******************************************************************************************************
*  20  *   106    164    226    265     *   124    184    247    287     *   139    201    265    305   *  1 *
*  45  *   104    162    221    284     *   125    183    247    311     *   138    202    265    329   *  1 *
*  70  *   100    159    221    283     *   122    183    247    311     *   137    201    265    329   *  1 *
* 100  *    99    161    222    284     *   120    183    247    310     *   138    201    265    329   *  1 *
* 150  *    96    159    221    283     *   120    183    246    311     *   137    201    265    329   *  1 *
* 200  *    96    159    223    284     *   120    184    246    310     *   137    202    266    329   *  1 *
*  20  *    75    118    162    207     *    93    142    192    240     *   105    154    203    253   *  2 *
*  45  *    68    114    160    207     *    91    142    192    240     *   105    155    203    253   *  2 *
*  70  *    67    112    161    206     *    92    142    192    241     *   105    154    203    253   *  2 *
* 100  *    63    110    156    207     *    94    141    191    241     *   105    155    203    253   *  2 *
* 150  *    65    106    158    205     *    92    142    191    241     *   105    154    203    253   *  2 *
* 200  *    63    106    156    207     *    92    141    192    241     *   107    153    204    253   *  2 *
*  20  *    64    103    143    185     *    84    127    165    209     *    96    141    186    231   *  3 *
*  45  *    59    100    141    186     *    79    127    167    209     *    96    141    186    231   *  3 *
*  70  *    57     98    141    185     *    82    121    165    209     *   101    141    186    231   *  3 *
* 100  *    57     97    142    183     *    76    119    165    209     *    96    141    186    231   *  3 *
* 150  *    54     94    138    183     *    74    120    165    209     *    96    141    186    231   *  3 *
* 200  *    53     96    138    184     *    75    120    165    209     *    96    141    186    231   *  3 *
*  20  *    64     97    130    164     *    82    117    152    185     *    86    121    156    192   *  4 *
*  45  *    59     95    130    162     *    82    117    152    185     *    86    121    156    192   *  4 *
*  70  *    61     94    127    162     *    81    116    150    185     *    86    121    156    192   *  4 *
* 100  *    59     93    129    162     *    82    117    150    185     *    86    121    156    192   *  4 *
* 150  *    59     92    129    161     *    82    116    150    185     *    86    121    156    192   *  4 *
* 200  *    59     94    128    161     *    80    115    152    186     *    86    121    157    192   *  4 *
*  20  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
*  45  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
*  70  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
* 100  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
* 150  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
* 200  *    61     89    116    144     *    69     96    124    152     *    69     96    124    152   *  5 *
*  20  *    54     76     98    120     *    54     76     98    120     *    54     76     98    120   *  6 *
*  45  *    54     76     98    120     *    55     76     98    120     *    55     76     98    120   *  6 *
*  70  *    54     76     98    120     *    54     76     98    120     *    54     76     98    120   *  6 *
* 100  *    54     76     98    120     *    54     76     98    123     *    54     76     98    123   *  6 *
* 150  *    54     76     98    120     *    54     76     98    120     *    54     76     98    120   *  6 *
* 200  *    54     76     98    120     *    54     76     98    120     *    54     76     98    120   *  6 *
*  20  *    58     81    104    127     *    58     81    104    127     *    58     81    104    127   *  7 *
*  45  *    58     81    104    127     *    58     81    104    127     *    58     81    104    127   *  7 *
*  70  *    58     81    104    127     *    58     81    104    127     *    58     81    104    127   *  7 *
* 100  *    58     81    104    127     *    58     81    104    127     *    58     81    104    127   *  7 *
* 150  *    58     81    104    127     *    58     81    104    133     *    58     81    104    133   *  7 *
* 200  *    58     81    104    127     *    58     81    104    127     *    62     81    104    127   *  7 *
*  20  *    82    115    148    180     *    82    115    148    180     *    82    115    148    180   *  8 *
*  45  *    82    115    148    180     *    82    115    148    180     *    82    115    148    180   *  8 *
*  70  *    82    115    148    180     *    84    115    148    180     *    84    115    148    180   *  8 *
* 100  *    82    115    148    180     *    82    115    148    180     *    82    115    148    180   *  8 *
* 150  *    82    115    148    180     *    82    115    148    184     *    82    115    148    184   *  8 *
* 200  *    82    115    148    180     *    82    115    148    180     *    82    115    148    180   *  8 *
*  20  *   106    149    192    235     *   107    150    193    236     *   107    150    193    236   *  9 *
*  45  *   106    149    192    234     *   107    150    193    236     *   107    150    193    236   *  9 *
*  70  *   106    149    191    234     *   107    150    193    236     *   107    150    193    236   *  9 *
* 100  *   105    148    191    234     *   107    150    193    236     *   107    150    193    236   *  9 *
* 150  *   105    148    192    234     *   107    150    193    236     *   107    150    193    236   *  9 *
* 200  *   105    148    191    236     *   107    150    193    236     *   107    150    193    236   *  9 *
*  20  *   126    183    239    293     *   140    197    255    310     *   144    202    260    312   * 10 *
*  45  *   125    182    239    296     *   140    197    255    313     *   144    202    260    317   * 10 *
*  70  *   125    182    239    296     *   140    197    255    313     *   144    202    260    317   * 10 *
* 100  *   126    182    239    297     *   140    197    255    313     *   144    202    260    317   * 10 *
* 150  *   125    182    239    296     *   140    197    255    313     *   144    202    260    317   * 10 *
* 200  *   125    182    239    296     *   140    197    255    313     *   144    202    260    317   * 10 *
*  20  *   120    177    235    280     *   139    199    258    296     *   146    205    266    303   * 11 *
*  45  *   118    177    236    295     *   139    199    260    319     *   146    205    266    326   * 11 *
*  70  *   117    177    236    296     *   137    198    260    319     *   144    205    266    326   * 11 *
* 100  *   117    176    237    296     *   139    198    258    319     *   144    205    266    326   * 11 *
* 150  *   119    176    237    296     *   139    198    258    319     *   146    206    266    326   * 11 *
* 200  *   117    175    236    296     *   137    200    258    321     *   144    205    267    326   * 11 *
*  20  *   120    181    243    273     *   150    215    283    304     *   156    224    292    313   * 12 *
*  45  *   115    179    243    309     *   148    215    284    351     *   156    224    292    360   * 12 *
*  70  *   116    176    244    309     *   149    216    284    351     *   156    224    292    360   * 12 *
* 100  *   113    177    244    310     *   148    216    284    351     *   156    225    292    360   * 12 *
* 150  *   113    177    244    310     *   149    216    284    352     *   156    225    292    360   * 12 *
* 200  *   111    178    244    310     *   147    216    284    352     *   156    224    292    360   * 12 *
*******************************************************************************************************
```

ZONE NO.518

RAINFALL STATION 479545 KARINA LAT 26 05 LONG 29 50 ALTITUDE 1648m 59 YEARS OF DATA

TEMPERATURE STATION 0480184A CAROLINA (TNK) LAT 26 04 LONG 30 07 ALTITUDE 1692m WIND REGION : 1

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 645.1mm	MEAN	118.2	81.3	67.8	41.5	15.7	7.1	7.9	8.2	23.7	64.5	111.8	107.6	645.0
	MEDN	115.9	69.0	59.3	32.0	10.9	0.1	1.0	0.4	14.6	49.6	112.6	109.0	706.0
	SDEV	64.0	54.3	42.2	33.7	19.0	16.3	14.5	14.0	26.7	47.7	62.7	57.0	233.0
	C.V.	54.2	66.9	62.3	81.2	121.6	229.5	184.0	172.0	112.2	73.9	56.1	52.9	36.0
	SKEW	0.8	0.8	0.7	0.9	2.1	3.7	2.5	2.6	1.4	1.2	0.4	0.6	0.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	24.3	23.7	23.0	20.5	18.9	16.5	16.6	19.0	22.1	23.2	22.8	24.0	
	MIN	13.5	13.0	12.1	8.7	5.2	2.7	2.4	5.1	8.0	10.1	11.6	12.6	

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	ESTIMATED IRRIGATION REQUIREMENT												
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	36	67	103	141	60	94	134	174	67	107	145	188	1
45	32	62	100	138	51	91	131	173	67	107	145	187	1
70	26	58	93	137	49	89	129	173	66	108	146	186	1
100	20	58	93	132	49	87	131	168	67	104	147	186	1
150	14	50	92	134	47	86	126	168	58	108	152	185	1
200	12	52	92	131	47	89	129	170	61	101	144	192	1
20	49	75	109	139	66	98	133	168	74	110	147	183	2
45	41	74	102	135	64	97	134	165	76	112	147	183	2
70	37	68	98	128	64	95	132	164	74	114	147	178	2
100	39	68	98	129	63	93	131	164	74	111	146	178	2
150	34	65	96	134	61	93	127	166	74	110	147	178	2
200	30	59	98	129	58	95	127	164	76	110	146	183	2
20	53	81	115	147	64	97	129	164	72	108	143	179	3
45	47	77	108	141	64	94	129	162	72	108	143	179	3
70	43	77	106	144	59	94	129	162	72	108	143	179	3
100	39	71	106	142	58	93	129	162	72	108	143	179	3
150	41	71	105	141	58	93	127	164	72	108	143	179	3
200	37	71	103	140	58	94	127	161	72	109	143	179	3
20	46	70	96	124	60	86	113	141	63	91	120	148	4
45	41	69	95	122	57	85	113	141	63	92	118	148	4
70	40	65	93	122	57	85	113	141	64	91	118	147	4
100	39	66	93	120	57	85	113	141	63	90	118	147	4
150	38	65	93	121	57	85	113	141	63	91	118	148	4
200	38	65	92	120	57	85	113	141	63	91	118	148	4
20	51	74	98	122	59	83	108	132	60	84	109	133	5
45	50	74	97	122	59	83	107	132	60	84	109	133	5
70	50	73	98	122	59	83	108	132	60	84	109	133	5
100	50	73	97	121	59	84	108	132	60	84	109	133	5
150	50	73	98	122	59	83	108	133	60	84	109	133	5
200	51	74	97	122	60	84	107	133	60	84	109	133	5
20	48	67	87	106	48	67	87	106	48	67	87	106	6
45	48	67	87	106	48	67	87	106	48	67	87	106	6
70	48	67	87	106	48	67	87	106	48	67	87	106	6
100	48	67	87	106	48	67	87	106	48	67	87	106	6
150	48	67	87	106	48	67	87	107	48	67	87	108	6
200	48	67	87	106	48	67	87	106	49	67	87	106	6
20	51	71	91	112	51	71	92	112	51	71	92	112	7
45	51	71	90	111	51	71	92	112	51	71	92	112	7
70	50	71	90	112	51	71	92	112	51	71	92	112	7
100	50	70	92	111	51	71	92	112	51	71	92	112	7
150	51	70	90	111	51	71	92	112	51	71	92	112	7
200	51	70	90	111	65	71	92	112	65	71	92	112	7
20	67	95	122	149	67	95	122	149	67	95	122	149	8
45	67	95	122	149	67	95	122	149	67	95	122	149	8
70	67	95	122	149	67	95	122	149	67	95	122	149	8
100	67	95	122	149	67	95	122	149	67	95	122	149	8
150	67	95	122	149	67	95	122	149	67	95	122	149	8
200	67	95	122	149	80	95	122	149	80	95	122	149	8
20	73	107	141	176	87	121	156	191	87	122	157	191	9
45	75	109	142	176	87	120	156	191	87	122	157	191	9
70	75	107	141	176	87	120	156	191	87	122	157	191	9
100	72	110	141	176	87	121	155	191	87	122	157	191	9
150	75	107	141	177	86	122	155	191	87	122	157	191	9
200	72	107	141	176	87	121	156	190	87	122	157	191	9
20	64	102	141	181	82	122	162	202	88	129	170	211	10
45	61	100	140	181	82	122	161	202	88	129	170	211	10
70	62	99	139	180	82	120	161	201	88	129	170	211	10
100	61	100	140	179	80	121	163	201	88	129	170	211	10
150	60	100	139	179	81	122	161	202	88	132	170	211	10
200	61	99	140	181	80	122	161	202	88	129	170	213	10
20	40	70	102	141	62	97	136	176	67	104	144	183	11
45	29	65	101	135	60	96	137	176	65	105	144	183	11
70	29	60	101	133	57	95	136	175	63	103	144	183	11
100	22	60	100	135	58	95	135	174	65	103	143	183	11
150	20	56	97	134	56	96	136	174	63	103	143	184	11
200	19	58	96	136	55	93	136	174	63	103	144	184	11
20	38	70	99	139	54	91	130	170	63	106	146	188	12
45	32	60	95	130	53	83	127	169	64	102	145	188	12
70	21	55	94	128	46	86	125	166	60	105	145	188	12
100	21	52	91	124	48	86	127	169	60	104	146	187	12
150	12	48	86	125	46	85	127	168	65	103	145	188	12
200	12	43	86	127	45	86	125	168	60	103	144	188	12

```
     ZONE NO.543

     RAINFALL STATION SUG0155  PONGOLA              LAT 27 25  LONG 31 31 ALTITUDE  290m  45 YEARS OF DATA

  TEMPERATURE STATION RES0041  MAGUT                 LAT 27 35 LONG 31 40 ALTITUDE  329m  WIND REGION :  3

                               JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC ANNUAL

 RAINFALL (mm)           MEAN 115.7  82.6  65.9  43.5  26.1  11.1  11.2  13.7  37.1  71.8  98.4  98.0  675.0
  M.A.P.  675.2mm        MEDN 107.4  75.5  64.5  38.4   9.6   0.8   2.0   5.1  26.3  59.4  93.0  83.3  639.0
                         SDEV  95.0  57.2  43.8  40.4  32.6  20.2  21.3  20.6  41.8  44.1  51.0  59.9  179.0
                         C.V.  82.1  69.3  66.5  92.9 124.8 182.3 190.6 150.7 112.5  61.4  51.8  61.1   26.0
                         SKEW   2.7   0.9   0.8   2.3   1.3   2.1   2.3   2.3   1.9   1.7   1.0   0.6    0.0

     MONTHLY
 MEAN TEMPERATURES       MAX   30.3  30.6  29.4  27.4  25.7  24.4  23.9  24.8  26.4  28.0  29.3  30.1
 (DEGREES CELSIUS)       MIN   18.7  17.8  15.9  13.9  10.9   8.1   7.7   9.8  12.9  15.5  17.2  18.3

                                    ESTIMATED IRRIGATION REQUIREMENT
                                    --------------------------------

 ------------------------------------------------------------------------------------------------------

 ******************************************************************************************************
 *P.A.M.*      50 TH PERCENTILE        **       80 TH PERCENTILE        **      90 TH PERCENTILE     **   *
 ******************************************************************************************************
 *      *          CROP FACTOR         *          CROP FACTOR          *         CROP FACTOR         * MTH*
 * (mm) *  0.5    0.7    0.9    1.1    *  0.5    0.7    0.9    1.1     *  0.5    0.7    0.9    1.1   *    *
 ******************************************************************************************************
                                    ESTIMATED IRRIGATION REQUIREMENT
 *                                                                                                     *
 *      *  (mm)   (mm)   (mm)   (mm)  *  (mm)   (mm)   (mm)   (mm)   *  (mm)   (mm)   (mm)   (mm)  *    *
 ******************************************************************************************************
 *  20  *   47     80    119    155   *   71    110    153    196    *   91    135    180    224   *  1 *
 *  45  *   38     65    118    147   *   72    111    153    198    *   91    135    180    224   *  1 *
 *  70  *   32     73    112    148   *   68    110    155    196    *   91    135    180    224   *  1 *
 * 100  *   34     65    104    140   *   68    113    155    198    *   91    135    180    224   *  1 *
 * 150  *   15     60     98    144   *   68    112    157    197    *   91    135    180    224   *  1 *
 * 200  *   21     55    104    141   *   68    109    156    201    *   91    135    181    224   *  1 *
 *  20  *   44     75    107    142   *   74    114    148    186    *   85    123    161    199   *  2 *
 *  45  *   45     70    105    139   *   77    111    148    186    *   85    123    161    199   *  2 *
 *  70  *   40     70    105    143   *   73    112    148    186    *   85    123    161    199   *  2 *
 * 100  *   33     66    104    142   *   77    111    150    186    *   85    123    161    199   *  2 *
 * 150  *   32     67    100    139   *   73    111    148    186    *   85    123    161    199   *  2 *
 * 200  *   28     61    104    137   *   73    111    149    186    *   85    123    161    199   *  2 *
 *  20  *   57     88    116    147   *   71    106    142    178    *   80    113    148    184   *  3 *
 *  45  *   47     83    106    142   *   71    106    142    178    *   78    114    146    182   *  3 *
 *  70  *   43     73    108    144   *   71    106    142    178    *   77    115    148    181   *  3 *
 * 100  *   46     70    107    143   *   71    106    142    178    *   76    108    148    188   *  3 *
 * 150  *   30     73    102    137   *   71    106    142    178    *   76    108    148    181   *  3 *
 * 200  *   30     71    111    135   *   71    106    141    178    *   75    110    145    181   *  3 *
 *  20  *   49     74     98    123   *   58     88    117    146    *   64     93    122    152   *  4 *
 *  45  *   44     69     94    123   *   59     88    117    146    *   64     93    122    152   *  4 *
 *  70  *   45     67     94    122   *   58     88    117    146    *   64     93    122    152   *  4 *
 * 100  *   37     66     94    121   *   59     88    117    146    *   64     93    122    152   *  4 *
 * 150  *   34     66     89    124   *   58     88    117    146    *   64     93    122    152   *  4 *
 * 200  *   37     65     88    116   *   58     88    117    146    *   64     93    122    152   *  4 *
 *  20  *   49     73     99    122   *   61     85    110    135    *   61     85    110    135   *  5 *
 *  45  *   50     73     97    122   *   61     85    110    135    *   61     85    110    135   *  5 *
 *  70  *   49     73     99    122   *   61     85    110    135    *   61     85    110    135   *  5 *
 * 100  *   49     74     97    122   *   61     85    110    135    *   61     85    110    135   *  5 *
 * 150  *   52     73     97    123   *   61     85    110    135    *   61     85    110    135   *  5 *
 * 200  *   48     73     97    122   *   61     85    110    135    *   61     85    110    135   *  5 *
 *  20  *   50     70     91    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 *  45  *   50     70     91    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 *  70  *   50     71     91    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 * 100  *   50     70     92    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 * 150  *   51     70     91    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 * 200  *   51     71     91    112   *   52     72     93    114    *   52     72     93    114   *  6 *
 *  20  *   52     74     96    118   *   54     76     98    120    *   54     76     98    120   *  7 *
 *  45  *   52     74     96    118   *   54     76     98    120    *   54     76     98    120   *  7 *
 *  70  *   52     74     96    118   *   54     76     98    120    *   54     76     98    120   *  7 *
 * 100  *   52     74     96    118   *   54     76     98    120    *   54     76     98    120   *  7 *
 * 150  *   52     74     96    118   *   54     76     98    120    *   54     76     98    120   *  7 *
 * 200  *   53     74     96    118   *   56     76     98    120    *   58     76     98    120   *  7 *
 *  20  *   58     82    110    134   *   65     92    118    144    *   65     92    118    144   *  8 *
 *  45  *   55     81    108    134   *   65     92    118    144    *   65     92    118    144   *  8 *
 *  70  *   55     81    108    134   *   65     92    118    144    *   65     92    118    144   *  8 *
 * 100  *   59     81    108    135   *   65     92    118    144    *   65     92    118    144   *  8 *
 * 150  *   55     82    108    134   *   65     92    118    144    *   65     92    118    144   *  8 *
 * 200  *   55     86    108    134   *   65     92    118    144    *   66     92    118    144   *  8 *
 *  20  *   64     93    125    156   *   76    108    140    172    *   78    110    142    174   *  9 *
 *  45  *   61     93    125    156   *   76    108    140    172    *   78    110    142    174   *  9 *
 *  70  *   59     92    125    155   *   76    108    140    172    *   78    110    142    174   *  9 *
 * 100  *   60     92    124    156   *   76    108    140    172    *   78    110    142    174   *  9 *
 * 150  *   62     92    123    156   *   76    108    140    172    *   78    110    142    174   *  9 *
 * 200  *   60     92    123    155   *   76    108    140    172    *   78    110    142    174   *  9 *
 *  20  *   61     94    130    162   *   73    111    150    189    *   79    117    156    194   * 10 *
 *  45  *   59     92    127    158   *   73    111    150    189    *   78    117    156    194   * 10 *
 *  70  *   50     90    122    158   *   73    111    150    189    *   78    117    156    196   * 10 *
 * 100  *   56     87    124    161   *   76    111    150    189    *   84    117    156    194   * 10 *
 * 150  *   48     86    120    160   *   74    111    150    189    *   78    117    156    194   * 10 *
 * 200  *   46     84    121    159   *   73    111    150    189    *   78    117    156    199   * 10 *
 *  20  *   52     80    121    157   *   65    105    140    179    *   79    120    162    204   * 11 *
 *  45  *   43     76    117    158   *   60    100    140    181    *   78    120    162    204   * 11 *
 *  70  *   45     76    117    157   *   56     99    142    181    *   79    120    162    204   * 11 *
 * 100  *   37     78    116    153   *   60    101    140    178    *   78    120    162    204   * 11 *
 * 150  *   27     76    116    158   *   56     95    138    178    *   79    120    163    204   * 11 *
 * 200  *   23     68    116    148   *   54     96    141    183    *   78    121    162    204   * 11 *
 *  20  *   58     99    139    178   *   75    114    161    203    *   86    124    167    211   * 12 *
 *  45  *   53     87    132    175   *   72    107    158    196    *   81    123    166    210   * 12 *
 *  70  *   50     87    133    171   *   69    111    152    198    *   78    124    167    210   * 12 *
 * 100  *   54     80    128    172   *   76    116    157    201    *   78    121    166    210   * 12 *
 * 150  *   41     92    125    176   *   63    110    161    205    *   77    121    166    210   * 12 *
 * 200  *   39     82    127    169   *   71    109    152    198    *   77    121    165    210   * 12 *
 ******************************************************************************************************
```

ZONE NO.594

RAINFALL STATION 633393 ZAAIPLAATS — LAT 24 04 LONG 28 42 ALTITUDE 1204m 56 YEARS OF DATA

TEMPERATURE STATION ATS0433 VAALWATER — LAT 24 17 LONG 28 03 ALTITUDE 1200m WIND REGION : 1

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 653.4mm	MEAN	120.3	103.6	76.4	42.5	14.3	5.4	4.4	4.6	16.1	44.6	93.8	116.5	653.0
	MEDN	101.9	80.0	65.1	32.7	6.5	0.0	0.0	0.0	5.1	38.8	89.5	103.5	670.0
	SDEV	81.1	71.2	48.6	38.2	18.9	13.9	12.1	10.5	23.0	36.1	53.0	63.1	146.0
	C.V.	67.4	68.8	63.6	90.0	132.0	258.2	273.6	229.6	142.4	81.0	56.5	54.2	22.0
	SKEW	1.9	0.9	0.7	1.4	2.1	3.3	3.3	2.8	1.8	1.4	0.8	0.7	0.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	29.3	29.1	29.2	25.3	23.0	21.3	20.7	23.5	25.9	28.8	28.6	29.4	
	MIN	15.3	16.3	13.8	9.7	5.5	3.8	2.9	7.1	9.5	12.7	14.4	14.6	

ESTIMATED IRRIGATION REQUIREMENT

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	53	90	131	171	74	115	159	199	82	125	169	213	1
45	50	86	128	168	69	110	156	199	78	122	168	211	1
70	46	83	125	169	69	110	153	202	74	118	167	211	1
100	40	78	124	167	65	112	154	198	72	119	164	210	1
150	39	78	121	164	63	109	153	201	71	118	163	211	1
200	37	67	125	160	64	107	153	201	71	116	164	211	1
20	53	86	121	161	65	103	142	182	78	118	153	195	2
45	51	83	119	159	65	101	142	181	73	109	150	192	2
70	42	77	119	157	63	101	142	181	70	110	157	191	2
100	40	79	118	154	65	100	140	179	72	109	151	191	2
150	39	75	115	157	58	101	141	179	70	110	152	192	2
200	39	71	115	152	58	98	140	181	70	111	152	194	2
20	62	97	131	169	80	121	160	201	84	126	167	209	3
45	56	88	127	168	80	121	162	204	85	125	165	209	3
70	50	91	127	165	80	120	162	204	84	125	165	208	3
100	49	88	127	167	79	120	162	204	83	125	165	207	3
150	45	87	126	169	79	120	162	202	83	123	165	209	3
200	46	86	126	165	78	118	162	204	83	123	165	208	3
20	56	86	115	145	69	99	131	162	74	104	134	165	4
45	55	83	111	144	69	100	131	162	71	104	134	165	4
70	55	77	110	142	68	99	131	162	72	102	134	165	4
100	51	81	110	142	68	99	131	161	71	102	134	165	4
150	51	84	110	142	68	99	131	161	71	102	134	165	4
200	49	77	112	143	67	99	131	161	70	102	133	165	4
20	58	84	110	137	65	91	117	144	66	92	119	145	5
45	58	83	110	137	64	90	117	144	66	92	119	145	5
70	58	83	110	136	65	91	117	144	66	92	119	145	5
100	57	84	110	137	65	90	117	144	66	92	119	145	5
150	58	83	110	136	64	91	117	144	66	92	119	145	5
200	58	83	110	137	65	90	117	144	66	92	119	145	5
20	56	78	101	123	56	78	101	123	56	78	101	123	6
45	56	78	101	123	56	78	101	123	56	78	101	123	6
70	56	78	101	123	56	78	101	123	56	78	101	123	6
100	56	78	101	123	56	78	101	123	56	79	101	123	6
150	56	78	101	123	56	78	101	123	56	78	101	123	6
200	56	78	101	123	56	78	101	123	56	78	101	123	6
20	57	79	102	125	57	79	102	125	57	79	102	125	7
45	57	79	102	125	57	79	102	125	57	79	102	125	7
70	57	79	102	125	59	79	103	125	59	79	103	125	7
100	57	79	102	125	57	79	102	125	57	79	102	125	7
150	57	79	102	125	57	79	102	129	57	79	102	129	7
200	57	79	102	125	57	79	102	125	57	79	102	125	7
20	77	108	139	170	77	108	139	170	77	108	139	170	8
45	77	108	139	170	77	108	139	170	77	108	139	170	8
70	77	108	139	170	77	108	140	170	77	108	140	170	8
100	77	108	139	170	77	108	139	170	77	108	139	170	8
150	77	108	139	173	77	108	139	174	77	108	139	174	8
200	77	108	139	170	77	108	139	170	77	108	139	170	8
20	89	127	165	203	94	132	170	208	94	132	170	208	9
45	89	127	165	203	94	132	170	208	94	132	170	208	9
70	89	127	165	203	94	132	170	208	94	132	170	208	9
100	89	127	165	203	94	132	170	208	94	132	170	208	9
150	89	127	165	203	94	132	170	208	94	132	170	208	9
200	89	127	165	203	94	132	170	208	94	132	170	208	9
20	91	133	180	227	109	157	205	253	119	167	215	262	10
45	88	131	175	225	109	157	205	253	119	167	213	262	10
70	84	133	175	223	109	157	205	253	118	166	215	263	10
100	84	127	174	222	109	157	205	253	119	167	213	263	10
150	84	129	175	223	109	157	205	253	119	165	213	262	10
200	80	129	175	223	109	157	205	253	119	165	213	262	10
20	67	106	149	194	83	129	170	214	94	138	184	231	11
45	59	102	148	190	79	122	169	214	93	137	184	231	11
70	55	102	147	190	78	122	168	214	91	137	184	231	11
100	55	101	148	188	80	124	168	214	90	137	184	231	11
150	52	100	142	190	77	129	170	214	91	138	184	231	11
200	51	96	144	187	76	122	174	214	90	137	184	231	11
20	54	95	137	178	75	115	162	204	87	128	171	216	12
45	46	90	132	178	70	111	159	201	82	122	167	210	12
70	45	85	130	179	68	109	155	200	87	115	162	214	12
100	39	85	126	168	62	106	151	200	72	120	161	209	12
150	36	82	125	172	62	106	152	200	79	117	162	210	12
200	32	78	127	169	57	105	153	199	66	120	162	210	12

ZONE NO.631

RAINFALL STATION 637609 INYOKO LAT 24 08 LONG 30 52 ALTITUDE 390m 44 YEARS OF DATA

TEMPERATURE STATION 0638052 INYOKO LAT 24 22 LONG 31 02 ALTITUDE 502m WIND REGION : 1

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm) M.A.P. 461.1mm	MEAN	86.1	71.0	49.3	33.6	7.2	5.9	7.0	2.3	15.3	29.8	63.2	83.8	461.0
	MEDN	76.3	45.3	37.3	23.0	0.7	0.0	0.0	0.0	3.3	24.8	51.3	75.8	453.0
	SDEV	66.0	79.7	42.5	41.1	11.2	16.4	15.4	5.0	28.5	26.8	41.6	60.9	150.0
	C.V.	76.6	112.2	86.1	122.3	155.0	278.3	222.0	222.1	185.9	90.0	65.9	72.7	32.0
	SKEW	1.6	2.2	1.1	2.5	1.9	3.6	3.0	3.1	2.6	1.1	0.8	1.9	0.0
MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	MAX	30.5	31.6	29.8	29.8	27.3	24.4	23.5	25.2	26.7	28.7	30.0	31.0	
	MIN	19.4	20.4	18.6	15.8	12.1	8.8	8.4	11.6	14.1	16.7	18.0	19.0	

ESTIMATED IRRIGATION REQUIREMENT

P.A.M.	50 TH PERCENTILE				80 TH PERCENTILE				90 TH PERCENTILE				MTH
	CROP FACTOR				CROP FACTOR				CROP FACTOR				
(mm)	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	0.5	0.7	0.9	1.1	
	ESTIMATED IRRIGATION REQUIREMENT												
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
20	71	106	144	182	85	124	163	206	93	134	176	219	1
45	62	100	140	175	86	126	165	205	92	134	176	220	1
70	61	95	139	178	83	120	164	203	92	133	177	219	1
100	56	93	135	177	83	121	163	203	90	133	176	220	1
150	54	90	135	175	78	120	164	203	91	133	176	219	1
200	48	90	133	179	78	121	169	202	90	133	176	219	1
20	64	101	136	174	80	119	158	196	94	134	174	215	2
45	62	99	137	175	80	119	153	193	94	134	174	215	2
70	59	98	136	174	78	119	153	193	94	134	174	215	2
100	60	96	139	175	79	115	154	193	94	134	174	215	2
150	57	99	135	174	76	117	154	194	94	134	174	215	2
200	57	96	136	175	77	119	156	194	94	134	174	215	2
20	72	105	141	178	87	122	159	197	93	130	169	205	3
45	66	104	141	177	84	122	159	197	93	127	165	204	3
70	66	100	140	176	84	121	159	197	88	126	164	202	3
100	64	99	139	174	84	122	159	197	93	126	164	203	3
150	63	101	138	177	82	122	158	197	88	127	164	203	3
200	64	98	138	174	82	121	158	196	88	126	164	202	3
20	66	99	129	162	81	115	148	182	84	118	152	185	4
45	65	99	129	162	81	115	148	182	84	118	152	185	4
70	61	96	129	162	81	115	148	182	84	118	152	185	4
100	63	94	129	161	81	115	148	182	84	118	152	185	4
150	63	96	127	160	81	115	149	182	84	118	152	185	4
200	63	94	129	160	81	115	148	182	84	118	152	185	4
20	69	96	125	152	69	97	125	153	69	97	125	153	5
45	69	96	124	152	69	97	125	153	69	97	125	153	5
70	69	96	124	152	69	97	125	153	69	97	125	153	5
100	69	96	125	152	69	97	125	153	70	97	125	153	5
150	68	96	125	152	69	97	125	153	69	97	125	153	5
200	69	97	124	153	69	97	125	153	69	97	125	153	5
20	54	76	97	119	54	76	97	119	54	76	97	119	6
45	54	76	97	119	54	76	97	119	54	76	97	119	6
70	54	76	97	119	54	76	97	120	54	76	97	120	6
100	54	76	97	119	54	76	97	121	54	76	97	121	6
150	54	76	97	119	54	76	97	119	54	76	97	119	6
200	54	76	97	119	54	76	97	119	54	76	97	119	6
20	54	76	97	119	54	76	97	119	54	76	97	119	7
45	54	76	97	119	54	76	97	119	54	76	97	119	7
70	54	76	97	119	54	76	97	119	54	76	97	119	7
100	54	76	97	119	54	76	97	119	54	76	97	119	7
150	54	76	97	119	54	76	97	119	54	76	97	119	7
200	54	76	97	119	54	76	97	119	54	76	97	119	7
20	69	96	124	152	69	96	124	152	69	96	124	152	8
45	69	96	124	152	69	96	124	152	69	96	124	152	8
70	69	96	124	152	69	96	124	152	69	96	124	152	8
100	69	96	124	152	69	96	124	152	69	96	124	152	8
150	69	96	124	152	69	96	124	152	69	96	124	152	8
200	69	96	124	152	69	96	124	152	72	96	124	152	8
20	77	110	142	175	81	114	146	179	81	114	146	179	9
45	77	110	142	175	82	114	146	179	82	114	146	179	9
70	78	110	142	175	81	114	146	179	81	114	146	179	9
100	77	110	142	176	81	114	146	180	81	114	146	180	9
150	77	110	142	175	81	114	146	179	81	114	146	179	9
200	78	110	142	175	81	114	146	179	81	114	146	179	9
20	82	119	158	198	96	137	177	218	101	142	182	223	10
45	79	119	158	198	96	137	177	218	101	142	182	223	10
70	78	119	158	198	96	137	177	218	101	142	182	223	10
100	78	118	158	198	98	137	179	218	101	142	182	223	10
150	78	118	157	198	96	137	177	218	101	142	182	223	10
200	78	117	158	198	96	137	177	220	101	142	182	223	10
20	71	110	149	189	90	131	172	215	95	138	177	220	11
45	69	107	148	189	88	130	172	215	94	138	179	219	11
70	65	106	148	189	86	129	172	214	91	134	176	221	11
100	69	105	146	188	85	129	170	213	96	134	177	219	11
150	63	106	147	189	85	127	171	213	91	138	176	219	11
200	63	105	147	189	86	128	170	213	91	134	180	219	11
20	67	106	148	187	82	123	165	209	89	132	175	221	12
45	62	103	141	183	77	118	164	209	88	131	176	221	12
70	58	101	144	183	77	120	163	207	87	131	176	221	12
100	53	101	145	180	78	117	165	208	85	130	176	221	12
150	57	94	137	183	75	119	163	208	92	130	176	221	12
200	57	98	137	181	74	119	164	208	85	131	175	221	12

APPENDIX F

Time series plots of observed and simulated soil moisture for sites at Roodeplaat and Cedara

<u>Note</u> The data points in the following time series have been joined with straight lines. These lines should therefore not be taken to reflect the soil moisture status between observations.

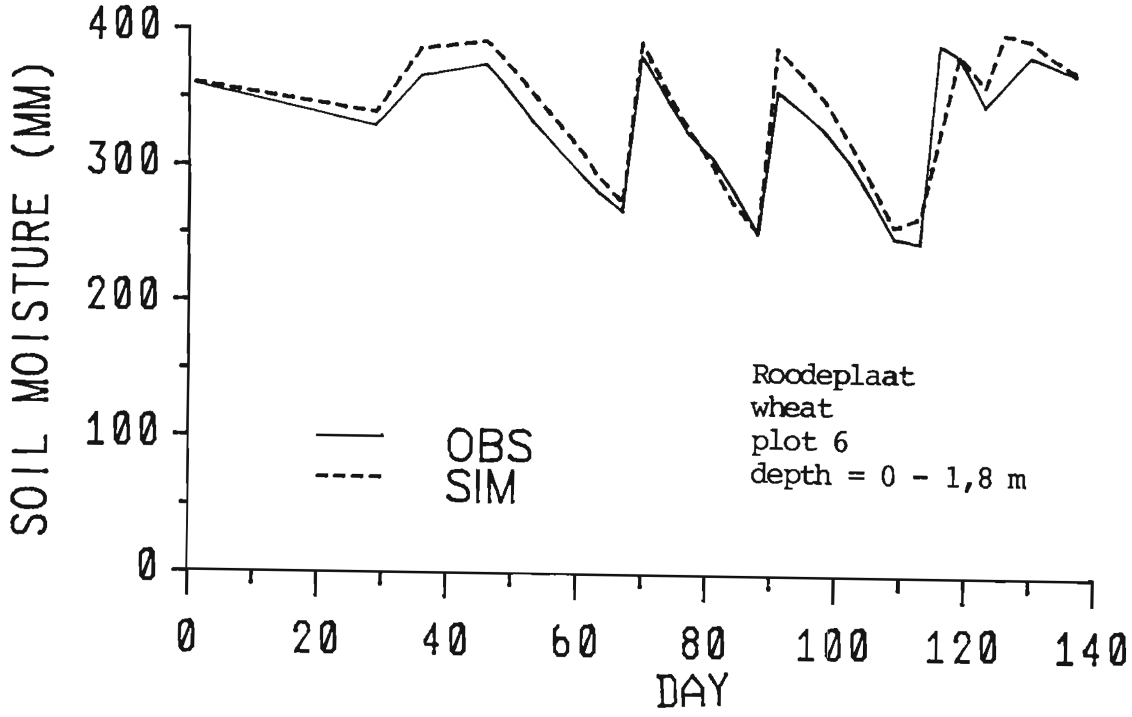


Figure F.1 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors from plot 6.

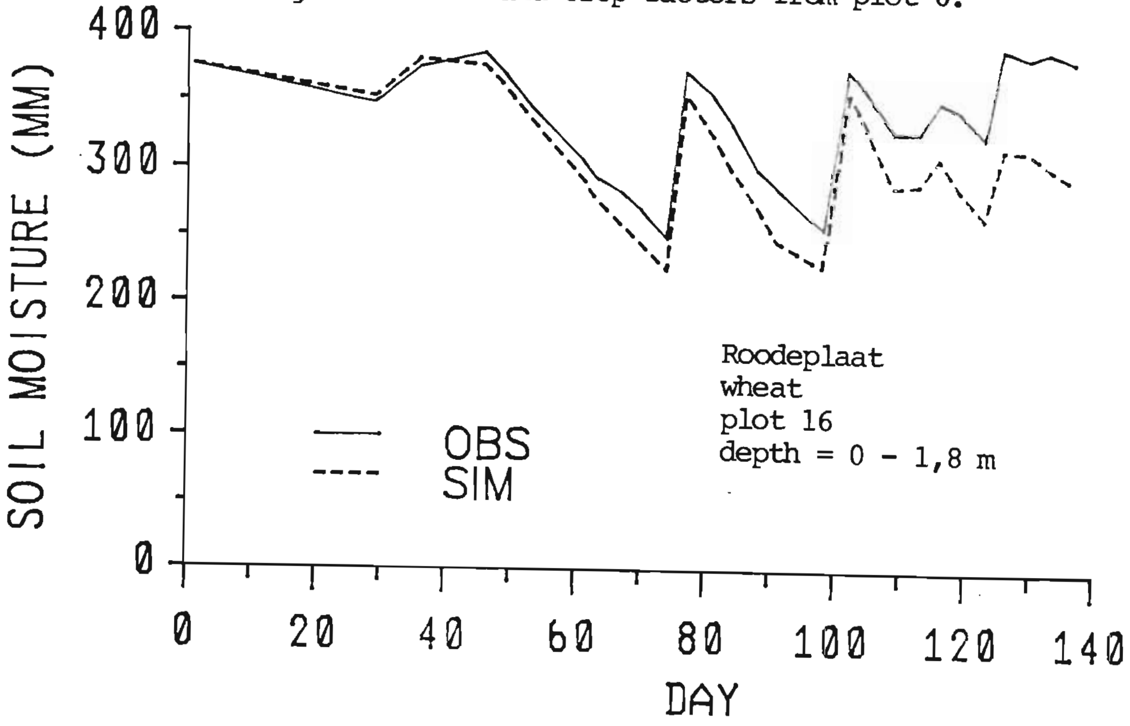


Figure F.2 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors from plot 6.

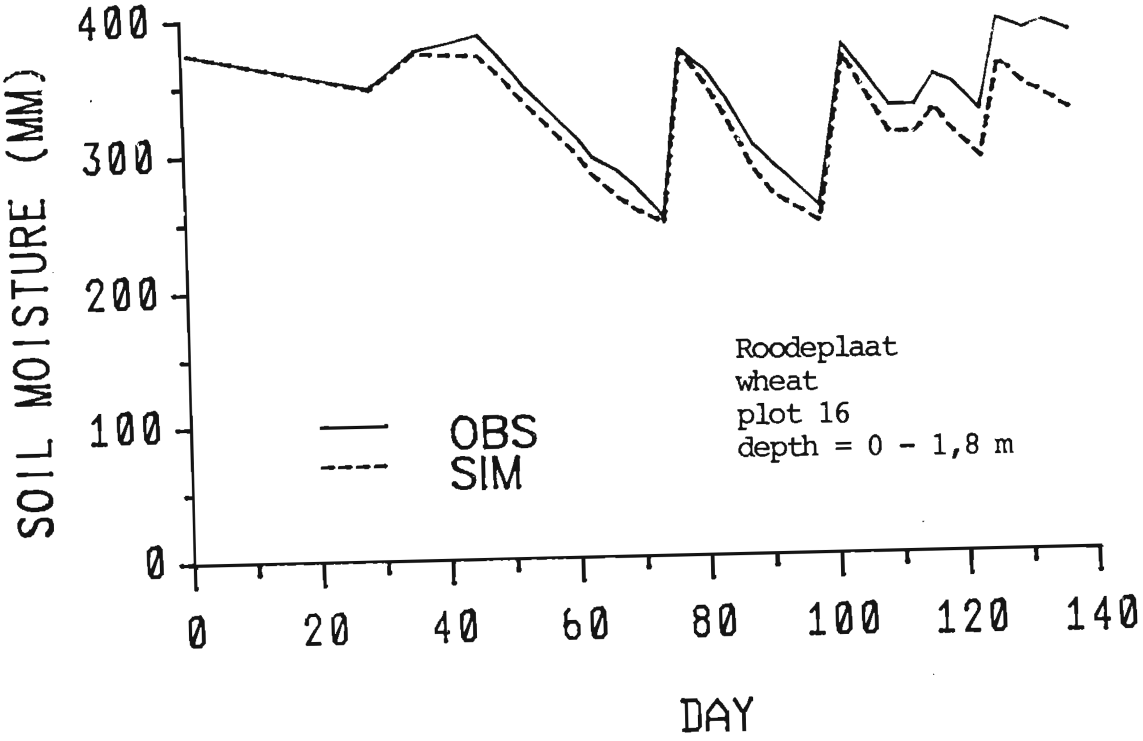


Figure F.3 Observed soil moisture and A and B horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

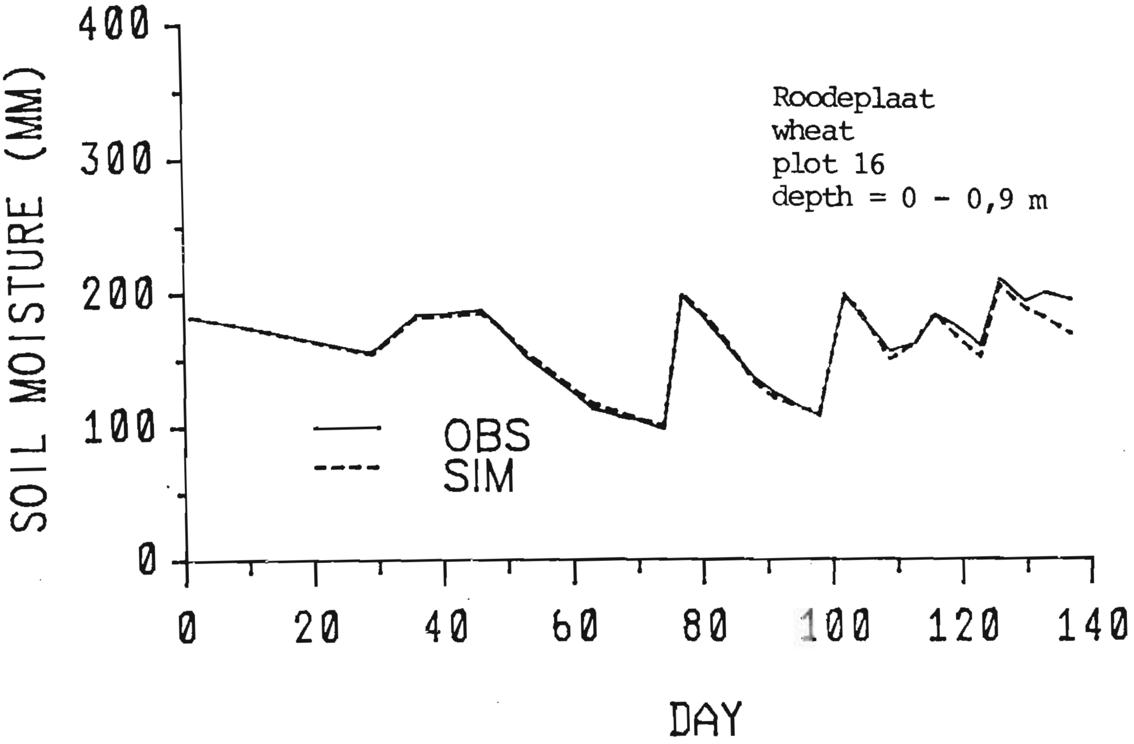


Figure F.4 Observed soil moisture and A horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

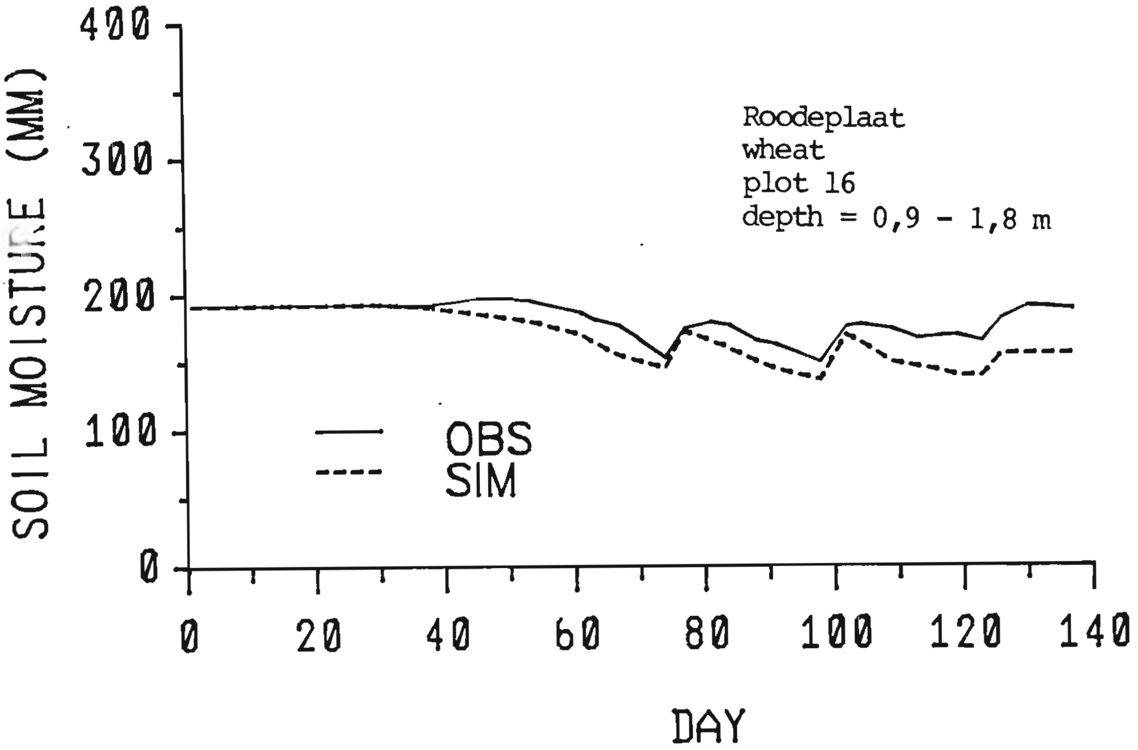


Figure F.5 Observed soil moisture and B horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

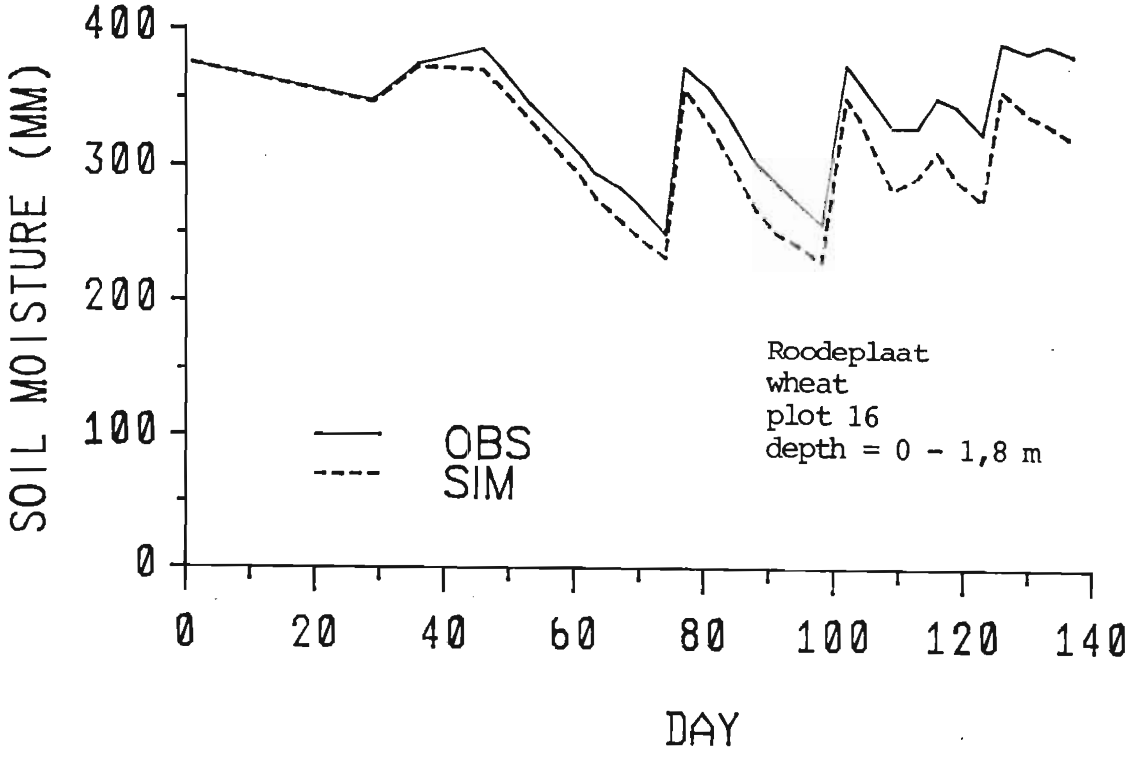


Figure F.6 Observed soil moisture and soil moisture simulated using the ACRU model as a single soil layer model and crop factors for plot 6.

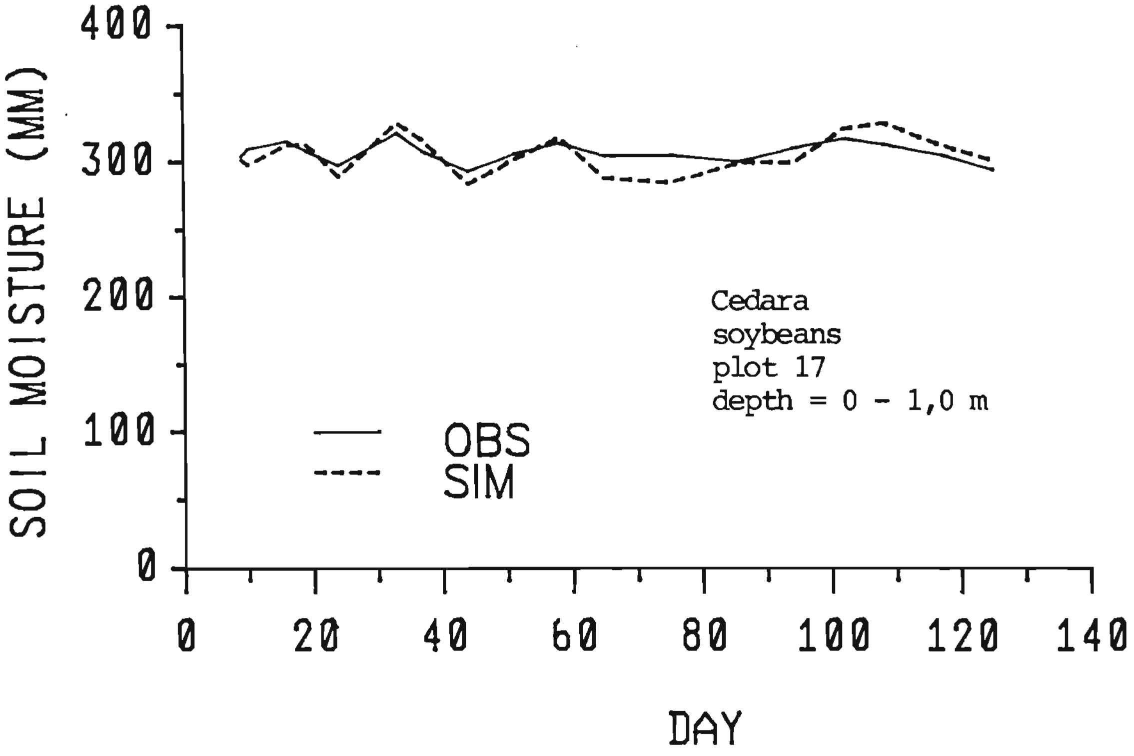


Figure F.7 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors for plot 8.

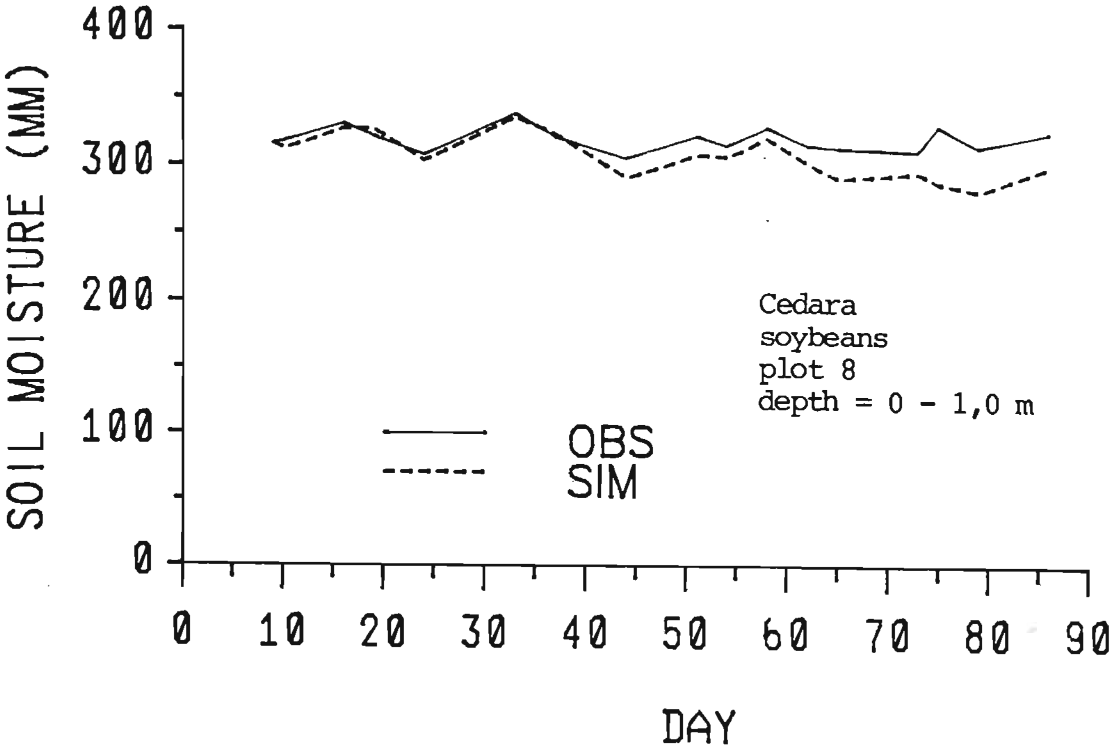


Figure F.8 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors for plot 8.

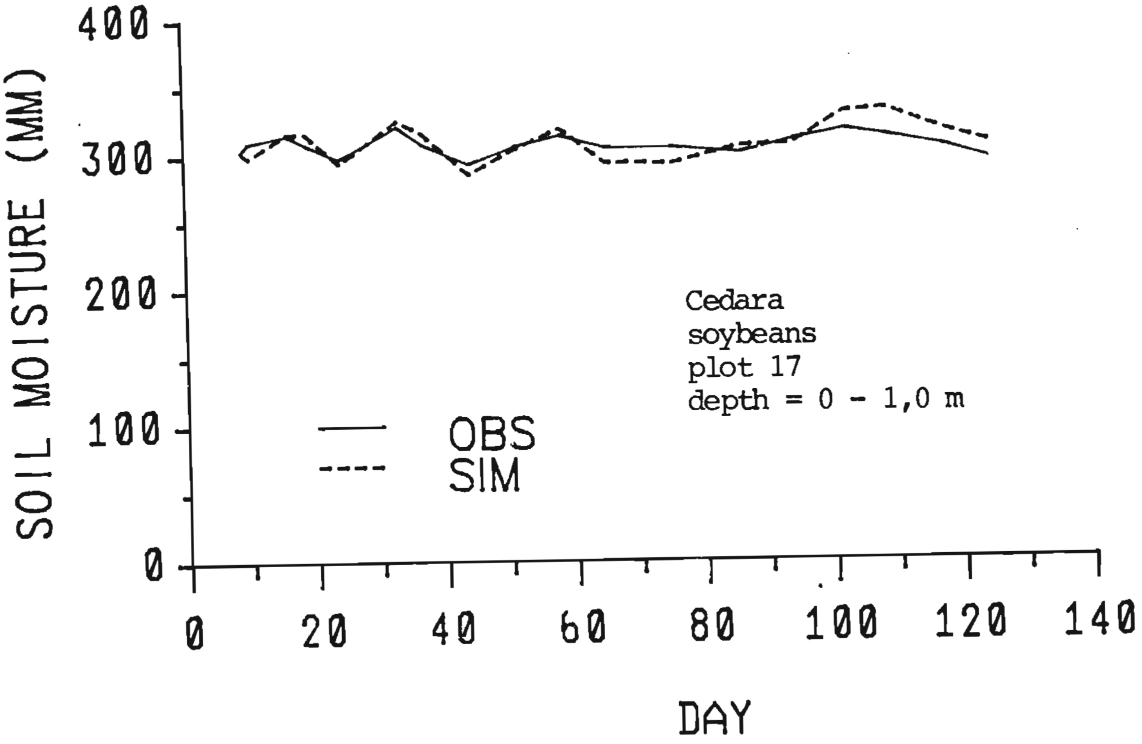


Figure F.9 Observed soil moisture and soil moisture simulated using the ACRU model and crop factors for plot 8.

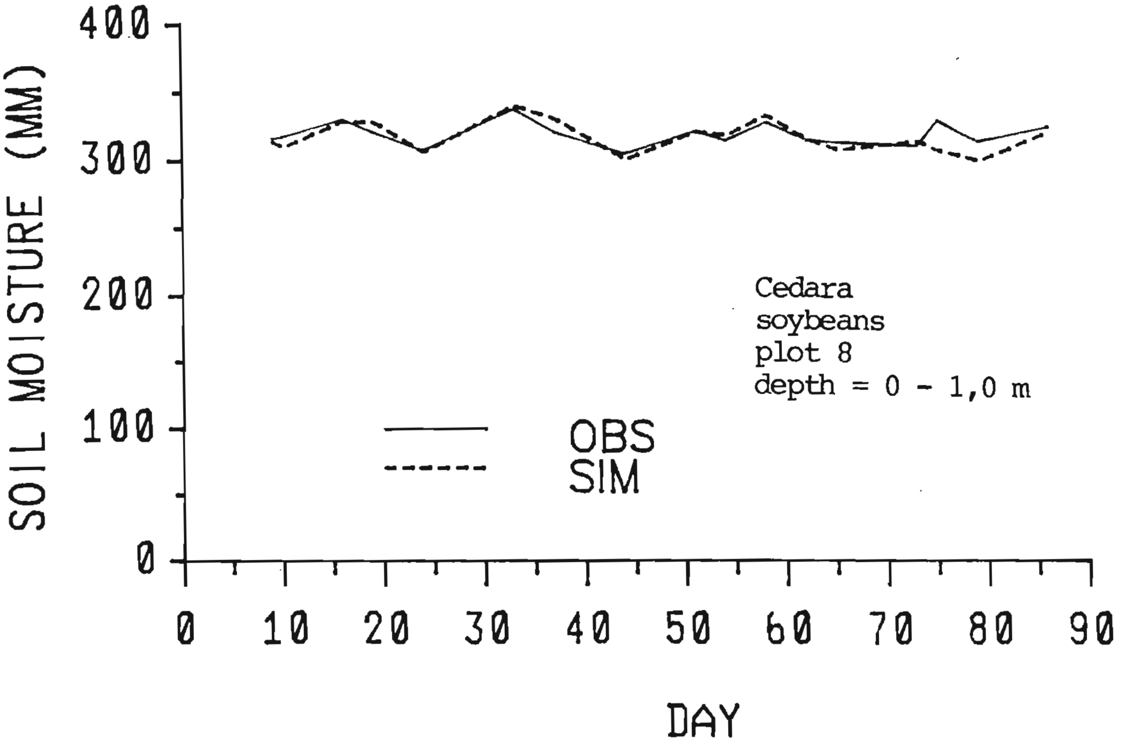


Figure F.10 Observed soil moisture and soil moisture simulated using the ACRU model and crop factors for plot 8.

APPENDIX G

Harmse et al (1984) declare the term moisture and all related terms in which it appears as obsolete. Harmse et al (1984) go on to say that the term water, referring to the chemical constituent H_2O, is preferred since moisture refers to a liquid phase in general and would include aqueous solutions and liquids other than water. Whilst recognising the need to distinguish between moisture and water in some applications, the liquid referred to throughout this thesis is certainly not chemically pure water (H_2O). Neither the liquid which falls as precipitation, nor that which is applied through irrigation, nor that which is measured by gravimetric, neutron probe, tensiometer or moisture block techniques nor that liquid which is taken up by the plant is chemically pure water. The dictionary definition of the word obsolete says that it is something which has quite gone out of reputable use. The words ancient, antiquated, archaic and disused are quoted as synonyms for obsolete. A thorough investigation of current papers from Water SA, Soil Science Society of America Journal, Advances in Irrigation, Irrigation Science, New Zealand Agricultural Science, Journal of Hydrology and the Journal of Agricultural Engineering Research revealed the continued use of the terms moisture, soil moisture content, soil moisture uptake by plants and soil moisture characteristics. These terms were used inter alia by Gunton and Evenson (1980); Faci and Fereres (1980); Hillel (1980); Hillel (1980a); Stegman (1982); Burman, Cuenca and Weiss (1983); Schulze (1985); Schulze, Hutson and Cass (1985); English, Taylor and John (1986); Watson and de Villiers (1986); du Pisani (1987); Hughes and Moolman (1987); Schmidt and Schulze (1987); Baligar, Wright and Smedley (1988); Ledieu, de Ridder, de Clerck and Dautrebaude (1988); Stafford (1988); Hanks and Malick (1989) and Istok and Boersma (1989). It is evident from the above that the term moisture is still accepted widely and is certainly not obsolete.