

**Crop Water Requirements, Deficits and Water
Yield for Irrigation Planning in Southern Africa**

**M C Dent, R E Schulze
and G R Angus**

WRC Report No.118/1/88

CROP WATER REQUIREMENTS, DEFICITS AND WATER YIELD
FOR IRRIGATION PLANNING IN SOUTHERN AFRICA

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Agricultural Catchments Research Unit

Report No. 28

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Report to the Water Research Commission on the Project
"A detailed regional soil moisture deficit analysis
for irrigation planning in Southern Africa"

Head of Department : Professor P. Meiring
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ISBN 0 908356 76 5

2nd Edition

118/1/88

EXECUTIVE SUMMARY

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Supplementary to ACRU Report No. 28 which is the full
report to the Water Research Commission on the Project
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for irrigation planning in Southern Africa"

Head of Department	:	Professor P. Meiring
Project Leader	:	Professor R.E. Schulze

In Southern Africa the areas in which the major crops are being grown under dryland conditions, have in the past been determined by a number of factors of which the economic factor plays a dominant role. Climatological disadvantages have often been masked by economics which have enabled crops to be grown "profitably" in regions where they are unsuited climatically. Profitability, although understandably a

The recent drought of the late 1970's and early 1980's, coupled with the mounting demand for water has brought the need for water resources planning into focus. Agriculture accounts for approximately 52 per cent of the water consumed in South Africa (Dept. Water Affairs, 1986). Apart from the individual farmer's need to plan, it is necessary to estimate irrigation water requirements for potential development in whole regions. This is essential in order to ascertain how much water will remain for urban and industrial use.

The practice of supplementary irrigation is increasing rapidly for several reasons. New crops are being introduced into areas which are climatically marginal. Development corporations in the National States are promoting total and supplementary irrigation schemes. Crop yields are boosted by supplementary irrigation and the practice is being used as a crop yield insurance measure. The production of crops under irrigation primarily for more intensive feeding of livestock is becoming an increasingly widespread phenomenon in parts of Southern Africa (Co-ordinating Committee for Irrigation Research, (CCIR), 1986).

Much of Southern Africa's arable farming is carried out on land which, in terms of typical soil moisture content, can be described as marginal. Information on likely soil moisture status is therefore an invaluable tool to the agricultural planner in regard to supplementary irrigation and for dryland farming.

BACKGROUND AND MOTIVATIONS

dominant factor in decision making, is also an unreliable and fickle phenomenon which can alter very suddenly and a change in 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 adopted in 1986/87 is a particularly recent (at the time of writing) and dramatic example of the above point.

It is at exactly this time, when the need to find alternative crops is most pressing, that scientific research such as that contained in this report is so valuable.

However, a manageable solution to the problem of estimating monthly water requirements for supplementary irrigation and dryland crops is complicated by the numerous factors which interact to form the water demand. The requirement is primarily a function of the rainfall amount and frequency in association with evapotranspiration, soil type, crop type, time of planting, as well as the stage of growth of the crop and its rooting depth. An estimate of the probabilities of occurrence of these water requirements is also essential in risk management planning.

The agricultural planner is often faced with a large number of possible crop, soil and risk management options which must be considered. Comprehensive planning therefore requires appraisals of the many combinations of the aforementioned variables. The presentation of estimated irrigation or dryland crop water requirements for all possible combinations of these variables, can be very cumbersome. It was essential to reduce this volume of information for use by agricultural planners.

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 were;

- (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-exceedance of certain levels of irrigation requirement, based on analyses of soil moisture budgets using long daily rainfall records,
- (d) to ensure that the results of these analyses do not become redundant in time due to improved estimates of crop factor, 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.

RESULTS AND CONCLUSIONS

In summary 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 (Welding and Havenga, 1974) 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, 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 stormflow runoff component was controlled by the top 200 to 300 mm of soil. 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.

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.

RECOMMENDATIONS FOR FURTHER RESEARCH AND TECHNOLOGY TRANSFER OF RESULTS

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. However, before commencing with such discussion it is important to state that it is recognised that 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.

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 aim 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.

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."

The results of this study are to be disseminated through the Computing Centre for Water Research on computer compatible media. In addition it is recommended that the authors present a series of one day workshops to agriculturalists, engineers and land use planners.

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ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled:

"A detailed regional soil moisture deficit analysis for irrigation planning in Southern Africa".

The Steering Committee responsible for this project, consisted of the following persons:

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The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

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 Rowsell, 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;

The Computing Centre for Water Research

a venture by ISM (Pty) Limited, the Water Research Commission and the University of Natal for 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;

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 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.

TABLE OF CONTENTS

	Page
LIST OF TABLES	viii
LIST OF FIGURES	x
1. INTRODUCTION	1
1.1 Background	1
1.2 Objectives	4
1.3 Overview of methodology	6
1.4 Note on terminology and conventions	8
2. SELECTED TOPICS RELATED TO THE ESTIMATION OF IRRIGATION REQUIREMENTS FOR PLANNING IN SOUTHERN AFRICA	
2.1 Past research covering the estimation of irrigation requirements in Southern Africa	10
2.2 Change in emphasis towards irrigation in humid regions in Southern Africa	12
2.3 Distinction between estimating irrigation requirements for planning and for scheduling	13
2.4 Comment on the complexity of soil moisture budgeting models	15
2.5 Selected components of the soil moisture modelling process	17
2.5.1 Rainfall intensity and effective rainfall	18
2.5.2 Irrigation timing and amount	19
2.5.3 Crop factors and the estimation of actual evapotranspiration	21
2.5.4 Root distribution and plant water uptake by roots	26

2.5.5	Drainage of soil water to groundwater	28
2.6	Choice of objective functions for verification of soil moisture budget models	29
3.	DELIMITATION OF HOMOGENEOUS CLIMATE ZONES	
3.1	Need for homogeneous climate zones	31
3.2	Existing delimitations of rainfall zones	32
3.3	Technique of delimiting the homogeneous climate zones	37
3.4	Computerisation of climate zone boundaries	41
3.5	Variation of MAP within the climate zones	43
4.	THE ACRU AND IRRIGATION SOIL MOISTURE BUDGET MODELS	
4.1	Concepts and structure of the ACRU model	44
4.1.1	Estimation of evapotranspiration in the ACRU model	45
4.1.2	Estimation of runoff in the ACRU model	49
4.2	The irrigation model	50
4.2.1	Design criteria adopted for the irrigation model	50
4.2.2	Concepts and general structure of the irrigation model	52
4.2.3	Procedures and sequences of soil moisture budgeting in the irrigation model	55
4.2.4	Irrigation application and the calendar month	61
4.2.5	The frequency analysis	63
5.	VERIFICATION OF THE OUTPUT OF THE MODELS	
5.1	Verification of the output of the ACRU model	65
5.1.1	Comparison with lysimeter estimates of actual evapotranspiration	66
5.1.2	Comparison with catchment runoff	67
5.1.3	Comparison with measured soil moisture	70

5.2	Verification of the output of the irrigation model	75
5.2.1	Comparison with measured soil moisture	75
5.2.2	Sensitivity tests on the irrigation model	77
5.2.3	Comparison of estimates of irrigation requirements in the discrete and continuous modes	80
5.3	Discussion on the verification of the models	81
6.	CLIMATIC DATA INPUT TO THE SOIL MOISTURE BUDGET MODELS	
6.1	Daily rainfall data	84
6.1.1	Selection of the rainfall station for each zone	84
6.1.2	Synthesising missing daily rainfall	86
6.1.3	Effect of synthetic rainfall on the soil moisture budget	89
6.2	Estimation of potential evaporation	93
6.2.1	Availability of data for estimating potential evaporation	93
6.2.2	Sensitivity of the soil moisture budget to techniques for estimating potential evaporation	95
6.2.3	Estimating potential evaporation by the Linacre equation	104
6.2.4	Regionalization of adjustments to the Linacre equation	106
6.2.5	Selection of temperature stations for each zone	109
7.	APPLICATION OF THE MODELS AND THEIR OUTPUT	
7.1	Purpose and value of the dryland analysis	111
7.2	Procedure for analysis of soil moisture under dryland conditions	112
7.3	Analysis of soil moisture under dryland conditions : output	113

7.3.1	Terminology used to describe the output	113
7.3.2	Application of the output	115
7.4	Discussion on some aspects of the soil moisture analysis under dryland conditions	120
7.5	Purpose and value of the irrigation analysis	123
7.6	Application of the output from the irrigation analysis	125
8.	DISCUSSION AND CONCLUSIONS	
8.1	Contribution to the state of knowledge	129
8.2	Achievement of objectives	133
8.3	Recommendations for future research	135
8.4	The future challenge	138
9.	REFERENCES	139
APPENDIXES		
A.	Variation of MAP within the climate zones	151
B.	Maps showing homogeneous climate zones	152
C.	Location of the crops used in the dryland analyses	152
D.	Tables of variable values including crop factors and rooting depths for crops used in the analyses of soil moisture under dryland conditions	154
E.	Tabular output from 5 stations used in the dryland analyses	156
F.	Tabular output from 10 stations used in the irrigation analyses	168
G.	Time series plots of observed and simulated soil moisture for sites at Roodeplaat and Cedara	179
H.	Note on terminology	184

LIST OF TABLES

	Page
2.1 Standard error of estimate of weekly evapotranspiration predictions compared to weighing lysimeter	24
4.1 Soil moisture retention values	59
4.2 Irrigation application amounts used in the model	60
5.1 Statistics of water yield simulation from the ACRU model at three different locations	68
5.2 Comparison of observed and simulated soil moisture from the ACRU model, using field plot data at Rooodeplaar and Cedarar	73
5.3 Comparison of observed and simulated soil moisture from the irrigation model, using field plot data at Rooodeplaar and Cedarar	76
5.4 Estimated monthly irrigation requirements for a range of locations and soil moisture holding capacity ratios	78
6.1 Amount of missing daily rainfall at the 712 stations used in this study	88
6.2 Comparison of selected output variables from the ACRU model when using observed and synthetic daily rainfall data	91
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	96
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	97
6.5 Sensitivity of the ACRU model to techniques for estimating potential evaporation	100
6.6 Monthly values of LINWIN for each of the 7 regions	109

7.1	Evapotranspiration deficit output from the dryland analysis (Zone 377, Bergville)	116
7.2	Index of stress days output from the dryland analysis (Zone 377, Bergville)	117
7.3	Water yield output from the dryland analysis (Zone 377, Bergville)	118
7.4	Extracts of evapotranspiration deficit and index of stress days from Tables 7.1 and 7.2	120
7.5	Estimates of irrigation water requirements for each month: example of output (Zone 377, Bergville)	124

LIST OF FIGURES

	Page
2.1 Location of the climate stations used in the irrigation study by Green (1985)	11
2.2 Various proposals for the relationship between AET/PET and available soil moisture	25
3.1 Rainfall regions (114) of Southern Africa	33
3.2 The 712 homogeneous climate zones delimited in this study	34
3.3 Reasonably homogeneous farming areas (RHFA) in the Highveld Region	36
3.4 Homogeneous climate zones in the Highveld Region, delimited in this study	36
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	39
3.6 Delimitation of homogeneous climate zones in the south-western Cape	42
4.1 The ACRU model structure	46
4.2 Frequency distributions of the ratio of daily evaporation to mean daily evaporation for the month, for rain days and non-rain days	48
4.3 Schematic flow chart of the main controlling program for the irrigation model	53
4.4 Graphical presentation of the procedure for budgeting soil moisture in the irrigation model	56
4.5 Illustration of the irrigation timing problem	61
4.6 Schematic illustration of the solution to the problem of expressing irrigation requirements in monthly time intervals	62

	Comparison of observed and estimated actual evapotranspiration from bare ground and sparse natural grassland, University of Natal lysimeters	67
5.2	Comparison of observed and simulated accumulated monthly streamflow at De Hoek VLM28, Natal	69
5.3	Comparison of observed and simulated flood hydrograph at De Hoek VLM28, Natal	69
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	81
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	90
6.2	Location of the climate stations used to test the effect of temperature based estimates of PE on the ACRU model output	99
6.3	Monthly AET estimated using the Linacre (1977) equation VS monthly AET estimated using daily A-pan values at Vaalharts under dryland conditions	103
6.4	Monthly AET estimated using the Linacre (1977) equation VS monthly AET estimated using daily A-pan values at Cedara under dryland conditions	103
6.5	Delimitation of major wind regions	108
7.1	Estimation of monthly irrigation demand curve for planning: example using selected values from Zone 377, Bergville	127

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.

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.

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.

1.3 Overview of methodology

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.

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 report 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 report 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 besproeiingsbehoefte 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

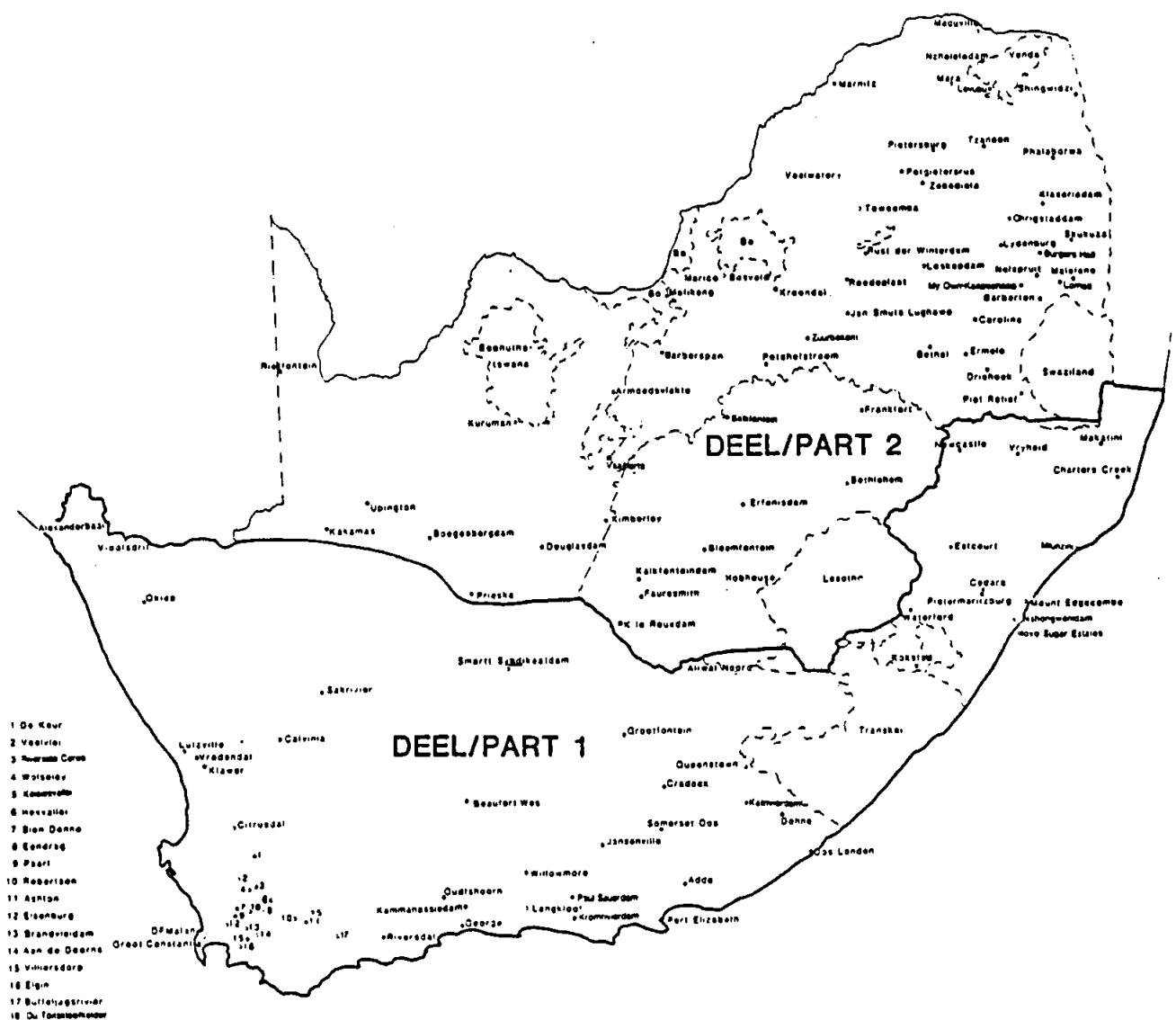


Figure 2.1 Location of the climate stations used in the irrigation study by Green (1985)

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 runoff 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 Perman 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.

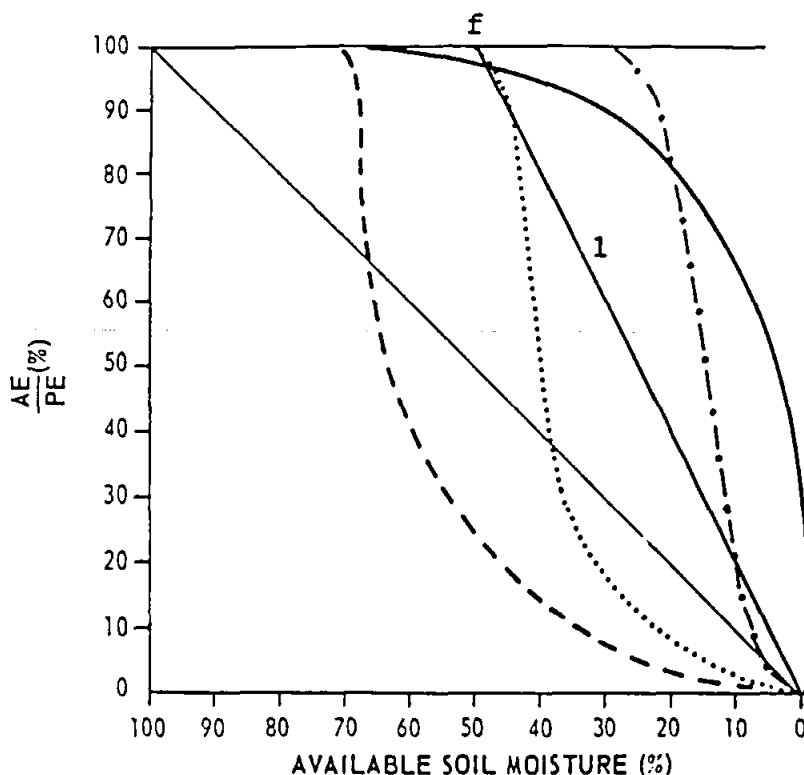


Figure 2.2 Various proposals for the relationship between AET/PET and available soil moisture (after Baier and Robertson, 1966)

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 *inter alia* by Johns and Smith (1975) and Calder *et al.* (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

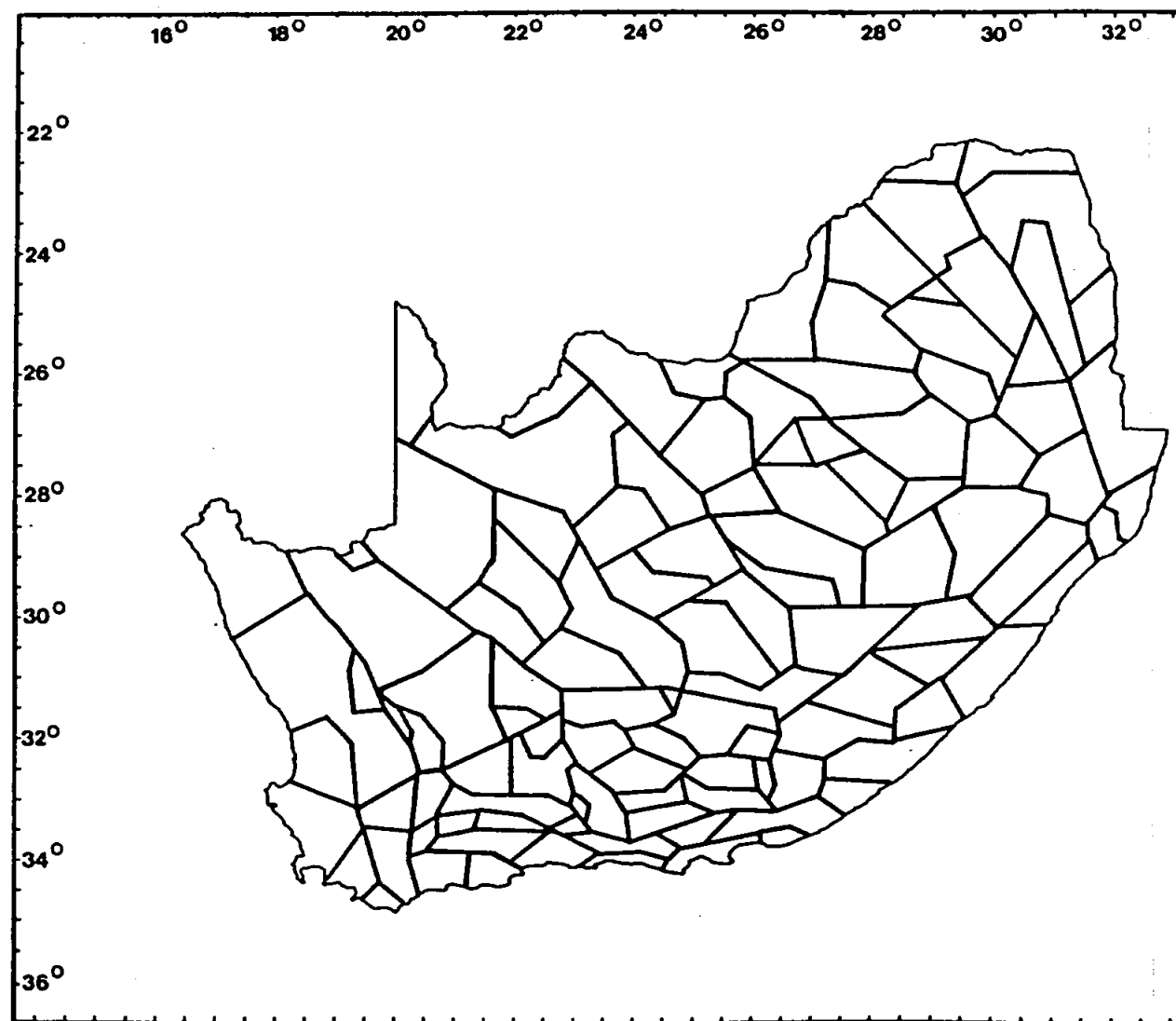


Figure 3.1 Rainfall regions (114) of Southern Africa (after Welding and Havenga, 1974)

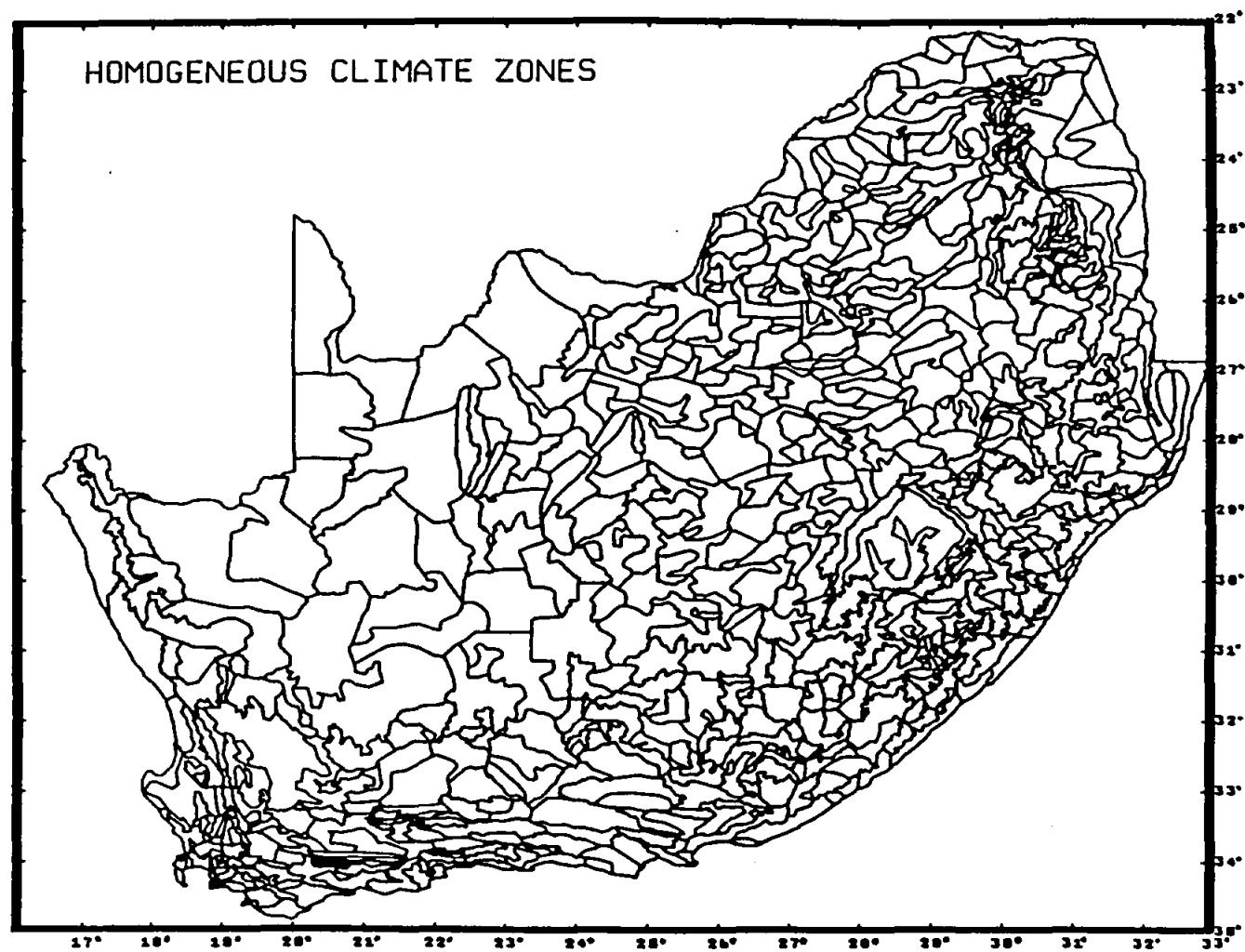


Figure 3.2 The 712 homogeneous climate zones delimited in this study

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 this.

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.

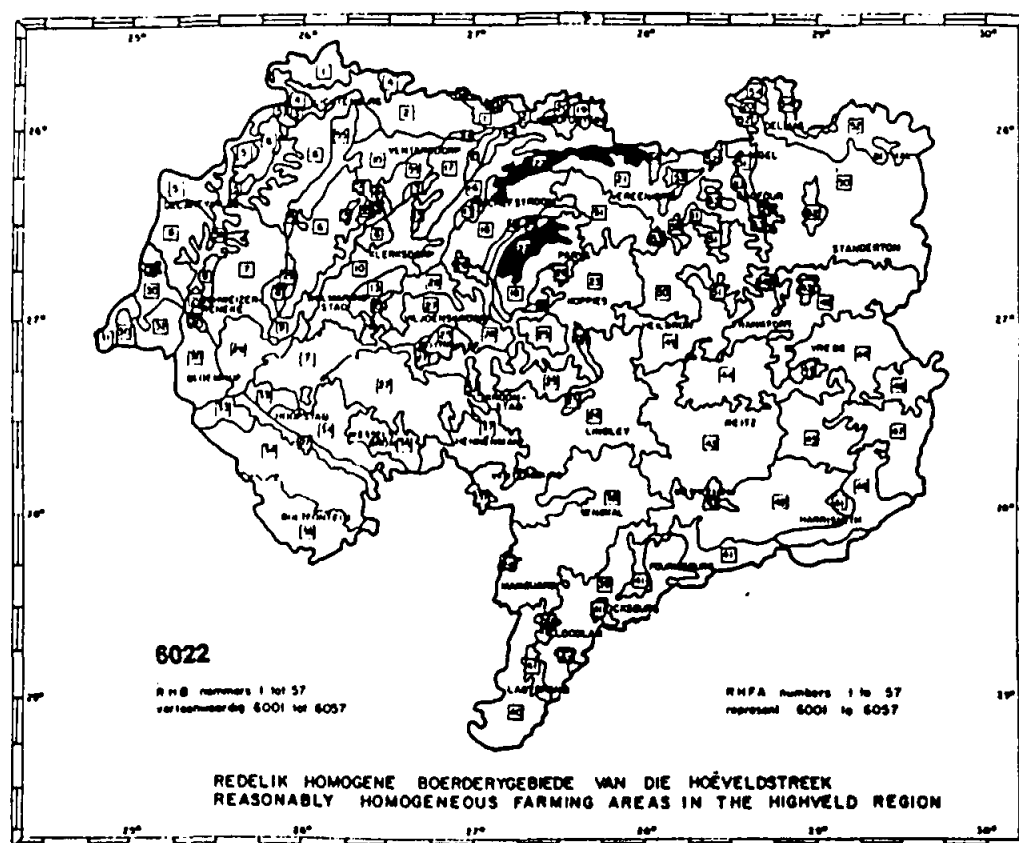


Figure 3.3 Reasonably homogeneous farming areas (RHFA) in the Highveld Region (Scheepers *et al.* 1984)

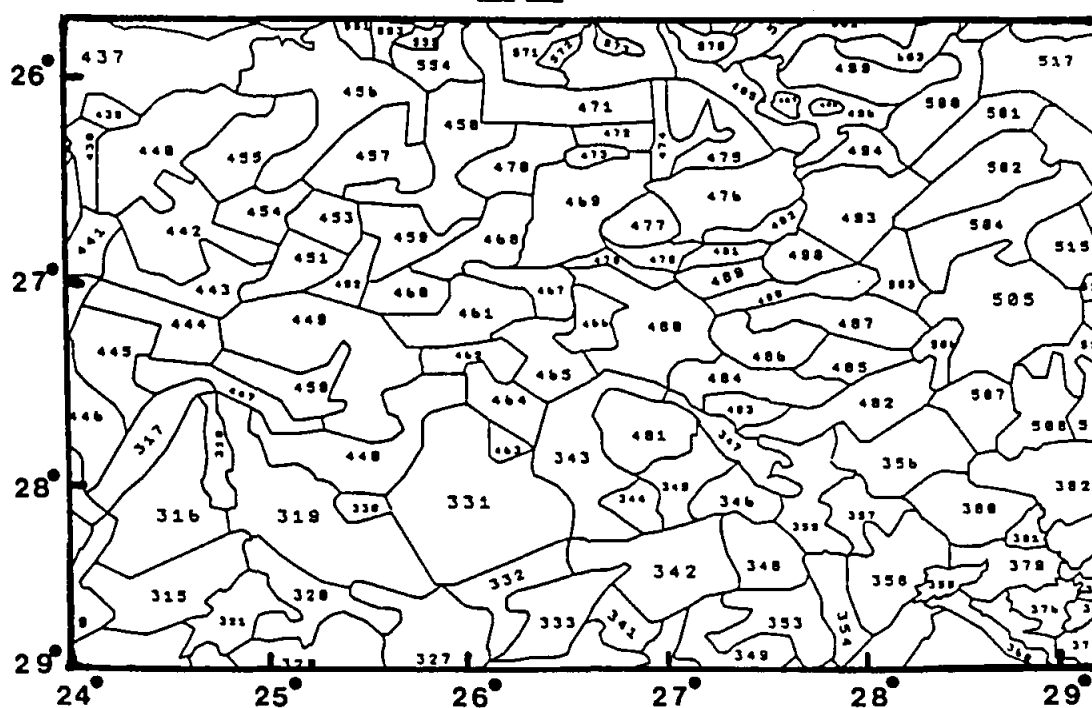


Figure 3.4 Homogeneous climate zones in the Highveld Region, delimited in this study

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.

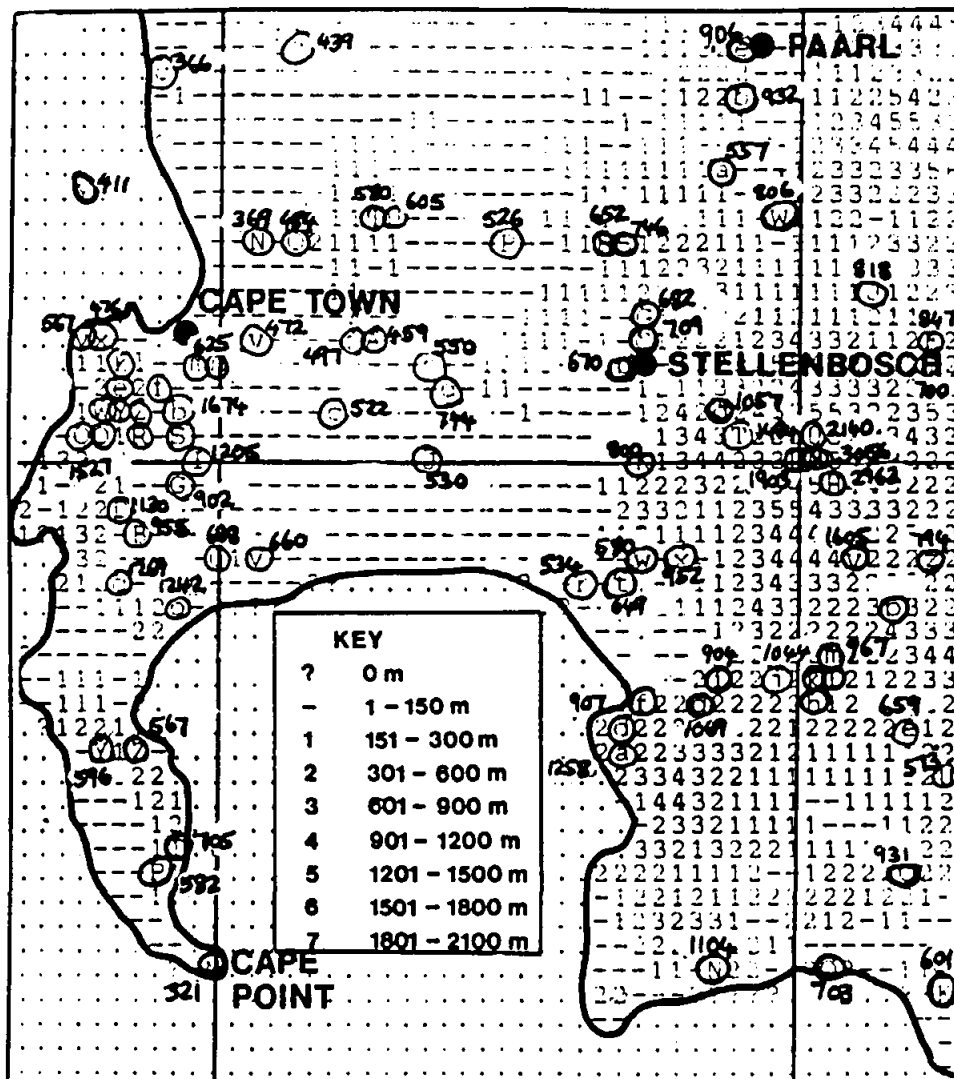


Figure 3.5 Classified image of altitude and the MAP at stations with 10 or more years of rainfall record for part of the south western Cape

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

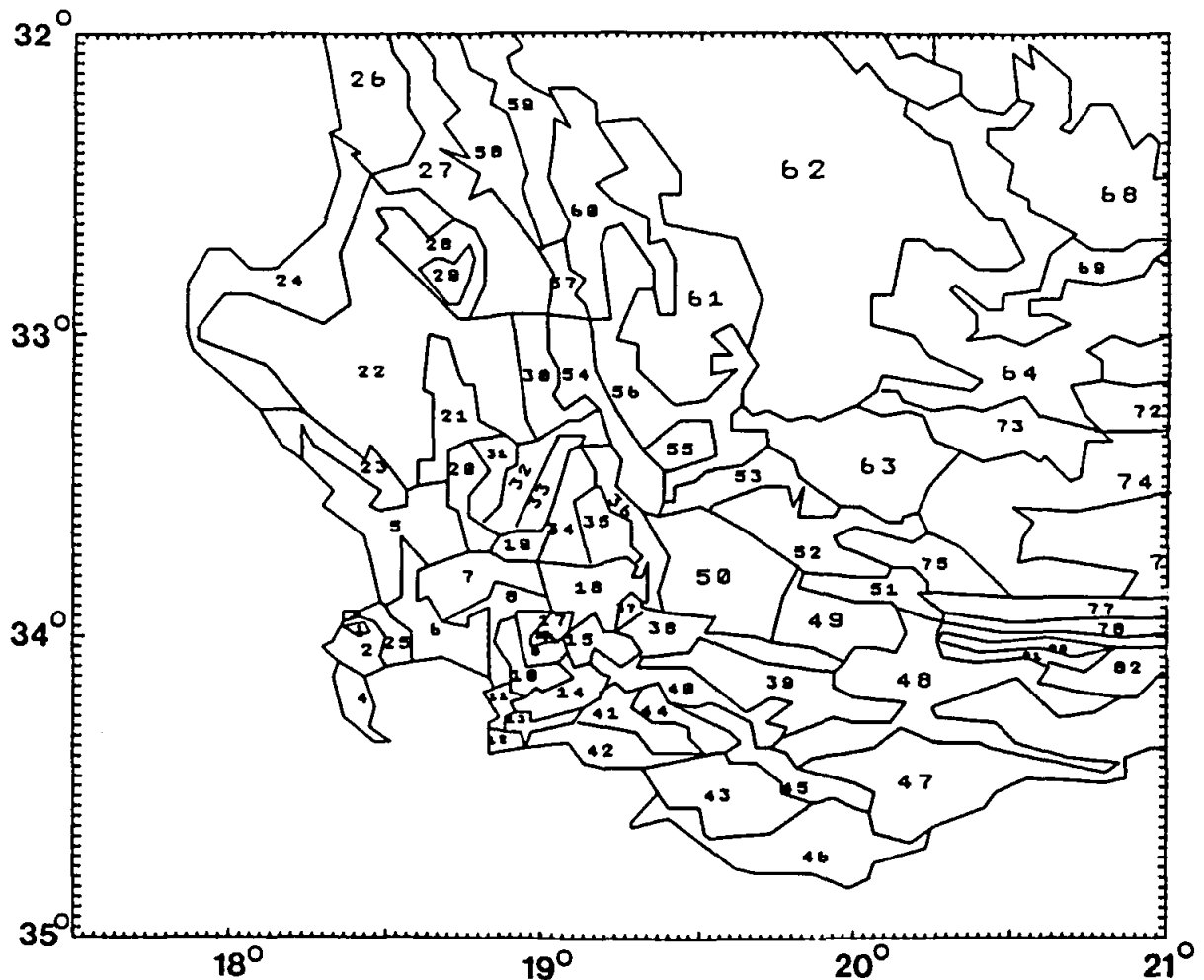


Figure 3.6 Delimitation of homogeneous climate zones in the south western Cape

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.

3.5 Variation of MAP within the climate zones

Two years after the zones were first delimited a study by Dent, Lynch and Schulze (1989) provided estimates of MAP at each 1 minute grid point described earlier. An algorithm was developed, by Lynch (1989), which assigned each grid point estimate of MAP into one of the 712 climate zones. The coefficient of variability (CV) of the estimated MAP was then determined for each zone. This analysis revealed that in 381 zones the CV of the MAP was less than 10 per cent. In 219 zones the CV of the MAP was between 10 and 20 per cent and in 112 zones it was greater than 20 per cent. These latter zones are primarily in the mountainous regions of the Cape, Lesotho, the Eastern Transvaal Drakensberg and the Soutpansberg. A map showing the CV of the MAP for each zone is presented in Appendix B.

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

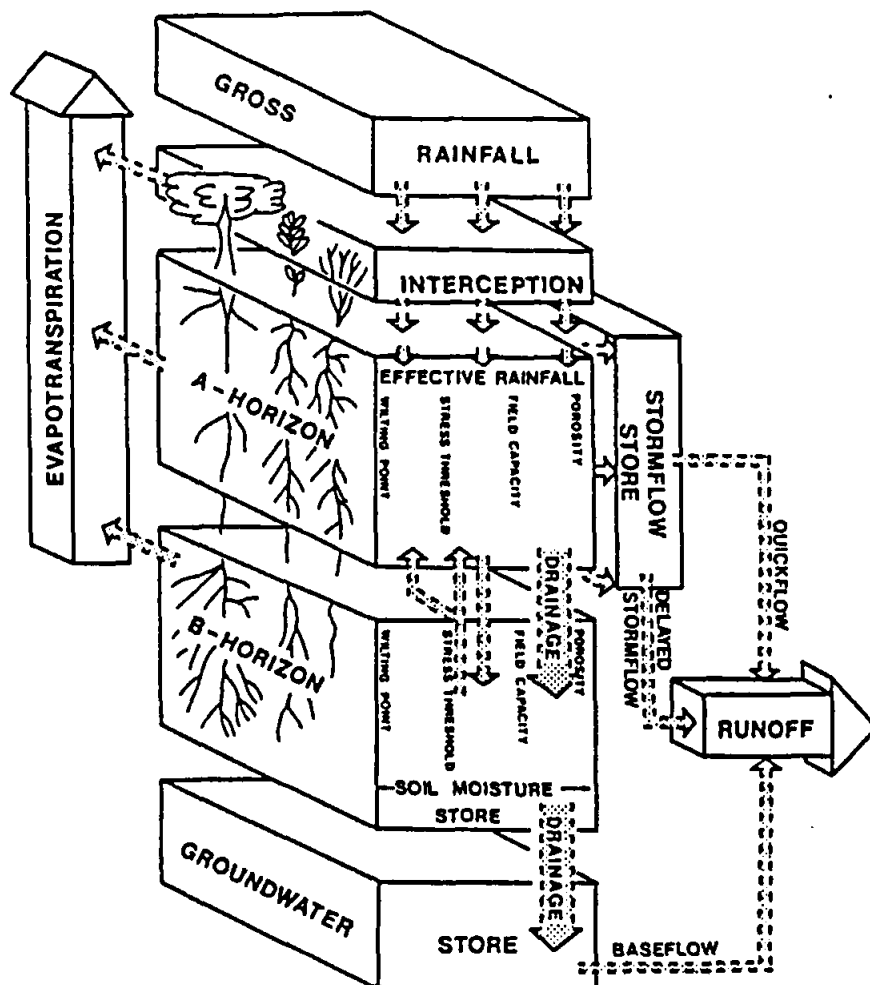


Figure 4.1 The ACRU model structure (Schulze, 1984b)

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.

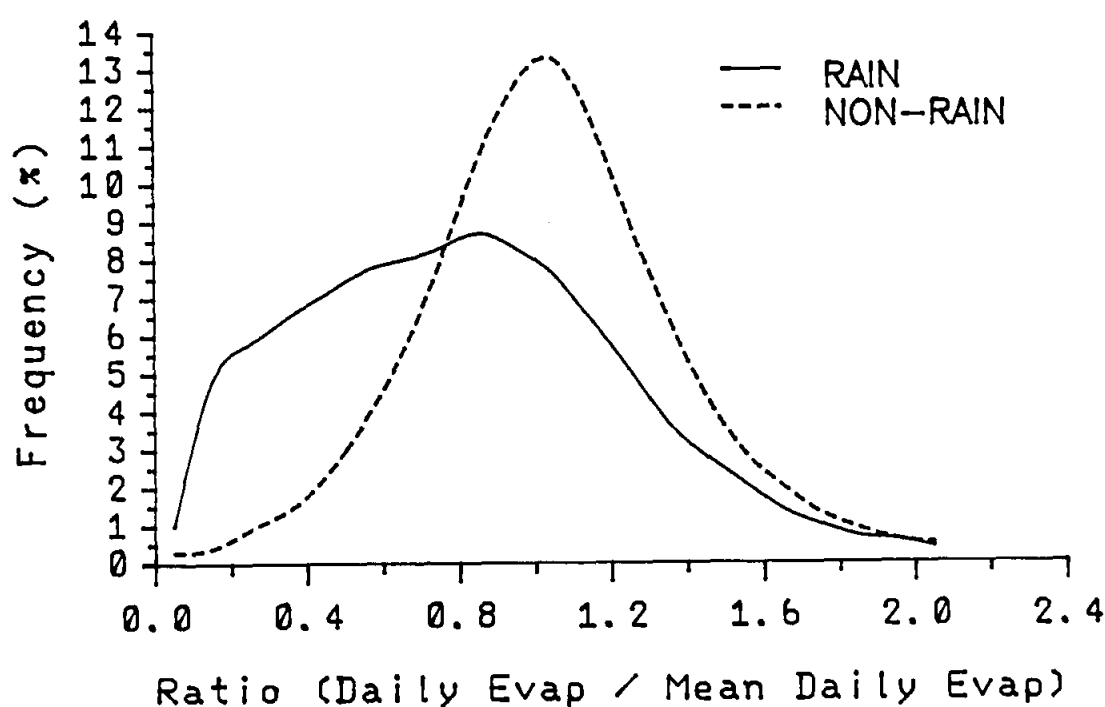


Figure 4.2 Frequency distributions of the ratio daily evaporation to the mean daily evaporation for the month, for rain days and non-rain days

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 per se" (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.

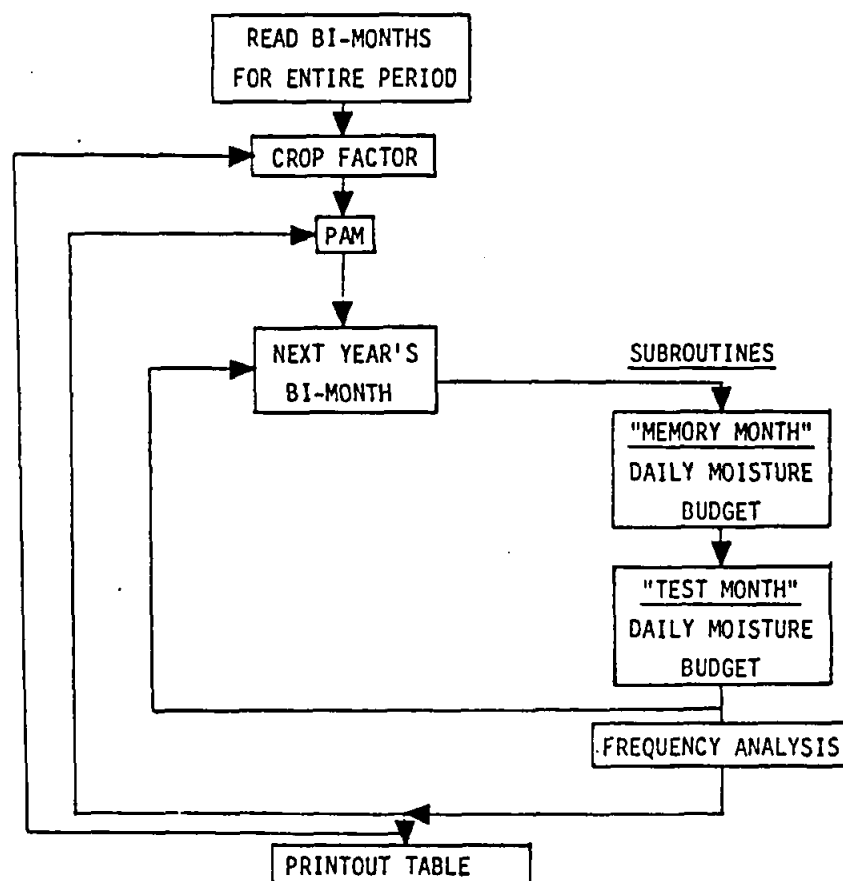


Figure 4.3 Schematic flow chart of the main controlling program for the irrigation model

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

PLANT AVAILABLE MOISTURE
IN ROOT ZONE

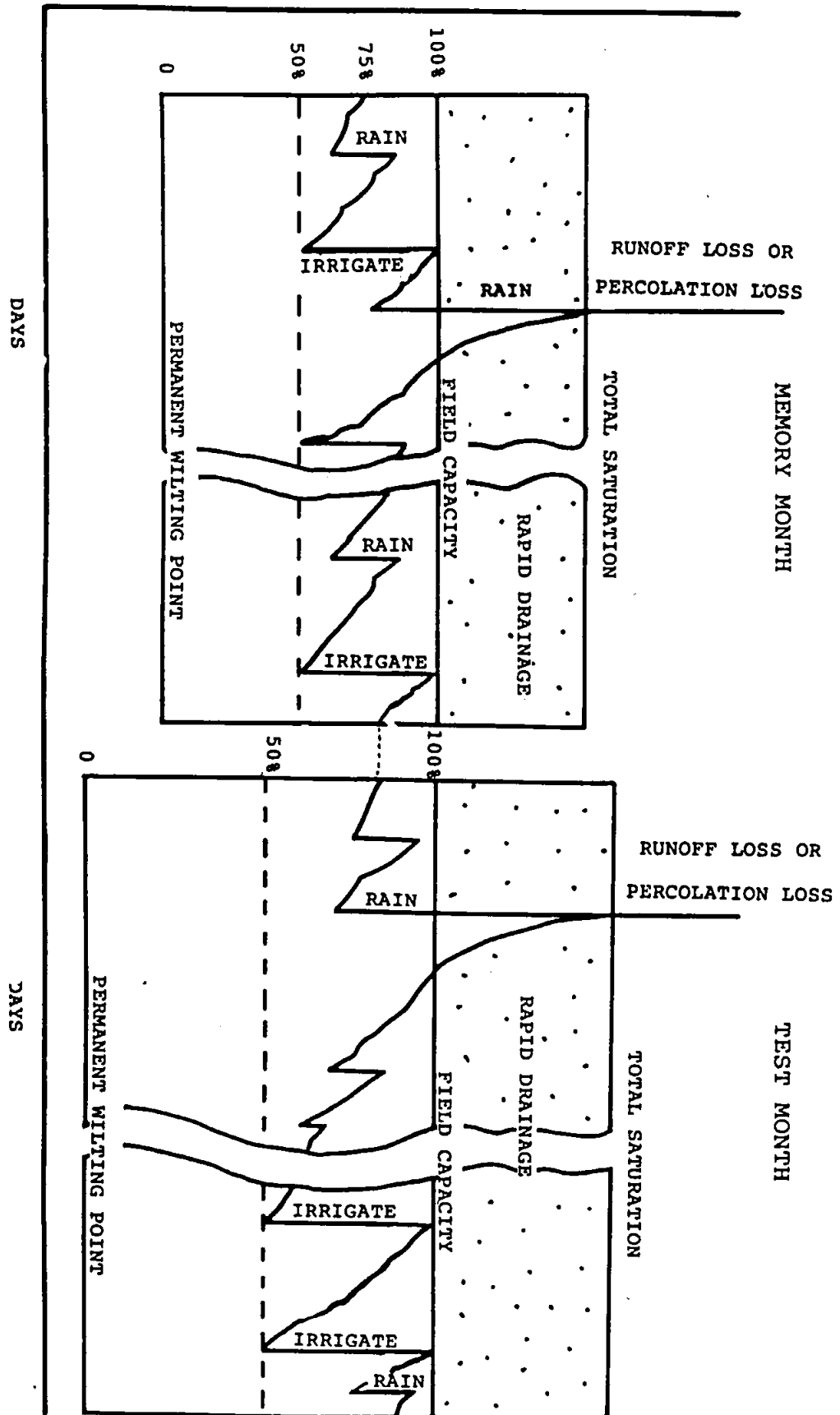


Figure 4.4 Graphical presentation of the procedure for budgeting soil moisture in the irrigation model

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)	<u>POR-FC</u> 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	75	3.85
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.

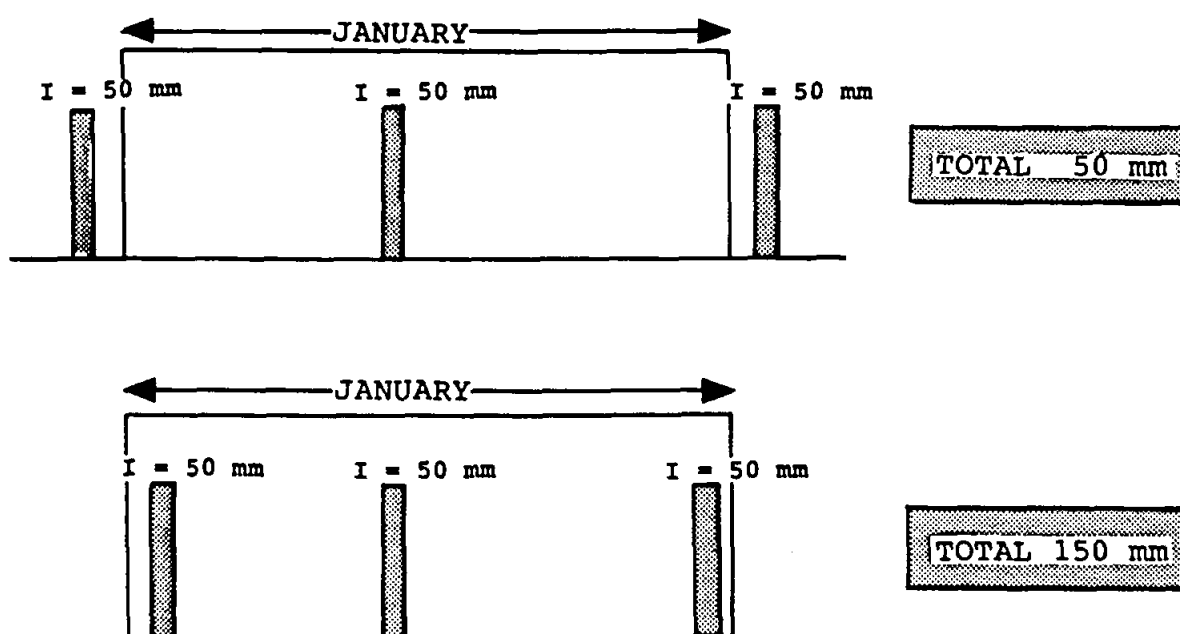


Figure 4.5 Illustration of the irrigation timing problem

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.

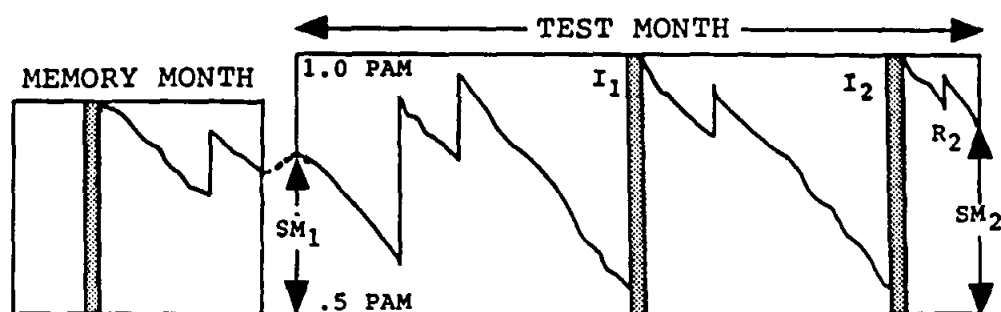


Figure 4.6 Schematic illustration of the solution to the problem of expressing irrigation requirements in monthly time intervals

This requirement is expressed as ;

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

where

$$\begin{aligned} I_{\text{test month}} &= \text{irrigation requirement (mm) in the test month,} \\ I_1, I_2 &= \text{irrigation application amounts (mm),} \\ SM_1 &= \text{soil moisture content (mm) above 0,5 PAM at} \\ &\quad \text{beginning of test month,} \\ SM_2 &= \text{soil moisture content (mm) above 0,5 PAM at end} \\ &\quad \text{of test month.} \end{aligned}$$

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 Roo-deplaat 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.

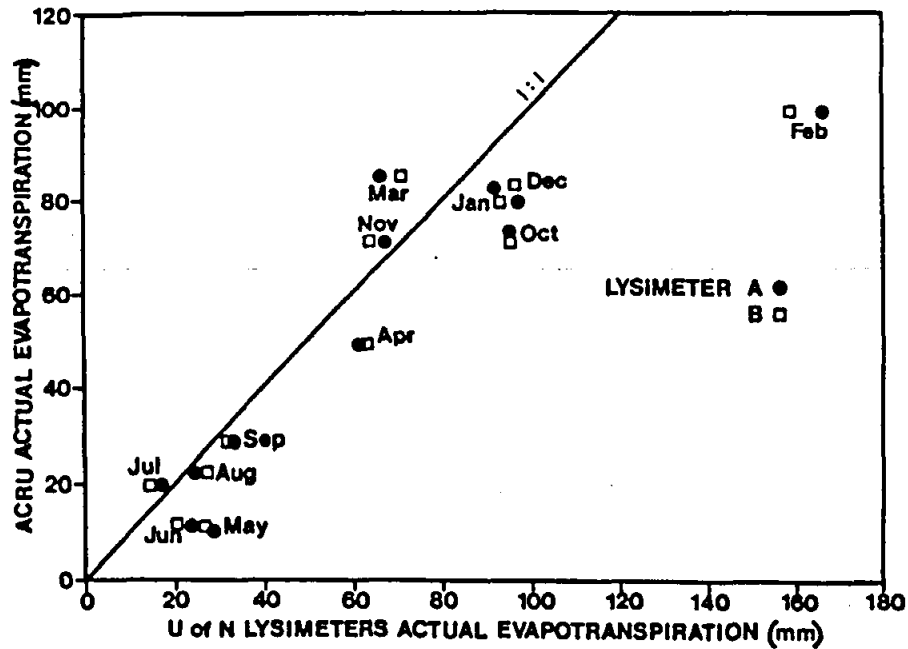


Figure 5.1 Comparison of observed and estimated actual evapotranspiration from bare ground and sparse natural grassland, University of Natal lysimeters (after Schulze, 1986)

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 VIM03, 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 km²) 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.

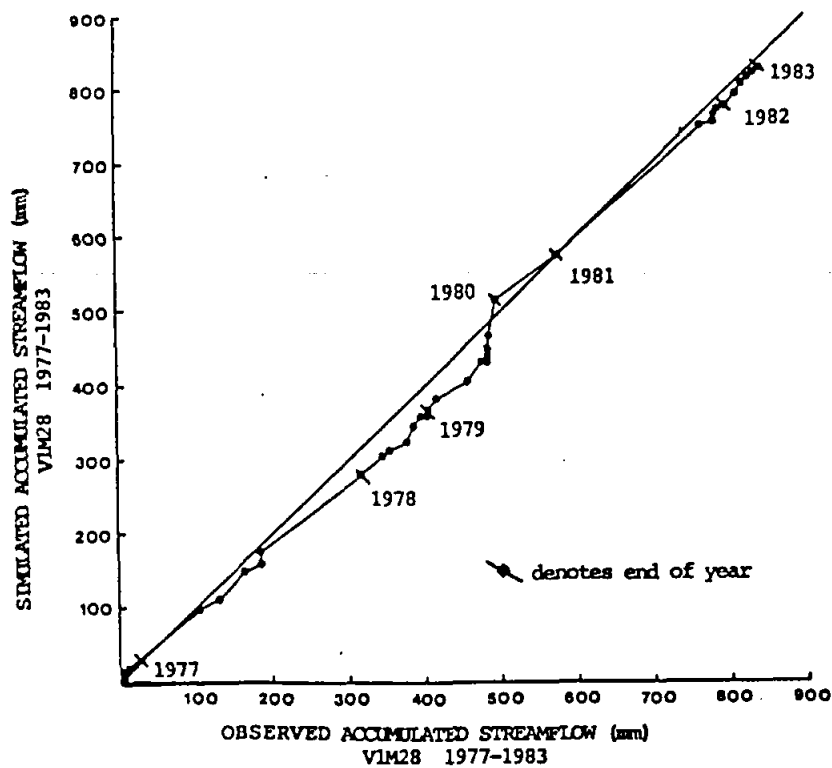


Figure 5.2 Comparison of observed and simulated accumulated monthly streamflow at DeHoek V1M28, Natal for 1977-1983 (after Schulze, 1986)

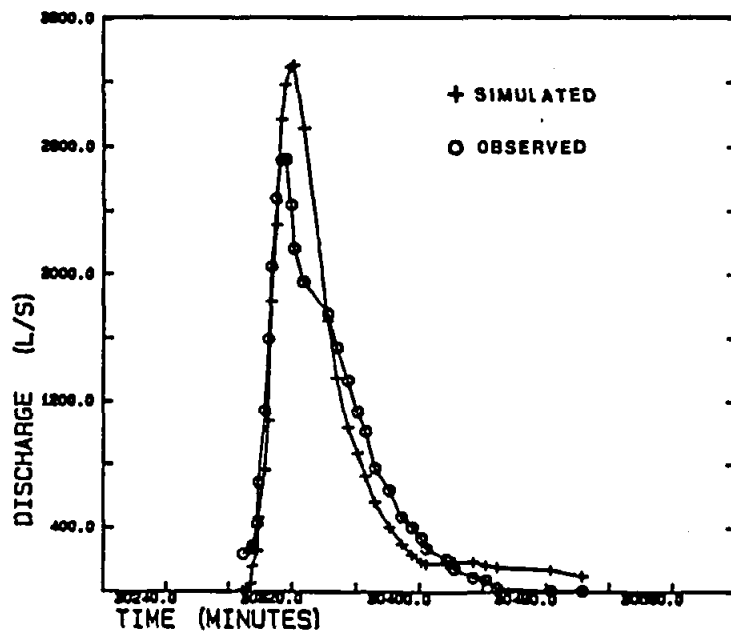


Figure 5.3 Comparison of observed and simulated flood hydrograph at DeHoek V1M28, Natal (Schulze, 1986)

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 Apan 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 Roo-depla-at and Cedara

STATISTIC	WHEAT AT ROODEPLAAT								SOYBEAN AT CEDARA	
	PLOT 6				PLOT 16				PLOT 8	PLOT 17
	SINGLE HORIZON (1.8m)	DOUBLE A (0.9m)	DOUBLE B (0.9m)	HORIZON TOTAL (A+B) (1.8m)	SINGLE HORIZON (1.8m)	DOUBLE A (0.9m)	DOUBLE B (0.9m)	HORIZON 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 andASMussen (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		SOYBEANS AT CEDARA	
	PLOT 6	PLOT 16	PLOT 8	PLOT 17
	SINGLE HORIZON		SINGLE HORIZON	
	(1.8m)		(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.

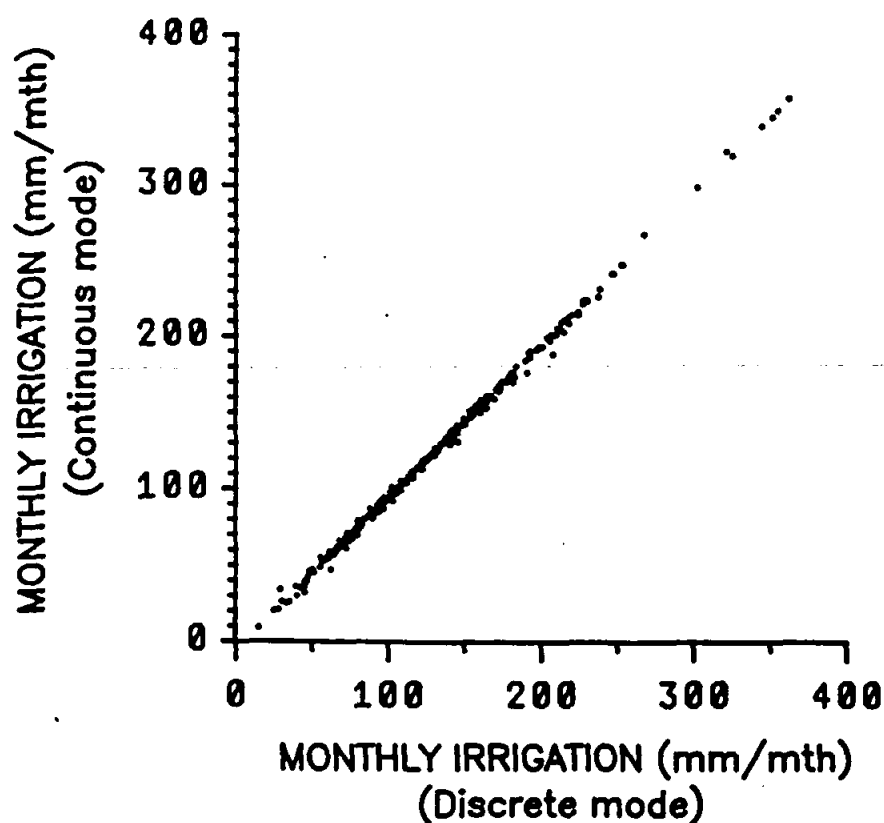


Figure 5.4 Scattergram of the estimated irrigation requirements using the discrete versus the continuous mode of operating the irrigation model at 17 stations, distributed throughout Southern Africa

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 rain gauge 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 km² and most of the homogeneous climate zones, delimited in this study, are smaller than 314 km² 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.

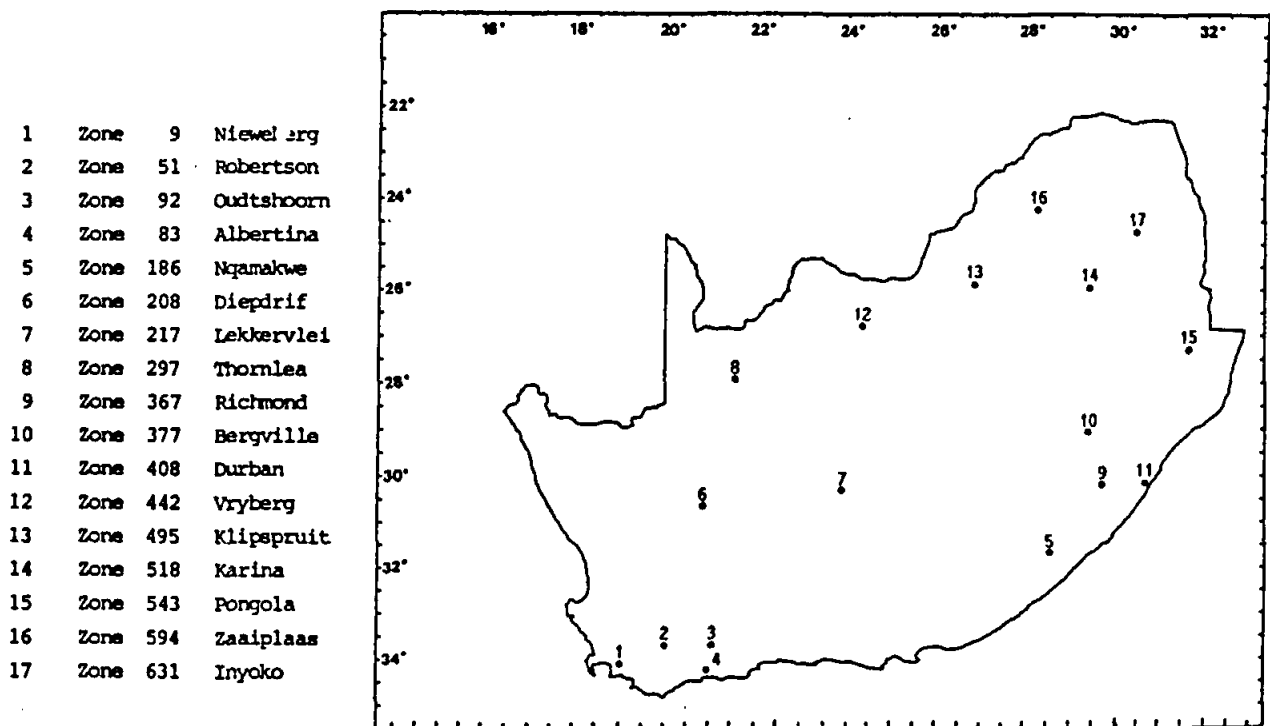


Figure 6.1 Location of the stations used to test the output from the ACRU model when comparing the effect of observed and synthetic daily rainfall data

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

STATION	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
1. Nieuwberg Zone 9 Lat. 34° 04' Long. 23° 03' Alt. MAP. 564 m 1605.9 mm	57	Wheat	Clay	obs syn	23.6 23.4	10.1 10.1	1.3 1.2	0.9 0.9	46.0 45.0	42.2 41.6	25.7 25.6	97.8 98.3	2.1 1.7	5.1 3.8	320.9 285.1	233.6 234.0	142.1 144.9
2. Robertson Zone 51 Lat. 33° 18' Long. 19° 33' Alt. MAP. 183 m 332.1 mm	104	Wheat	Sand	obs syn	22.2 22.1	10.3 10.2	1.2 1.1	0.9 0.7	44.6 43.9	41.5 40.6	24.5 24.0	99.1 99.5	1.8 1.3	4.5 2.7	257.1 248.3	207.5 198.1	137.2 139.4
3. Albertinia Zone 83 Lat. 34° 12' Long. 21° 36' Alt. MAP. 168 m 438.4 mm	54	Wheat	Clay	obs syn	20.9 21.2	11.8 12.0	1.4 1.3	1.6 1.5	48.1 48.9	42.6 44.4	23.0 23.1	8.5 9.2	4.6 3.2	29.0 13.5	38.2 39.5	22.7 26.1	8.7 11.1
4. Oudshoorn Zone 92 Lat. 33° 35' Long. 22° 12' Alt. MAP. 315 m 242.2 mm	101	Veld	Clay	obs syn	14.6 14.6	11.8 11.8	1.1 1.0	0.8 0.8	38.2 37.9	31.5 31.6	21.4 21.4	1.7 1.4	5.5 3.7	6.4 4.8	57.4 29.1	10.6 7.6	4.4 0.6
5. Nqunakwe Zone 186 Lat. 32° 12' Long. 27° 57' Alt. MAP. 1060 m 686.6 mm	94	Maize	Clay	obs syn	34.4 36.4	26.5 26.6	1.2 1.1	0.5 0.3	92.9 94.6	75.1 76.6	51.0 56.1	11.9 11.9	20.0 17.2	52.5 45.3	33.7 32.8	15.3 17.3	
6. Diepdriif Zone 208 Lat. 31° 34' Long. 20° 18' Alt. MAP. 1039 m 129.1 mm	49	Sparse Veld	Clay	obs syn	8.0 8.4	10.3 10.7	2.0 1.9	4.7 4.2	30.6 30.3	21.9 24.9	11.8 12.8	1.1 1.0	4.5 4.5	6.1 9.0	43.3 100.9	6.4 5.1	1.5 2.3
7. Letkervlei Zone 217 Lat. 31° 03' Long. 23° 36' Alt. MAP. 1292 m 271.1 mm	61	Sparse Veld	Clay	obs syn	15.9 15.6	16.6 14.9	1.5 1.4	2.1 1.9	51.4 46.9	40.0 35.9	23.6 22.9	2.6 2.4	7.7 6.2	5.4 5.3	40.6 41.1	15.3 13.0	6.9 7.3
8. Thornlea Zone 297 Lat. 28° 39' Long. 21° 31' Alt. MAP. 911 m 199.3 mm	67	Sparse Veld	Clay	obs syn	12.3 13.4	15.7 15.7	1.8 1.5	3.5 2.4	47.7 47.5	35.9 35.8	17.3 21.8	2.5 2.3	8.2 7.0	6.7 4.8	49.5 32.5	16.3 16.1	7.2 7.7
9. Richmond, Natal Zone 367 Lat. 29° 52' Long. 30° 16' Alt. MAP. 884 m 1032.7 mm	56	Maize	Clay	obs syn	43.0 43.2	35.1 35.0	0.9 0.9	-0.6 -0.6	110.8 109.9	103.3 104.9	60.2 60.2	30.6 29.6	39.2 33.1	3.5 1.6	22.3 95.2	101.3 76.8	44.5 46.4

Table 6.2 (continued)

LENGTH OF RECORD (yrs)	STATION	CROP	SOIL	RAIN	MONTHLY ACTUAL EVAPOTRANSPIRATION (mm)					MONTHLY RUNOFF (mm)								
					MEAN	STD DEV	SKEW-NESS	KURT-OSS	PERCENTILES 75 90	MEAN	STD DEV	SKEW-NESS	KURT-OSS	PERCENTILES 75 90				
46	10. Bergville Zone 377 Lat. Long. 28°44' 29°21' Alt. MAP. 11130 m 740.9 mm	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	
62	11. Durban Zone 408 Lat. Long. 29°51' 31°00' Alt. MAP. 91 m 1013.5 mm	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	28.9	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	28.9	2.4	9.1	77.5	56.9	30.7	
46	12. Vryburg Zone 442 Lat. Long. 28°58' 24°44' Alt. MAP. 11190 m 463.4 mm	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	25.3	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	28.4	29.3	1.3	1.1	92.0	70.8	41.0	6.5	11.9	5.3	44.5	26.2	16.3	7.3	
75	13. Klipspruit Zone 495 Lat. Long. 26°16' 27°55' Alt. MAP. 1615 m 688.7 mm	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	
67	14. Karinga Zone 518 Lat. Long. 26°05' 29°30' Alt. MAP. 1648 m 645.1 mm	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	
27	15. Pongola Zone 543 Lat. Long. 27°25' 31°31' Alt. MAP. 290 m 675.2 mm	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	
65	16. Zaziaplaas Zone 594 Lat. Long. 24°04' 28°22' Alt. MAP. 1204 m 653.4 mm	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	
57	17. Inyoko Zone 631 Lat. Long. 24°08' 30°52' Alt. MAP. 390 m 461.1 mm	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	9.8	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_0	b_1	r^2	RMSE	b_0	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); Perman (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, Perman 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

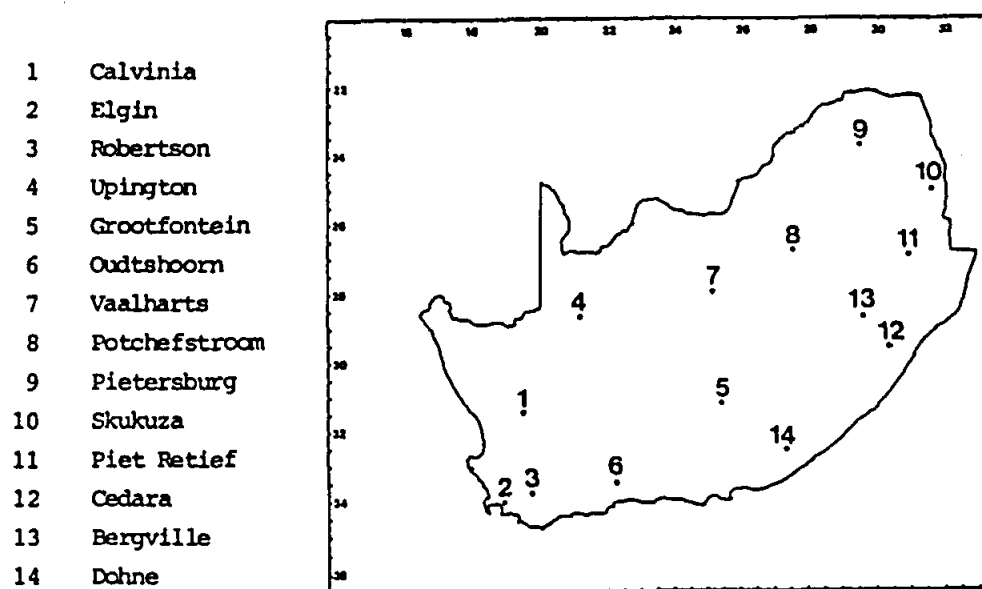


Table 6.5 Sensitivity of the ACRU model to techniques for estimating potential evaporation

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															
				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

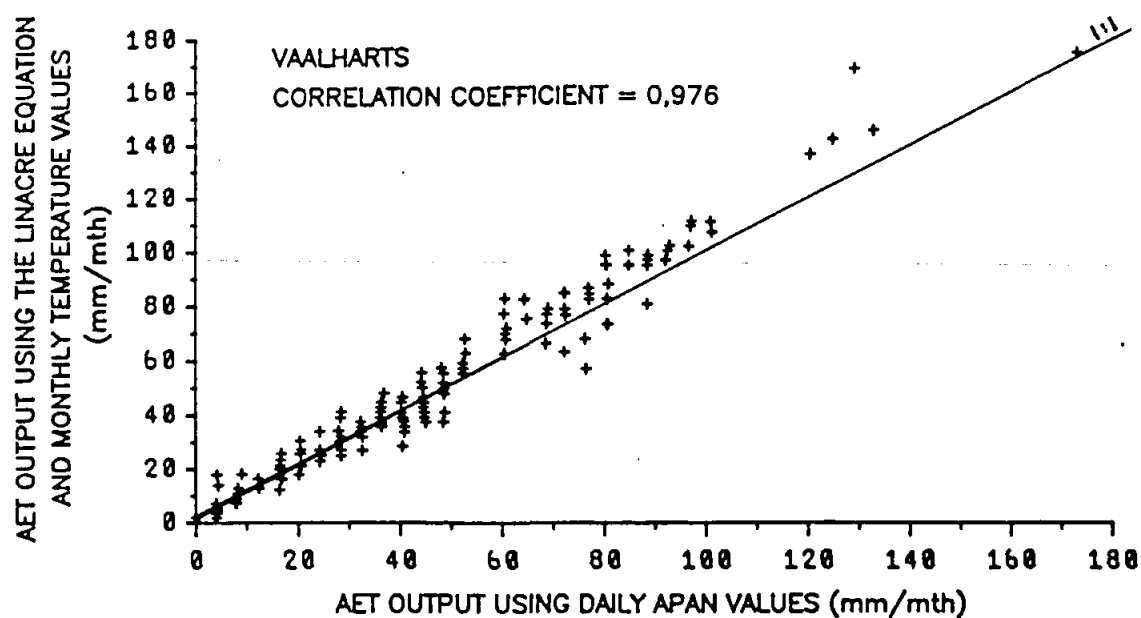


Figure 6.3 Monthly AET estimated using the Linacre (1977) equation vs. monthly AET estimated using daily A-pan values at Vaalharts under dryland conditions

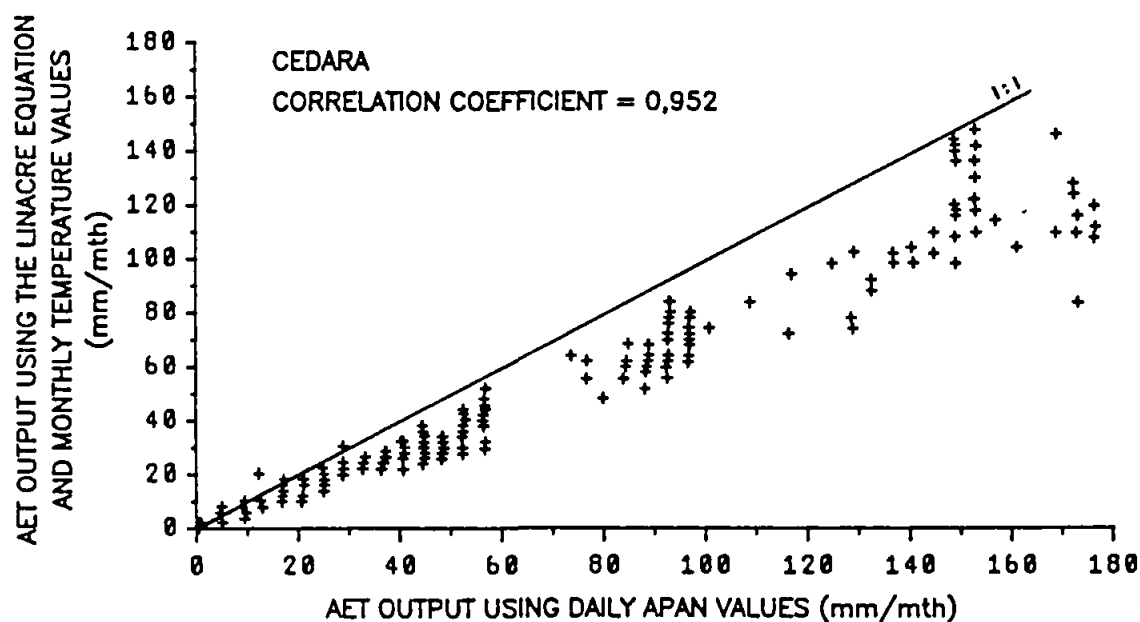


Figure 6.4 Monthly AET estimated using the Linacre (1977) equation vs monthly AET estimated using daily A-pan values at Cedara under dryland conditions

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 = $T_a + 0,006 \text{ ELEV}$, with

T_a = mean air temperature ($^{\circ}\text{C}$),

T_d = mean dew point temperature ($^{\circ}\text{C}$),

ELEV = elevation above sea level (m),

ALAT = latitude in degrees, and

$(T_a - T_d)$ = difference between air and dew point temperature,
 $= 0,0023\text{ELEV} + 0,37T_a + 0,53R + 0,35 R_{an} - 10,9$ in $^{\circ}\text{C}$

in which

R = the mean daily or monthly range of temperature ($^{\circ}\text{C}$) and

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

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.

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

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.

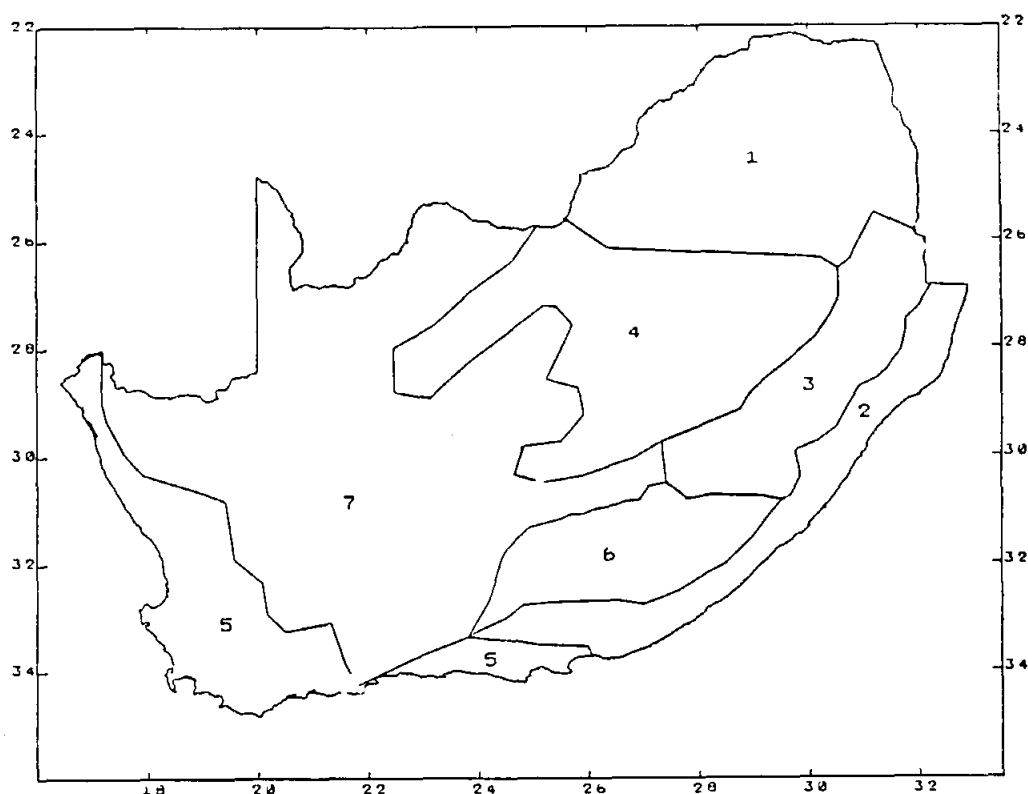


Figure 6.5 Delimitation of major wind regions

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

LAT 28 44 LONG 29 21 ALTITUDE 1130m 55 YEARS OF DATA

LAT 28 45 LONG 29 19 ALTITUDE 1121m WIND REGION : 3

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

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 (DEGREES CELSIUS)

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

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 SOIL

DATE TYPE DEPTH TEXT

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 23 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 68 98 142 198 176 229 136 203 63 88 12 26 21 27 19 24 26 28 31 33 31 45 25 41

1 NV MAIZE SHALW CLAY 66 100 171 217 196 237 162 203 63 88 12 26 21 27 19 24 26 28 31 33 31 45 25 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 31 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

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

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

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

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

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

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

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

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

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 9 25

15 DC SUNFL DEEP LOAM 2 22 22 91 72 132 81 128 69 93 46 55 22 27 22 27 30 35 29 42 9 25

15 DC SUNFL DEEP SAND 7 31 39 83 89 145 133 176 72 100 47 56 22 27 22 27 30 35 29 42 9 25

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

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

15 DC SUNFL MEDM SAND 9 34 51 94 95 154 93 139 75 102 48 56 22 27 25 27 32 35 29 43 25 41

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

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

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

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

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

NV = November MEDM = medium SUNFL = sunflowers
DC = December SHALW = shallow

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

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

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
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.

Problem: 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.

Analysis: 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
ET deficit (mm)	9	33	[64]	105

[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
Index stress (days)	4	17	[11]	19

[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 AT50288 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

***** 50 TH PERCENTILE ** 80 TH PERCENTILE ** 90 TH PERCENTILE ** *													
***** 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 * MTH* *****													
***** 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

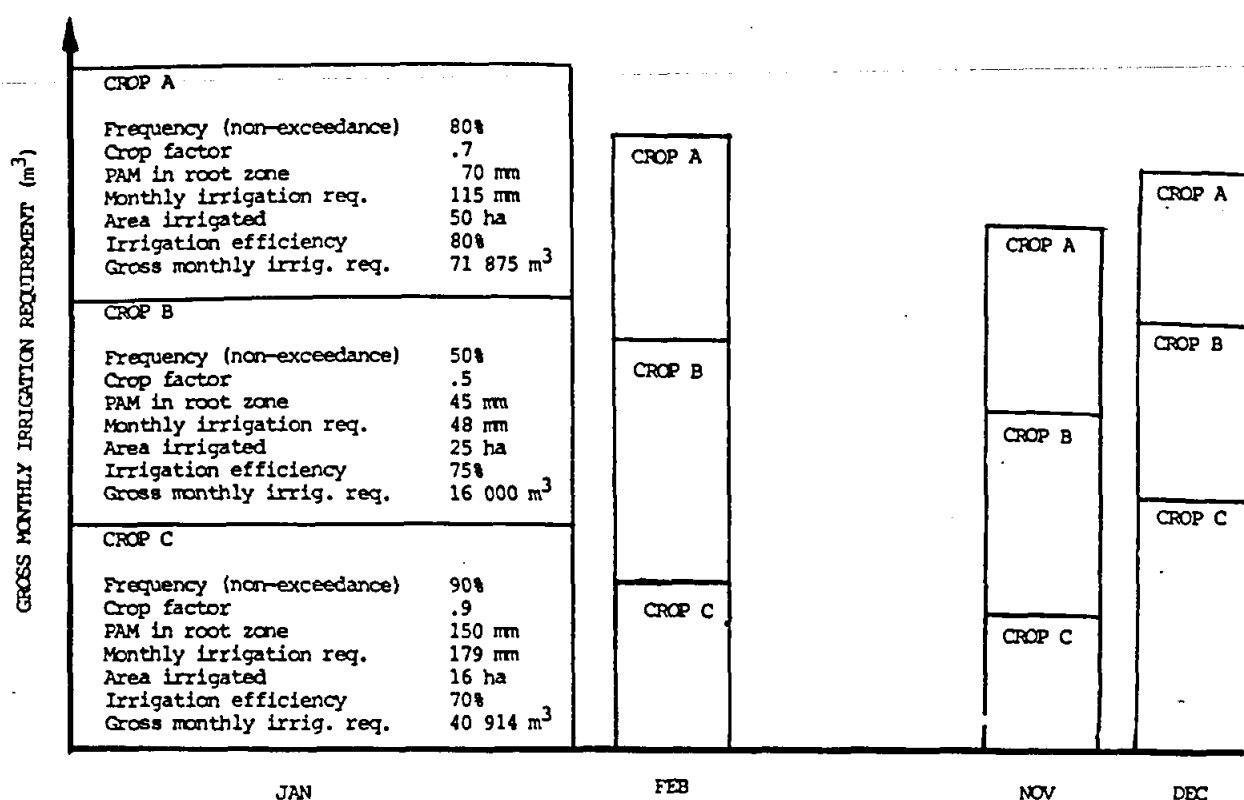


Figure 7.1 Estimation of monthly irrigation demand curve for planning:
example using selected values from Zone 377, Bergville

The values of PAM (mm/m) for most South African soil series may be obtained, inter alia, 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 propagation 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 superseded 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

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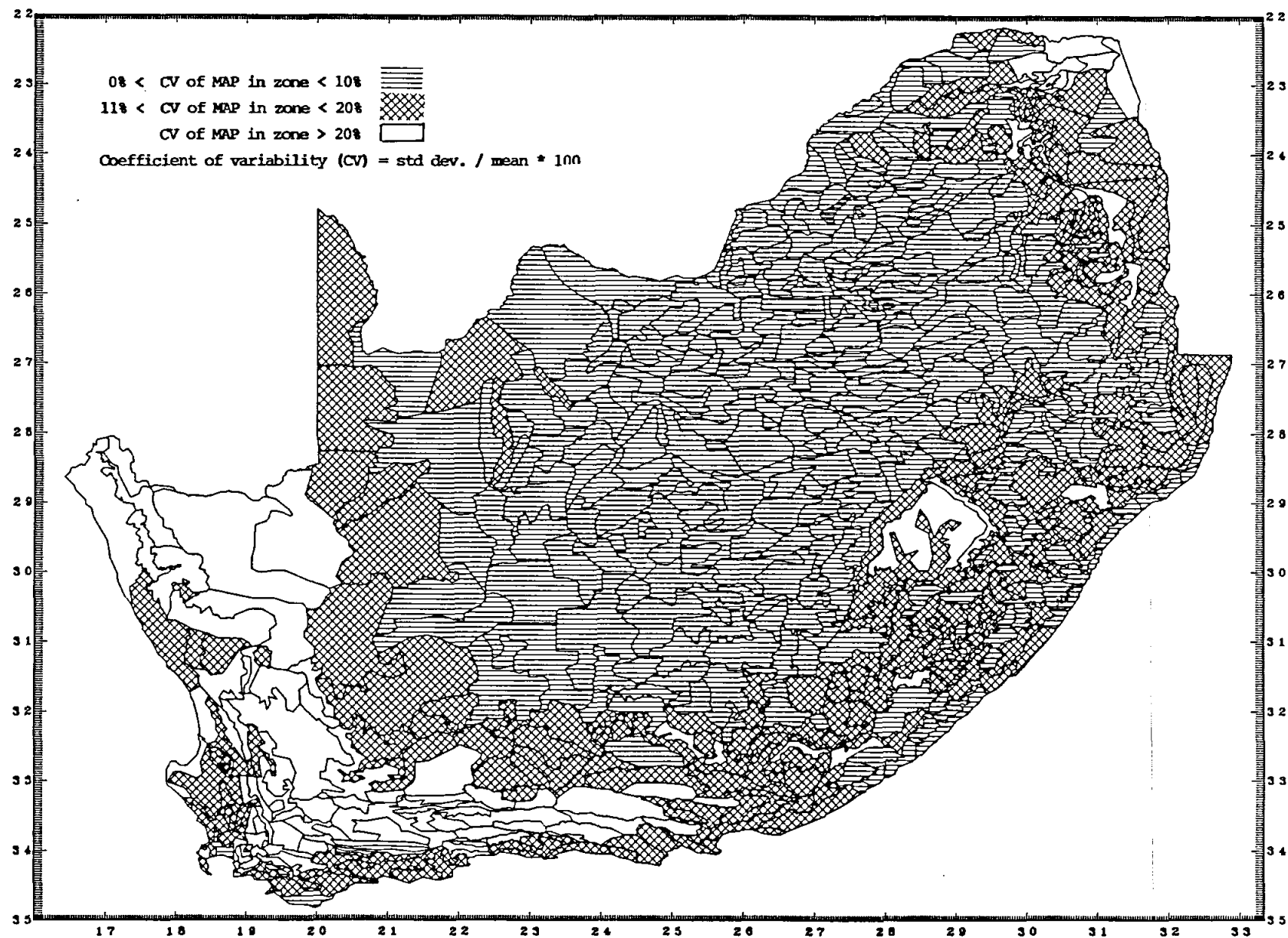
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APPENDIX A

Variation of MAP within the climate zones

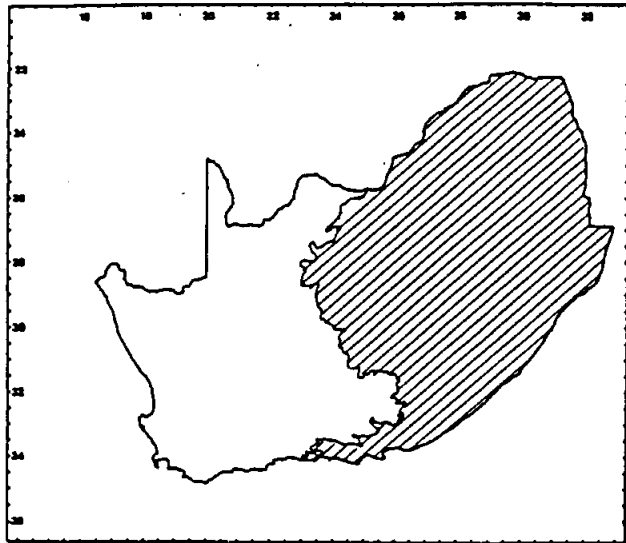


APPENDIX B

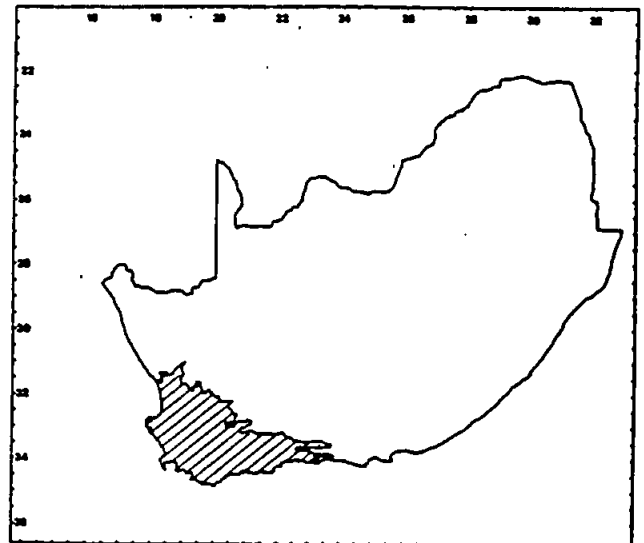
Homogeneous climatic zones in southern Africa (Map supplied)

APPENDIX C

Assumed spatial distribution of the crops used in the dryland analyses



MAIZE

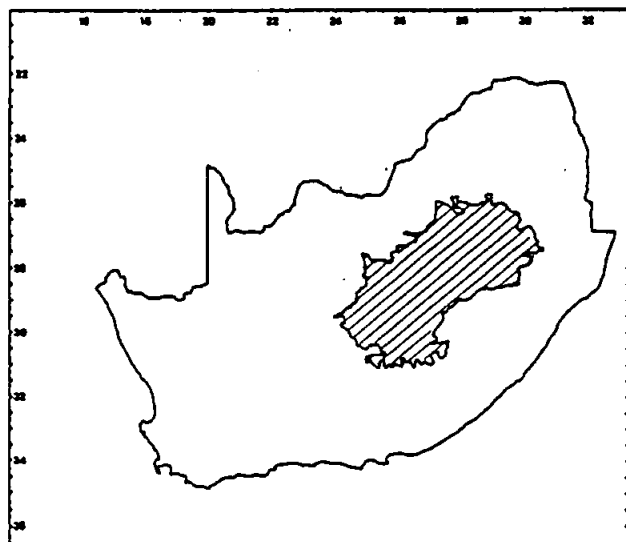


SOYBEANS

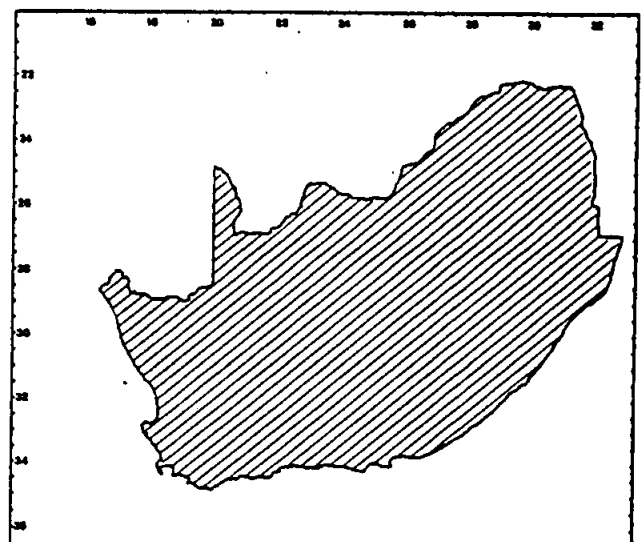
WHEAT (WINTER)

SUNFLOWER

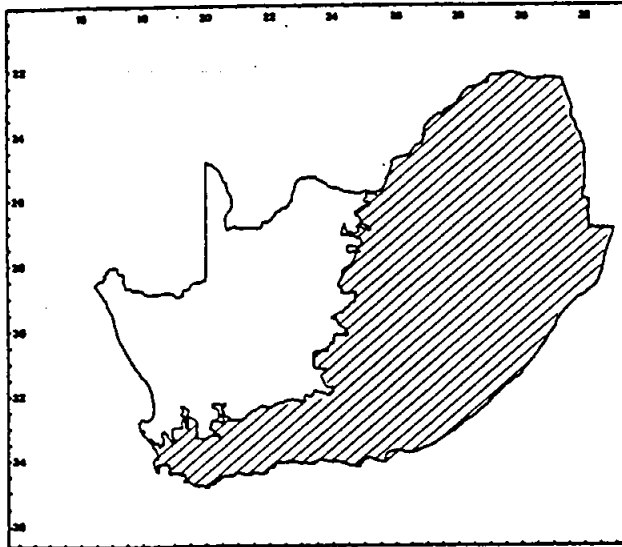
SORGHUM



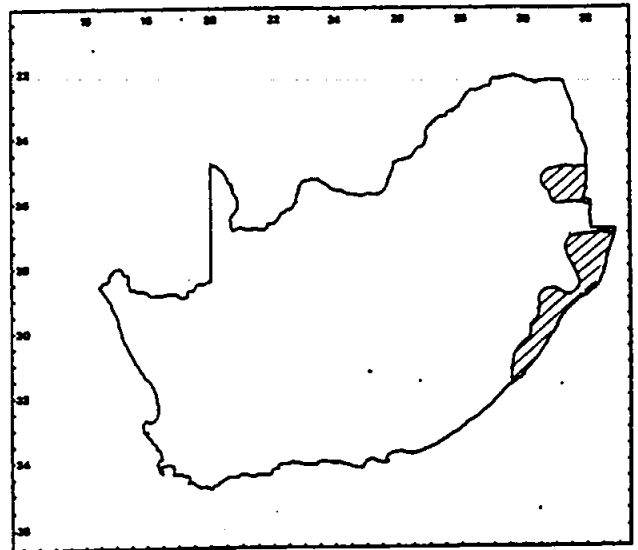
WHEAT (SPRING)



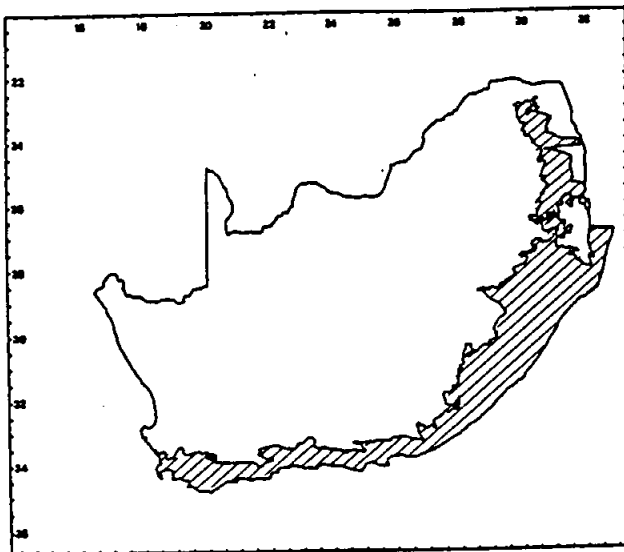
SPARSE VELD



GOOD VELD



SUGARCANE



TIMBER

APPENDIX D

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
SPARSE 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
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
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 E

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)	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
M.A.P. 1605.9mm	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 50% 90%	MONTH 2 50% 90%	MONTH 3 50% 90%	MONTH 4 50% 90%	MONTH 5 50% 90%	MONTH 6 50% 90%	MONTH 7 50% 90%	MONTH 8 50% 90%	MONTH 9 50% 90%	MONTH 10 50% 90%	MONTH 11 50% 90%	MONTH 12 50% 90%
15	MY WHEAT	DEEP	CLAY	0	0	0	0	0	0	0	0	8	13	27	22
15	MY WHEAT	DEEP	LOAM	0	0	0	0	0	0	0	0	8	13	27	22
15	MY WHEAT	DEEP	SAND	0	2	0	4	0	0	0	2	19	20	36	24
15	MY WHEAT	MEDM	CLAY	0	0	0	1	0	0	0	2	11	16	31	23
15	MY WHEAT	MEDM	LOAM	0	0	0	1	0	0	0	2	11	16	31	23
15	MY WHEAT	MEDM	SAND	0	3	0	5	0	1	0	3	9	22	37	24
15	MY WHEAT	SHALW	CLAY	0	3	0	7	0	16	0	2	21	22	36	25
15	MY WHEAT	SHALW	LOAM	0	3	0	7	0	12	0	3	8	21	21	36
15	MY WHEAT	SHALW	SAND	1	6	3	17	4	21	0	5	26	27	39	30
1	JA SVELD	DEEP	CLAY	93	115	107	128	73	98	18	41	3	11	0	0
1	JA SVELD	DEEP	LOAM	89	114	103	127	72	98	17	40	0	9	0	0
1	JA SVELD	DEEP	SAND	101	124	109	132	72	101	15	42	0	9	0	0
1	JA SVELD	MEDM	CLAY	100	123	113	133	76	101	19	42	3	11	0	0
1	JA SVELD	MEDM	LOAM	97	121	108	131	73	100	17	41	0	10	0	0
1	JA SVELD	MEDM	SAND	106	126	111	133	75	101	17	42	0	9	0	0
1	JA SVELD	SHALW	CLAY	108	128	116	137	79	103	22	46	2	10	0	0
1	JA SVELD	SHALW	LOAM	106	128	114	135	75	102	18	43	0	9	0	0
1	JA SVELD	SHALW	SAND	106	128	114	137	74	104	19	46	1	10	0	0
1	JA GVELD	DEEP	CLAY	141	169	162	185	113	142	36	67	9	20	0	4
1	JA GVELD	DEEP	LOAM	139	165	160	184	110	141	34	64	4	18	0	1
1	JA GVELD	DEEP	SAND	150	175	162	188	108	143	33	66	2	16	0	0
1	JA GVELD	MEDM	CLAY	148	175	166	188	113	143	36	69	8	19	0	3
1	JA GVELD	MEDM	LOAM	145	172	163	188	110	143	34	65	2	17	0	0
1	JA GVELD	MEDM	SAND	154	176	164	189	110	143	32	66	2	16	0	0
1	JA GVELD	SHALW	CLAY	156	177	166	189	115	145	40	72	8	22	0	3
1	JA GVELD	SHALW	LOAM	154	176	165	189	112	144	33	71	4	18	0	0
1	JA GVELD	SHALW	SAND	155	177	165	189	110	145	36	71	5	21	0	3
1	JA TIMBR	DEEP	CLAY	180	201	191	213	137	165	60	92	23	43	3	15
1	JA TIMBR	DEEP	LOAM	180	200	190	213	133	165	57	92	14	38	0	9
1	JA TIMBR	DEEP	SAND	180	203	193	214	133	167	55	93	12	36	0	8
1	JA TIMBR	MEDM	CLAY	180	202	192	213	139	166	60	95	22	44	2	15
1	JA TIMBR	MEDM	LOAM	180	202	192	213	134	166	55	91	11	38	0	7
1	JA TIMBR	MEDM	SAND	181	204	193	216	133	167	55	97	12	36	0	8
1	JA TIMBR	SHALW	CLAY	183	204	196	216	139	168	62	98	26	50	4	23
1	JA TIMBR	SHALW	LOAM	182	203	195	216	137	168	57	98	20	41	2	15
1	JA TIMBR	SHALW	SAND	184	205	194	216	135	169	57	98	22	49	6	22

INDEX OF STRESS DAYS

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

ZONE NO. 51

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

TEMPERATURE STATION AT50004 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 DATE	CROP TYPE	SOIL DEPTH	SOIL TEXT	MONTH 1 50% 90%	MONTH 2 50% 90%	MONTH 3 50% 90%	MONTH 4 50% 90%	MONTH 5 50% 90%	MONTH 6 50% 90%	MONTH 7 50% 90%	MONTH 8 50% 90%	MONTH 9 50% 90%	MONTH10 50% 90%	MONTH11 50% 90%	MONTH12 50% 90%
15 MY	WHEAT	DEEP	CLAY	15	25	29	53	55	74	30	40	8	20	17	31
15 MY	WHEAT	DEEP	LOAM	14	24	24	47	48	71	27	38	7	20	17	31
15 MY	WHEAT	DEEP	SAND	14	25	20	46	46	68	25	39	10	23	21	37
15 MY	WHEAT	MEDM	CLAY	15	25	28	52	55	74	29	41	8	21	19	33
15 MY	WHEAT	MEDM	LOAM	14	24	21	47	48	70	27	38	8	20	18	32
15 MY	WHEAT	MEDM	SAND	15	26	22	45	52	71	26	42	11	23	23	38
15 MY	WHEAT	SHALW	CLAY	16	26	32	51	62	77	31	43	12	23	23	38
15 MY	WHEAT	SHALW	LOAM	15	25	26	48	57	76	28	43	11	23	22	37
15 MY	WHEAT	SHALW	SAND	16	27	33	52	61	78	29	43	15	24	26	39
1 JA	SVELD	DEEP	CLAY	179	187	173	181	121	134	63	74	29	38	11	21
1 JA	SVELD	DEEP	LOAM	179	186	173	181	121	133	62	74	29	37	10	21
1 JA	SVELD	DEEP	SAND	179	187	173	180	120	134	60	74	26	37	8	21
1 JA	SVELD	MEDM	CLAY	179	187	173	180	121	134	63	74	29	38	10	21
1 JA	SVELD	MEDM	LOAM	179	187	173	180	120	134	61	74	29	38	10	21
1 JA	SVELD	MEDM	SAND	179	187	174	180	120	134	60	74	26	37	7	22
1 JA	SVELD	SHALW	CLAY	179	188	174	181	122	134	63	74	29	39	11	22
1 JA	SVELD	SHALW	LOAM	179	188	174	180	121	134	61	74	27	38	9	21
1 JA	SVELD	SHALW	SAND	179	188	174	181	121	134	61	73	25	39	8	21
1 JA	GVELD	DEEP	CLAY	246	255	239	247	170	184	96	108	48	58	18	31
1 JA	GVELD	DEEP	LOAM	246	254	239	247	169	184	96	108	47	57	18	31
1 JA	GVELD	DEEP	SAND	246	255	239	248	169	184	94	108	45	57	16	31
1 JA	GVELD	MEDM	CLAY	246	255	239	248	170	184	97	108	47	58	18	31
1 JA	GVELD	MEDM	LOAM	246	255	239	248	169	184	95	108	46	57	17	31
1 JA	GVELD	MEDM	SAND	246	255	240	248	170	184	94	107	45	57	15	30
1 JA	GVELD	SHALW	CLAY	246	255	240	248	170	184	96	108	47	58	19	31
1 JA	GVELD	SHALW	LOAM	246	255	240	248	170	184	95	108	46	58	16	31
1 JA	GVELD	SHALW	SAND	244	255	238	247	170	184	94	107	45	60	16	31
1 JA	TIMBR	DEEP	CLAY	282	290	273	283	197	210	131	142	87	99	53	68
1 JA	TIMBR	DEEP	LOAM	282	290	273	283	197	210	130	142	87	99	53	68
1 JA	TIMBR	DEEP	SAND	282	290	274	283	197	210	129	143	87	100	50	67
1 JA	TIMBR	MEDM	CLAY	282	290	273	283	197	210	131	142	87	99	53	67
1 JA	TIMBR	MEDM	LOAM	282	290	273	283	197	210	131	142	87	99	52	67
1 JA	TIMBR	MEDM	SAND	282	290	274	283	198	210	131	143	86	101	50	68
1 JA	TIMBR	SHALW	CLAY	282	290	274	283	198	210	132	143	87	101	53	68
1 JA	TIMBR	SHALW	LOAM	282	290	274	283	198	210	131	143	87	101	51	68
1 JA	TIMBR	SHALW	SAND	282	290	274	283	198	210	130	142	87	102	51	68

INDEX OF STRESS DAYS

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

WATER YIELD (mm)

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

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

RAINFALL (mm) MEAN 92.0 76.6 75.8 39.9 15.0 7.2 6.8 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
SOEV 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	CROP	SOIL	DEPTH	TEXT	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5	MONTH 6	MONTH 7	MONTH 8	MONTH 9	MONTH 10	MONTH 11	MONTH 12
DATE	TYPE	TYPE	TYPE	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	119 151	232 284	275 312	196 243	70 103	30 10	14 26	16 15	21 21	32 32	43 46	48 58
1	NV	MAIZE	DEEP	LOAM	118 147	222 278	266 308	191 241	68 101	29 8	14 26	15 15	20 22	30 30	43 46	48 58
1	NV	MAIZE	DEEP	SAND	119 144	209 268	267 314	192 242	68 101	31 13	19 29	17 17	22 23	31 31	44 46	59 58
1	NV	MAIZE	MEDM	CLAY	121 149	235 285	277 317	198 243	71 102	12 10	16 27	19 19	21 21	30 30	43 46	58 58
1	NV	MAIZE	MEDM	LOAM	118 147	220 276	270 313	191 242	68 102	10 10	16 27	16 20	21 22	30 30	43 46	58 58
1	NV	MAIZE	MEDM	SAND	118 144	222 276	268 316	192 242	69 104	15 14	20 29	19 20	22 24	31 31	44 46	60 60
1	NV	MAIZE	SHALW	CLAY	124 148	247 289	283 319	206 244	73 104	14 14	20 29	19 20	22 24	31 31	44 46	60 60
1	NV	MAIZE	SHALW	LOAM	119 145	236 284	276 318	198 243	70 102	12 12	20 29	19 20	22 24	31 31	44 46	60 60
1	NV	MAIZE	SHALW	SAND	121 146	237 288	268 312	192 243	73 102	17 17	22 22	20 20	22 24	31 31	44 46	60 60
1	DC	MAIZE	DEEP	CLAY	92 138	206 242	215 261	159 202	58 82	23 23	17 21	22 22	24 24	30 30	44 53	64 64
1	DC	MAIZE	DEEP	LOAM	89 135	192 235	204 259	152 198	56 81	23 23	19 22	21 21	24 24	31 31	44 53	64 64
1	DC	MAIZE	DEEP	SAND	94 133	184 226	207 261	155 201	58 82	24 24	22 23	23 23	24 24	30 30	44 53	64 64
1	DC	MAIZE	MEDM	CLAY	91 134	188 235	207 260	155 201	56 82	24 24	21 21	22 22	24 24	31 31	44 53	64 64
1	DC	MAIZE	MEDM	LOAM	97 134	193 233	211 264	157 203	59 82	24 24	21 21	22 22	24 24	31 31	44 53	64 64
1	DC	MAIZE	MEDM	SAND	97 134	193 233	211 264	157 203	59 82	24 24	21 21	22 22	24 24	31 31	44 53	64 64
1	DC	MAIZE	SHALW	CLAY	102 137	216 252	227 265	167 204	62 82	25 25	19 22	23 23	24 24	31 31	44 53	64 64
1	DC	MAIZE	SHALW	LOAM	99 134	203 245	219 262	160 204	60 80	24 24	22 22	23 23	24 24	31 31	44 53	64 64
1	DC	MAIZE	SHALW	SAND	105 137	206 248	213 262	158 203	61 83	26 26	20 24	22 22	24 24	31 31	44 53	64 64
15	DC	SUNFL	DEEP	CLAY	30 66	131 174	157 203	118 158	70 105	46 46	21 24	21 21	23 23	31 31	48 58	65 65
15	DC	SUNFL	DEEP	LOAM	28 64	112 164	147 199	111 157	75 105	44 44	21 24	21 21	23 23	31 31	48 58	65 65
15	DC	SUNFL	DEEP	SAND	33 64	113 158	150 201	111 158	76 106	45 45	22 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	MEDM	CLAY	31 63	131 176	161 205	111 158	80 105	46 46	22 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	MEDM	LOAM	29 63	113 164	150 202	113 158	77 105	45 45	22 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	MEDM	SAND	36 64	120 166	154 203	115 160	78 106	45 45	22 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	SHALW	CLAY	37 66	125 180	171 208	127 163	85 107	48 48	24 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	SHALW	LOAM	35 65	133 177	161 206	119 162	85 107	47 47	24 24	22 22	23 23	31 31	48 58	65 65
15	DC	SUNFL	SHALW	SAND	43 67	140 179	161 205	121 162	83 107	47 47	24 24	22 22	23 23	31 31	48 58	65 65
1	JA	SVELD	DEEP	CLAY	116 149	91 132	67 103	48 74	38 48	31 31	39 49	50 50	53 53	74 78	119 160	160 160
1	JA	SVELD	DEEP	LOAM	109 149	82 130	62 101	42 71	34 48	31 31	37 48	40 52	54 54	78 78	119 160	160 160
1	JA	SVELD	DEEP	SAND	118 149	93 132	68 105	50 75	39 48	31 31	38 40	52 52	54 54	78 78	119 160	160 160
1	JA	SVELD	MEDM	CLAY	111 149	83 131	63 101	42 72	35 48	31 31	36 40	50 50	53 53	78 78	121 159	161 161
1	JA	SVELD	MEDM	LOAM	108 149	85 131	64 103	46 72	37 49	31 31	37 40	50 50	53 53	78 78	121 159	161 161
1	JA	SVELD	MEDM	SAND	123 151	100 136	76 109	56 76	41 49	35 35	39 40	53 53	54 54	78 78	126 151	162 162

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%	50%
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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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		MONTH 10		MONTH 11		MONTH 12	
				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	0	6	0	4	0	0	0	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	0	0	0
1 NV	MAIZE	MEDM	LOAM	0	1	0	12	0	15	0	15	0	19	0	8	0	5	0	0	0	0	0	0	0	0	0	1
1 NV	MAIZE	MEDM	SAND	0	8	3	15	3	12	1	14	1	23	1	18	1	17	1	9	1	0	0	0	0	0	0	1
1 NV	MAIZE	SHALW	CLAY	1	21	9	44	11	55	12	50	13	60	3	37	0	12	0	3	0	1	1	0	0	0	0	4
1 NV	MAIZE	SHALW	LOAM	0	10	6	26	4	30	5	31	5	41	2	24	1	16	0	8	5	5	4	0	0	0	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	3	0	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	0	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	0	12	0	4	0	0	0	1	0	1	0	0	0	0	0	0	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	0	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	0	0	2
1 DC	MAIZE	MEDM	SAND	3	20	7	21	4	19	2	20	1	9	0	8	0	3	0	2	0	0	0	0	0	0	0	9
1 DC	MAIZE	SHALW	CLAY	9	49	12	58	11	47	11	53	2	29	0	13	0	0	0	0	0	0	0	0	0	0	0	28
1 DC	MAIZE	SHALW	LOAM	7	31	10	33	6	32	4	35	2	17	0	0	0	3	0	2	0	0	0	0	0	0	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	0	0	0	0	18
15 DC	SUNFL	DEEP	CLAY	3	33	4	42	4	29	3	37	0	14	0	0	0	0	0	0	0	0	0	0	0	0	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	0	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	0	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	0	0	0	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	0	0	0	0	29
15 DC	SUNFL	SHALW	LOAM	8	35	12	41	7	35	5	39	2	15	1	7	0	1	0	1	0	0	0	0	0	0	0	13
15 DC	SUNFL	SHALW	SAND	14	35	18	45	11	40	9	42	6	19	4	15	2	7	1	4	0	0	0	0	0	0	0	17
1 JA	SVELD	DEEP	CLAY	5	44	4	32	4	42	0	16	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	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	0	0	0	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	0	0	0	0	8
1 JA	SVELD	MEDM	CLAY	7	51	6	37	6	46	0	21	0	8	0	1	0	0	0	0	1	0	0	0	0	0	0	37
1 JA	SVELD	MEDM	LOAM	1	18	1	17	1	19	0	16	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	14
1 JA	SVELD	MEDM	SAND	1	18	1	20	2	25	1	16	0	9	0	5	0	3	0	2	0	0	0	0	0	0	0	11
1 JA	SVELD	SHALW	CLAY	14	70	14	55	13	59	2	33	0	13	0	4	0	0	0	1	0	0	0	0	0	0	0	50
1 JA	SVELD	SHALW	LOAM	5	41	7	37	6	42	3	18	1	10	0	4	0	2	0	0	0	0	0	0	0	0	0	29
1 JA	SVELD	SHALW	SAND	7	39	10	37	10	43	7	25	4	18	2	9	1	5	0	3	0	0	0	0	0	0	0	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	0	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	0	0	0	0	0	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	0	0	0	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	0	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	0	0	0	0	10
1 DC	SOYAS	SHALW	CLAY	11	53	14	64	12	50	13	59	2	36	0	12	0	3	0	0	0	0	0	0	0	0	0	30
1 DC	SOYAS	SHALW	LOAM	8	35	12	38	7	35	6	42	3	23	1	15	0	7	0	4	0	0	0	0	0	0	0	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 UPLINGTON LAT 28 24 LONG 21 16 ALTITUDE 825m WIND REGION : 7

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 3.8 0.0 0.0 0.0 0.0 3.3 6.4 8.3 193.0
SDEV 41.3 33.2 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 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
(DEGREES CELSIUS) 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	CROP	SOIL	SOIL	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5	MONTH 6	MONTH 7	MONTH 8	MONTH 9	MONTH 10	MONTH 11	MONTH 12
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	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 95	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	79 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	79 79	113 118	176 184	189 200
1	JA	SVELD	MEDM SAND	194 204	169 191	120 148	78 95	45 55	41 44	44 44	52 53	78 79	113 118	176 184	190 200
1	JA	SVELD	SHALL CLAY	194 204	171 191	124 149	82 97	49 55	41 44	45 45	52 53	79 79	113 118	178 184	191 200
1	JA	SVELD	SHALL LOAM	194 204	169 191	121 149	81 97	47 55	41 44	44 45	52 53	79 79	113 118	177 184	191 200
1	JA	SVELD	SHALL 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	CROP	SOIL	SOIL	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5	MONTH 6	MONTH 7	MONTH 8	MONTH 9	MONTH 10	MONTH 11	MONTH 12
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	JA	SVELD	DEEP CLAY	31 31	27 29	28 31	28 30	31 31	30 30	31 31	31 31	31 30	31 30	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	31 30	31 30	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	31 30	31 30	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	31 30	31 30	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	31 30	31 30	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	31 30	31 30	30 30	31 31
1	JA	SVELD	SHALL CLAY	31 31	26 28	27 31	27 30	31 31	30 30	31 31	31 31	31 30	31 30	30 30	31 31
1	JA	SVELD	SHALL LOAM	31 31	26 28	26 31	27 30	31 31	30 30	31 31	31 31	31 30	31 30	30 30	31 31
1	JA	SVELD	SHALL SAND	30 31	25 28	25 31	26 30	29 31	30 30	31 31	31 31	31 30	31 30	30 30	31 31

WATER YIELD (mm)

PLANT	CROP	SOIL	SOIL	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5	MONTH 6	MONTH 7	MONTH 8	MONTH 9	MONTH 10	MONTH 11	MONTH 12
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	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 13	0 14	0 13	0 2	0 0	0 0	0 0	0 0	0 0	0 1	0 2
1	JA	SVELD	DEEP SAND	0 0	0 1	0 3	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 3
1	JA	SVELD	MEDM CLAY	0 8	0 15	0 19	0 13	0 4	0 0	0 0	0 0	0 0	0 2	0 7	0 3
1	JA	SVELD	MEDM LOAM	0 0	0 6	0 7	0 13	0 1	0 0	0 0	0 0	0 0	0 0	0 2	0 3
1	JA	SVELD	MEDM SAND	0 1	0 4	0 5	0 6	0 3	0 1	0 0	0 0	0 0	0 4	0 1	0 8
1	JA	SVELD	SHALL CLAY	0 0	0 3	0 15	0 13	0 0	0 0	0 0	0 0	0 0	0 1	0 6	0 2
1	JA	SVELD	SHALL LOAM	0 0	0 13	0 15	0 13	0 0	0 0	0 0	0 0	0 0	0 0	0 6	0 2
1	JA	SVELD	SHALL SAND	0 6	0 12	0 17	0 15	0 9	0 4	0 0	0 2	0 0	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)	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
M.A.P. 645.1mm	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		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MEAN TEMPERATURES	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
(DEGREES CELSIUS)	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	CROP	SOIL	SOIL	MONTH 1	MONTH 2	MONTH 3	MONTH 4	MONTH 5	MONTH 6	MONTH 7	MONTH 8	MONTH 9	MONTH 10	MONTH 11	MONTH 12
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	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 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		MONTH 10		MONTH 11		MONTH 12			
				50%	90%	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	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	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	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	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	25	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	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	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	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	31	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	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	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	31	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	31	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	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	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	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	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	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	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	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	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	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	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	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	31	28	30	21	31	13	26	12	25
1	JA	GVELD	SHALW	SAND	14	25	18	25	21	28	22	29	29	31	30	30	31	31	31	31	31	27	30	21	29	14	24	14	24
1	DC	SOYAS	DEEP	CLAY	0	13	0	22	15	26	18	29	3	29	5	31	25	30	31	31	31	30	31	25	30	9	26	0	11
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	11	
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	11	
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	11	
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	11	
1	DC	SOYAS	MEDM	SAND	3	18	6	20	18	26	17	28	7	27	20	31	30	30	31	31	31	31	25	30	13	25	0	12	
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	12	
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	12	
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	13	

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	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	1	0	8		
1	NV	MAIZE	DEEP	SAND	12	42	13	42	11	30	6	23	4	18	2	18	0	19	0	11	0	8	0	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	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	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	2	3	0	3	0	1	21	7	54	
1	NV	MAIZE	SHALW	LOAM	21	57	22	61	16	49	9	44	8	34	4	32	2	19	1	11	3	8	0	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	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	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	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	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	0	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	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	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	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	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	10	9	43	
15	DC	SUNFL	MEDM	CLAY	22	87	22	79	11	55	6	34	2	19	0	6	0	1	0	0	0	0	0	12	34	24	61	
15	DC	SUNFL	MEDM	LOAM	21	69	30	73	17	50	10	27	5	15	2	6	0	3	0	1	0	0	0	0	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	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	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	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	28	30	65	
1	JA	SVELD	DEEP	CLAY	11	67	6	49	4	31	0	19	0	4	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	3	0	3	5	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	0	5	22	2	34		
1	JA	SVELD	MEDM	CLAY	14	75	8	53	6	36	1	22	0	6	0	1	0	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	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	0	4	0	2	0	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	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	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	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	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	2	0	1	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	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	14	1	31	15	43	12	55	
1	JA	GVELD	MEDM	LOAM	3	31	2	26	1	13	0	9	0	2	0	0	0	0	0	0	4	0	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	3	0	8	3	27	4	29	
1	JA	GVELD	SHALW	CLAY	21	88	13	60	11	45	3	30	0	7	0	4	0	3	0	2	23	5	27	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	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	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	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	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	12	0	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	3	0	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	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	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	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	17	10	31	31	67		

APPENDIX F

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.

LAT 34 04 LONG 19 03 ALTITUDE 564m 47 YEARS OF DATA

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)	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
M.A.P. 1605.9mm	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
	SDCV	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	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
(DEGREES CELSIUS)	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

P.A.M.	50 TH PERCENTILE				**	80 TH PERCENTILE				**	90 TH PERCENTILE				**	*
* (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 *	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	37	* 7 *
* 150 *	0	0	0	0	* 15	12	17	23	* 26	28	30	37	* 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	164	214	262	* 12 *

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 : S

	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	30.5	28.6	30.5	24.9	21.6	16.1	5.3	335.0
SDEV	22.8	24.6	17.6	26.0	25.7	24.2	27.0	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	72.0	62.7	71.6	71.6	85.3	99.3	166.7	26.0
SKEN	3.9	2.5	1.1	1.9	1.3	0.8	1.4	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				
* (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	* MTH	
ESTIMATED IRRIGATION REQUIREMENT														
(mm)	(mm)	(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	240	308	376	172	241	310	379	1	
150	163	231	301	368	170	239	310	376	172	241	311	379	1	
200	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	204	263	321	146	204	263	323	2	
150	139	197	255	313	145	204	263	321	146	204	263	323	2	
200	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	103	151	200	248	116	165	214	263	121	170	219	268	3	
100	103	151	200	248	117	167	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	248	116	165	214	263	121	170	219	268	3	
250	67	99	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	132	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	62	98	131	166	76	111	145	180	79	114	148	183	4	
250	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	61	86	111	50	74	98	124	58	83	109	134	5	
100	37	61	87	111	48	73	99	124	58	83	109	134	5	
150	36	61	87	112	48	74	99	125	58	83	109	134	5	
200	38	61	86	112	48	74	99	125	58	83	109	134	5	
250	25	39	54	72	33	51	68	87	38	56	75	92	6	
45	21	35	50	69	31	49	68	86	37	56	75	92	6	
70	16	31	50	69	31	49	68	86	37	56	75	92	6	
100	16	31	50	69	31	49	68	86	37	56	75	92	6	
150	16	31	50	69	31	49	68	86	37	56	75	92	6	
200	13	33	50	68	30	50	68	86	37	56	75	92	6	
250	26	43	61	79	33	52	70	89	38	56	75	92	6	
45	23	41	59	78	33	51	69	88	37	56	74	94	7	
70	23	41	59	78	33	51	69	88	37	56	74	94	7	
100	22	40	57	76	32	50	68	88	37	56	74	94	7	
150	21	40	57	76	32	50	68	88	37	56	74	94	7	
200	21	39	56	75	31	49	68	87	37	56	74	94	7	
250	20	38	56	75	31	49	68	87	37	56	74	94	7	
45	21	48	69	91	42	63	84	106	46	66	88	109	8	
70	27	48	68	89	42	62	84	106	45	66	88	109	8	
100	26	48	68	89	42	62	84	106	45	66	88	109	8	
150	25	46	67	89	42	62	84	106	45	66	88	109	8	
200	25	45	67	88	41	62	84	106	45	66	88	109	8	
250	24	45	67	88	40	62	84	106	45	66	88	109	8	
45	50	78	105	133	60	90	119	148	65	94	124	153	9	
70	47	75	104	133	60	90	119	148	65	94	124	153	9	
100	47	75	104	133	60	90	119	148	65	94	124	153	9	
150	45	75	104	133	60	90	119	148	65	94	124	153	9	
200	45	75	104	133	60	90	119	148	65	94	124	153	9	
250	45	75	104	133	60	90	119	148	65	94	124	153	9	
45	85	128	177	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	138	180	222	102	145	188	230	10	
200	83	125	167	209	95	138	180	222	102	145	188	230	10	
250	83	125	167	209	95	138	180	222	102	145	188	230	10	
45	115	167	219	222	127	180	233	286	131	184	238	291	11	
70	115	167	219	222	127	180	233	286	131	184	238	291	11	
100	115	167	219	222	127	180	233	286	131	184	238	291	11	
150	114	167	219	222	127	180	233	286	131	184	238	291	11	
200	114	167	219	222	127	180	233	286	131	184	238	291	11	
250	114	167	219	222	127	180	233	286	131	184	238	291	11	
45	157	222	287	323	163	228	293	359	163	228	293	359	12	
70	157	222	287	323	163	228	293	359	163	228	293	359	12	
100	156	221	287	323	163	228	293	359	163	228	293	359	12	
150	156	221	287	323	163	228	293	359	163	228	293	359	12	
200	156	221	287	323	163	228	293	359	163	228	293	359	12	
250	156	221	287	323	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 AT50099 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)	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
M.A.P. 438.4mm	MEAN 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
	SDEN 29.1	30.5	27.7	41.7	37.6	26.9	28.6	38.7	33.4	32.2	38.8	22.6	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 *****													
***** (mm) * 0.5 CROP FACTOR 1.1 * 0.5 CROP FACTOR 0.9 1.1 * 0.5 CROP FACTOR 0.7 0.9 1.1 * MTH *****													
***** 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	114	147	183	91	127	164	200	91	127	164	200	1
* 150	77	111	147	183	91	127	164	200	91	127	164	200	1
* 200	77	111	150	183	91	127	164	200	91	127	164	200	1
* 250	59	91	121	152	72	103	135	166	78	110	142	174	2
* 300	59	90	120	152	72	103	135	166	78	110	142	174	2
* 350	58	90	121	152	72	103	135	166	78	110	142	174	2
* 400	58	90	120	152	72	103	136	166	78	110	142	174	2
* 450	57	89	120	153	72	104	135	167	78	110	142	174	2
* 500	58	89	120	153	72	104	135	167	78	110	142	174	2
* 550	52	79	106	138	65	96	126	156	73	103	133	164	3
* 600	49	77	107	135	65	95	125	155	73	103	133	164	3
* 650	47	78	105	136	65	95	125	155	73	103	133	164	3
* 700	48	74	105	136	65	95	126	156	74	103	133	164	3
* 750	44	75	104	135	65	95	126	156	74	103	133	164	3
* 800	37	58	81	103	45	66	89	112	52	74	97	121	4
* 850	34	55	78	102	43	64	88	111	51	74	97	121	4
* 900	33	55	78	101	43	64	88	112	51	74	97	121	4
* 950	32	55	78	102	42	65	88	112	51	74	97	121	4
* 1000	32	55	78	102	42	65	88	112	51	74	97	121	4
* 1050	26	39	57	73	35	55	75	93	44	64	83	103	5
* 1100	23	38	55	71	36	54	74	94	46	64	83	103	5
* 1150	18	34	52	72	37	54	74	93	46	64	83	103	5
* 1200	17	34	52	72	35	54	74	93	46	64	83	103	5
* 1250	17	33	52	68	35	54	74	93	46	64	83	103	5
* 1300	17	31	52	68	35	54	74	93	46	64	83	103	5
* 1350	17	31	52	68	35	54	74	93	46	64	83	103	5
* 1400	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1450	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1500	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1550	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1600	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1650	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1700	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1750	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1800	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1850	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1900	15	27	41	53	31	40	56	70	35	50	64	78	6
* 1950	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2000	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2050	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2100	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2150	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2200	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2250	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2300	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2350	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2400	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2450	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2500	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2550	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2600	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2650	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2700	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2750	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2800	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2850	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2900	15	27	41	53	31	40	56	70	35	50	64	78	6
* 2950	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3000	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3050	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3100	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3150	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3200	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3250	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3300	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3350	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3400	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3450	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3500	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3550	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3600	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3650	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3700	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3750	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3800	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3850	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3900	15	27	41	53	31	40	56	70	35	50	64	78	6
* 3950	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4000	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4050	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4100	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4150	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4200	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4250	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4300	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4350	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4400	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4450	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4500	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4550	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4600	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4650	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4700	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4750	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4800	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4850	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4900	15	27	41	53	31	40	56	70	35	50	64	78	6
* 4950	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5000	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5050	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5100	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5150	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5200	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5250	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5300	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5350	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5400	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5450	15	27	41	53	31	40	56	70	35	50	64	78	6
* 5500													

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	**
* (mm) *	CROP FACTOR	*	CROP FACTOR	*	CROP FACTOR	* MTH*
	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)	(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	144	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)	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		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
MEAN TEMPERATURES	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	
(DEGREES CELSIUS)	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

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	*	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	152	*	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)	92.0	76.6	75.8	39.9	15.0	7.2	4.8	6.7	8.5	26.5	41.3	463.0
M.A.P. 463.4mm	77.9	71.3	62.8	31.0	6.5	0.5	0.0	0.0	0.9	16.8	33.0	66.8
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
C.V.	71.4	57.3	71.2	95.5	146.4	188.0	278.3	196.1	166.5	96.3	77.0	29.0
SKEN	1.2	0.4	1.0	1.2	2.3	2.4	4.3	2.6	2.0	1.3	1.1	0.5

MONTHLY MEAN TEMPERATURES (DEGREES CELSIUS)	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
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	16.4

ESTIMATED IRRIGATION REQUIREMENT

***** 50 TH PERCENTILE ***** 80 TH PERCENTILE ***** 90 TH PERCENTILE *****												
* P.A.N.*												
* (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
***** CROP FACTOR *****												
***** ESTIMATED IRRIGATION REQUIREMENT *****												
* (mm) *	106	164	226	265	124	184	247	287	139	201	265	305
* 20 *	106	162	221	284	125	183	247	311	138	202	265	329
* 45 *	100	159	221	283	122	183	247	310	137	201	265	329
* 70 *	99	161	222	284	120	183	246	311	137	201	265	329
* 100 *	96	159	221	283	120	183	246	310	137	201	265	329
* 150 *	96	159	223	284	120	184	246	310	137	202	264	329
* 200 *	75	118	162	207	93	142	192	240	105	154	203	253
* 45 *	68	114	160	207	91	142	192	240	105	154	203	253
* 70 *	67	112	161	206	92	142	191	241	105	154	203	253
* 100 *	63	110	156	207	94	141	191	241	105	155	203	253
* 150 *	65	106	158	205	92	142	191	241	105	154	204	253
* 200 *	63	106	156	207	92	141	192	241	107	153	204	253
* 45 *	59	103	143	185	84	127	165	209	96	141	186	231
* 70 *	57	98	141	186	82	127	165	209	96	141	186	231
* 100 *	57	97	142	183	76	119	165	209	96	141	186	231
* 150 *	54	94	138	183	74	120	165	209	96	141	186	231
* 200 *	53	96	138	184	75	120	165	209	96	141	186	231
* 45 *	59	95	130	164	82	117	152	185	86	121	156	192
* 70 *	61	94	127	162	81	116	150	185	86	121	156	192
* 100 *	59	93	129	162	82	117	150	185	86	121	156	192
* 150 *	59	92	129	161	82	116	150	185	86	121	156	192
* 200 *	59	94	128	161	80	115	152	186	86	121	157	192
* 45 *	61	89	116	144	69	96	124	152	69	96	124	152
* 70 *	61	89	116	144	69	96	124	152	69	96	124	152
* 100 *	61	89	116	144	69	96	124	152	69	96	124	152
* 150 *	61	89	116	144	69	96	124	152	69	96	124	152
* 200 *	54	76	98	120	54	76	98	120	55	76	98	120
* 45 *	54	76	98	120	55	76	98	120	55	76	98	120
* 70 *	54	76	98	120	54	76	98	120	54	76	98	120
* 100 *	54	76	98	120	54	76	98	120	54	76	98	120
* 150 *	58	81	104	127	58	81	104	127	58	81	104	127
* 200 *	58	81	104	127	58	81	104	127	58	81	104	127
* 45 *	82	115	148	180	82	115	148	180	82	115	148	180
* 70 *	82	115	148	180	84	115	148	180	84	115	148	180
* 100 *	82	115	148	180	82	115	148	180	82	115	148	180
* 150 *	82	115	148	180	82	115	148	180	82	115	148	180
* 200 *	106	149	192	235	107	150	193	236	107	150	193	236
* 45 *	106	149	192	234	107	150	193	236	107	150	193	236
* 70 *	105	148	191	234	107	150	193	236	107	150	193	236
* 100 *	105	148	192	234	107	150	193	236	107	150	193	236
* 150 *	105	148	191	236	107	150	193	236	107	150	193	236
* 200 *	126	183	239	293	140	197	253	310	144	202	260	317
* 45 *	125	182	239	296	140	197	255	313	144	202	260	317
* 70 *	126	182	239	297	140	197	255	313	144	202	260	317
* 100 *	125	182	239	296	140	197	255	313	144	202	260	317
* 150 *	125	182	239	296	140	197	255	313	144	202	260	317
* 200 *	125	182	239	296	140	197	255	313	144	202	260	317
* 45 *	120	177	236	295	139	199	258	319	146	205	266	326
* 70 *	117	176	237	296	139	198	258	319	144	205	266	326
* 100 *	119	176	237	296	139	198	258	319	146	206	266	326
* 150 *	117	175	236	296	137	200	258	321	156	207	267	326
* 200 *	120	181	243	273	150	215	283	304	156	224	292	313
* 45 *	115	179	243	309	148	215	284	351	156	224	292	360
* 70 *	115	176	244	310	148	216	284	351	156	225	292	360
* 100 *	113	177	244	310	149	216	284	352	156	225	292	360
* 150 *	111	178	244	310	147	216	284	352	156	224	292	360
* 200 *	111	178	244	310	147	216	284	352	156	224	292	360

LAT 26 05 LONG 29 50 ALTITUDE 1648m 59 YEARS OF DATA

LAT 26 04 LONG 30 07 ALTITUDE 1692m WIND REGION : 1

MONTHLY													
MEAN TEMPERATURES	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
(DEGREES CELSIUS)	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

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	*		*			

	(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																	

RAINFALL STATION SUG0155 PONGOLA

LAT 27 25 LONG 31 31 ALTITUDE 290m 45 YEARS OF DATA
LAT 27 35 LONG 31 40 ALTITUDE 320m WIND REGION : 3

TEMPERATURE STATION RES0041 MAGUT

	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 (DEGREES CELSIUS)	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
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

***** 50 TH PERCENTILE ***** 80 TH PERCENTILE ***** 90 TH PERCENTILE *****													
P.A.M.													
***** 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 * MTH*													
***** ESTIMATED IRRIGATION REQUIREMENT *****													

* (mm) *	* (mm) *	* (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 *	34	73	112	148	68	110	153	198	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	146	182	3
* 45 *	47	83	106	142	71	106	142	178	77	115	148	181	3
* 70 *	43	73	108	144	71	106	142	178	76	108	148	188	3
* 100 *	46	70	107	143	71	106	142	178	76	108	148	181	3
* 150 *	30	73	102	137	71	106	142	178	76	108	148	181	3
* 200 *	30	71	111	135	71	106	141	178	73	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	89	124	58	88	117	146	64	93	122	152	4
* 150 *	37	66	88	116	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	74	97	122	61	85	110	135	61	85	110	135	5
* 100 *	52	73	97	123	61	85	110	135	61	85	110	135	5
* 150 *	48	73	97	122	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	71	91	112	52	72	93	114	52	72	93	114	6
* 70 *	50	70	92	112	52	72	93	114	52	72	93	114	6
* 100 *	51	70	91	112	52	72	93	114	52	72	93	114	6
* 150 *	51	71	91	112	52	72	93	114	52	72	93	114	6
* 200 *	52	74	96	118	54	76	98	120	54	76	98	120	7
* 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 *	53	82	110	134	56	76	98	120	58	76	98	120	7
* 200 *	53	81	108	134	56	76	98	120	58	76	98	120	7
* 20 *	55	81	108	134	56	76	98	120	58	76	98	120	7
* 45 *	55	81	108	134	56	76	98	120	58	76	98	120	7
* 70 *	55	81	108	134	56	76	98	120	58	76	98	120	7
* 100 *	55	81	108	134	56	76	98	120	58	76	98	120	7
* 150 *	55	86	108	134	56	76	98	120	58	76	98	120	7
* 200 *	55	86	108	134	56	76	98	120	58	76	98	120	7
* 20 *	61	93	125	156	76	108	140	172	78	110	142	174	8
* 45 *	61	93	125	156	76	108	140	172	78	110	142	174	8
* 70 *	59	92	125	155	76	108	140	172	78	110	142	174	8
* 100 *	60	92	124	156	76	108	140	172	78	110	142	174	8
* 150 *	62	92	123	156	76	108	140	172	78	110	142	174	8
* 200 *	60	94	123	155	76	108	140	172	78	110	142	174	8
* 20 *	59	92	127	158	73	111	150	189	78	117	156	194	9
* 45 *	59	92	127	158	73	111	150	189	78	117	156	194	9
* 70 *	50	90	122	158	73	111	150	189	78	117	156	194	9
* 100 *	56	87	124	161	76	111	150	189	84	117	156	194	9
* 150 *	48	86	120	160	74	111	150	189	78	117	156	194	9
* 200 *	46	84	121	159	73	111	150	189	78	117	156	194	9
* 20 *	52	80	121	157	65	105	140	179	79	120	162	204	10
* 45 *	52	80	121	157	65	105	140	179	79	120	162	204	10
* 70 *	43	76	117	158	60	100	140	181	78	120	162	204	10
* 100 *	45	76	117	158	60	100	140	181	78	120	162	204	10
* 150 *	37	78	116	153	56	101	140	178	79	120	162	204	10
* 200 *	27	76	116	153	56	101	140	178	79	120	162	204	10
* 20 *	23	68	116	148	54	96	141	183	78	121	163	204	10
* 45 *	38	68	116	148	54	96	141	183	78	121	163	204	10
* 70 *	33	68	116	148	54	96	141	183	78	121	163	204	10
* 100 *	38	68	116	148	54	96	141	183	78	121	163	204	10
* 150 *	53	87	132	175	72	107	158	196	81	123	166	210	11
* 200 *	50	87	133	171	69	111	152	198	78	124	167	210	11
* 20 *	54	80	128	172	76	116	157	201	78	124	167	210	11
* 45 *	41	92	125	176	63	110	161	205	77	121	165	210	11
* 70 *	39	82	127	169	71	109	152	198	77	121	165	210	11

ZONE NO.594

RAINFALL STATION 633393 ZAAIPLAATS

LAT 24 04 LONG 28 42 ALTITUDE 1204m 56 YEARS OF DATA

TEMPERATURE STATION ATSO433 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)	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
M.A.P. 653.4mm	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	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	
(DEGREES CELSIUS)	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

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	* 0.5	0.7	0.9	1.1	* MTH*

ESTIMATED IRRIGATION REQUIREMENT

*	(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	78	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
TEMPERATURE STATION 0638052 INYOKO

LAT 24 08 LONG 30 52 ALTITUDE 390m 44 YEARS OF DATA
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)	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
M.A.P. 461.1mm	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	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	
(DEGREES CELSIUS)	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	**	*
* (mm) *	CROP FACTOR	*	CROP FACTOR	*	CROP FACTOR	*	MTH*
	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 *	68	96	125	152	*	69	97	125	153	*	69	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	*	69	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 G

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

Note 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.

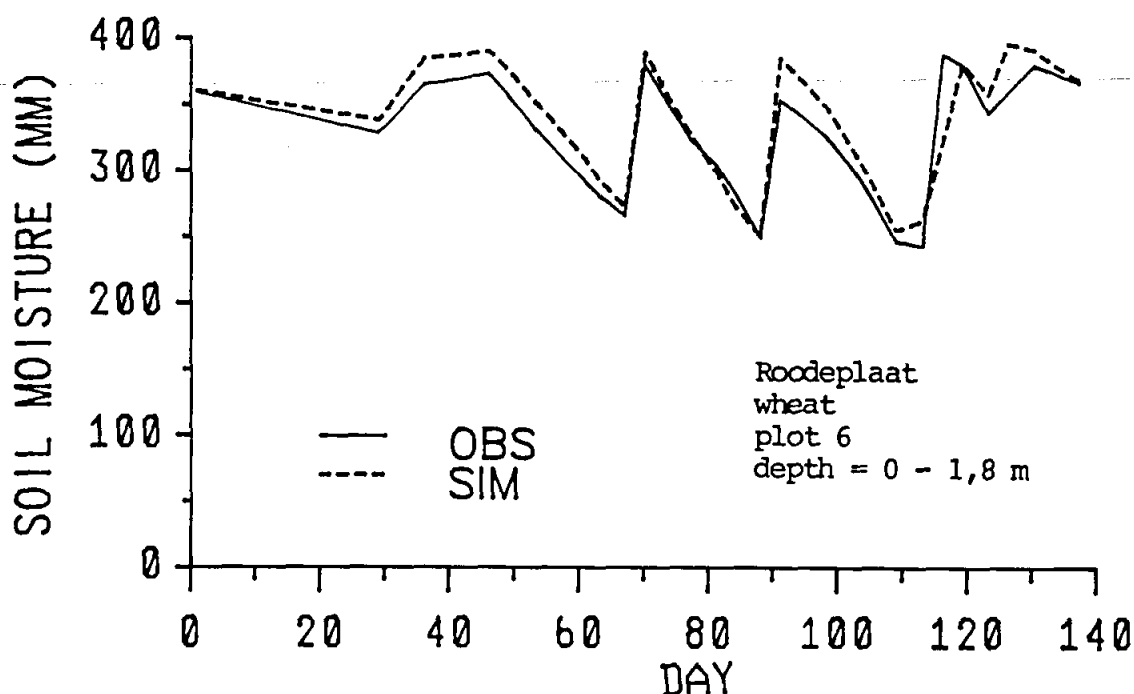


Figure F.1 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors from plot 6.

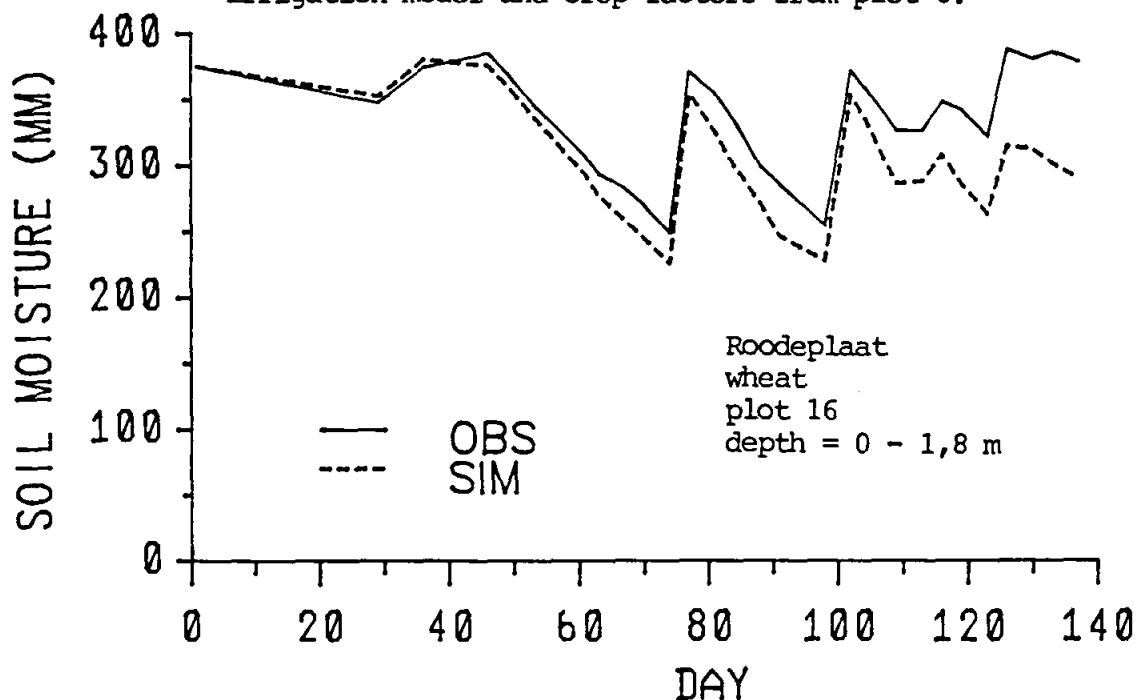


Figure F.2 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors from plot 6.

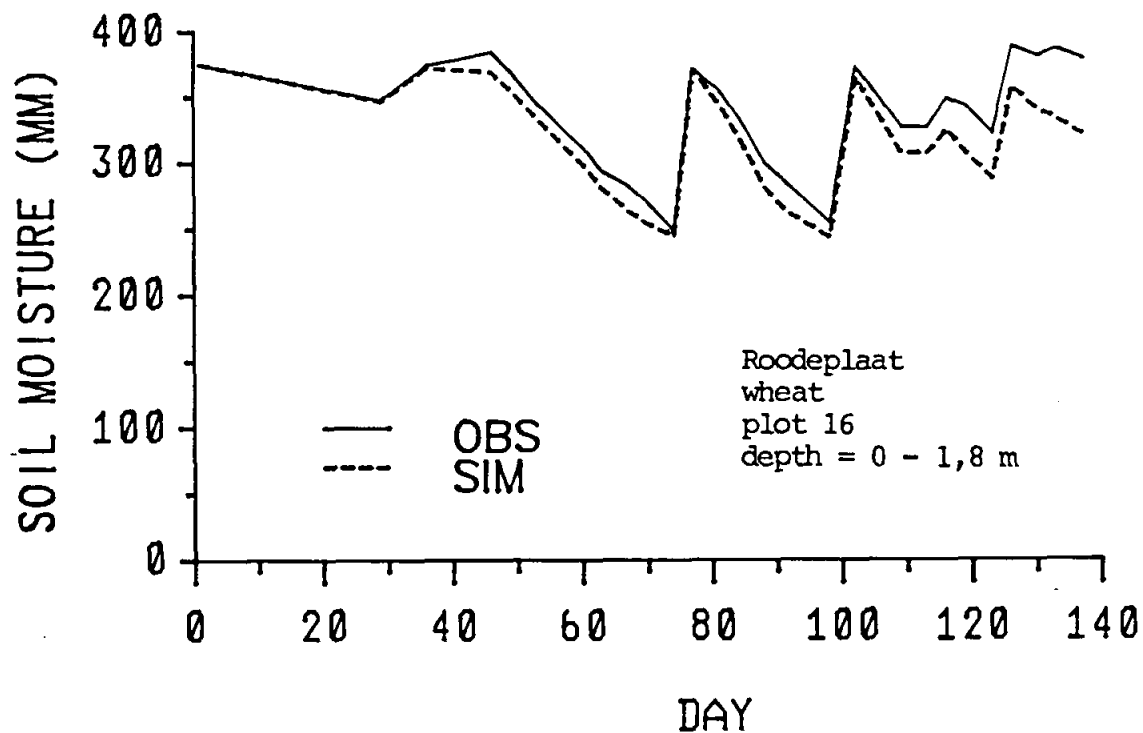


Figure F.3 Observed soil moisture and A and B horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

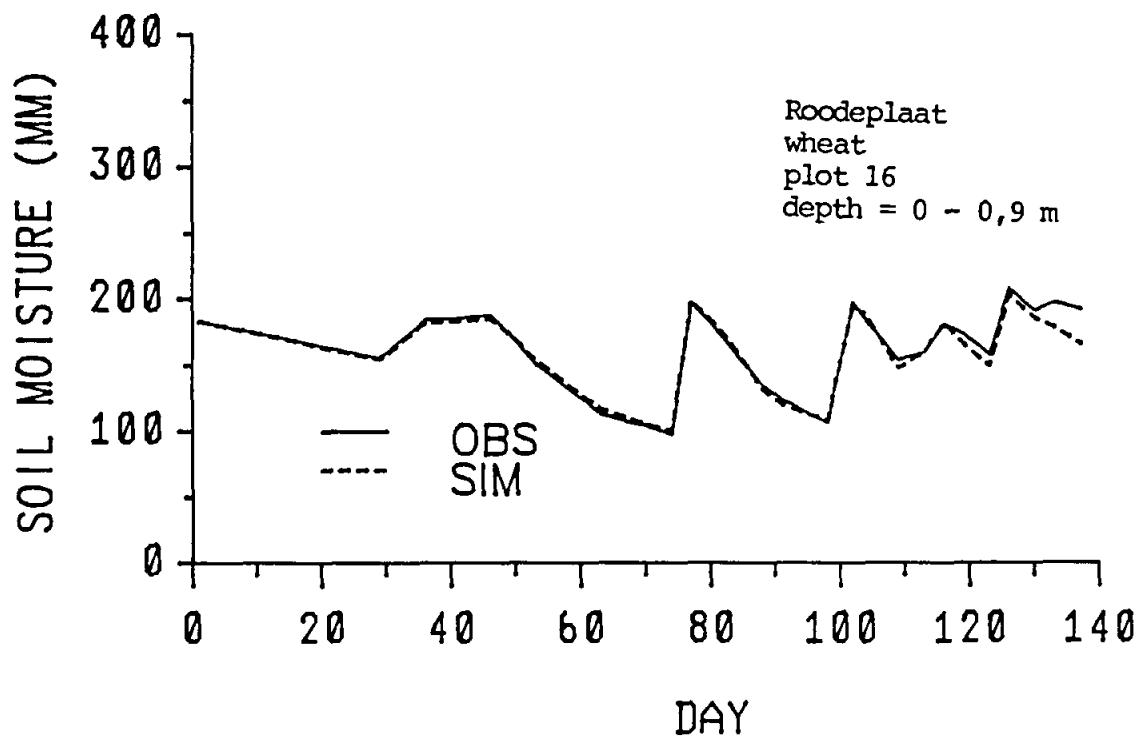


Figure F.4 Observed soil moisture and A horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

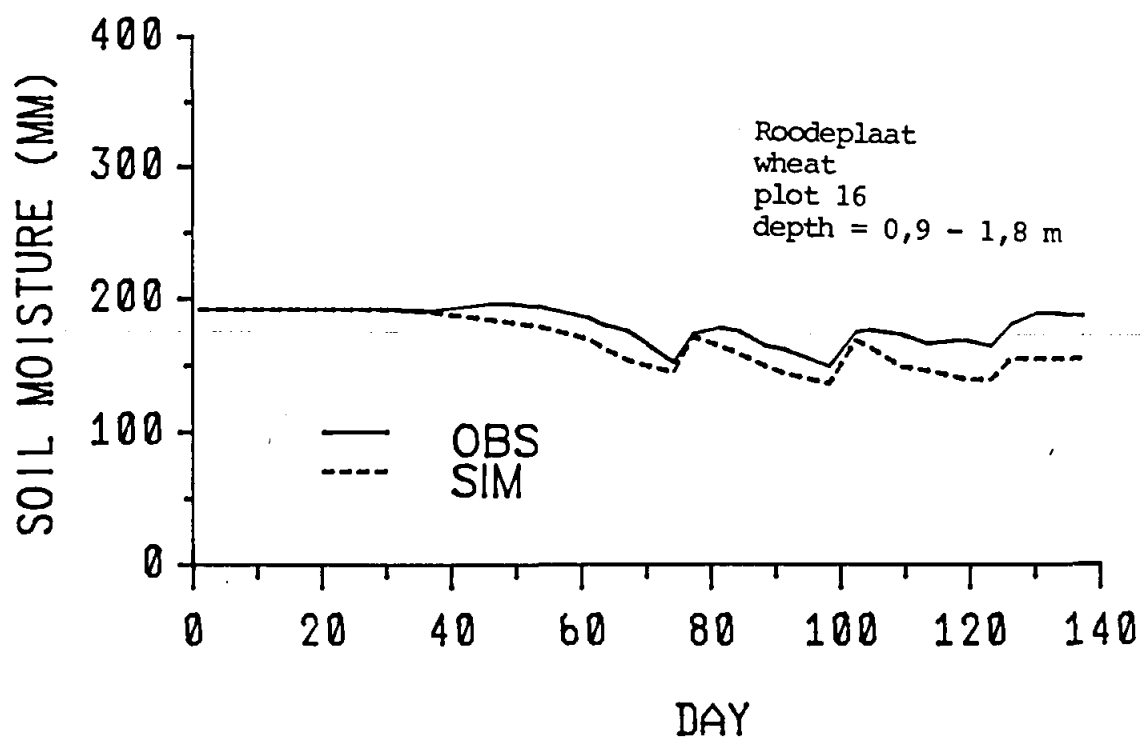


Figure F.5 Observed soil moisture and B horizon soil moisture simulated using the ACRU model and crop factors for plot 6.

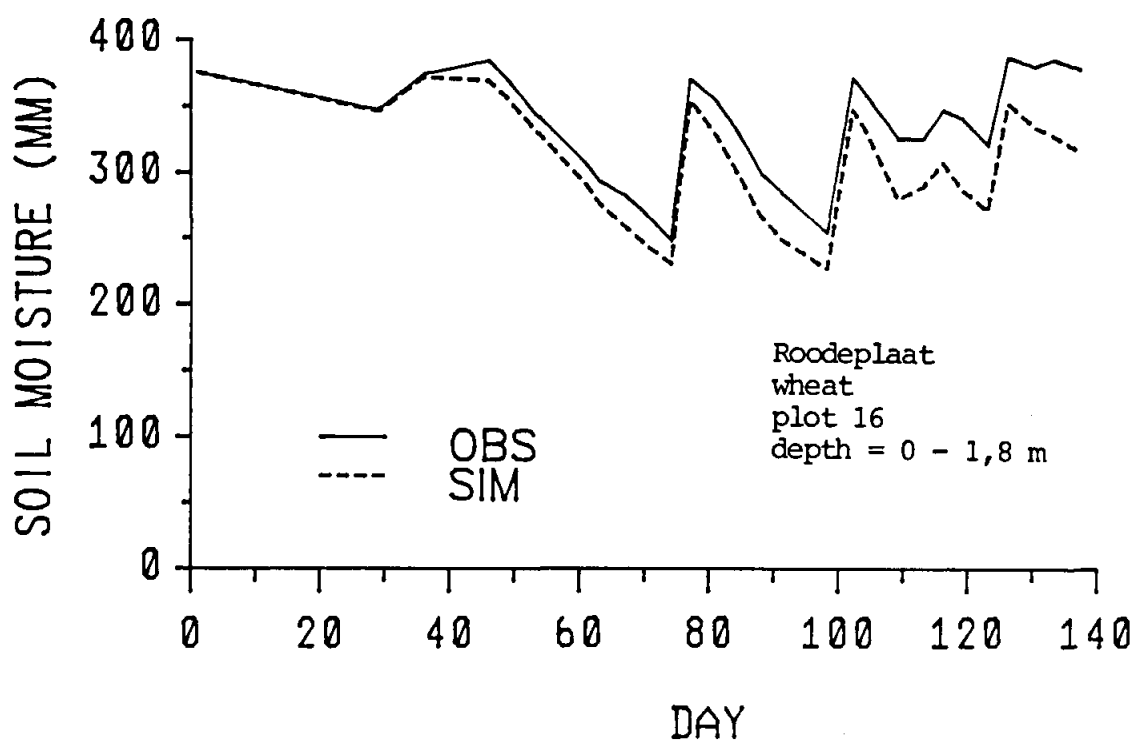


Figure F.6 Observed soil moisture and soil moisture simulated using the ACRU model as a single soil layer model and crop factors for plot 6.

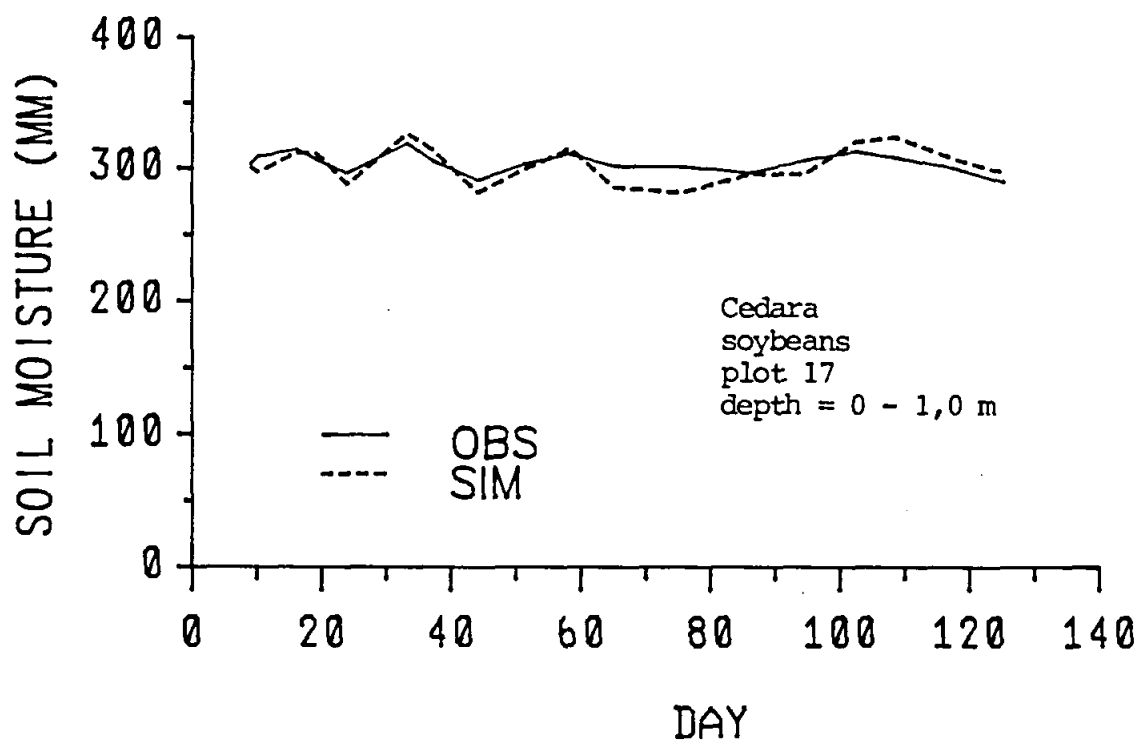


Figure F.7 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors for plot 8.

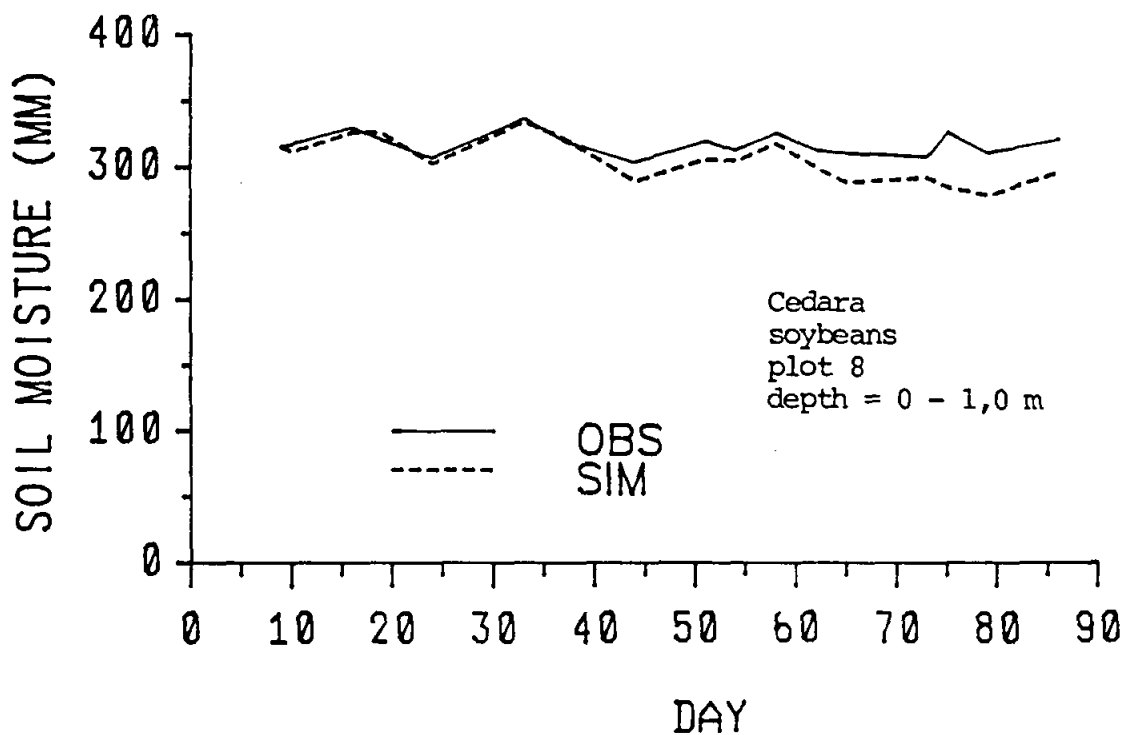


Figure F.8 Observed soil moisture and soil moisture simulated using the irrigation model and crop factors for plot 8.

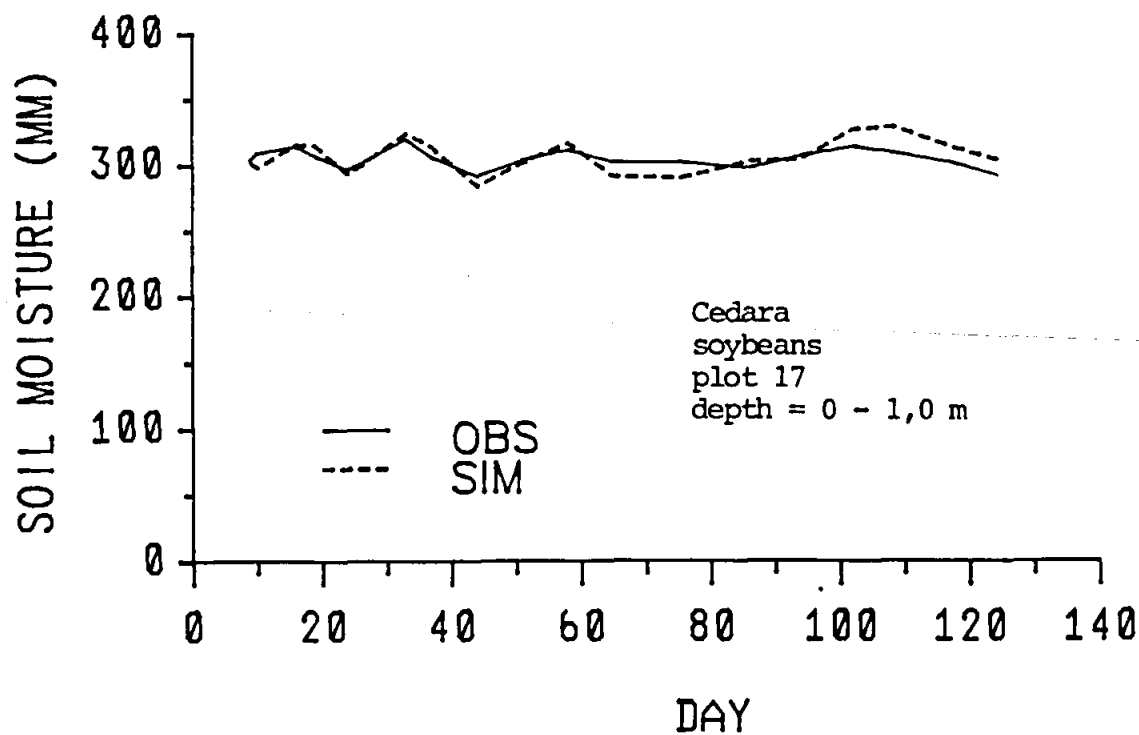


Figure F.9 Observed soil moisture and soil moisture simulated using the ACRU model and crop factors for plot 8.

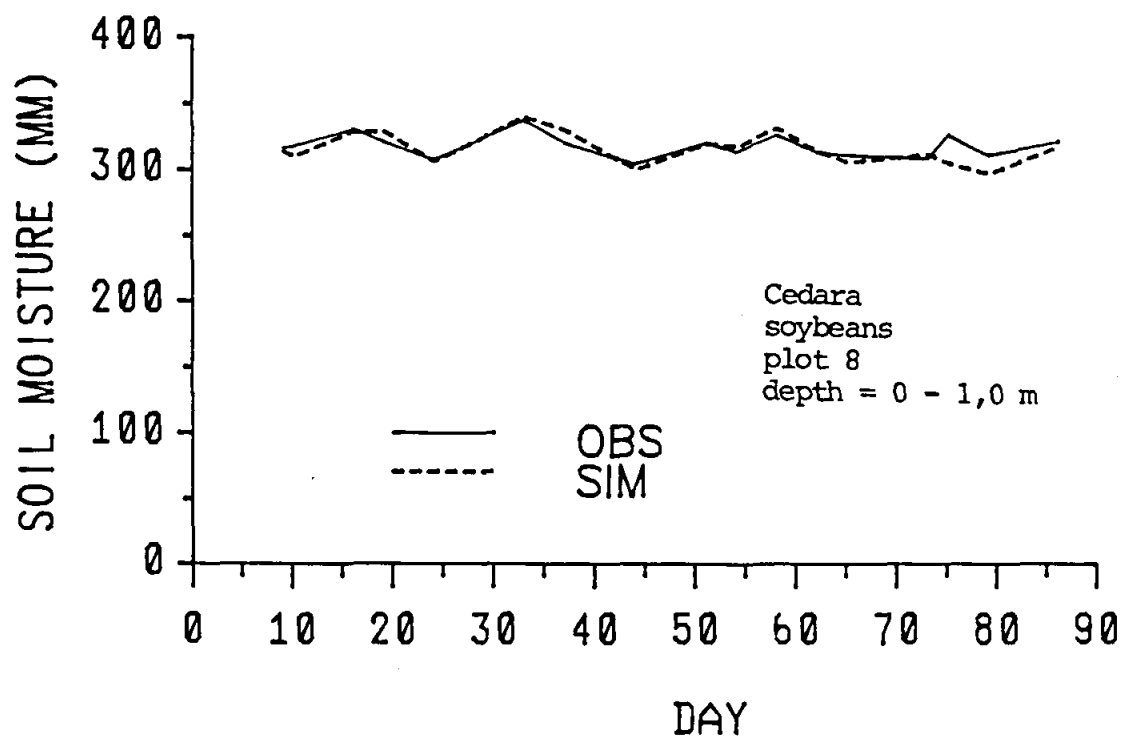


Figure F.10 Observed soil moisture and soil moisture simulated using the ACRU model and crop factors for plot 8.

APPENDIX H

Note on terminology

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.