SAPWAT 1.0 - A COMPUTER PROGRAM FOR ESTIMATING IRRIGATION REQUIREMENTS IN SOUTHERN AFRICA

by

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REPORT TO THE WATER RESEARCH COMMISSION

on

The pilot project

"The development of decision making procedures for the estimation of crop water requirements for application in irrigation system design"

by

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

TABLE OF CONTENTS

1. INTRODUCTION

The estimation of crop water requirements is an essential starting point when both farm scale and major irrigation projects are planned or upgraded. Inappropriate estimates can have a major impact on both policy and design decisions and on the eventual economic viability and operational efficiency of projects.

2. PRESENT STATE OF THE ART

South Africa

The well-known "Green Book" or more correctly: "Estimated irrigation requirements of crops in South Africa", published by the Department of Agriculture and Water Supply in 1985, has been the comprehensive source document available to planners and designers. The procedures for estimating irrigation requirements used in design in South Africa are endorsed by the Directorate of Irrigation Engineering, the SA Irrigation Institute, University Departments and most practitioners.

However, as far as is known, no critical confirmation studies have been undertaken on the procedures. It also appears that research results published in the RSA and overseas during the past decade have had little or no impact on estimation procedures used for design purposes in South Africa.

Consultants operating in neighbouring countries on behalf of the major international funding agencies, apply FAO procedures which have not yet been adopted in South Africa.

International recommendations : FAO

An FAO expert consultation (Smith, 1991) on procedures for prediction of crop water requirements, supported the essential soundness of the principles in FAO Irrigation and Drainage Paper No 24: "Guidelines for predicting crop water requirements" (Doorenbos and Pruitt, 1977), and gave clear indications of the direction in which revision, research and development should take place. It is advisable that South Africa take note of these findings.

3. RESEARCH OBJECTIVES

The primary objective of this pilot project was to assess the feasibility of establishing a personal computer (PC) based decision support system for the estimation of crop water requirements under irrigation. The intention was that the procedures should

- be suitable for use by practitioners with limited computer experience and training,
- be in line with current international practice, and
- incorporate both interpreted research results and the practical experience of specialists.

An implied secondary objective was to incorporate in the procedure the results of WRC supported research projects dealing directly, or indirectly, with irrigation crop water requirements.

4. SAPWAT - COMPUTER PROCEDURE FOR ESTIMATING CROP WATER REQUIREMENTS

A PC based program, SAPWAT, is the main product of this pilot project. SAPWAT (Southern African Procedure for estimating irrigation WATer requirements), is a computerised procedure for estimating crop irrigation requirements, which demonstrates that by linking existing data, procedures and programs, and by incorporating recent international recommendations, it is possible to provide an updated and effective successor to the "Green Book".

SAPWAT is a self standing program with menus and graphics to facilitate calculations and to cater for users with limited computer literacy.

5. RESEARCH APPROACH

Inter-disciplinary co-ordination

A wide range of disciplines are concerned with irrigation and crop water requirements. The designer must extract the specific data and processes that he needs from knowledge and information originally developed for other purposes. **In the course of developing SAPWAT, there was close contact with a wide spectrum of disciplines and it is felt that this networking was mutually beneficial.**

Incorporation of international recommendations

This study has taken note of the current internationally accepted approach to the estimation of crop water requirements.

SAPWAT, in common with similar procedures, is an aid to estimation, not a calibrated simulation model. **Each element in the procedure is, however, an improvement on what is currently available even in the accepted FAO procedures.**

Incorporation of existing WRC research results

In addition to the incorporation of international recommendations, SAPWAT leans on research supported by the WRC, particularly Dent et al (1988), Schulze (1989) and Bennie et al (1988). It has been possible to use the FAO procedures as a foundation and incorporate the information generated by South African research. Notable examples of this are the detailed climatic zones with ZONEFINDER and their extensive data bases, long term daily rainfall data, surrogate methods for developing potential evaporation estimates and ACRU, PAWC, PMBWAT and BEWAB models at the heart of the calculations.

The computerised procedure SAPWAT is, therefore, a synthesis of international trends and local research.

Considerations during software development

To be acceptable to the ordinary practitioner any new procedure must present advantages that go beyond mere technical excellence. It must also be more convenient to use than present methods. **Considerable attention has been given to programming style, and it is believed that a satisfactory approach has been achieved.** Extensive use has been made of menus and graphics, and none of the procedures have to be "learned". Input data is "packaged" and immediately available. It is possible to move around in all the linking programs incorporated in SAPWAT, encouraging "what-iffing".

SAPWAT is suitable for use on PCs with a graphics card.

6. ACHIEVEMENTS OF THE PILOT PROJECT

The primary objective of the contract was to assess the feasibility of establishing a computer oriented decision support system for the estimation of crop water requirements.

Determination of the factors influencing crop water use

A study was made of the factors that influence crop water use. The study included a literature study and consultations with members of the Steering Committee and other specialists. The objective was to bridge the gap between the engineer, designer and planner on the one hand, and the agriculturist and scientist on the other, and to ensure that there was agreement in interpretation. In the development of SAPWAT, the following were considered:

- Current approaches to crop water requirements in design.
- Plant physiological aspects.
- Reference evaporation and crop coefficients.
- Crop water : yield functions.
- Profile available water capacity (PAWC).
- Deficit irrigation.
- Peak water requirements and irrigation system capacity.
- Irrigation system efficiencies and coefficient of uniformity.
- Precipitation and supplementary irrigation.
- Scheduling strategies and methods.
- Data bases.
- FAO irrigation papers no's 24 & 33.
- Models and simulations.

Clarification of the decision making process and establishment of a procedure

One of the important achievements of the pilot project has been to clarify the decision making process involved in estimating crop irrigation requirements. Clarity has been reached on the structure of a procedure for the estimation of irrigation requirements for design purposes.

Software development and incorporation of existing programs and databases

Progress has been made in developing software for key elements of the procedure for the estimation of irrigation requirements. Existing programs and databases have been incorporated where applicable. (See section 7: Steps (and subroutines) in the procedure for estimating crop water requirements - SAPWAT)

Identification and definition of "Non-standard" situations

SAPWAT, in common with most methods of estimating irrigation requirements, is based on "maximum" crop water use. That is when there is no shortage of water in the profile *and* the crop is well adapted and healthy. This assumption is adequate for normal commercial irrigation. There are situations where this assumption does not apply, and these are beyond the scope of **SAPWAT**.

Deficit irrigation

Deficit irrigation comes into its own when irrigable land is not the limiting factor, and it is possible to increase total production by utilising the water and inputs available on a larger area. The implication is that the percentage decrease in yield is significantly less than the percentage water deficit and that the cost of irrigating the larger area is minimal. It is feasible to reduce water requirements by over 25 percent with yield decreases of only about 10 percent. While it is possible for a practitioner to develop a deficit irrigation strategy, the application of crop growth models by a specialist is indicated.

Limited irrigation

The situation arises in the case of some commercial and emerging farmers that irrigation is used to ensure good "dry land" yields when precipitation is below average or badly timed. Inputs such as seed and fertiliser are considerably less than would have been the case had "full irrigation" been the objective. This approach differs from the conventional approach to "supplementary irrigation", where irrigation augments precipitation up to full irrigation levels. **SAPWAT** is appropriate for supplementary irrigation but not for limited irrigation; here crop growth models and simulations can provide valuable guidelines.

Crop growth models

All irrigation farming is, to a greater or lesser extent, non-standard. Bennie (1992) stresses that the decision-making criteria developed by successful irrigation farmers as a result of years of past experience and intimate contact with crop, soil and climate, are mostly applicable to one set of farming circumstances only. Crop growth models can play an important part in developing irrigation guidelines for specific areas and situations.

It cannot be left to planners or designers to use crop growth models, nor should it be the task of the modeller or the researcher, because their interests and abilities are focused on developing and calibrating better models. It is important that there be practitioners from a variety of disciplines who are crop growth model literate. Models promote interdisciplinary co-operation and a better understanding of the fundamentals.

Crop growth models can play an important part in augmenting the **SAPWAT** type procedure in arriving at comprehensive regional guidelines.

Identification of the need for regional guidelines

The water requirement of crops is only one aspect of irrigation and must be seen in the context of irrigation farming as a whole. A computerised approach such as **SAPWAT** represents progress, in that it enables the ordinary practitioner to make better estimates than is presently possible, but its overall place in the scheme of things should not be over-rated.

SAPWAT is a computerised procedure for estimating crop irrigation requirements, as such it is only a component of a decision support system. A computerised approach to irrigation planning must be supplemented by guidelines developed on a multidisciplinary basis, by people dedicated to irrigation and farmers' needs. Bennie (1992) makes the valid point that presently, each irrigator has the unenviable task to decide whether to adopt or reject recommended technologies, taking into account his own specific circumstances and the hidden interest of the advisors or researchers. There should be guidelines available that at least ensure that "hidden interests" are not a factor, and that all involved are concentrating on the realities of farming circumstances. The Soil Conservation Service in the USA has for many years published such guidelines, developed by permanent interdisciplinary teams. Guidelines are of immediate importance to farmers, but are equally useful to planners and designers.

Demonstration of the feasibility of "packaged" PC based regional guidelines - WATER, ROBERTS

There is merit in packaging guidelines for a specific region which has characteristics peculiar to it, in the form of PC programs which can supplement printed material. A prototype program was developed that illustrates this approach. The objective was to draw designers' attention to the soils, crops and management practices applicable to the area, and to prompt their decisions by providing appropriately "packaged" input data and even crop water requirements.

This concept was applied to wine grape production in the Robertson area. This is a well researched crop, so that the program can be regarded as being based on valid inputs. This program, **ROBERTS**, includes the facility to combine the requirements of a number of vineyards.

SAPWAT estimates should be augmented by zone specific guidelines developed on an inter-disciplinary basis. In a sophisticated form, if adequate information is available, this process can be computerised as has been done on a preliminary basis with **ROBERTS**.

7. STEPS (AND SUBROUTINES) IN THE PROCEDURE FOR ESTIMATING CROP WATER REQUIREMENTS - SAPWAT

SAPWAT - General

The current procedures for estimation of crop water requirements used in South Africa are well defined, and the norms employed have, through usage, become generally accepted. However, while there is sufficient depth of experience in the RSA to ensure good irrigation design, there are latent vulnerabilities in existing procedures which should be addressed. This is particularly true of "non-standard" situations.

To be acceptable, a new approach must have common ground with present procedures and be well packaged, have a "built-in" infrastructure and require only a limited level of computer literacy.

SAPWAT is conventional in that it uses monthly reference evaporation (ETo) and crop coefficients (Kc) to calculate crop water requirements. Irrigation requirements are then derived by taking into account effective precipitation and soil water balances. **SAPWAT** leans on research supported by the WRC, particularly Dent et al (1988), Schulze (1989) and Bennie et al (1988). **SAPWAT** conforms to the principles embodied in FAO 24 and the recommendations of the Rome consultation Smith (1991).

SAPWAT is a synthesis of a number of existing data bases and computer programs. These are linked by Turbo Pascal programs which rely on menus and graphic presentations to facilitate the exercise of judgement while developing estimates.

ZONER - Climatic zones

The first step in the **SAPWAT** procedure is to establish the zone in which the irrigation scheme is located by entering the latitude and longitude into the PC program **ACRU ZONEFINDER 1.01**. The output is initially in the form of a map of the country, showing the number and location of the zone, followed by a map of the zone and its position relative to surrounding zones. **SAPWAT** uses the 712 climatic zones developed by the Department of Agricultural Engineering, University of Natal and utilised by Dent et al (1988) to calculate the irrigation requirements of crops.

RAIN - Long-term precipitation

A graphic and tabular presentation of precipitation for the zone, by month and year, is then called onto screen, utilising the program **RAIN**, which was written for this project. The historical rainfall pattern can be reviewed at a glance, so that vulnerabilities can be identified and an irrigation strategy developed. This makes it possible to select, by month, a "normal" season, or a one in five, or one in ten "dry" season.

MONTHKC - Crop coefficients

Crop coefficients for each month of the crop growing season are then developed by another program written for this project, **MONTHKC**. Default values are provided for a wide range of crops (some derived from FAO 24) and the generic crop co-efficient curve appears on screen. Planting dates and the lengths of crop growth stages can be edited. The output is the integrated crop co-efficient for each month.

NATAL/PMBWAT - Crop irrigation and total water requirements

The monthly crop coefficients, zone and climatic circumstances are transferred by a linking program, **NATAL**, to the modified output files developed for the zone by **PMBWAT**. This is a major advance in that an extensive data base and powerful model are utilised to provide a "packaged" infrastructure which becomes part of **SAPWAT**.

In the interests of brevity the Dent et al (1988) program is referred to in the report as **PMBWAT**. The **PMBWAT** outputs consisting of monthly irrigation and total water requirements, have been developed from the **ACRU** irrigation routine based on daily weather inputs and soil water balances.

OFS/BEWAB - Incorporating pre-programed irrigation scheduling and PAWC

The final linking PC program, **OFS**, is a reprogramming in Turbo Pascal, with graphic menus, of **BEWAB**, Bennie et al (1988). The principles are used to extend the application of **BEWAB** to include all the crops and zones covered by **SAPWAT**.

BEWAB was developed to facilitate pre-programed irrigation scheduling of a specific range of crops in the area researched by Bennie et al (1988).

Models are included for estimating profile available water capacity (PAWC) and the effect of the water content of the profile at the start of the season on scheduling at seasonal peaks.

SCHEME - Scheme water requirements

No standard procedures are available to facilitate the estimation of monthly water requirements on a scheme, where the mix of crops, areas planted and planting dates can be varied. Some planners have developed spreadsheets for this purpose, but **SAPWAT** caters for this requirement as part of the comprehensive procedure.

GROSS - Converting net to gross water requirements

The net irrigation outputs developed by **SAPWAT** are corrected for the clothes-line and island effects of advection, and are checked against crop water : yield curves, to assess if there is a realistic relationship between estimated water requirements and expected yields. Procedures for estimating crop irrigation requirements, concentrate on establishing *net requirements*. However, the *gross requirement* is required in planning and design. The normal procedure is to convert net values to gross by applying an application efficiency factor which takes losses into account. A promising simulation approach is proposed by English et al (1986), but this is still under development.

In the interim, present estimates can be improved by applying a statistical approach developed by Clemmens (1992). A computer routine, **GROSS**, has been written based on this approach. Inputs are default coefficient of variation (CV) values for various irrigation systems, and estimated wind and runoff losses. Output is in the form of a table, which provides application efficiency and storage deficiency for a range of irrigation adequacies.

8. IMPLEMENTATION

Application of SAPWAT in practice

SAPWAT is still in demonstration form. Modifications are necessary to some component programs, the data bases need further expansion and the overall program requires packaging before distribution. Limited exposure has been favourable and comments constructive. It is recommended that SAPWAT be demonstrated to SAIAE and SABI branches, the Directorate of Irrigation Engineering, scientists engaged in irrigation research and lecturers at the Technicons and Universities, with a view to gaining their support for future standardisation on SAPWAT and to solicit their constructive participation and criticism.

9. RECOMMENDATIONS FOR FURTHER RESEARCH

Further development of SAPWAT

It is recommended that SAPWAT be developed to the stage where it is accepted as the standard procedure for estimating irrigation requirements of crops in Southern Africa.

SAPWAT should be available as a personal computer program suitable for use by planners, designers, counsellors and extension specialists, with possibly limited computer literacy.

Recent developments to ACRU and the 712 climatic zone data base by the Department of Agricultural Engineering, University of Natal, open up new opportunities. Instead of storing the output files of an upgraded PMBWAT in the SAPWAT program, it could now be possible to run the ACRU irrigation routine for any of the zones on demand, and obtain continuously updated and customised output equivalent to that of PMBWAT.

This would enable a specialist located in a region to utilise the facilities of the Computing Centre for Water Research (CCWR) to prepare, on request, SAPWAT diskettes tailored to the needs of regional users.

The further work required is largely detail oriented, and would comprise the following:

- The development of a program, equivalent to NATAL, to link the proposed ACRU run outputs to SAPWAT.
- The upgrading of the monthly precipitation input to RAIN, to the most recent data available from the 712 climatic zone data base.
- The expansion of the range of crops for which default values of the crop coefficients are available, to cater for the bulk of crops and varieties.
- The provision of a soils data base to facilitate PAWC estimations.

- The extension of **GROSS** to make provision for the influence of irrigation methods on irrigation requirements.

- The general editing of the **SAPWAT** component programs to ensure uniformity and coherence.

<u>Regional irrigation guidelines</u>

It is highly desirable that **SAPWAT** be augmented by guidelines that will take into account non-standard situations. The application of crop growth models and simulations will be an important component of guideline development. The participation of inter-disciplinary specialists and the establishment of farmer needs and perceptions will be essential. The final product could be a comprehensive decision support system which would be of great value.

It is recommended that a workshop be organised to consider ways and means of developing such regional guidelines.

10. REFERENCES

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

Mr DS van der Merwe	:	Water Research Commission (Chairman)
Mr FP Marais	:	Water Research Commission (Secretary)
Dr GC Green	:	Water Research Commission
Dr PC Reid	:	Water Research Commission
Mr GR Backeberg	:	Department of Agriculture
Prof ATP Bennie	:	University of the OFS
Prof JM de Jager	:	University of the OFS
Mr DFM Korff	:	Department of Water Affairs and Forestry
Mr JK Murray	:	MBB Incorporated
Prof LK Oosthuizen	:	University of the OFS
Mr FB Reinders	:	Department of Agriculture
Prof RE Schulze	:	University of Natal
Dr A Streutker	:	Department of Agriculture
Ms A Vaughn	:	University of Durban-Westville
Prof MF Viljoen	:	University of the OFS

This project was only possible with the active co-operation of members of the Steering Commmittee and other individuals and Institutions. People gave generously of their time, and provided information, encouragement and advice. They can not, of course, be held responsible for the final product, and it would be wrong to assume that they necessarily agree with the way in which their information was interpreted and applied!

In particular Murray Biesenbach & Badenhorst Inc would like to acknowledge the following for their contribution to the project.

The programmers

The programming of the linking and "up-front" programs, which required a sympathetic insight into the ultimate application of SAPWAT, was undertaken by two graduate engineers working on higher degrees, Ela Romanowska and CP Crosby. Their creative contributions went far beyond programming.

Computing Centre for Water Research

The approach adopted in SAPWAT is based on the research on crop water requirements undertaken by Dr MC Dent, and the program is dependent on the data bases and computing power of the CCWR. The friendly pro-active support and encouragement of the CCWR staff is greatly appreciated.

Department of Agricultural Engineering, University of Natal

ACRU and the 712 climatic zones are important elements of SAPWAT and Prof RE Schulze and his staff were always helpful. The readiness with which SD Lynch and M Maharaj made ZONER available is greatly appreciated while discussions with N Lecler were informative and constructive.

Department of Soil Science, University of the OFS

The innovative program BEWAB is incorporated in SAPWAT and many hours were spent discussing principles with Prof ATP Bennie and LD van Rensburg, they made a major contribution.

Department of Agrometeorology, University of the OFS

In developing a program such as SAPWAT, intended for use by engineers and planners, it is important that simplicity be achieved without compromising the basic principles on which estimates are based. Prof JM De Jager, Prof WH van Zyl, Dr A Singels and Dr R Mottram helped ensure that the basic principles were understood and applied. In addition they provided an initiation into the applications of PUTU.

Directorate of Irrigation Engineering, Department of Agriculture

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Dr S Walker provided valuable insights into the plant physiological factors that influence crop water use and irrigation management.

Department of Soil Science and Plant Nutrition, University of Pretoria

The concept of profile available water capacity (PAWC) has important implications for the estimation of the irrigation requirements of crops. Prof MC Laker not only assisted by his interpretations of PAWC but negotiated the acquisition of a copy of the FAO computer program CROPWAT.

CHAPTER 1

INTRODUCTION

1-1 OBJECTIVES OF STUDY

The primary objective of this pilot study was to establish a decision making procedure for the estimation of crop water requirements, to assist irrigation engineers, planners and agriculturalists and ultimately implement the procedure in the form of a computer program. The intention was that the procedure should be suitable for use by practitioners, be in line with current international practice and incorporate both interpreted research results and the practical experience of specialists.

This amounts to the development of an approach to estimating the irrigation requirements of crops, that could acceptably supersede the Green Book and the procedures recommended by the South African Irrigation Institute and the Directorate of Irrigation Engineering, Department of Agriculture. The people who have been involved in this study are engineers with extensive knowledge of irrigation design and development and with insight into the processes of policy implementation, project assessment and official decision making. They are not scientists, agronomists or agricultural meteorologists. This background is important in assessing the value of this pilot study as a link in the technology transfer chain. The researchers involved in the project believe that they are representative of many of the "*customers*".

This is a *pilot project, intended to establish the inputs required to develop a realistic procedure.* It is anticipated that should the pilot study identify a promising approach, consideration would be given to extending the scope of the project to provide for the development of a comprehensive decision support system, which would become a standard for Southern Africa.

An implied objective was to identify WRC supported research that has a bearing on the subject and to incorporate the results, after processing, in the procedure, which would also complement the computer design program, IDES, developed with WRC support by Murray, Biesenbach and Badenhorst (1987).

A proto-type PC computer based procedure which conforms to these objectives, has been developed and given the preliminary identification of **SAPWAT** (Southern African Procedure for estimating irrigation **WAT**er requirements).

1-2 THE NEED FOR A REVISED PROCEDURE

There is no dearth of literature on crop water requirements or irrigation management, but recent monographs by the American Society for Agricultural Engineers and the American Agronomy Society review the field comprehensively. It is difficult, however, to reduce this mass of information to understandable, usable and practical procedures that can be applied in the planning office and the field.

Nonetheless, this was achieved in two FAO publications in the Irrigation and Drainage papers series, viz. *Guidelines for predicting crop water requirements*, Doorenbos and Pruitt (1977) (FAO 24) and *Yield response to water*, Doorenbos and Kassam (1979) (FAO 33). The very fact that these papers reduce the existing knowledge to such a practical form, explains why they had such an impact and were accepted as an international standard. The FAO then published *CROPWAT-a computer program for* *irrigation planning and management*. Martin Smith (1992) (FAO 46), that incorporates both FAO 24 and FAO 33.

There is merit in basing a Southern African procedure on the foundations provided by the widely accepted FAO initiatives. Research undertaken in South Africa during the past decade has developed innovative approaches to estimating crop water requirements and extensive data bases have been established. It was felt that the best way to improve the estimation of irrigation requirements, was to devise a program that incorporated both the local results and the FAO approach.

1-3 PRACTITIONERS' RELUCTANCE TO ACCEPT CHANGE

The current procedures for estimation of crop water requirements are well established and are endorsed by the South African Irrigation Institute and the Directorate of Irrigation Engineering and are taught at academic institutions. The procedures are clear cut and the norms employed have, through application, become generally accepted by the irrigation industry in South Africa. There is a reluctance to accept the idea that there is a need to revise methods for estimating crop water requirements. Designers feel that on the present basis it is possible to design adequate systems with sufficient flexibility to ensure that they can be managed so as to compensate for any problems that may arise. Crosby (1992) discussed this reluctance to change and comes to the conclusion that, while there is sufficient depth of experience in the RSA to ensure good irrigation design, there are inherent vulnerabilities in the existing approaches which should be addressed. This is particularly true of "non-standard" situations.

The introduction of a modified procedure for the estimation of crop water requirements, is a classical example of "technology transfer". Van Vliet and Gerber (1992), discuss the factors that influence the acceptance of a newly introduced procedure.

* "Good enough" is the basis for the acceptance of a procedure.
* Choice of procedure is strongly influenced by convention and past practice.
* The infrastructure required to support the procedure is often the determining factor.
* The achievement of acceptability requires establishing standards, imposing constraints and attaining routine.

To gain acceptance, any procedure or support system must be well packaged, including readily available databases, editing facilities and the option of moving back and forth between procedures to allow the user to explore various scenarios. This "built-in" infrastructure must at the same time remain easy to use and provide an automated routine. **BEWAB**, Bennie *et al* (1988), is an example of such an approach in this study field. In developing **SAPWAT** these factors have been taken into account.

1-4 DEVELOPMENT OF THE SAPWAT CONCEPT

SAPWAT is a compilation which has developed during the period of the project. It is certainly different to what was envisaged when the first research proposals were submitted, for reasons discussed here.

1-4-1 Approaches evaluated

The first avenue to be explored, was that of so-called 'Expert Systems', in the belief that there exist specialists with the necessary knowledge of irrigation and that the main task was to mobilise their expertise. It soon became evident that this approach was not very promising. Expert systems appear to be more suited to individual tasks and processes such as managing a pivot, but not to more complex management situations. It also proved difficult to identify general specialists. Bennie (1992) was quite right when he commented that the decision making criteria developed by farmers over the years are mostly applicable to a particular set of farming circumstances only. The scientists on the other hand have in-depth knowledge of their specialities, but are less concerned with practical management.

Attention was given to the possibility of utilising crop water-yield, functions rather than relying on empirical crop coefficients. This route has possibilities, but there are disparities and it was not possible to arrive at a sufficiently generalised approach.

Crop models are relatively new to the uninitiated in the RSA, but their application in irrigation planning is attractive and their possibilities were explored in some detail. Time was spent running, or attempting to run, a number of models. This exercise proved to be an enriching experience and helped the researchers to develop a fundamental understanding of irrigation principles. With the benefit of hindsight, it is now realised that it was probably naive to suppose that crop models could be used directly in irrigation planning and design in Southern Africa when this is not the practice internationally. The indirect use of crop models, however, is discussed in detail in Chapter 15.

Crop models of various levels of sophistication are, however, utilised internationally for "real time" scheduling of irrigation. The main purpose of these models, is to develop soil water balances related to the actual day-to-day variations in atmospheric evaporation and precipitation, in order to establish irrigation requirements. Planning and design, on the other hand, are based on long term averages and are not site-specific so that attempts to achieve the level of precision warranted by scheduling, are not justified. The factors discussed by Van Vliet et al (1992) which determine the acceptability of "routine" procedures, (see paragraph 1-3), are generally applicable.

1-4-2 Programming approach

The main objective of the program **SAPWAT** is to promote better planning and design through the accurate estimation of crop irrigation requirements. However, if this new procedure is to be accepted in the place of the old well-established routines, it must present advantages that go beyond technical excellence. It must also be more convenient to use than present methods. Considerable attention has been given to programming style, and it is believed from the reaction of practitioners who have seen demonstrations, that a satisfactory approach has been achieved.

SAPWAT is programmed in Turbo Pascal and extensive use is made of menus and graphics. None of the procedures have to be "learned". Input data is packaged and immediately available. It is possible to move around in the program and to back-track, encouraging "what-iffing".

The procedure followed in the prototype support system, **SAPWAT**, is conventional in that it utilises monthly estimates of atmospheric reference evaporation and crop coefficients to calculate crop atmospheric demand. Irrigation requirements are then derived by taking effective precipitation and soil water balances into account. **SAPWAT**, as will be seen, leans heavily on FAO Irrigation and Drainage papers No's 24 and 33 and on research financed by the WRC, particularly Dent et al (1988), Schulze (1989), Dent et al (1988), and Bennie et al (1988).

CHAPTER 2

ESTIMATING IRRIGATION REQUIREMENTS - QUO VADIS?

2-1 INTRODUCTION

Before establishing a new South African procedure for estimating the irrigation requirements of crops, it was necessary to establish the direction in which the international irrigation community is moving. It was fortunate that the FAO undertook an authoritative review recently and published guidelines for future action.

An expert consultation on procedures for the revision of FAO guidelines for prediction of crop water requirements, was held in Rome in 1990. Amongst the organisations collaborating, were the International Commission for Irrigation and Drainage (ICID), the American Societies for Civil and Agricultural Engineers, the World Meteorological Organization (WMO) and the International Crop Research Institute for the Semi-arid Tropics (ICRISAT).

High-level experts from seven countries participated full time in the meeting. Representatives were from Australia, France, Italy, Netherlands, Portugal, UK and USA. The principal participants were Dr PM Fleming, Dr A Perrier, Prof L Cavazza, Prof R Feddes, Prof L Santos Pereira, Dr H Gunston, Dr Richard Allen, Dr ME Jensen, Dr WO Pruitt, Dr JL Monteith, Mr A Segeren and Dr D Rijks. Mr Martin Smith of the FAO Land and Water Development Division was the organiser and prepared the report.

2-2 MOTIVATION FOR EXPERT CONSULTATION ON FAO 24

In the introduction to the report on the consultation, a brief history is given of the circumstances that led to the consultation.

> In the Irrigation and Drainage Paper series, the FAO methodology for the prediction of crop water requirements has proved to be quite outstanding. FAO 24, as it is now known, has become an international standard, extensively used worldwide by irrigation engineers, agronomists, hydrologists and environmentalists.
>
> More than 20 000 copies of the publication have been distributed in four languages. The methodology is commonly applied in many studies and development proposals, and endorsed by the major financing and development agencies as the recommended method.
>
> No doubt the sound concepts introduced in the methodology, combined with the practical calculation procedures facilitated by tables and examples, are the basis of the methodology's success. In many educational institutes and universities, the FAO methodology is part of the curriculum.
>
> Since the methodology was developed and published in the early seventies, much new research has been carried out in the field of crop-water-soil relationships, more refined equipment has been developed, allowing more accurate and extensive data on crop water requirements.

The introduction of computers drastically changed both data recording and data processing techniques.

Frequent contacts are maintained with different users of FAO 24 and with several research institutes worldwide. These contacts have shown that a revision of the methodology to estimate crop water requirements has become opportune.

2.3 FAO TECHNICAL CONSULTATION PROCEEDINGS

In four technical sessions, the various themes of the meeting were introduced:

* Evaluation of various methods for prediction of reference evapotranspiration (ETo).
* Analysis of concepts and procedures for the calculation of ETo.
* Physical parameters and climatic data measurements, availability and reliability. Recommended timesteps for various ETo methods.
* Crop evapotranspiration and crop coefficients, methods for verification of crop coefficients under various climatic conditions.

At the conclusion of the consultation, a number of follow-up studies were identified. The report comments:

> FAO does not have sufficient resources to undertake these studies on its own. The experts representing various worldwide research stations indicated their willingness to contribute to the studies.
>
> FAO would co-ordinate such efforts and address research institutes worldwide to assist in these efforts, by making available data and carrying out part of the research work. Assistance would be sought in this through the international agencies, such as the ICID.

It would appear that the RSA would be well advised to take note of these developments on two counts. Firstly, any research or development work done in the field of estimating crop irrigation requirements should be in harmony with the international effort and secondly, there may be opportunities for co-ordinated participation in these research studies.

2-4 RECOMMENDATIONS AND CONCLUSIONS OF THE FAO CONSULTATION

The outcome of the discussions can be regarded as an indication of the direction in which research and development can be expected to progress.

It was concluded that several methods should be recommended, based on the type of climatic data available, but it was stressed that a clear relationship should be established among the various methods.

Unanimous agreement was reached that the Penman-Monteith approach is presently the best performing equation. It was recognised that a temperature method will need to be included, but it was decided not to recommend the further use of the Blaney-Criddle method. A more satisfactory approach could be developed by using maximum and minimum temperatures, but further studies were recommended to come up with a more satisfactory method for different climatic conditions.

The use of a single climatic parameter to estimate reference evapotranspiration seems attractive. Extensive use and testing of the evaporation from standardised evaporation pans such as the A-pan have shown, however, the great sensitivity of the daily evaporation of the water in the pan, influenced by a range of environmental conditions such as wind, soil heat flux, vegetative cover around the pan, painting and maintenance conditions, and use of screens. Use of the pan evaporation method for estimating reference evapotranspiration should be recommended only if properly calibrated, in comparative studies and for practical irrigation scheduling.

The reference evaporation will now be defined as the rate of evapotranspiration from a hypothetic crop with fixed crop height (120mm) and canopy resistance (69), and albedo (0.23), which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water. Thus defined, the method would allow meaningful calibration from reference data collected for different climate and crop conditions.

It was considered that the crop coefficients were still valid, but an update was justified and that the following aspects should be considered:

* update in particular of coefficients for tree and fruit crops, as well as several of the perennial crops;

* review of the crop coefficient at the initial stage by evaluating soil evaporation and basal crop transpiration separately;

* review of the effect of climate and advective conditions on the crop factor;

* a review and update of the length of the various growth stages, possibly introducing a growth function related to temperature and dry matter production.

PUTU addresses several of these aspects. Ultimately a one-step approach eliminating the need for crop coefficients and reference evapotranspiration used in the present two-step approach should be feasible but development could take 10 years. This will, however, require reliable values for crop resistance under various growth and soil moisture conditions. The consultation supported the essential soundness of the principles embodied in FAO 24 and gave clear indications of the direction in which further development is likely to take place. In the development of **SAPWAT** the principles outlined at the consultation have been kept in mind.

CHAPTER 3

OVERVIEW OF SAPWAT

3-1 THE ELEMENTS OF SAPWAT

Each element of SAPWAT (Southern African Procedure for estimating irrigation WATer requirements) is discussed in the report in detail, with examples of computer screens. This brief review will provide the initiated with an overview of the procedure.

SAPWAT is characterised by the programming style that was adopted. It was essential that **SAPWAT** should have the potential to be the preferred approach for estimating crop irrigation requirements. This implied that **SAPWAT** be understandable, self contained, flexible, convenient and reduce the time required to make estimates.

Ms Ela Romanowska was responsible for **RAIN**, **MONTHKC**, and **GROSS**.

Mr CP Crosby was responsible for **NATAL**, **OFS**, **SCHEME** and **ROBERTS**.

3-1-1 The 712 climatic zones and ACRU ZONE FINDER

A key element in the system is the utilisation of 712 climatic zones as developed by the Department of Agricultural Engineering, University of Natal and used by Dent et al (1988) to calculate the irrigation requirements of crops. In the interests of brevity this program by Dent et al is referred to in this report as **PMBWAT**. The first step in the procedure is to establish the zone in which the farm is located, by inputting latitude and longitude into the PC program **Zone Finder 1.01**.

3-1-2 Display of seasonal rainfall data

A graphic presentation of long-term rainfall for the zone is then called up and displayed by month and year in the program **RAIN**. This makes it possible to review at a glance the historical rainfall pattern so that vulnerabilities can be identified and irrigation strategy developed. The rainfall data is updated from the records utilised by Dent et al (1988). The 50th (average year), 80th or 90th (dry year) percentile is then selected for each month of the crop growing season and these percentiles become inputs for the calculation of irrigation water requirements.

3-1-3 Crop coefficients

Crop coefficients for each month of the crop growing season are then developed by **MONTHKC**. Default values at key developmental stages are derived from FAO 24 and presented in the form of the "generic" crop coefficient curve. Editing of stage lengths, if desired, is possible in 15 day increments in each growth stage.

3-1-4 Monthly irrigation requirements

The integrated monthly crop coefficients and weather percentiles are then inputs to the program **NATAL** where the monthly crop water requirements are developed, utilising **PMBWAT LINEV**[1] files, while the monthly irrigation requirements are derived from the **IRRIG** file (corresponding to the particular zone) by interpolation and an adjustment made from A-pan to "short grass" reference evaporation. The **IRRIG** files have been developed from the full **ACRU** (Schulze et al (1989)) irrigation routine, based on daily weather inputs and soil water balances and have the advantage that they "package" many of the factors that have to be included in irrigation requirement calculations.

3-1-5 Preprogrammed irrigation

The system up until this stage has been concerned with determining monthly water requirements, with the emphasis on atmospheric demand. No account has been taken of the part played by reserve water in the soil profile. The program **OFS** is an unashamed rewrite, in Turbo Pascal, of the **BEWAB** programme, (Bennie et al (1988)), in Turbo Pascal and provides the same facilities including the **PAWC** model and provision for supplementing peak water requirements by drawing on water stored in the profile earlier in the season. The options of commencing the season with a full, half full and dry profile are retained, as is that of keeping pace with atmospheric demand. The main difference is that, in addition to the normal **BEWAB** application to a specific range of crops in the area researched by Bennie et al (1988), the principles are extended to apply to all crops and the 712 zones.

3-1-6 Manual adjustments

There are two further stages which have yet to be programmed and are presently dealt with on a manual basis. The first allows adjustments to be made to nett values, to allow for the clothes-line and island effects resulting from advection. The second is the application of crop water-yield functions, to cross-check.estimates of crop water requirements and yield levels.

3-1-7 Estimating gross irrigation requirements

An additional facility is provided by the program **GROSS** that assists in transforming nett irrigation values to gross values.

3-1-8 Scheme monthly water requirements

No standard procedures are available locally to facilitate the estimation of monthly water requirements on a scheme, where the mix of crops, areas planted and planting dates can be varied. Some planners utilise spreadsheets for this purpose, but the program **SCHEME** caters for this requirement.

3-1-9 Packaging of program

The intention is to package the various elements in one program that will require virtually no computer literacy. Particular attention has been paid to the option of editing default values with the help of menus and the facility to move back and forth between **SAPWAT** elements, without leaving the program.

---

[1] Both the LINEV and IRRIG files originate in Dent et al (1988) and form part of the procedure referred to in this report as PMBWAT.

CHAPTER 4

THE 712 CLIMATIC ZONES

4-1 INTRODUCTION

Crop water use is dependent on atmospheric evaporative demand and one of the main requirements is the availability of climatic data. Data is available for 712 zones in South Africa as a result of the developmental work done by the Department of Agricultural Engineering, University of Natal. These zones form the core of the **SAPWAT** procedure.

4-2 THE DEMARCATION OF THE ZONES

The demarcation of these zones is set out in some detail in Dent et al (1988) and in the interest of completeness is summarised here.

> The irrigation planner or designer would have to choose the rainfall station most appropriate to the design site. 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. Often, spatial proximity of rainfall stations to the farm in question does not necessarily provide the best choice and can thus be misleading.
>
> It was therefore decided to delimit zones of more or less homogeneous climate surrounding the daily rainfall stations. It was evident on the examination of research work that any delimination of homogeneous climate zones would have to be based on altitude and mean annual precipitation (MAP).
>
> The methodology followed involved firstly the printing of a classified altitude map of the country. Next the locations of all stations with ten or more years of record were superimposed on this image. Thereafter followed the time consuming process of deliminating the zones based mainly on MAP, altitude and aspect, whilst keeping the zones reasonably small and consulting 1:250 000 topographic maps. Human judgement was used in the delimitation of the zones in preference to relying on a set of computerised rules.
>
> The following criteria were used 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.
>
> (b) MAP at long term daily rainfall stations:
> Since rainfall is the primary driving force in the water budget and certainly the element which is the most erratic, it was decided to concentrate on rainfall as the main climatic element in the delimitation and allow the more conservative variable, temperature, to be estimated from a station within the zone or even

from a station in a nearby zone if necessary. The zones were chosen to reflect a limited range in MAP.

(c) Geographic proximity.

(d) Aspect:
The direction of movement of weather systems can have a marked effect on rainfall amounts, especially in mountainous areas. An attempt was made to delimit according to broad aspect in mountainous areas.

(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.

(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.

Based on these criteria, 712 zones were delimited and the boundaries of these zones were stored to a resolution of 1 minute of a degree (1.6 km) for computerised plotting.

4-3 ACRU ZONE FINDER

The first element in **SAPWAT** is the program **ACRU ZONEFINDER**, which is used to establish the zone in which the irrigated area in question is located. This program was kindly made available on an experimental basis and is easy to use. The only inputs required are the co-ordinates of the site. Output is in the form of a map of the country on which the applicable zone is plotted together with the corresponding zone number. A large scale map of the particular zone and its neighbouring zones together with their areas, can also be viewed.

In the running of this program, special attention must be paid to whether there are topographical features which can influence the climate. It could be meaningful to compare the zone map with a topographical map to enable an intelligent zone selection.

Once the zone has been established, access to climatic data and subsequent calculations in the remaining elements of **SAPWAT** is automatic.

4-4 EXAMPLE SCREENS

The program **ZONER** is used to find the appropriate zone on a map of the RSA. The position of the zone is first indicated on a map of the entire country. Then a more detailed map of the zone is drawn, indicating the positions of weather stations inside the zone. The inputs to the program are straightforward, and examples of typical inputs are given in Screens 1, 2 and 3. The first map, showing the postion of the zone in the country, is given as Screen 4, and the detailed map as Screen 5.

ACRU
ZONE FINDER
Version 1.01

S D Lynch
Dept Agricultural Engineering
University of Natal
Pietermaritzburg
(0331) 955412

Spacebar to continue

Screen P001

ZONER Screen 1: **Header Screen**

Screen P002

0 for coordinates in degrees decimal
1 for coordinates in minutes of a degree
0

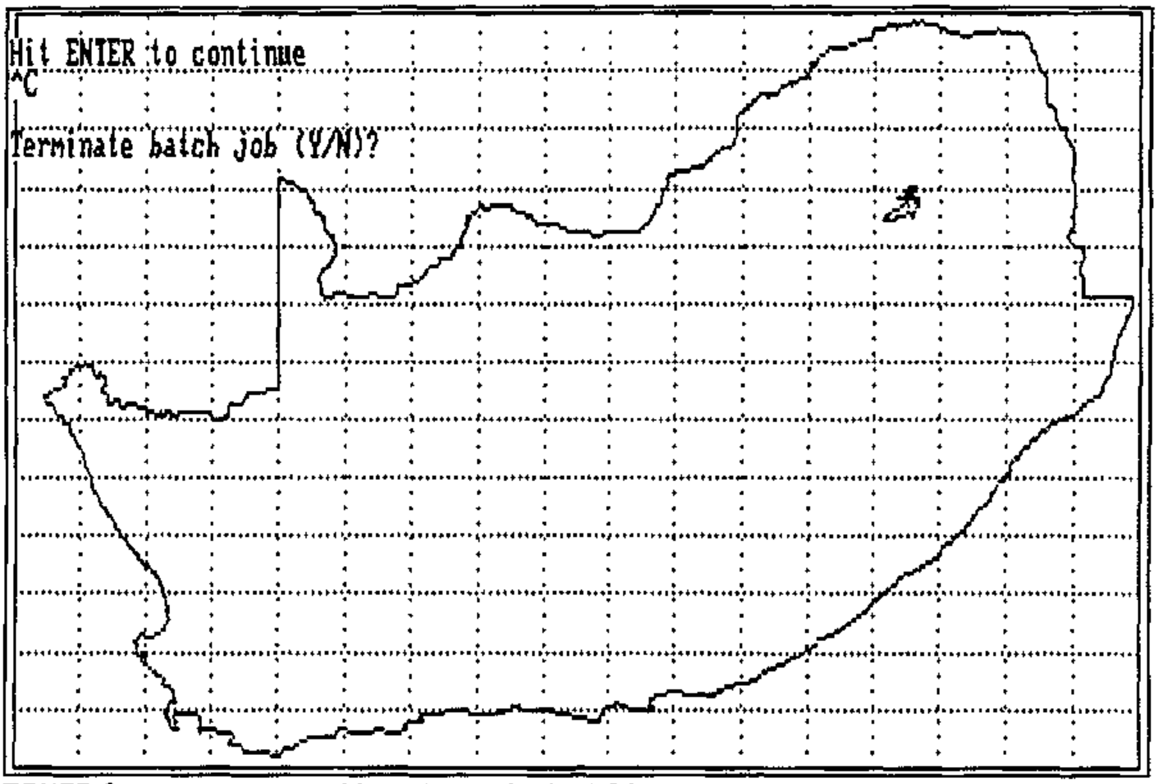
Esc Accept page

ZONER Screen 2: **Station Co-ordinate Input Mode.**

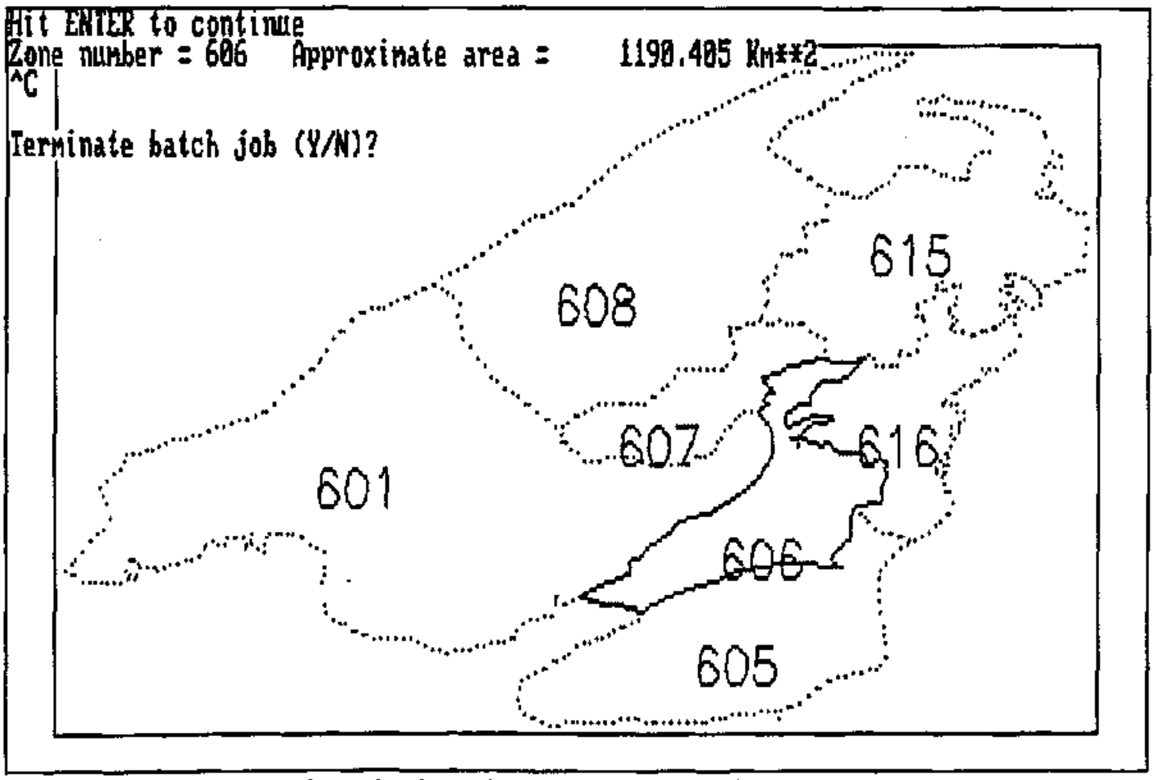
Latitude	25.167
Longitude	29.517

Esc Accept page

ZONER Screen 3: **Station Co-ordinate Input.**



ZONER Screen 4 : Position of zone in the RSA.



ZONER Screen 5 : Map of selected zone as well as neighbouring zones.

CHAPTER 5

DISPLAY OF SEASONAL RAINFALL DATA

5-1 PROGRAM RAIN

Except in the arid western parts of the country, an understanding of rainfall and its variations is important to the irrigation planner and designer. Average values give some indication of what can be expected, but reliable long term monthly rainfall records can provide a valuable support to decision making. The monthly rainfall records for the stations used in developing the 712 zones were kindly provided by SD Lynch of the Department of Agricultural Engineering at the University of Natal.

A program **RAIN** was developed that requires only the zone number and season, summer or winter, as input. Rain displays monthly rainfall over the full period of record, which is up to 100 years in some cases. On the left hand side of the graphical display the zone number, station ID number, period of record, the specific season (marked by a vertical cursor), season total and season average are displayed. On the right hand side of the screen average rainfall for each month is provided over the period for which data is available, as well as the actual rainfall for the season under consideration.

The display assists the planner to decide for each month what the risks are if he should assume average rainfall. If he should decide that rainfall inconsistency or the sensitivity of the crop is such that this would involve unwarranted risk, the planner can decide to base his design on a dry, year where rain is virtually ignored. This is statistically expressed as the 90^{th} percentile, or the driest year in ten. Another alternative is to compromise and accept the 80^{th} percentile, or one in five dry year.

It will be seen from the example screens that the display helps a farmer or decision maker to relate his own experiences and memories to the statistical realities of the situation over the years in the various regions.

5-2 EXAMPLE SCREENS

The program **RAIN** is used to present available rain data in such a format, that the data can be evaluated and interpreted by an analyst. Data are available for all 712 zones, and can be viewed over two six month periods: summer and winter. The value of this program is that it aids the judgement of the analyst, because a large amount of information is made available in an orderly and readable fashion. The analyst could, for example, decide to do all his planning for a "DRY" January, and a "NORMAL" February, if it is clear that the rainfall figures for January vary a great deal from the average, and those for February do not vary much. Such information can be obtained relatively easily, by inspecting the arrays of bar graphs. A cursor can be moved around on the screen to obtain exact figures for the monthly and seasonal rainfall. An editor is provided for setting the percentiles for each of the 12 months of the year. These percentiles are then passed on to the program **MONTHKC**, where another editor is provided for the same purpose. The percentiles are used by the program **NATAL**, to calculate total water requirements and irrigation requirements.

Type in the zone number: 313

RAIN Screen 1: **Inputs required for RAIN**

ZONE : 313

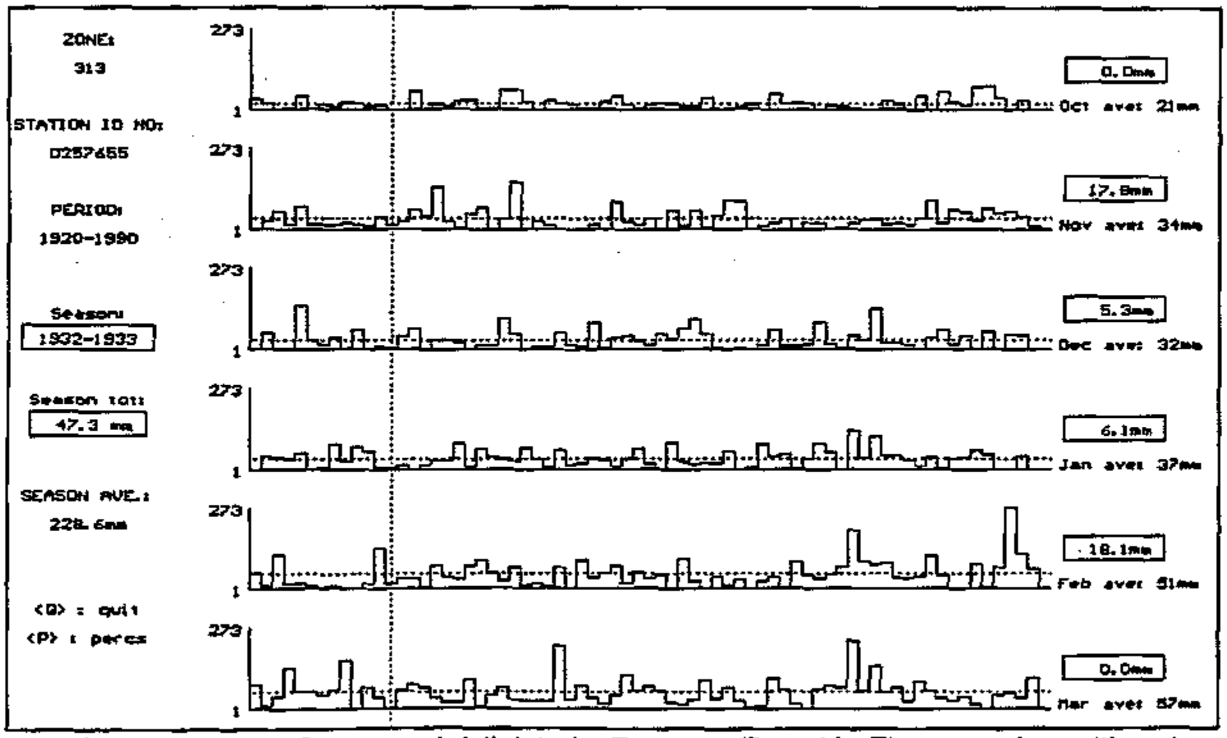
PERCENTILES FOR EACH MONTH:

N: 50th percentile month (normal)
M: 80th percentile month (medium)
D: 90th percentile month (dry)

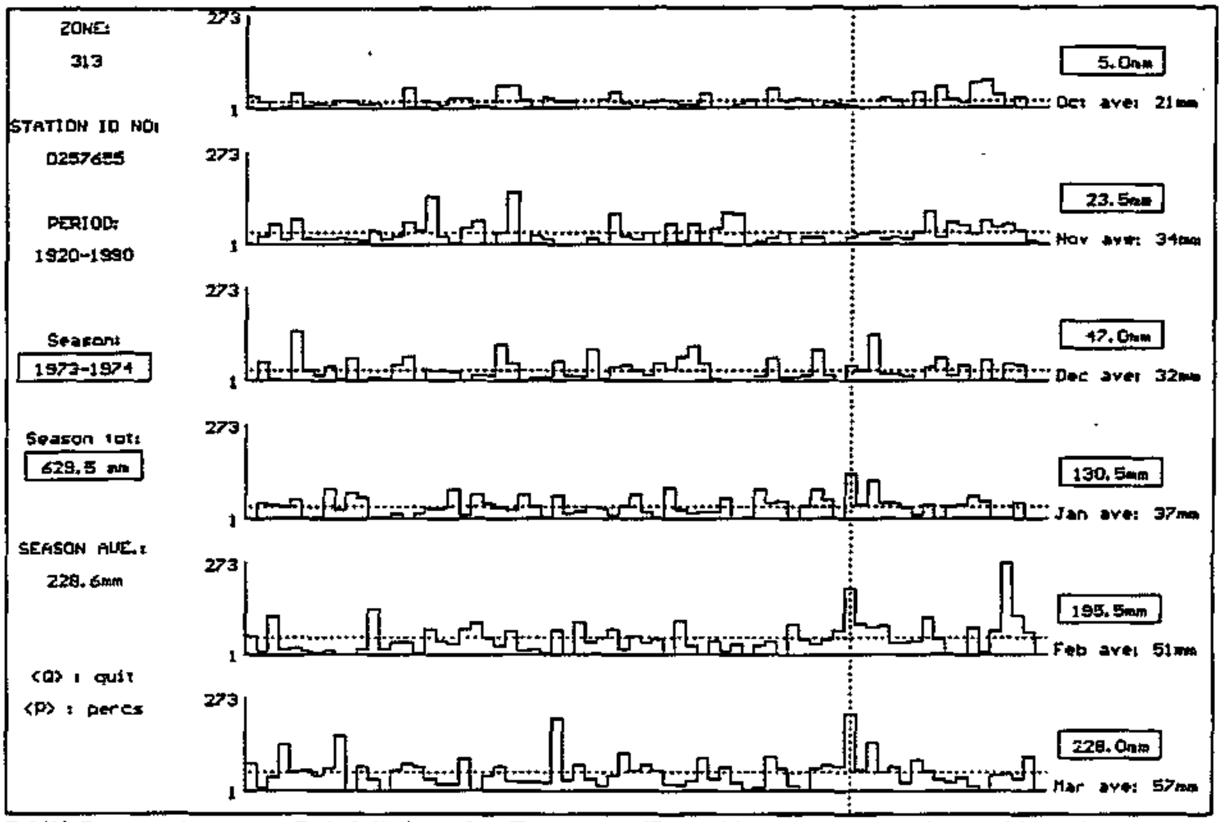
January:	D
February:	N
March:	M
April:	D
May:	D
June:	D
July:	D
August:	D
September:	D
October:	M
November:	N
December:	D

<Enter> to leave entry as is <Q> to quit <G> for graphics

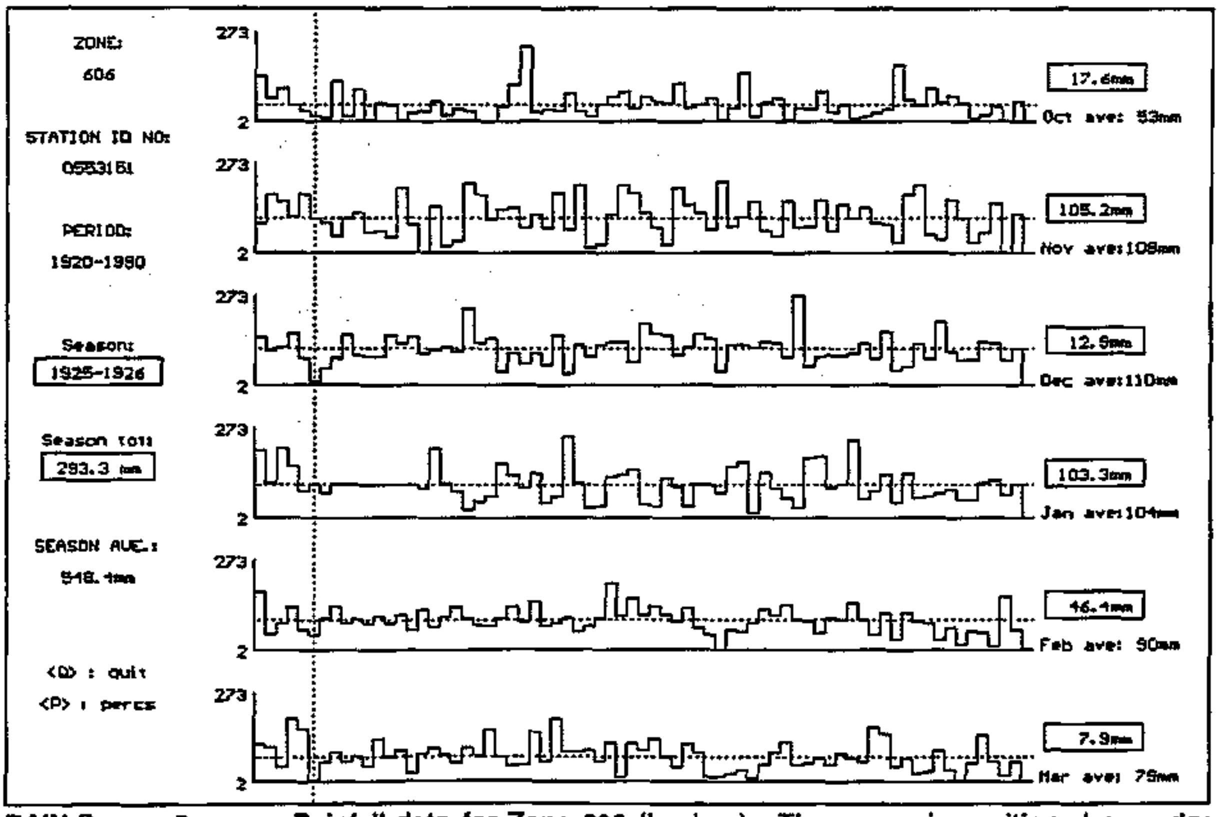
RAIN Screen 2: **Selection of percentiles for each month. The data graphically displayed by RAIN aids in the selection of the appropriate values.**



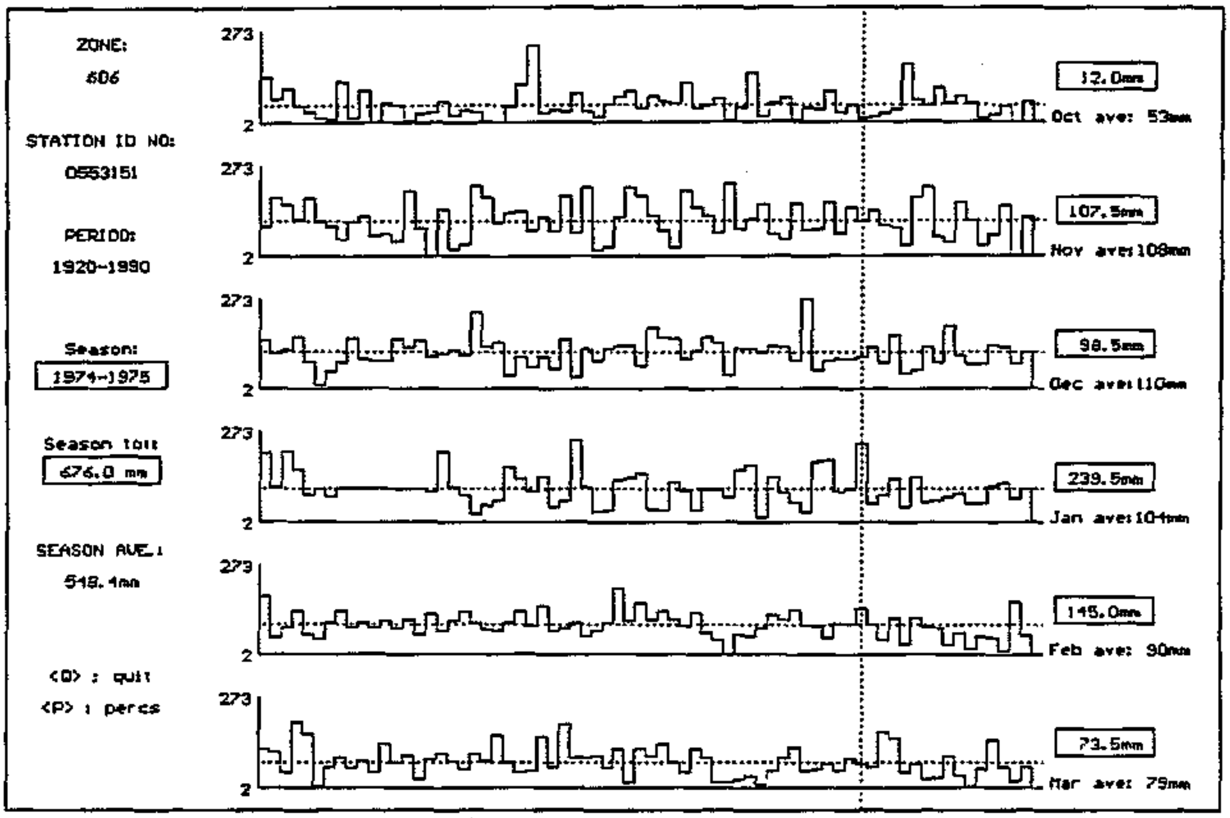
RAIN Screen 3: **Summer rainfall data for Zone 313 (Ramah). The cursor is positioned on a very dry year.**



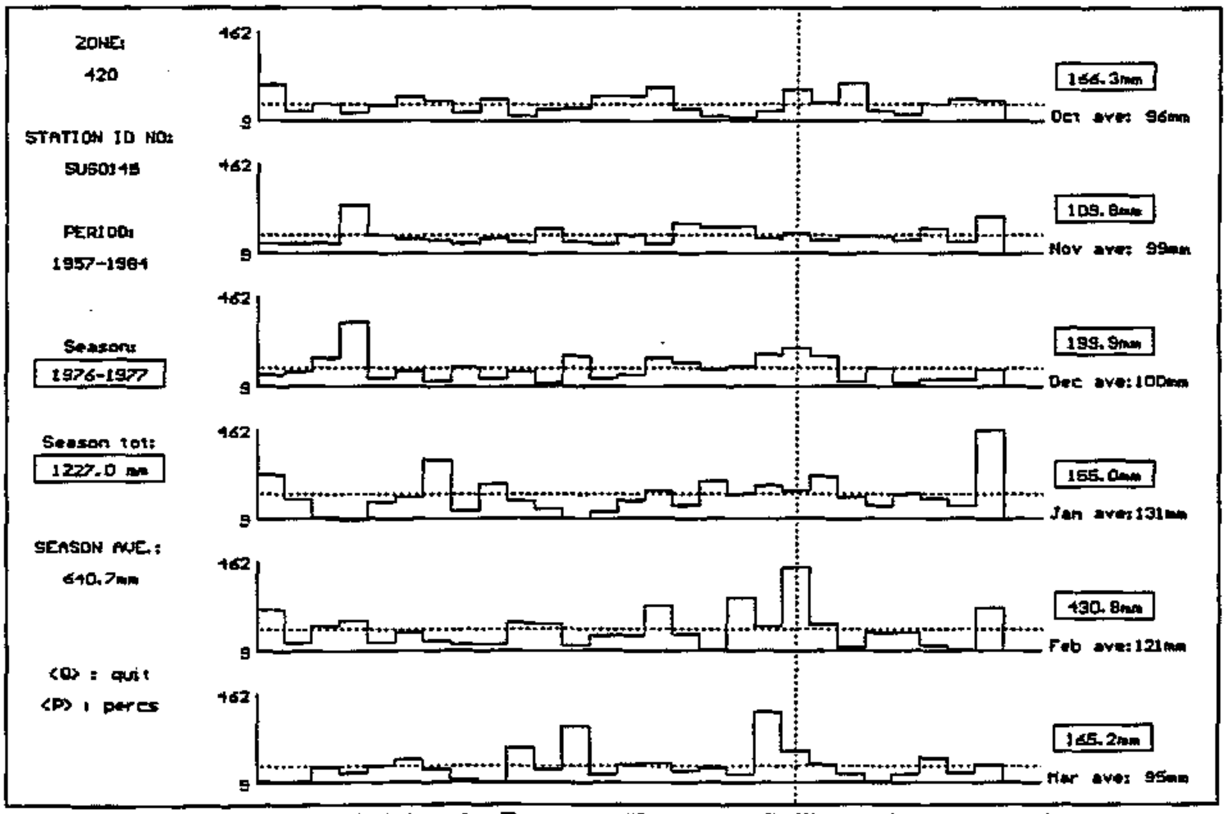
RAIN Screen 4 : Rainfall data for Zone 313 (Ramah). The cursor is positioned on a wet season.



RAIN Screen 5 : Rainfall data for Zone 606 (Loskop). The cursor is positioned on a dry season.



RAIN Screen 6 : Rainfall data for Zone 606. *The cursor is positioned on a wet season.*



RAIN Screen 7 : Rainfall data for Zone 420 (Empangeni), illustrating patterns in a wet zone.

CHAPTER 6

CROP COEFFICIENTS

6-1 INTRODUCTION

In the two-step approach to estimating crop water requirements, the crop coefficient applicable to the various stages of crop development is of great importance. **SAPWAT** utilises "short grass" based crop coefficients, essentially those provided as defaults in FAO 24 and **CROPWAT**.

The crop coefficient approach followed by FAO 24, **CROPWAT** and **SAPWAT**, is considered in some detail, because there are other approaches which are similar, but differ in important detail and misunderstandings can lead to significant errors. It will be noted that the FAO expert consultation suggested further development. These recommendations have, to some extent, been anticipated by De Jager et al (1989). In the interests of conformity, the first version of **SAPWAT** utilises the established FAO 24 approach, which can be modified in later versions depending on international and local developments.

The approach is set out in FAO 33.

> Climate is one of the most important factors determining the crop water requirements needed for unrestricted optimum growth and yield. Crop water requirements are normally expressed by the rate of evapotranspiration (ET) in mm/day. The level of ET has been shown to be related to the evaporative demand of the air. The evaporative demand can be expressed as the reference evapotranspiration (ETo) which, when calculated, predicts the effect of climate on the level of crop evapotranspiration. ETo represents the rate of evapotranspiration of an extended surface of an 80 to 150 mm tall green grass cover, actively growing, completely shading the ground and not short of water.
>
> Empirically-determined crop coefficients (Kc) can be used to relate ETo to maximum crop evapotranspiration (ETmax) when water supply fully meets the requirements of the crop. The value of Kc varies with crop, development stage of the crop and to some extent with wind speed and humidity.
>
> For a given climate, crop and crop development stage, the maximum evapotranspiration (ETmax) in mm/day for the period considered is:
>
> $$ETmax = Kc \cdot ETo$$
>
> Maximum evapotranspiration (ETmax) refers to conditions when water is adequate for unrestricted growth and development; ETmax represents the rate of maximum evapotranspiration of a healthy crop, grown in large fields under optimum agronomic and irrigation management

FAO 24 further illuminates the approach.

> The effect of crop characteristics on the relationship between ETcrop and ETo is

important. The wide variations between major groups of crops are largely due to the resistance to transpiration of different plants, such as closed stomata during the day (pineapple) and waxy leaves (citrus). Also, differences in crop height, crop roughness, reflection and ground cover, produce the variations in ETcrop.

Factors affecting the value of the crop coefficient, are mainly the crop characteristics, crop sowing date, rate of crop development, length of growing season and climatic conditions. Particularly following sowing and during the early growth stage, the frequency of rain or irrigation is important.

General climatic conditions, especially wind and humidity, are to be considered; compared with a smooth grass cover, wind will affect the rate of transpiration of taller crops more, due to air turbulence above the rougher crop surface. This is more pronounced in dry than in humid climates.

ETcrop is the sum of transpiration by the crop and evaporation from the soil surface. During full ground cover, evaporation is negligible; just following sowing, evaporation from the soil surface (Esoil) may be considerable, particularly when the soil surface is wet for most of the time from irrigation and rain.

Transpiration and evaporation are governed by different physical processes. However, since for the crop growing season Esoil forms part of ETcrop, and for the sake of simplicity, the coefficient relating ETo and Esoil is given by the appropriate "crop" factor (Kc). There is a great range of Kc values during initial growth stages. The value of Kc largely depends on the level of ETo and the frequency with which the soil is wetted.

The generic FAO crop coefficient curve used in **SAPWAT** is based on dividing the crop growing season into four stages. FAO 24 explains the procedure as follows.

Crop coefficients for given stages of crop development and different climatic conditions are presented in Table 6-1. The need to collect local data on growing seasons and rate of crop development is stressed.

The four stages of crop development are described as:

(1) initial stage:	germination and early growth, when the soil surface is hardly covered by the crop (groundcover < 10%)
(2) crop development stage:	from the end of initial stage to attainment of effective full groundcover (groundcover 70 - 80%)
(3) mid-season stage:	from attainment of full effective groundcover, to time of start of maturing as indicated by discolouring of leaves or leaves falling off
(4) late season stage:	from end of mid-season stage until full maturity or harvest

CROP	CROP DEVELOPMENT STAGES					TOTAL GROWING PERIOD
	Initial	Crop development	Mid-season	Late season	At harvest	
Banana tropical	0.4-0.5	0.7-0.85	1.0-1.1	0.9-1.0	0.75-0.85	0.7-0.8
subtropical	0.5-0.65	0.8-0.9	1.0-1.2	1.0-1.15	1.0-1.15	0.85-0.95
Bean green	0.3-0.4	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
dry	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7-0.8
Cabbage	0.4-0.5	0.7-0.8	0.95-1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.9	0.65-0.7	0.8-0.9
Grape	0.35-0.55	0.6-0.8	0.7-0.9	0.6-0.8	0.55-0.7	0.55-0.75
Groundnut	0.4-0.5	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize sweet	0.3-0.5	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
grain	0.3-0.5*	0.7-0.85*	1.05-1.2*	0.8-0.95	0.55-0.6*	0.75-0.9*
Onion dry	0.4-0.6	0.7-0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8-0.9
green	0.4-0.6	0.6-0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4-0.5	0.7-0.85	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Pepper, fresh	0.3-0.4	0.6-0.75	0.95-1.1	0.85-1.0	0.8-0.9	0.7-0.8
Potato	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.7	0.2-0.25	0.65-0.7
Sorghum	0.3-0.4	0.7-0.75	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soybean	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugarbeet	0.4-0.5	0.75-0.85	1.05-1.2	0.9-1.0	0.6-0.7	0.8-0.9
Sugarcane	0.4-0.5	0.7-1.0	1.0-1.3	0.75-0.8	0.5-0.6	0.85-1.05
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0.35-0.45	0.75-0.85
Tobacco	0.3-0.4	0.7-0.8	1.0-1.2	0.9-1.0	0.75-0.85	0.85-0.95
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Water melon	0.4-0.5	0.7-0.8	0.95-1.05	0.8-0.9	0.65-0.75	0.75-0.85
Wheat	0.3-0.4	0.3-0.4	.05-1.2	0.65-0.75	0.2-0.25	0.8-0.9
Alfalfa	0.3-0.4				1.05-1.2	0.85-1.05
Citrus clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4-0.6

First figure : Under high humidity (RHmin > 70%) and low wind (U < 5 m/sec).
Second figure : Under low humidity (RHmin < 20%) and strong wind (> 5 m/sec).

Table 6-1 Crop coefficient values from FAO 33

6-2 MONTHKC

SAPWAT utilises a program **MONTHKC** for estimating monthly crop coefficients based on a visual presentation of the generic FAO crop coefficient (Kc) versus time curve. The graphic presentation facilitates the derivation of the monthly values.

The program requires several inputs and executes as follows:

> The crop type, planting month and planting time are entered on a menu system.
>
> The crop's growing season is divided into four stages: initial, development, mid season and late season.
>
> Crop Kc values are required for the early, mid and late stages. Default values exist (on file) for the mid and late stages whilst the coefficient for the early stage is estimated from the daily reference evaporation at planting time and expected precipitation and irrigation frequencies; both of these inputs are also entered from the menu.
>
> Default stage duration values are used for the plotting of the crop coefficients versus time after planting and for calculation of the average coefficient values for each month. If required the stage lengths can be altered (in steps of 15 days) within the program. Average Kc values are then re-calculated for the new stage lengths.

Default values are provided for a wide range of crops, for both the corresponding stage lengths and crop coefficients. The default crop coefficients do not vary significantly. At the mid-season stage the crop coefficient for most crops will be approximately 1.0, in other words, ETcrop will be close to that of the selected reference crop (short grass) provided there is no water stress. Tall crops will have different aerodynamic characteristics and can be expected to have a crop coefficient greater than 1.0.

The program develops the average crop factor values for each month by interpolation, and these adjust automatically during the process of the varying of inputs. Thus the user can alter various inputs to suit varying circumstances and see the effects of these changes without having to restart the program. The desired percentile values can also be entered for each month and together with the average crop coeficient values for each month, are carried forward to the next phase of **SAPWAT**.

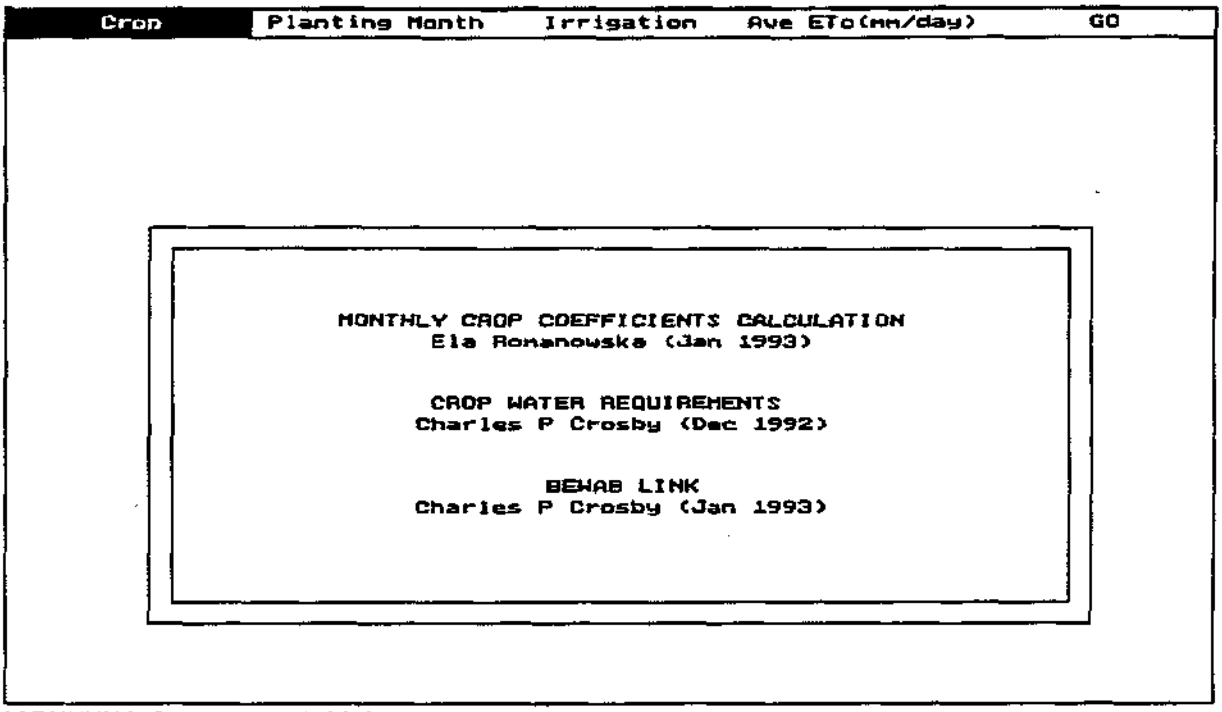
6-3 AVAILABILITY AND RELIABILITY OF CROP COEFFICIENTS

The generic approach to crop coefficients has certain distinct advantages and helps to bring order to what can at times be a confusing situation. The Rome expert consultation considered the FAO 24 crop coefficients still valid but that an update was justified. It was decided to stay with the range of FAO default values, but to recommend modification and consequent editing when this could be motivated.

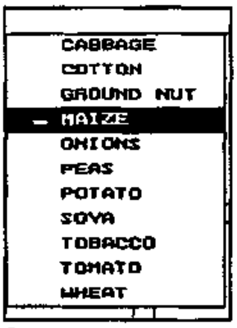
The example screens from **MONTHKC** are based on a sample set of 11 field and horticultural crops. and these screens are typical of the generic curve for crops of this nature. Table 6-1 from FAO 33 provides crop coefficients for a wide range of crops. It is important to note that generic curves can also be synthesised and extended for fodder and perennial crops and that these curves are not confined to a single season or year.

6-4 EXAMPLE SCREENS AND MENU APPLICATIONS

Average monthly crop coefficients for each month of the growing season are established by MONTHKC. The crop coefficients are used to calculate crop total and irrigation water requirements. Total water requirements become the inputs into the irrigation preprogramming model BEWAB.



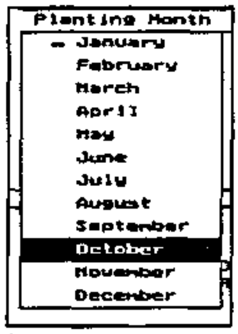
MONTHKC Screen 1 : Initial screen



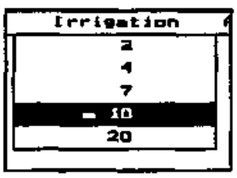
Screen 2 :
Crop selection

The program is menu driven and the first step is to select the crop. Presently only 11 crops are included in the menu (screen 2) but it is anticipated that ultimately 30 crops will be included.

The next step (screen 3) is to select the planting date. Currently this is limited to the begining or middle of each month (15 day intervals), but should a finer division prove desireable this will be feasible.

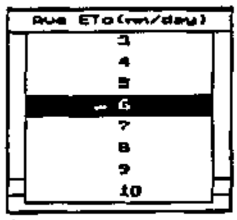


Screen 3 :
Planting month



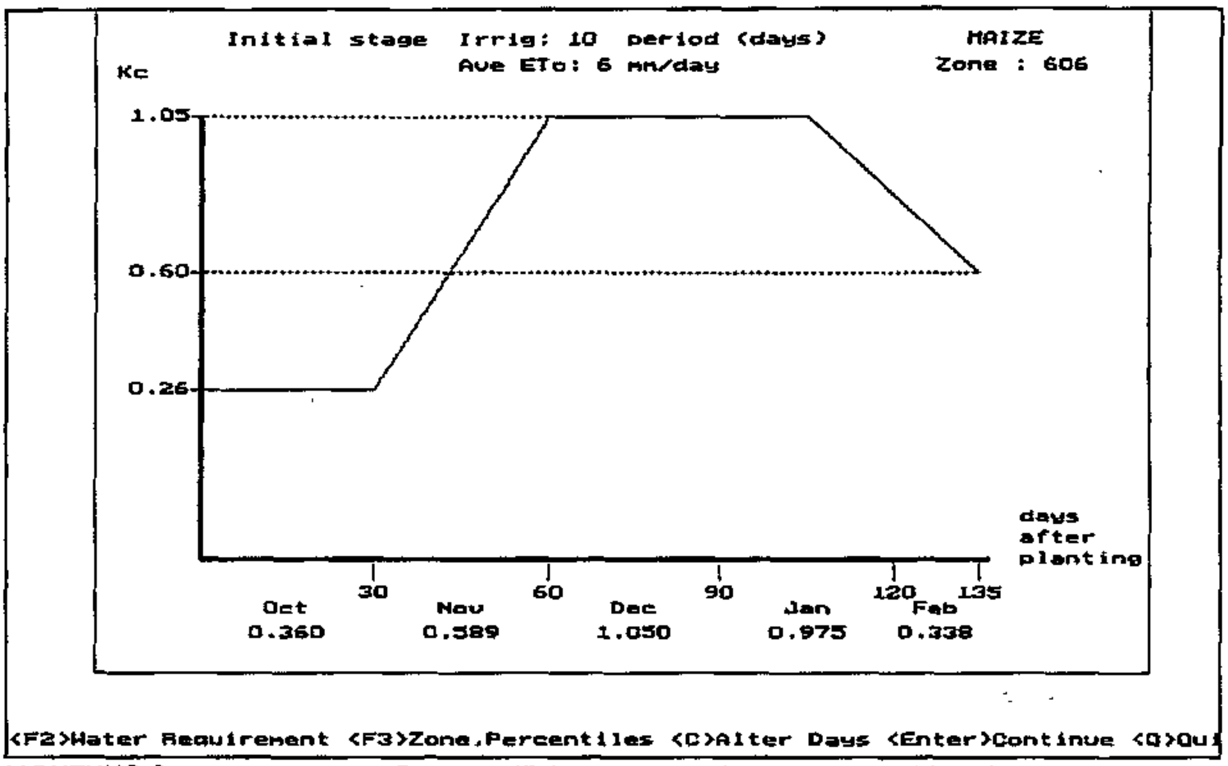
Screen 4 :
Irrigation frequency

During the initial growth stage, until canopy cover becomes significant, soil evaporation as opposed to crop transpiration is important. The water requirement as a consequence of evaporation from the soil is estimated by means of a crop coefficient derived from the estimated number of days between showers or irrigations "Irrigation" (screen 4) and the average atmospheric evaporative demand during the planting month, "Average ETo" (screen 5).



Screen 5 :
Average ETo

The average crop coefficients are presented on screen 6, which combines the default generic crop coefficient curve with a tabulation of monthly values. The curve can be edited to allow for variations in growth period lengths. This program includes the facility to change from one climatic zone to another and to select the applicable monthly percentiles which reflect the design crop irrigation requirements for normal, intermediate and dry periods, see Chapter 7.



MONTHKC Screen 6 : Crop coefficient curve and average monthly values

ZONE : 420

PERCENTILES FOR EACH MONTH:

N: 50th percentile month (normal)

M: 80th percentile month (medium)

D: 90th percentile month (dry)

January:	N
February:	N
March:	N
April:	N
May:	D
June:	D
July:	D
August:	D
September:	N
October:	M
November:	M
December:	N

MONTHKC Screen 7 : Editing of percentiles.

The selection of the appropriate zone from the 712 zones included in the program, is done by typing <Z> and the zone number.

The applicable "percentile" for each month is edited once the long-term monthly rainfall for the zone has been assessed with the help of RAIN, Chapter 5.

Screen 7 is typical of the zone and percentile editing screen.

CHAPTER 7

APPLICATION OF THE ACRU MODEL : PMBWAT

7-1 INTRODUCTION

The WRC Report No 118/1/88 - *Crop water requirements, deficits and water yield for irrigation planning in Southern Africa* by MC Dent, RE Schulze and GR Angus, includes an approach to estimating crop water requirements, **PMBWAT**, which is possibly unique in the extent to which a comprehensive data base has been integrated and packaged and the output generalised. The report has not as yet become part of routine planning and design. However, when procedures for a decision support system were being considered, it became clear that incorporation of the procedure contained in this report, was both desireable and feasible.

PMBWAT is an application of the **ACRU** irrigation routine. A salient feature of **ACRU** is that, while the model is run using long-term daily weather data for each of the 712 zones (a massive computational task), the output is a file of reasonable size, containing information for each zone from which monthly irrigation requirements can be estimated. These **IRRG** files (one for each zone) have been utilised, with some modification, in the next element of **SAPWAT**, the linking program **NATAL**.

7-2 PMBWAT

The **ACRU** model operates on daily climatic data. Great care was taken to identify rainfall stations with long records when delimiting the 712 climatic zones, thus at least one rainfall record of long duration exists for each zone. Potential evaporation (PE), which corresponds to FAO 24 reference crop evapotranspiration (ETo), presents more difficulty, but this problem was solved by using the Linacre (1977) equation to estimate equivalent A-pan evaporation. Apart from the elevation and latitude of a location, all the variables in the equation are obtained from maximum and minimum temperatures, which are available together with the rest of the climatic record. This equation was refined by introducing two variables with physical importance, viz. day length and wind. The equation was used to develop long term average values of potential evaporation (PE). These average PE values for each month are contained in the file **Linev.out**.

ACRU utilises daily time steps, but in the case of PE, which is a cyclic, conservative and less sensitive variable, the monthly values are discretized to daily values by Fourier analysis. A further refinement is that on rain days the PE was reduced to 80% of the given value, since it was assumed that on these days the clouds associated with rain will reduce the PE to below the average daily value. Conversely, on non-rain days the PE was adjusted up by 5%, since it was assumed that on such days the PE would be above the mean daily value for the month.

The **ACRU** daily water balance accounts for various elements which normally are considered as entities e.g. runoff, effective precipitation and deep percolation. This water balance also provides for a range of plant available water capacities of the soil profile.

The model catered for daily rainfall interception, actual evapotranspiration, rooting depth and soil texture. The irrigation water was applied when the soil moisture reached 50 percent 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 data record at each station, were ranked and the 50, 80 and 90 percentile values were extracted. In practice, this amounts to the irrigation requirement in a median year, the driest year in five years and the driest year in ten years.

The **ACRU** output for a given zone is shown in table 7-1 and consists of irrigation requirement values (in millimetres) for four different crop coefficients, viz 0.5, 0.7, 0.9 and 1.1. The user is expected to interpolate for intermediate values.

7-3 INCORPORATING ACRU OUTPUT IN SAPWAT

It was decided to incorporate the available data contained in the **IRRG** and **LINEV** files in the **SAPWAT** decision support system. It is necessary to realise that this is a compromise only suitable for demonstrating the feasibility of the procedure. Because of a possible misinterpretation in the development of the **IRRG** files from the **LINEV** data there may be minor inconsistencies in the **NATAL** program outputs. When the final version of **SAPWAT** is developed there would be no change in principle, but some reprogramming would be required.

The output from **MONTHKC** consists of monthly crop coefficients and selected percentiles. The linking program **NATAL** interpolates for values that fall between the fixed crop coefficients 0.5, 0.7, 0.9 and 1.1 as given in the **IRRG** files. This is adequate for the purposes of demonstrating the procedure, but it is not elegant.

The complete **IRRG** files provide for six values of plant available moisture (PAM), ranging from 20mm to 200mm, but it would appear that there would be little error for normal applications if all but the 100mm PAM value entries were eliminated, thus reducing required disc space. These abbreviated **IRRG** files, identified by the extension **SHO**, are used in **SAPWAT**. The **IRRG** files are based on demand irrigation and this should not create any problems at this stage, but in a final version other options could be considered.

SAPWAT utilises reference evaporation based on short grass, while **PMBWAT** utilises A-pan evaporation derived from the Linacre (1977) equation for evaporation from a lake. This differs from the Linacre (1977) equation for evaporation from well watered vegetation in the albedo constant, which is 0,25 instead of 0,05. In order to provide for the application of the short grass option in **SAPWAT**, the crop factors in **PMBWAT** have been adjusted by a factor 500/700. This is a temporary expedient and in the long term should be replaced by the best available proven and feasible procedure.

NATAL does the necessary modifications to the **IRRG** files to provide a read-out of nett irrigation water requirements without, the need for any additional inputs by the user. **MONTHKC** provides the necessary inputs of crop coefficient values and percentiles, as entered by the user, directly to **NATAL**. For some applications it is desireable to have crop water requirements independently of irrigation requirements. The **NATAL** routine provides this by applying the crop factors developed by **MONTHKC** to the average monthly evaporation figures provided by the **LINEV** file. The output from **NATAL** is, therefore, both monthly irrigation and total water requirements. It is presented in either tabular or graphic form and can be saved to file or printed.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL (mm)	MEAN	124.2	119.4	79.5	38.6	15.6	7.6	9.5	6.8	19.3	42.5	91.2	162.2	659.9
M.A.P. 659.9mm	MEDN	89.7	94.3	56.7	34.3	10.1	0.3	0.3	0.3	10.2	26.8	85.1	55.4	591.0
	SDEV	109.5	100.9	64.9	29.7	18.9	16.6	19.0	12.7	27.7	30.1	58.0	68.0	227.0
	C.V.	88.1	84.5	81.6	76.9	120.9	219.8	200.0	185.8	143.5	70.8	63.6	66.5	34.0
	SKEW	2.3	2.6	2.1	0.9	2.3	4.1	2.7	2.3	2.3	0.7	0.9	1.2	0.0

MONTHLY													
MEAN TEMPERATURES	MAX	25.2	26.5	25.1	25.0	23.0	19.6	18.2	21.7	24.2	25.4	24.0	26.0
(DEGREES CELSIUS)	MIN	14.3	14.8	12.5	10.7	6.0	6.4	7.1	7.7	8.5	11.6	13.0	13.8

ESTIMATED IRRIGATION REQUIREMENT

P.A.M. (mm)	50 TH PERCENTILE CROP FACTOR 0.5 (mm)	0.7 (mm)	0.9 (mm)	1.1 (mm)	80 TH PERCENTILE CROP FACTOR 0.5 (mm)	0.7 (mm)	0.9 (mm)	1.1 (mm)	90 TH PERCENTILE CROP FACTOR 0.5 (mm)	0.7 (mm)	0.9 (mm)	1.1 (mm)	MTH
20	47	74	103	138	63	98	134	169	73	109	143	180	1
45	35	71	101	137	60	99	132	168	68	106	142	180	1
70	33	66	97	129	61	93	134	167	67	105	144	179	1
100	31	63	96	132	57	93	132	168	67	106	141	179	1
150	26	59	95	129	58	92	130	168	67	103	141	179	1
200	25	60	93	132	60	93	130	167	64	103	139	179	1
20	38	64	93	121	57	88	121	156	61	95	131	164	2
45	31	54	85	115	53	86	120	155	58	93	130	162	2
70	29	53	80	116	52	85	120	155	59	94	128	162	2
100	23	44	77	110	52	86	120	155	58	94	129	162	2
150	22	50	72	108	52	85	121	155	59	90	126	166	2
200	21	45	73	110	51	85	121	156	58	94	126	162	2
20	44	74	110	135	63	98	132	169	74	110	146	182	11
45	36	71	99	137	62	97	131	166	73	109	146	182	11
70	34	66	95	125	58	97	133	166	73	109	146	182	11
100	24	56	92	131	59	94	130	166	73	110	146	182	11
150	32	62	91	125	58	97	130	166	73	111	146	182	11
200	29	55	89	130	61	94	132	166	73	109	146	182	11
20	47	75	110	148	67	102	142	179	78	112	153	190	12
45	43	72	110	144	65	102	140	181	73	112	150	190	12
70	39	72	104	144	63	101	141	176	72	112	150	189	12
100	32	69	104	142	62	99	137	176	72	112	149	190	12
150	27	68	103	145	63	100	141	181	71	112	149	189	12
200	24	64	105	142	62	96	139	176	69	109	150	189	12

Table 7-1: **Contents of a typical IRRG file.**

The monthly irrigation requirements can also be an input into the program **SCHEME**. No standard procedures are available locally to facilitate the estimation of monthly water requirements on a scheme, where the the mix of crops, areas planted and planting dates can be varied. The program **SCHEME** caters for this requirement.

7-4 EXAMPLE SCREENS

The program **NATAL** is run from **MONTHKC**, and should be seen as an integrated part of **MONTHKC**, since the results of **MONTHKC** are direct inputs to **NATAL**. The following screens are an extension of the example screens presented in 6-4. **MONTHKC** screens are included to illustrate the progression from **MONTHKC** to **NATAL** (**MONTHKC** Screen 7).

Warning: If you have not checked the zone and percentiles,
you may wish to do so before running NATAL.

Press <Enter> to run NATAL, or any other key to abort.

MONTHKC/NATAL Screen 8: **Warning before running NATAL**

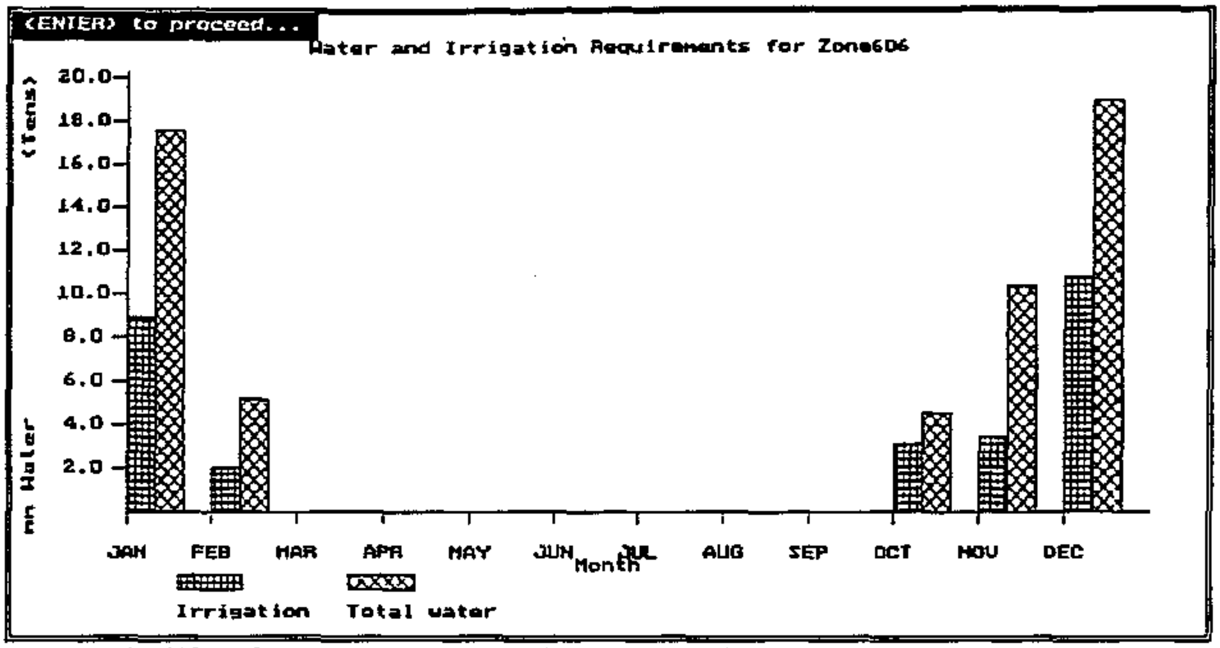
Total Water and Irrigation Requirements for Zone 606

Month	Irrigation Requirement(mm)	Total Crop Water Requirement(mm)
JAN	89	175
FEB	20	52
MAR	0	0
APR	0	0
MAY	0	0
JUN	0	0
JUL	0	0
AUG	0	0
SEP	0	0
OCT	31	45
NOV	35	103
DEC	108	189
Totals:	282	565

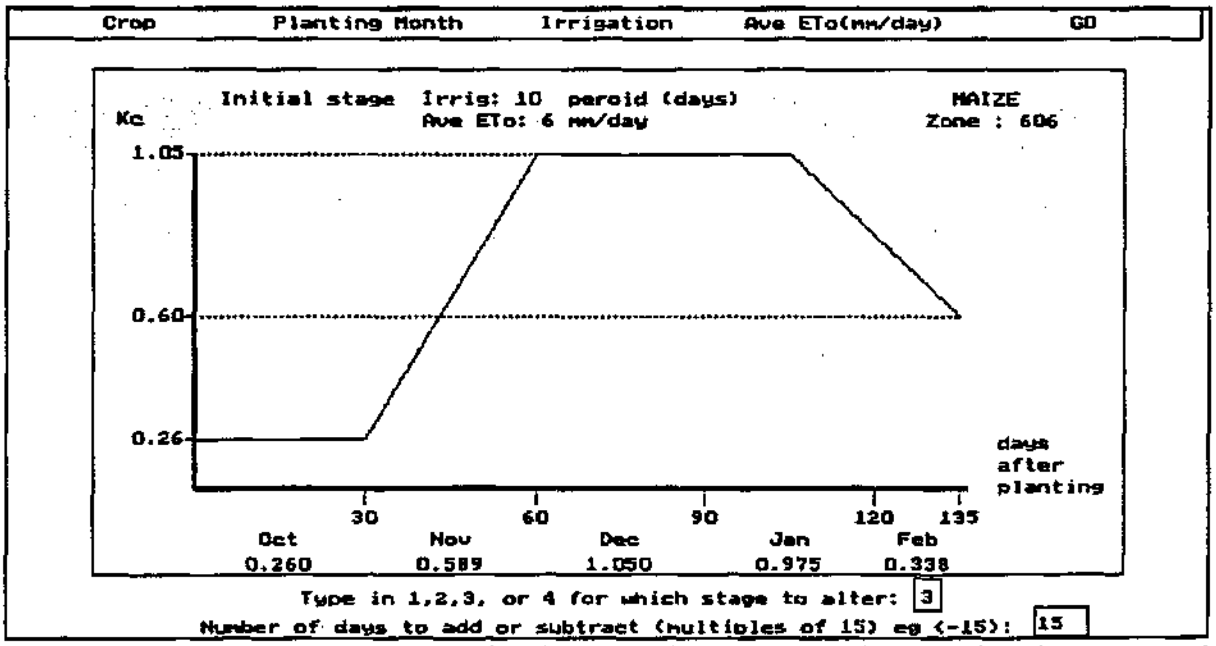
Type "P" to print, "F" to save in a file, "G" for a graph, "Q" to quit

---

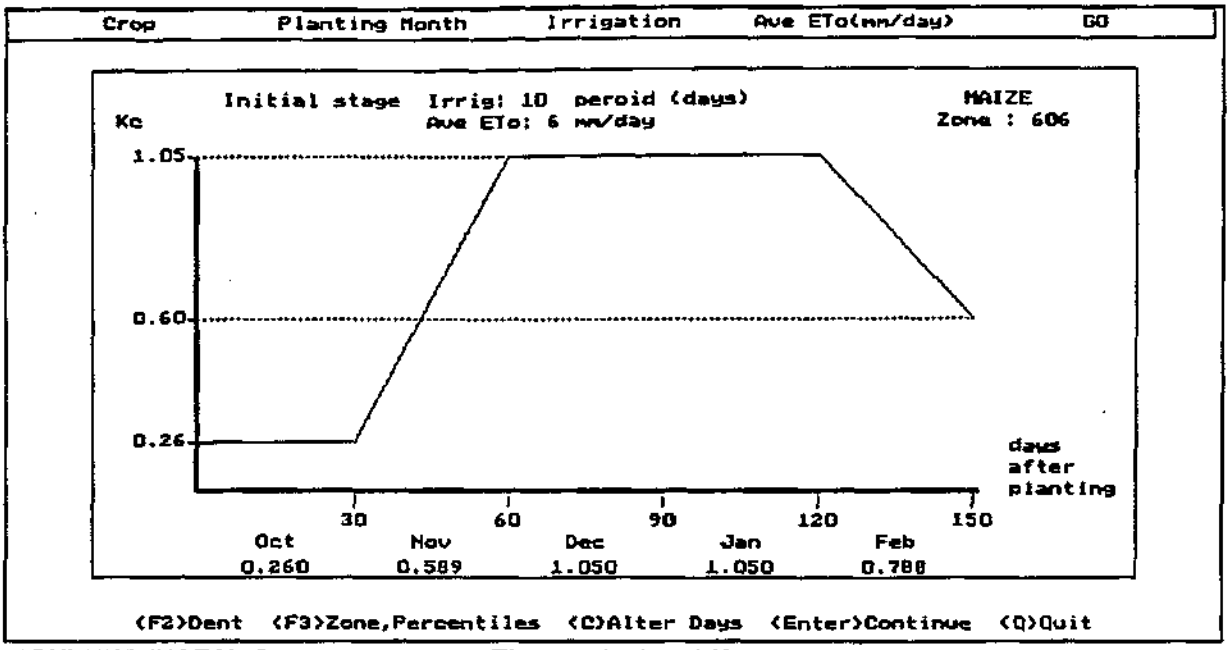
MONTHKC/NATAL Screen 9: **Total water and irrigation requirements, as calculated by NATAL, presented in tabular format.**



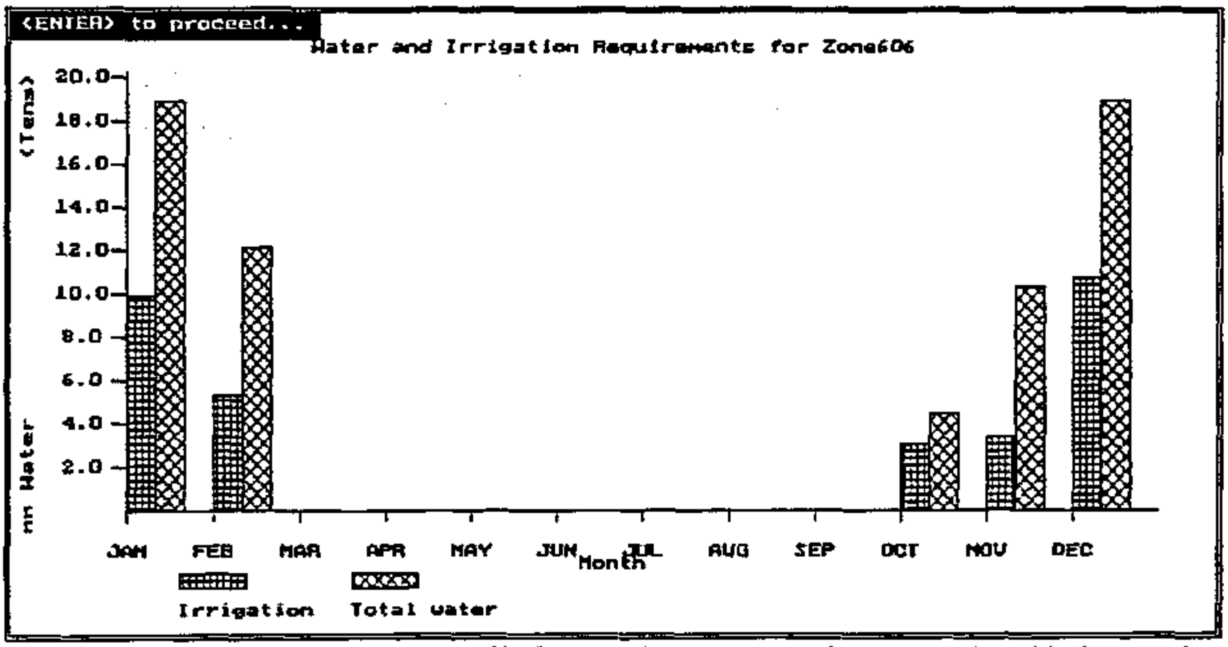
MONTHKC/NATAL Screen 10: Total water and irrigation requirements, as calculated by NATAL, presented graphically.



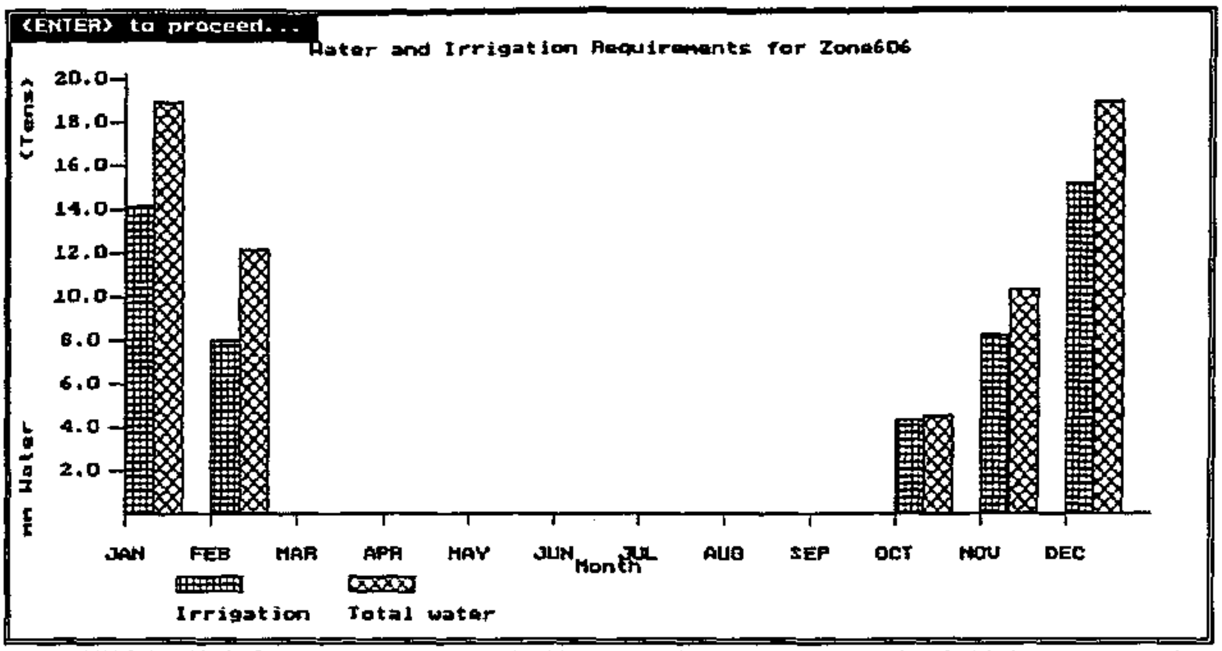
MONTHKC/NATAL Screen 11: Modification of the example (screen 6) to increase total growing period to 150 days.



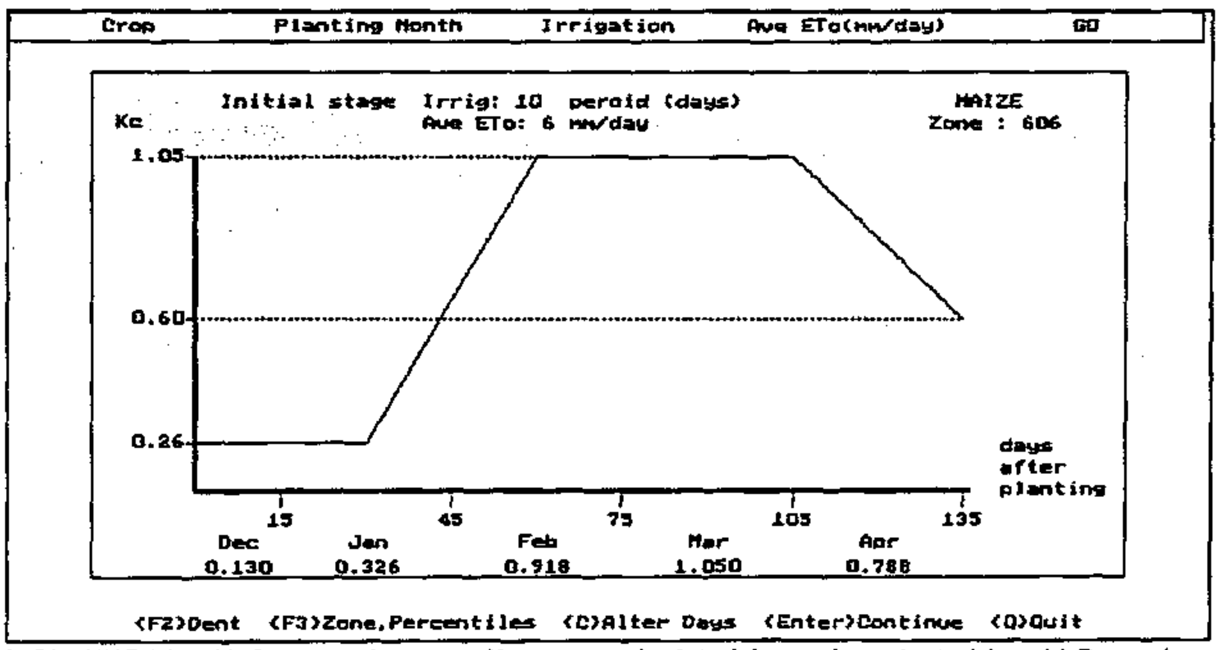
MONTHKC/NATAL Screen 12: The recalculated Kc curve.



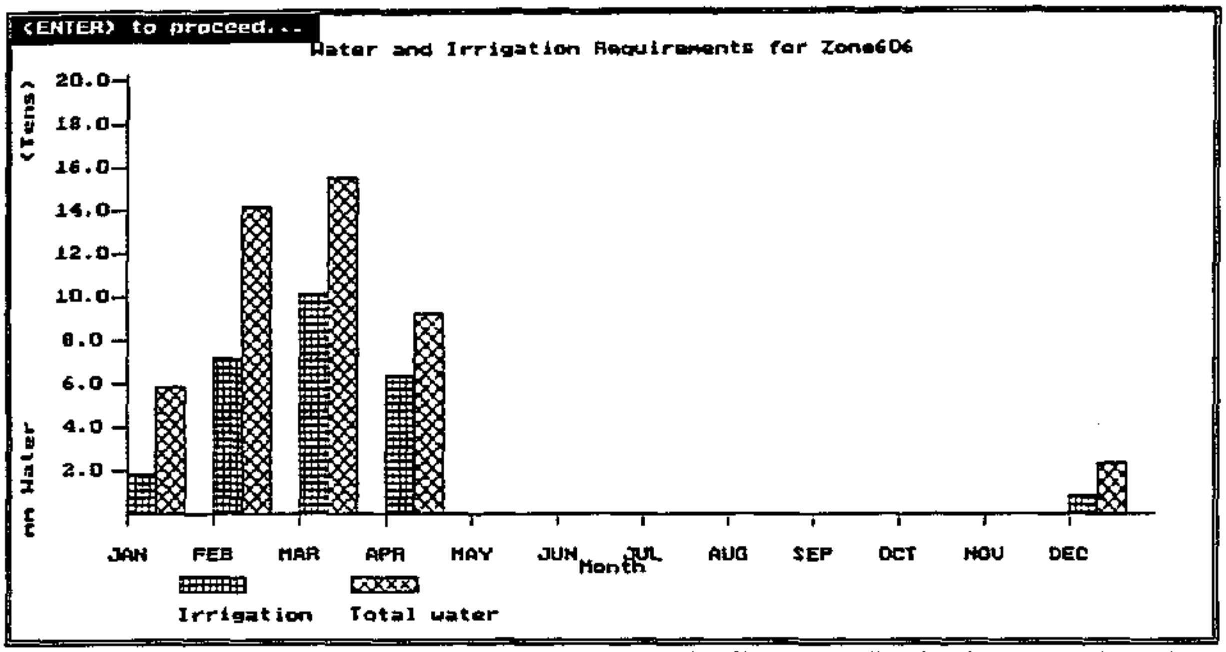
MONTHKC/NATAL Screen 13: NATAL results for the previous example, with the growing period extended to 150 days.



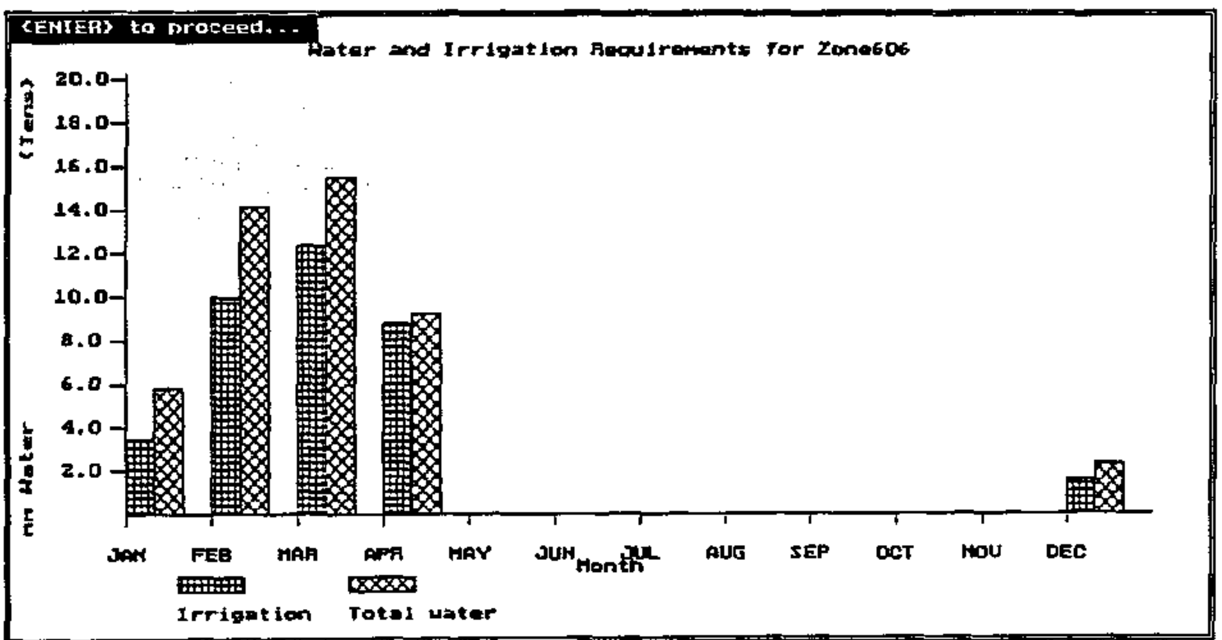
MONTHKC/NATAL Screen 14: NATAL results for Zone 606 (Loskop), Maize, 135 growing days, all percentiles set to "DRY". Note increased irrigation requirements.



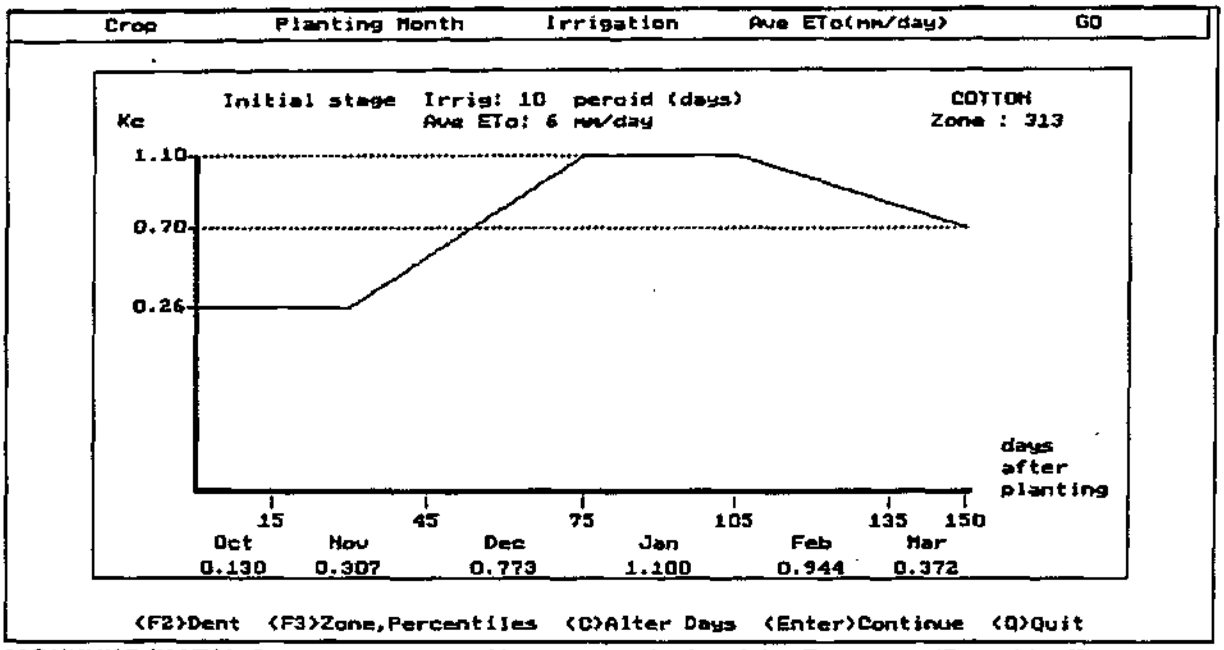
MONTHKC/NATAL Screen 15: Kc curve calculated for maize, planted in mid December, and growing for 135 days.



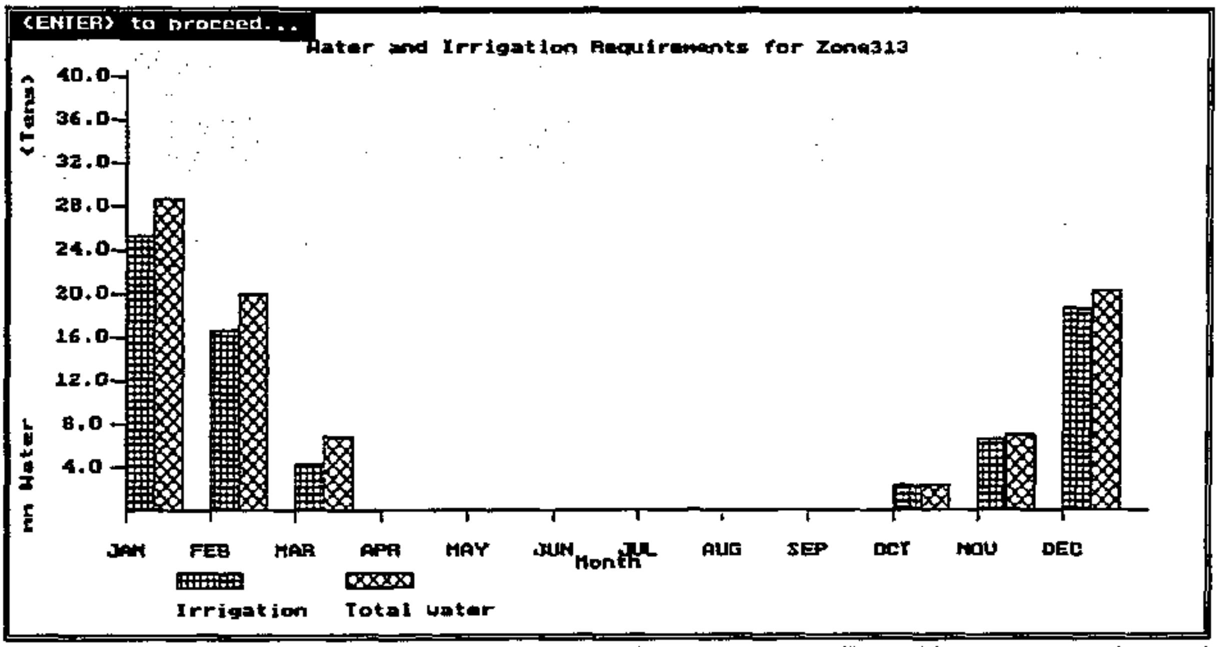
MONTHKC/NATAL Screen 16: NATAL results for Zone 606 (Loskop), maize planted 15 December, growing 135 days, with all percentiles set to "NORMAL".



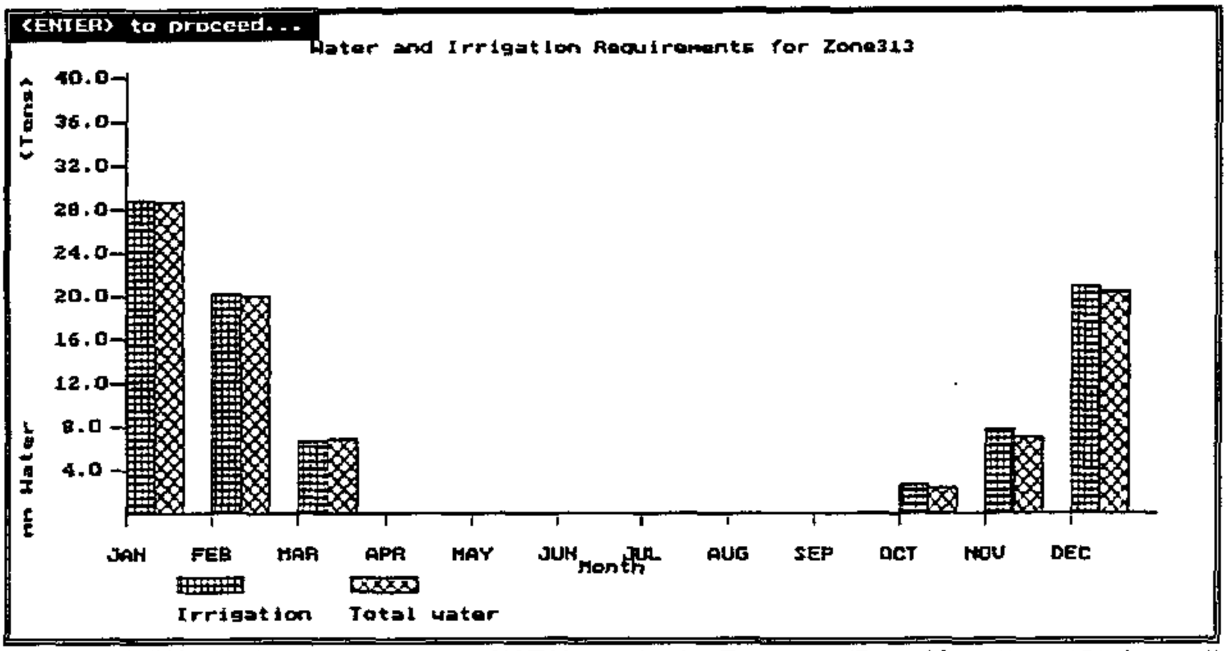
MONTHKC/NATAL Screen 17: NATAL results for Zone 606 (Loskop), maize planted 15 December, growing for 135 days, all percentiles set to "DRY".



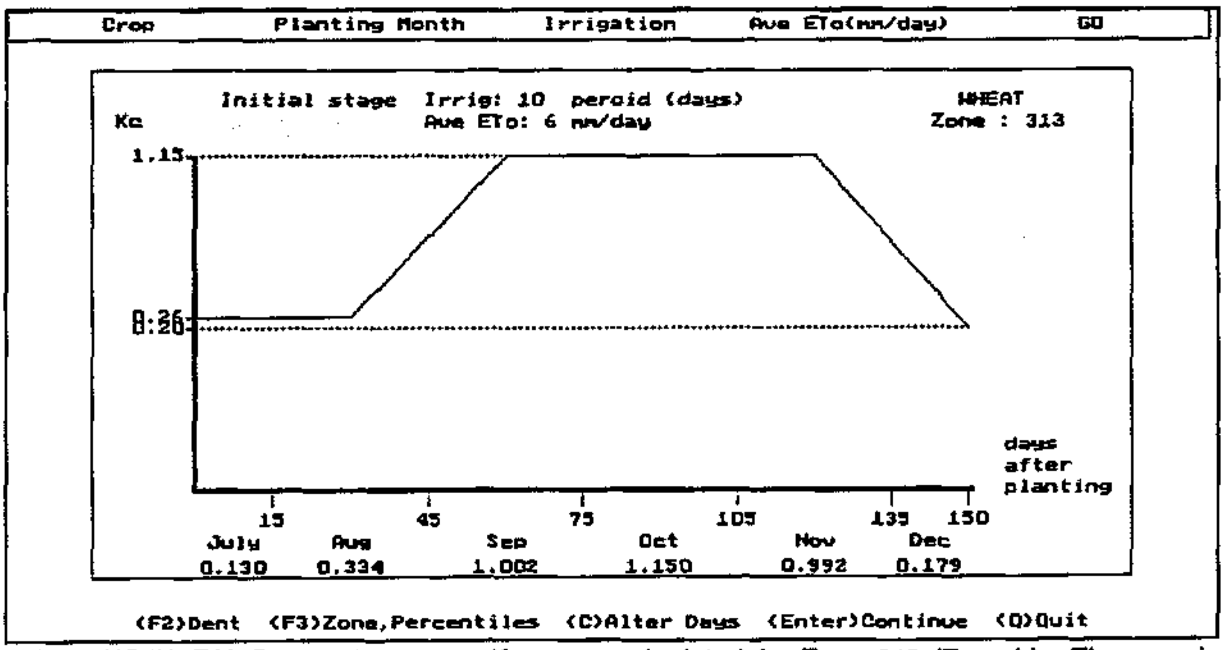
MONTHKC/NATAL Screen 18: Kc curve, calculated for Zone 313 (Ramah). The crop is cotton, planted on 15 October and growing for 150 days.



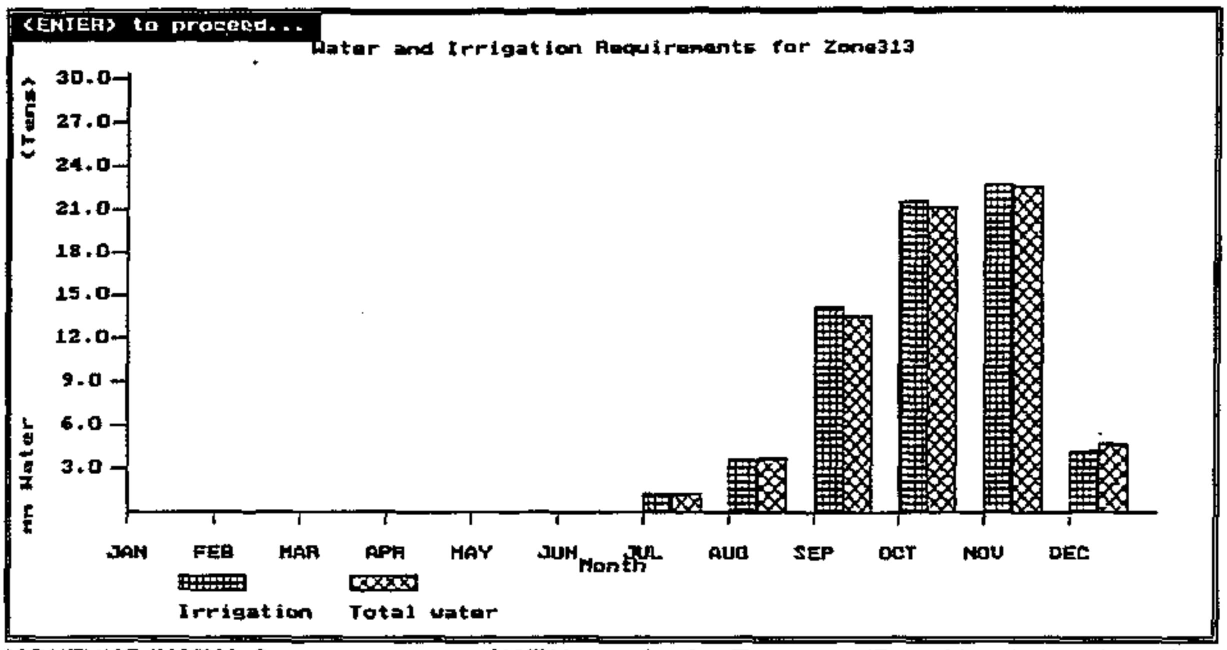
MONTHKC/NATAL Screen 19: NATAL results for Zone 313 (Ramah), cotton, 150 days, all percentiles set to "NORMAL".



MONTHKC/NATAL Screen 20: NATAL results for Zone 313 (Ramah), cotton, 150 days, all percentiles set to "DRY".



MONTHKC/NATAL Screen 21: Kc curve calculated for Zone 313 (Ramah). The crop is wheat, planted on 15 July, growing for 150 days.



MONTHKC/NATAL Screen 22: NATAL results for Zone 313 (Ramah), wheat, planted 15 July, growing time 150 days, all percentiles "NORMAL".

CHAPTER 8

PRE-PROGRAMMED IRRIGATION

8-1 INTRODUCTION

Pre-programmed irrigation has, until recently, received little attention in the RSA. The main emphasis is now moving away from fixed cycle irrigation to properly scheduled demand irrigation, which is based on the depletion of water in the soil profile to allowable levels. Pre-programmed irrigation, even if it is regarded as an interim measure, can be a step forward.

> The scheduling of irrigation by applying predetermined amounts at prescribed times or intervals, called prescheduled irrigation, is still the most widely used technique by South African irrigators. The technique is successful under low rainfall conditions, deep soils with plant available water capacity (PAWC) values higher than 80mm and crops that can control water loss under extreme conditions of evaporative demand. An example of this approach is the BEWAB computer program that calculates water application schedules for different crop-soil combinations and management options. (Bennie (1992))

It can be argued that programmed scheduling falls outside the scope of a decision support system targeted at estimating the water requirements of crops. Programmed scheduling is, however, very closely related to planning and design, and can be regarded as an extension of the first part of **SAPWAT**. **BEWAB** is such a good example of pre-scheduling on the one hand and of a straightforward pc program requiring minimal computer literacy on the other, that the latest version of **BEWAB**, which includes flood irrigation, has been included almost in its entirety in **SAPWAT**. The PAWC model routine based on full soil information has been omitted, as it is still undergoing further processing. **BEWAB** has been re-programmed in Turbo Pascal, which holds some advantages in the presentation and storage of output.

BEWAB was developed from the results of research undertaken in the Orange Free State and North-West Cape and is applicable to the crops, conditions and climate of the area. The crops in the menus are limited to those for which research results are available. The inherent structure of **BEWAB** has been extended to provide the same facility for any of the crops included in **SAPWAT**, and for the 712 zones. At this stage neither the "target yield" feature has been included in this extension to **BEWAB** (which assumes "full irrigation"), nor the provision of allowing for possible rain. Input for the extended **BEWAB** routine comes directly from **NATAL**.

8-2 IRRIGATION AND SOIL WATER

In the interests of clarity and to ensure that the full implications of the "new" way of thinking, which is an intrinsic component of **BEWAB** and the crop growth models, is appreciated, an outline of the "classic" approach and some of the less familiar concepts follows.

8-2-1 The generally applied approach

The approach to soil water in irrigation planning, which leads to some of the newer ideas is clearly set out in the introduction to the Green Book (1985) and is included here in a paraphrased form.

Field capacity (FC) is the water content of a soil profile which has been saturated with water and allowed to drain freely for 2 to 3 days. The water content at which water ceases to be available to plants is the permanent wilting point (WP). The difference in the quantity of water held in the root zone between FC and WP is known as plant available water (PAW). The relative availability of water to plants is not necessarily the same throughout the entire range of available water. Relative availability tends to decline rapidly once the soil water content is below a certain threshold value situated between FC (100% available water) and WP (0% available water).

Many factors can influence this threshold water content, but there is evidence to suggest that the threshold often coincides with 20% to 30% available water, i.e. a depletion of approximately 75% of available water. During periods of active growth, an upper limit of 50% depletion is usually considered a safe soil water regime which, for normal atmospheric conditions, will not cause a reduction in growth or limit production. During periods of either very low atmospheric demand, or of insensitivity to water stress, extraction of nearly all water may be allowed to take place, without any adverse effects on yield.

The designer will be called upon to select an appropriate irrigation application, called the design application, which may be governed by either a preferred method of irrigation (for instance a microjet system) or may be determined by the quantity of available water that the soil can store in the root zone. When the latter consideration applies, a good estimate of the available water capacity (the total available water per unit depth of soil) is required. The design application is obtained by multiplying the total available soil water per unit depth with the useful soil depth and taking that percentage of the product which represents the permissible depletion. Example:

$$\begin{aligned} \textit{Design application} &= (100mm/m) \times (0.9m) \times (\frac{50}{100}) \\ &= 45mm \end{aligned}$$

It is important to note that the design application is no more than a realistic estimate for a particular soil and crop during an active and important stage of growth.

8-2-2 The profile available water capacity (PAWC) approach

Understanding the pattern of water depletion that takes place when a growing crop extracts water from an irrigated profile, is useful in understanding irrigation management strategies. The PAWC concept is a development from the plant available water and allowable depletion procedure and represents the actual amount of water that plants can withdraw from the profile.

As an adjunct to their work on PAWC, Boedt and Laker (1985), Vanassche and Laker (1989) and Van Averbeke (1991) plotted soil water abstraction over time. The "triangular" pattern presented by the graphic presentations in figure 8-1 provides useful insights into the pattern of water abstraction.

Water is first extracted from the shallow soil layers and eventually the surface soil may be significantly drier than WP. This results in a "fan" effect with the "fan pivot" at the point of maximum extraction depth where the soil will still be at FC for the initial period.

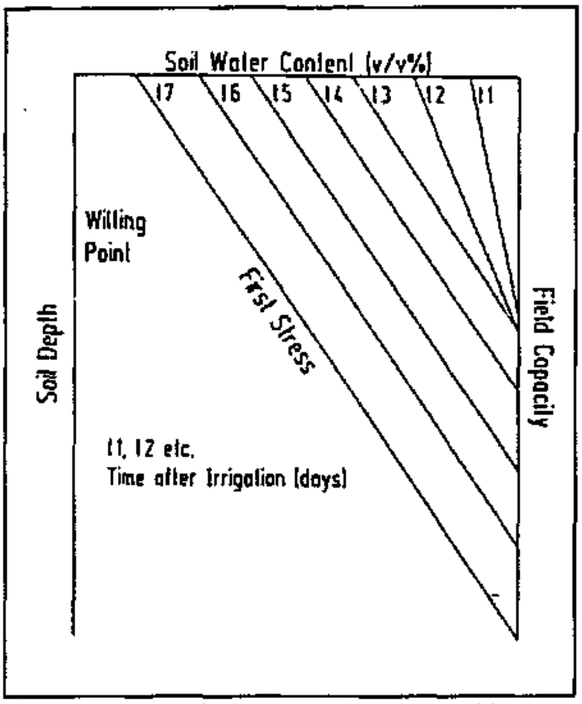


Figure 8-1 Soil water depletion with time, Boedt (1985).

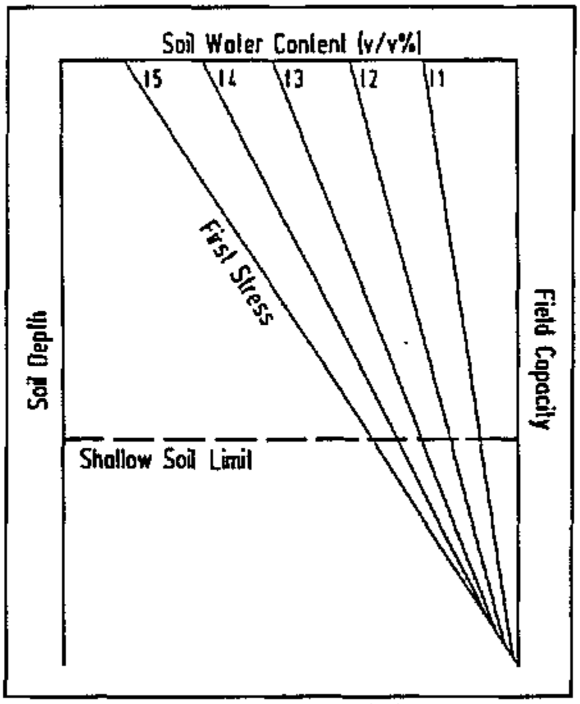


Figure 8-2 Soil water depletion shallow soil limit, Boedt (1985)

With further extraction, the line undergoes parallel displacement. This results in a progressively increasing depth from which soil water is extracted. Another pattern is the "fan" effect throughout the total rooting zone, from the start of the drying cycle onwards, as shown in figure 8-2. There is proportional extraction at all depths. In a shallow soil, the pivot of the fan is situated at an imaginary point below the lower boundary of the rooting zone.

The main reason for this "triangular" pattern is that root density decreases and total flow resistance increases with depth. In practice, there are wide variations in the water extraction patterns established by researchers. The physical characteristics of the soil horizons, compaction, clay layers, high water tables, as well as soil depth all influence the position of the "pivot" point, as do the rooting characteristics of the crop.

The main thrust of PAWC research has been to determine how much water a plant can extract before being subjected to stress which has a measurably adverse impact on yield. This point, known as first material stress (FMS), has been defined in various ways and much of the research has been devoted to determining how the onset of stress can be identified by measuring various physiological parameters.

The engineer and planner is less concerned with identifying the onset of stress (while it is certainly important to the researcher and scheduling advisor), but is concerned more with the impact of stress on crop water use in relation to scheduling strategies.

PAWC research has required the accurate measurement of soil water extraction with the neutron probe at depths that was not possible with augers. Sampling with augers seldom took place below 1.2 m, a depth previously associated with maximum practical root zone depth. Streutker (1991) commented that he could hardly credit the high PAWC values published, until he realised the implications of the greater sampling depths. ***Research has thus confirmed that crops draw water from depths considerably greater than is currently assumed by designers.***

8-2-3 Progressive depletion of soil water

It has been practice to assume that early season irrigations should keep pace with the demands of the juvenile crop and its relatively shallow rooting system. Bennie et al (1988) suggest maintaining a relatively full profile from early season to provide a reserve for the peak demand periods. Vanassche et al (1989) started drying cycles at various phenological stages and found that even when a cycle was started early in the season, the maize plant was capable of extracting a surprisingly large amount of water from a full profile.

Bennie et al (1988) has shown the importance of the soil reservoir in reducing the peak capacity requirements of irrigation equipment and supply systems. A soil with a measured PAWC of 200 mm has in fact the capacity to supplement peak requirements by 2mm per day for 100 days or 4mm per day for 50 days.

Martin et al (1990) support this approach:

> In arid and semi-arid areas, where rainfall is insignificant during the growing season, it is possible to compute a normal irrigation schedule based on average climatic data. In such areas, the variability of ET from year to year is small and may be neglected, thus it is feasible to predict normal irrigation dates and amounts for a specific soil/planting date combination.
>
> High frequency irrigation (usually 3 to 7 day intervals) is applicable to modern systems (centre pivot, micro, drip, solid set) that are capable of high uniformity and controlled amounts of water application. With high frequency irrigation, management allowed depletions or plant water stress thresholds become less important to Irrigation timing. High frequency irrigation of field crops can be applied either with full or partial ET replacement.
>
> The concept of partial ET replacement and high frequency irrigation is illustrated in figure 8-3. This regime typifies management of centre pivot systems with pumping capacities which are inadequate to replace mid-season ET rates. The root zone profile is maintained near field capacity early in the season, when pumping supply is adequate. In the period of inadequate capacity (illustrated from day 60 to 90), the crop water requirement is met by the successive partial ET replacements from irrigation, rainfall, and the depletion of stored soil water. In late season (shown from day 90), pumping capacity is adequate to supply irrigation at full ET replacement, however, the root zone deficit may not be reduced to a low depletion. High frequency irrigation maintains relatively high soil water contents in the upper root zone, where plant nutrients are usually in greater supply.

Interestingly enough the Soil Conservation Service in the USA (1982) advocate much the same regime:

> The use of light, frequent irrigation makes it practical to gradually deplete deep soil moisture during the peak use periods when the system capacity is inadequate to meet crop moisture withdrawal rates.
>
> Light, frequent watering of the topsoil, plus the gradual withdrawal of water from the subsoil, can produce optimum crop yield when the system capacity is limited. But when subsoil moisture is inadequate, light, frequent irrigation resulting in heavy moisture

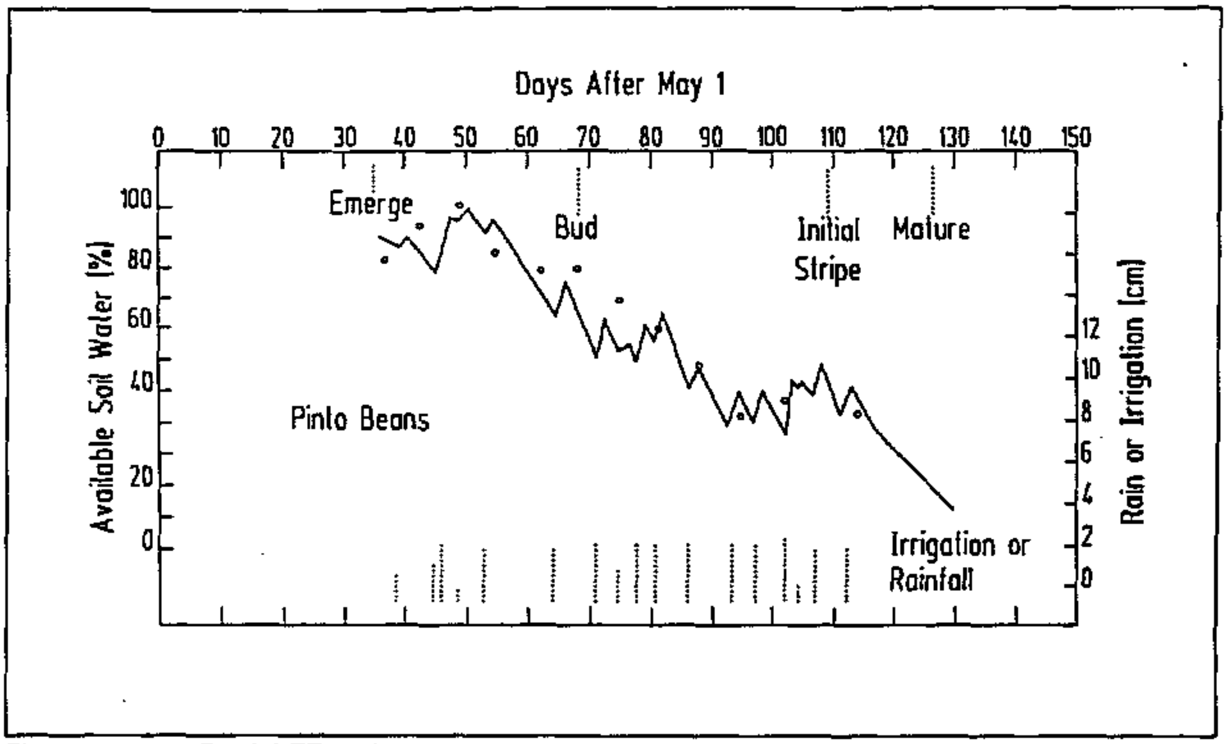


Figure 8-3 **Partial ET replacement.**

losses from evaporation may be an inefficient use of a limited supply of water and may also increase salinity. Under these circumstances, deeper less frequent irrigations may produce better yields.

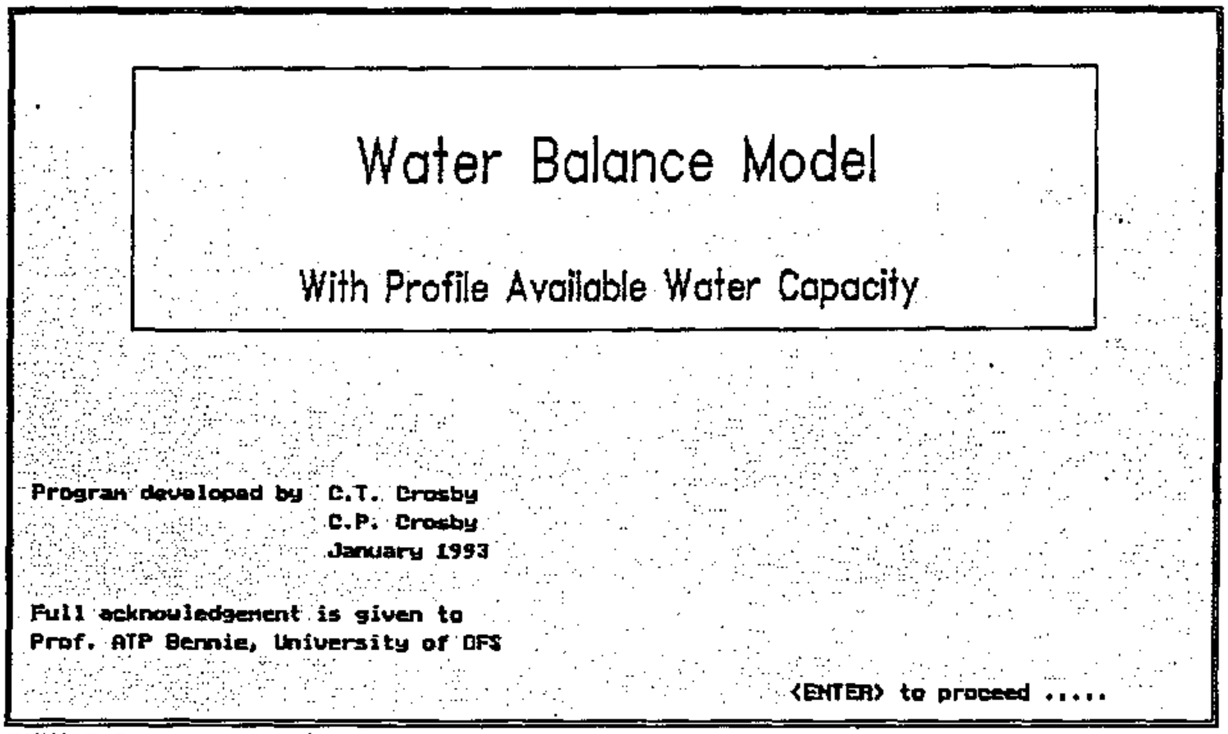
8-3 STANDARD BEWAB AND ITS APPLICATIONS

BEWAB (BEsproeiingsWAter Bestuursprogram) is in line with the concept of progressive soil water depletion outlined above. It offers the facility to programme for full or partial ET replacement and further provides for the soil profile at planting to be at 100%, 50% and 0% of PAWC (not PAW). The essence of the approach to partial ET replacement is the PAWC concept and extensive research was undertaken to determine PAWC values in the field. The seasonal distribution of plant water requirements is based on regressions derived from field water studies.

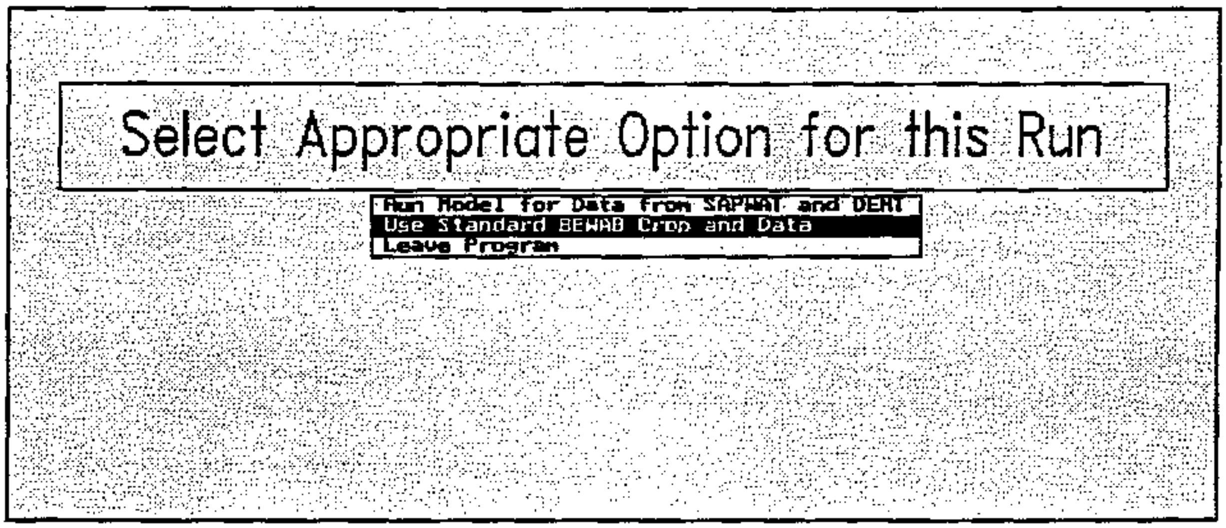
8-3-1 Example screens : standard BEWAB

The program **BEWAB** is a rewrite of Prof. ATP Bennie's program of the same name. However, the new **BEWAB** is written in Turbo Pascal, and most of the inputs menu-driven. This **BEWAB** can also make use of the water requirements calculated by **NATAL**, by means of the linking program **OFS**.

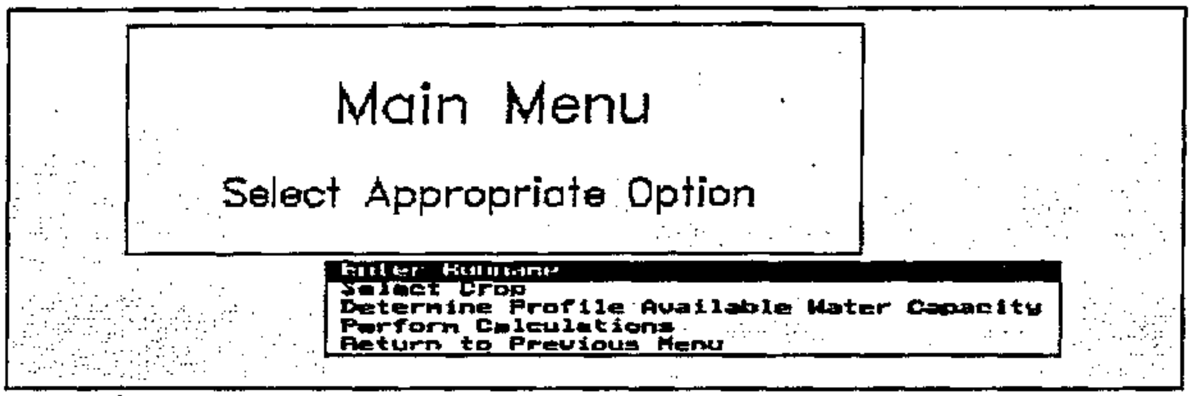
The first example is a standard **BEWAB** run for maize:



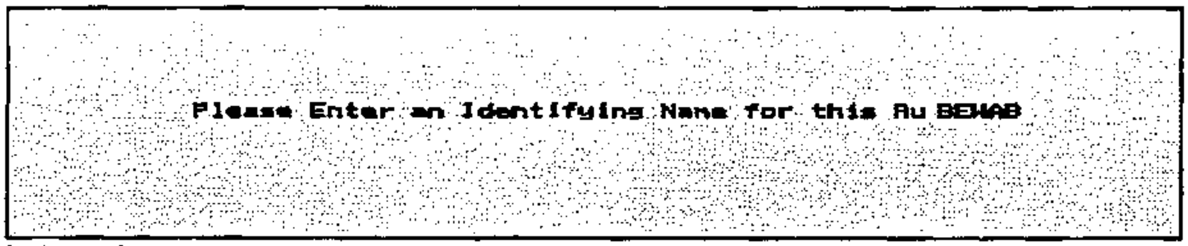
BEWAB Screen 1 : Header screen.



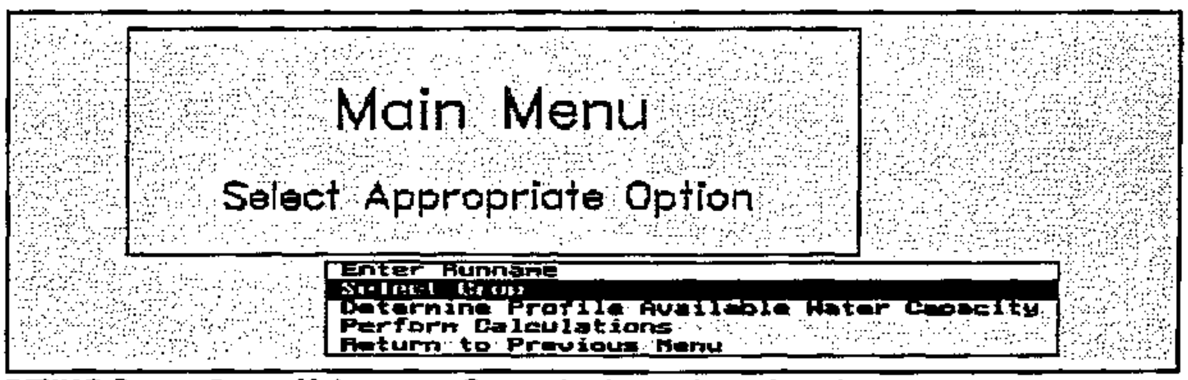
BEWAB Screen 2 : Select standard BEWAB, or make use of NATAL results.



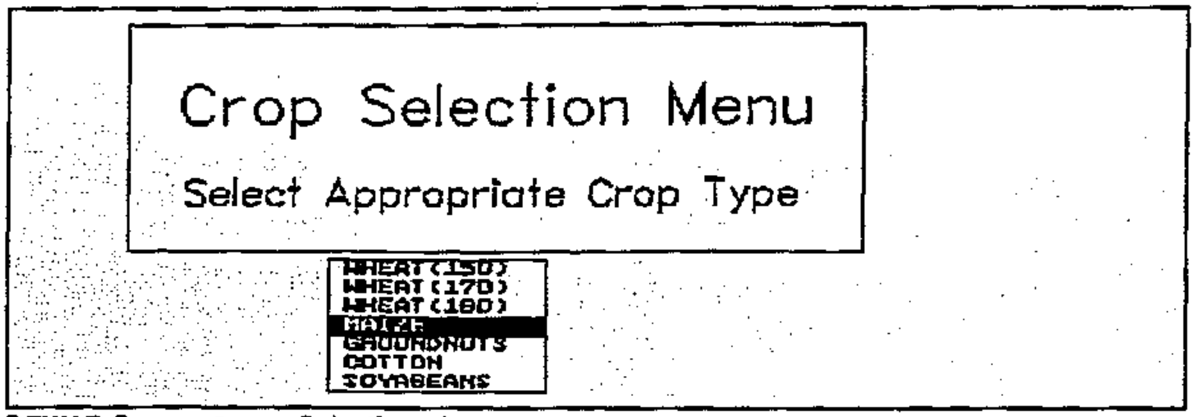
BEWAB Screen 3: Main menu. Input of run name selected.



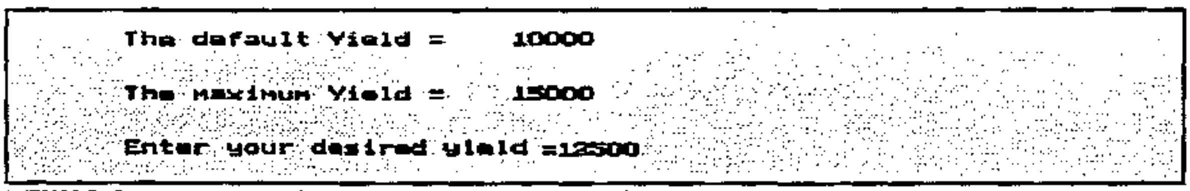
BEWAB Screen 4: Input of run name.



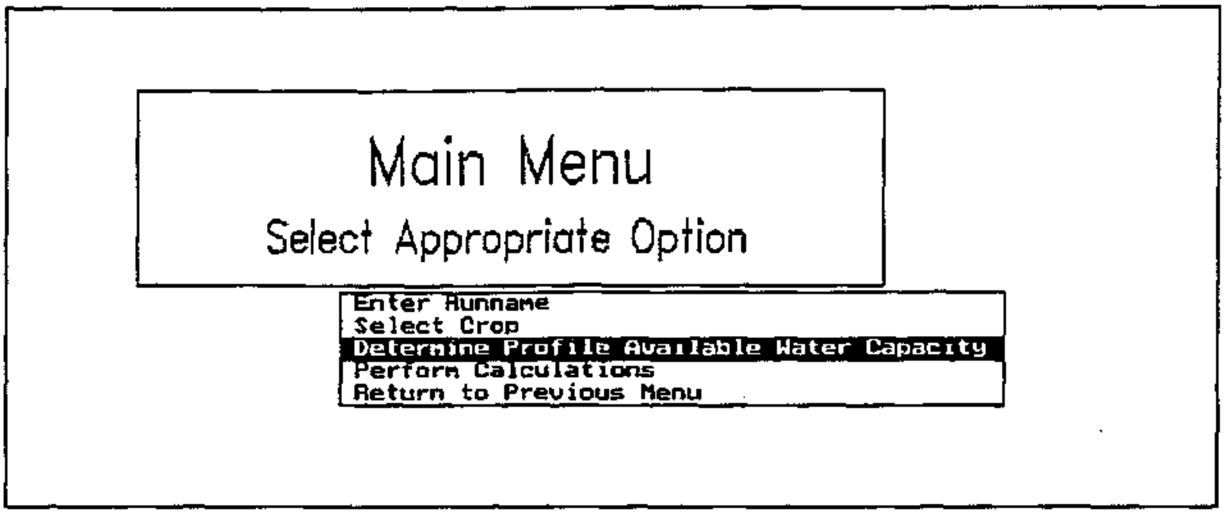
BEWAB Screen 5: Main menu. Crop selection option selected.



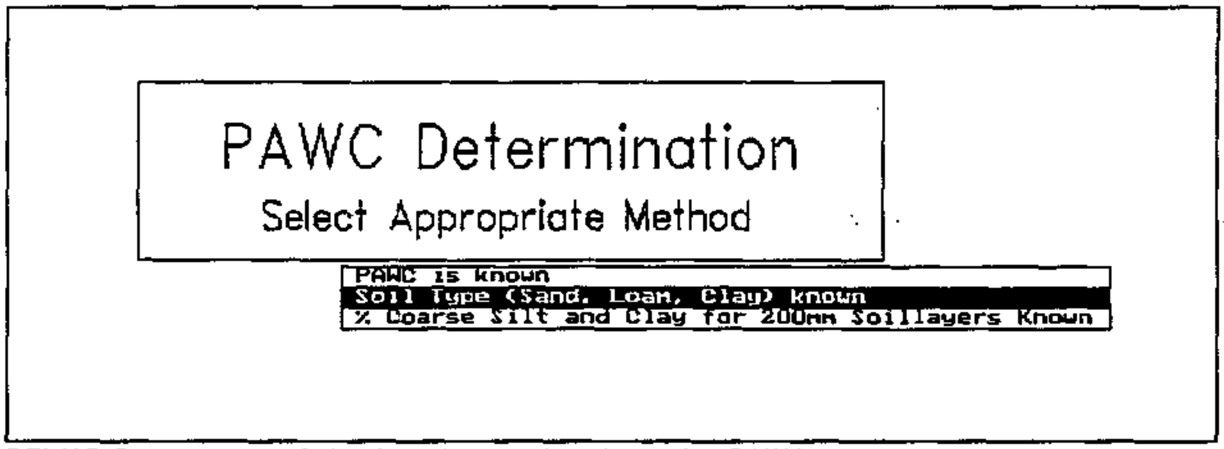
BEWAB Screen 6: Selection of crop.



BEWAB Screen 7: Input of desired yield level.



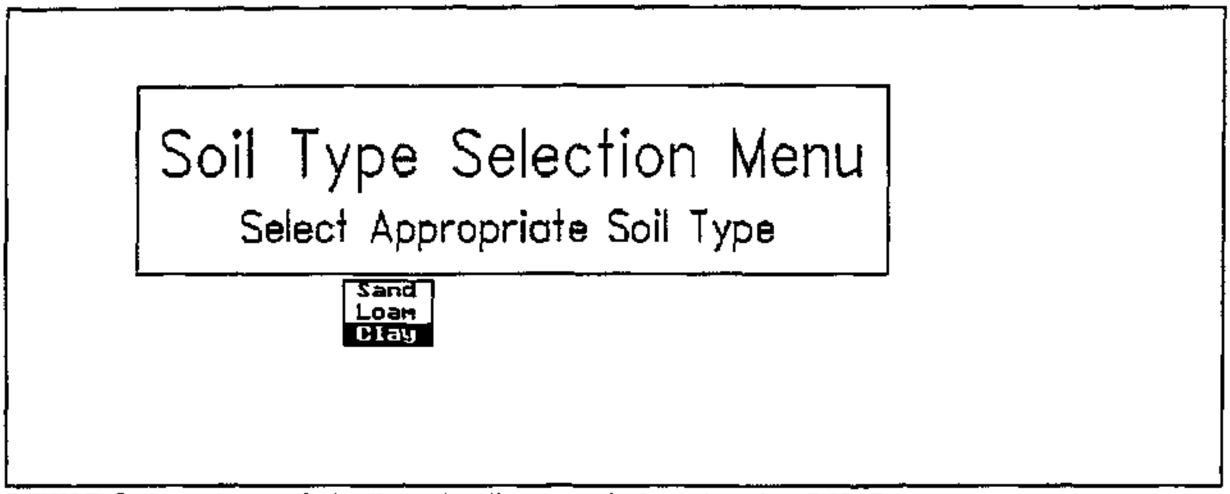
BEWAB Screen 8 : Main menu. Select PAWC determination.



BEWAB Screen 9 : Selection of method to determine PAWC.

Enter the Soil Depth in mm (Max 2000 mm) : 2000

BEWAB Screen 10: Entry of soil depth to help determine PAWC.

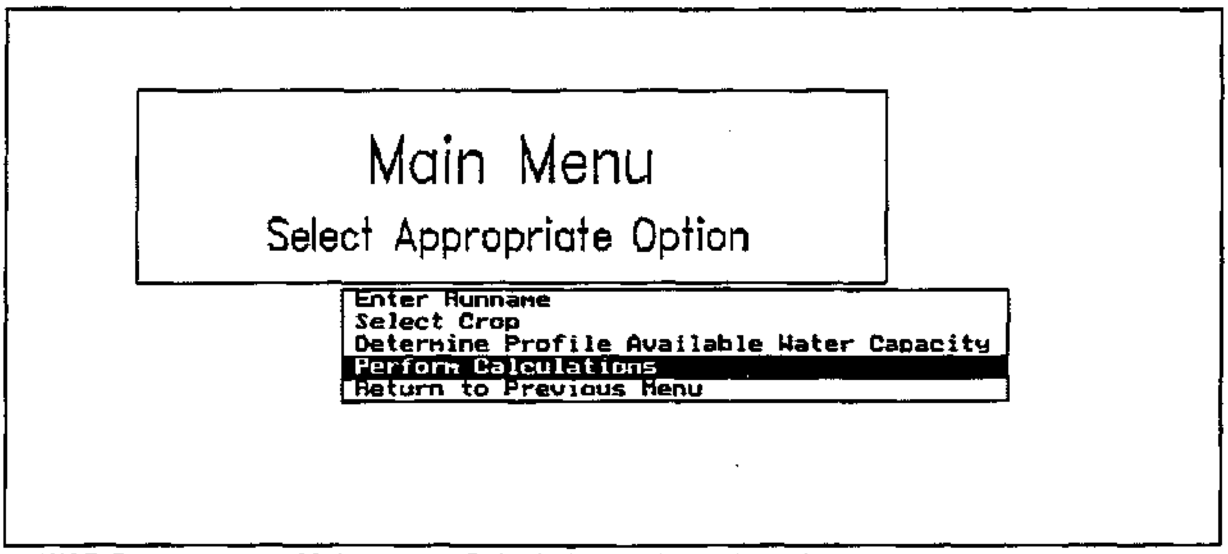


BEWAB Screen 11 : **Selection of soil type to help determine PAWC.**

An approximate guesstimate of the PAWC is 152 mm

<ENTER> to proceed ....

BEWAB Screen 12: **Result of the PAWC calculation.**



BEWAB Screen 13 : **Main menu. Calculation option selected.**

Enter the required irrigation cycle in days : 7

BEWAB Screen 14: Input of the required irrigation cycle.

Irrigation Method Selection Menu

Select Appropriate Irrigation Method

Sprinkle Irrigation
Flood Irrigation

BEWAB Screen 15 : Selection of irrigation method.

Select Appropriate Output Device

Screen
File
Printer

BEWAB Screen 16 : Selection of output device.

Identification: bewab1

Water application programme and minimum effective irrigation requirement
IR mm per cycle for MAIZE with a target yield of
12500kg/ha

Partial crop water requirement (CWR)
replenishment during peak consumption.
(Finish season with soil dry)

Days after planting	Full CWR replenishment during peak		Profile fully wet at planting		Profile partially wet at planting		Profile dry at planting	
	IR	total	IR	total	IR	total	IR	total
10	2	2	2	2	6	6	7	7
24	44	46	44	46	88	94	97	103
38	71	116	71	116	88	182	97	200
52	92	208	85	202	88	270	97	296
66	106	314	86	287	88	358	97	393
80	115	430	86	373	88	446	97	489
94	118	548	86	459	88	534	97	586
108	116	664	86	545	88	622	97	683
122	107	771	86	630	88	710	97	779
136	93	863	86	716	88	798	96	875

REMARKS

Profile available water capacity during peak consumption = 152mm
Any precipitation more than IR mm per rainfall should be disregarded
if the full replenishment option is being used.
Usable profile available water during peak consumption = 152mm
The irrigation system should be capable of delivering
8.4 mm/day for the full SWB replenishment option and
6.9 mm/day for the partial replenishment option.

BEWAB Screen 17: Output follows:

8-4 EXTENDED BEWAB AND ITS APPLICATIONS

Two facets of **BEWAB** are particularly important. One is the routine for modelling PAWC when field values or estimates are not available, and the other is the development of schedules which will ensure the storage of water early in the growing season, to augment irrigation capacity in mid-season when ET demand is high. **BEWAB** also provides options for profile water status at planting.

In addition to the original **BEWAB**, an extended version is included in the **SAPWAT** procedure which does not utilise the default crops, crop production curves, target yields or the relative crop water use curves built into **BEWAB**. Instead, any of the crops for which monthly crop coefficients are estimated by **MONTHKc** can be assessed for any of the zones. The monthly average total water requirements, as calculated by **NATAL**, are inputs into the **BEWAB** routines. A curve is fitted using these values, thus enabling **BEWAB** to produce a schedule of water applications and frequencies for the specific crop, zone and percentile combination.

8-4-1 Example screens : extended BEWAB

The following BEWAB runs were done for wheat and maize, where the water requirements had been calculated by MONTHKC and NATAL. All inputs are identical to the basic BEWAB, except that there is no crop selection menu, and no target yield input, as the total water requirement is established by NATAL.

Identification: Ramah_Wheat

Water application programme and minimum effective irrigation requirement
IR mm per cycle for WHEAT .

Partial crop water requirement (CWR)
replenishment during peak consumption.
(Finish season with soil dry)

Days after planting	Full CWR replenishment during peak		Profile fully wet at planting		Profile partially wet at planting		Profile dry at planting	
	IR	total	IR	total	IR	total	IR	total
10	1	1	1	3	1	3	4	4
17	5	6	5	6	22	25	28	32
24	6	12	6	12	22	47	28	60
31	8	20	8	20	22	69	28	88
38	12	31	12	31	22	91	28	116
45	15	47	15	47	22	113	28	144
52	20	67	20	67	22	135	28	172
59	25	92	25	92	22	157	28	200
66	30	121	30	121	22	179	28	228
73	34	156	33	155	28	208	31	259
80	39	195	33	188	33	241	33	292
87	42	237	33	221	33	274	33	325
94	45	282	33	254	33	307	33	358
101	47	330	33	287	33	340	33	391
108	48	377	33	320	33	374	33	424
115	47	424	33	354	33	407	33	458
122	44	468	33	387	33	440	33	491
129	39	507	33	420	33	473	33	524
136	32	540	32	452	32	505	32	556
143	23	563	23	475	23	528	23	579

REMARKS

Usable profile available water during peak consumption = 100mm
The irrigation system should be capable of delivering
6.8 mm/day for the full SWB replenishment option and
4.7 mm/day for the partial replenishment option.

BEWAB Screen 18: Output for wheat in Zone 313 (Ramah)

Identification: Loskop_Maize

Water application programme and minimum effective irrigation requirement IR mm per cycle for MAIZE .

Partial crop water requirement (CWR) replenishment during peak consumption. (Finish season with soil dry)

Days after planting	Full CWR replenishment during peak		Profile fully wet at planting		Profile partially wet at planting		Profile dry at planting	
	IR	total	IR	total	IR	total	IR	total
10	1	1	1	1	4	4	5	5
17	8	8	8	8	27	31	32	37
2	4	12	20	12	20	27	32	69
31	16	37	16	37	27	85	32	102
38	21	58	21	58	27	112	32	134
45	26	84	26	84	27	139	32	167
52	31	115	30	114	28	168	32	199
59	35	150	30	144	30	198	32	231
66	39	188	30	175	30	229	32	264
73	42	230	30	205	30	259	32	296
80	44	274	30	235	30	289	32	328
87	45	319	30	265	30	319	32	361
94	45	363	30	296	30	350	32	393
101	43	406	30	326	30	380	32	426
108	40	446	30	356	30	410	32	458
115	35	481	30	387	30	440	32	490
122	28	510	28	415	28	469	29	519
129	19	529	19	434	19	488	19	539

REMARKS

Profile available water capacity during peak consumption = 100mm
Any precipitation more than IR mm per rainfall should be disregarded if the full replenishment option is being used.
Usable profile available water during peak consumption = 100mm
The irrigation system should be capable of delivering
6.4 mm/day for the full SWB replenishment option and
4.6 mm/day for the partial replenishment option.

BEWAB Screen 19: Output for MAIZE in Zone 606 (Loskop)

CHAPTER 9

ADJUSTMENTS TO NETT CROP WATER REQUIREMENTS

9-1 INTRODUCTION

The nett values estimated using **SAPWAT** may require adjustment for local circumstances before the gross irrigation requirement is calculated. The FAO 24 recommendations dealing with advection are included here, but factors such as a high water table and salinity can also have a significant influence and should not be ignored.

9-2 ADVECTION INFLUENCES AND SIZE OF IRRIGATION DEVELOPMENT

Weather data used for design purposes may apply to periods of time before the establishment of irrigation schemes. Irrigated lands can produce a different micro-climate and ETcrop may not equal predicted values that are based on the available data. This is more pronounced for large schemes in arid and windy climates. In arid and semi-arid climates, irrigated fields surrounded by extensive dry fallow areas are subject to advection. An air mass moving into the irrigated fields gives up heat as it passes over the field. This results in a "clothesline" effect at the upwind edge and an "oasis" effect inside the irrigated field. With warm, dry winds, an appreciably higher ETcrop can be expected at the upwind edge of the field. This air then becomes cooler and more humid with increased distance over the irrigated land. This "clothesline" effect becomes negligible as distance from the field border increases. It follows that due to the "clothesline" effect, results of irrigation trials conducted on a patchwork of small fields and located in dry surroundings may show up to double the ETcrop as compared with that of future large schemes. Conversely, crop water use data obtained from a well established scheme, may have to be drastically modified if applied to new patchy fields in a developing area.

Due to the oasis effect, ETcrop will be higher in fields surrounded by dry fallow land as compared to that of fields surrounded by extensively vegetated land. However, air temperature is generally lower and humidity higher inside the large irrigated schemes as compared to outside the scheme. Therefore, when ETcrop is predicted using climatic data collected outside, or prior to irrigation development, ETcrop could be over-predicted by 5-15 % for fields of 5 to 20 hectares and 10-25 % for large schemes with cropping density, close to 100%. The main cause of this over-prediction due to cropping density is the distribution in fallow and cropped lands; above the fallow fields the air is heated and also becomes drier before moving into the next field. Figure 9-1 suggests the correction factors needed to obtain ETcrop for irrigated fields of various sizes, located in dry fallow surrounds in arid hot conditions and with moderate wind, when using climatic data collected outside or prior to irrigation development.

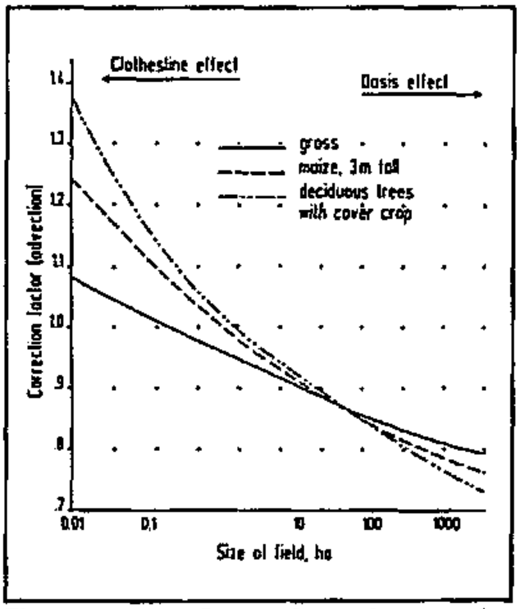


Figure 9-1 Correction factor for ETcrop. From FAO 24.

CHAPTER 10

CROP WATER: YIELD FUNCTIONS

10-1 INTRODUCTION

Crop water: yield curves are not normally used in design, planning or scheduling, but they can be useful in a decision support system. There is a relationship between the yield of a crop and its water consumption. In its simplest form, when only transpiration is taken into consideration, this approximates to a linear relationship. Under irrigation, where soil evaporation, runoff and deep percolation have to be taken into account, the relationship will no longer be linear and variations can be expected from one season to the next.

Despite these limitations if, crop water:yield curves that have been developed under practical irrigation conditions are available for an area, they are a valuable cross-check to seasonal water requirements of crops. In arriving at estimates of irrigation requirements, it is necessary to remember that this water may be obtained from rain and soil reserves in addition to irrigation. Crop water:yield functions have been developed in the RSA and have their origin in analyses of the experimental results of agronomic experiments, where irrigation applications and yield have been measured. These functions are useful in that they provide a broad indication as to whether yields and irrigation requirements estimated in an area are in line with what can be expected on a well-managed farm. In this respect, they conform at least to the levels of accuracy achieved in applying planning procedures, based on average monthly evaporative demand and crop coefficients.

10-2 CROP-WATER FUNCTIONS AS AN AID TO JUDGEMENT

A typical example of cross-checking are some estimates done for Kroondal to compare **SAPWAT** values to those of the Green Book (1985). This should be regarded as an example of the methodology only as the actual values estimated are suspect. As explained in Chapter 7, the present reference evaporation used in **SAPWAT** is based on "short grass" and is derived from **PMBWAT** A-pan based reference evaporation by applying a correction factor of 500/700 in the Linacre (1977) equation. This is only a rough approximation. In addition, there may be discrepancies in planting dates and season lengths, which could have a considerable influence on crop water use. In addition, the straight line relationships depicted in Figure 10-1 are controversial.

Early maize at Kroondal had a nett water requirement of 626mm as calculated by **SAPWAT**, while the Green Book gives a value of 859mm. Checking the yields shows that the **SAPWAT** figure would imply a yield of 9 ton/ha, which seems reasonable.

The **SAPWAT** requirement for groundnuts is 540mm, which is close to the Green Book value of 566mm, and the yield at 2 ton/ha is low, but realistic.

Wheat, according to the **SAPWAT** calculation, only required 370mm of water, which implies a yield of 4 ton/ha and appears to underestimate the value. The Green Book's value of 520mm (6 ton/ha) seems more reasonable.

The figures in this example should not be taken as being representative, for reasons already explained,

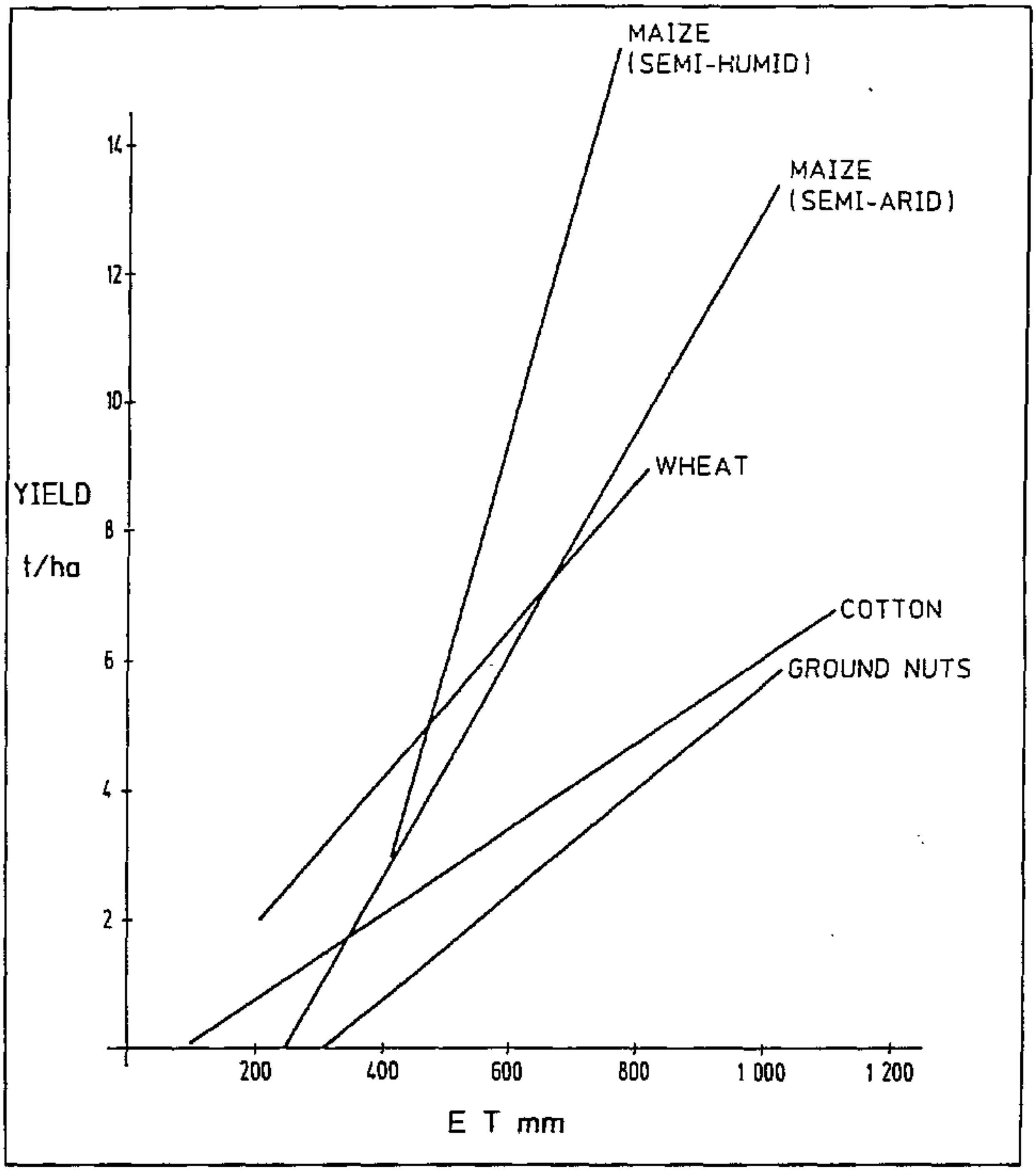


Figure 10-1 : **Crop water use versus yield functions for various crops.**

but they do stress the importance of local knowledge and experience in developing guidelines for irrigation. All available inputs can aid judgement and the crop water : yield functions can provide valuable additional insight into water requirements.

It has yet to be decided if the available curves (such as those in Figure 10-1) should be directly included in **SAPWAT**, but the concept of using them to further judgement when estimating crop water requirements, should not be ignored.

CHAPTER 11

SCHEME WATER REQUIREMENTS

No standard procedures are available locally to facilitate the estimation of monthly water requirements on a scheme, where the the mix of crops, areas planted and planting dates can be varied. Some planners utilise spreadsheets for this purpose, but in **SAPWAT** the program **SCHEME** caters for this requirement.

One of the output options offered on the **NATAL** screen, which tabulates total water and irrigation requirements, is "S" for Scheme. This writes the irrigation requirements, resulting from the runs done for each of the crops and fields on a scheme, to a file where they are consolidated. The user is asked to enter the name of the scheme, the field number and field area. Output is in the form of a table, which provides monthly irrigation requirements in cubic metres for each field and month, with the corresponding annual totals.

Total Water and Irrigation Requirements for Zone 606

Month		Irrig Req(mm)	Total Req(mm)
JAN		89	175
FEB		20	52
MAR		0	0
APR		0	0
MAY		0	0
JUN		0	0
JUL		0	0
AUG		0	0
SEP		0	0
OCT		31	45
NOV		35	103
DEC		107	189
Totals :	282	565	

"P" = Print "F" = Save in file "G" = Graph "S" = Scheme "Q" = Quit

MONTHKC/NATAL Screen 9: Total water and irrigation requirements, as calculated by NATAL, presented in tabular format.

On the selection of "S" the following prompts appear:

Enter acc. water requirement file name without extension:
PLAAS606

SCHEME Screen 1: Filename

Enter Field Number: 1

SCHEME Screen 2: Field number

Enter Field Size in Hectares: 55

SCHEME Screen 3: Field size

View Irrigation Requirement Files

By selecting the file from the following list

COAST.ACC
BRITS.ACC
EMPM.ACC
LOSKOP.ACC
DUMMY.ACC
606MZOCT.ACC
FARM606.ACC
PLAAS606.ACC
Leave Program

SCHEME Screen 4: Select scheme

Total accumulated irrigation requirements (m^3) /1000

Fld	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
1	49	11	0	0	0	0	0	0	0	17	19	59	155
2	20	21	15	0	0	0	0	0	0	0	6	9	71
3	0	0	0	0	0	0	5	106	182	185	40	0	567
4	32	18	0	0	0	0	0	0	20	26	32	41	169
5	0	0	7	18	37	32	13	0	0	0	0	0	107
Tot	101	50	22	18	37	32	67	106	202	228	97	109	1069

"F" = Save in a file "P" = Print "G" = Display results graphically "Q" = Quit

SCHEME Screen 5: Annual irrigation requirements

CHAPTER 12

GROSS IRRIGATION REQUIREMENTS

12-1 INTRODUCTION

Procedures for the estimation of actual crop irrigation requirements focus on establishing nett values, but it is the gross requirement that is needed in planning and design. The normal procedure is to convert nett to gross values by applying an irrigation application efficiency factor, which takes losses into account.

Possibly the best general discussion of the relationship between nett and gross requirements is contained in English et al (1986) and is summarised here:

> Figure 12-1 shows two functions that relate water use to crop yield. The linear function represents the relationship beween evapotranspiration and yield. The curvilinear function relates gross water use (i.e. the sum of precipitation and irrigation) to yield.
>
> Initially, when water applications are light, the two functions will nearly coincide, because small amounts of irrigation water can be captured and retained within the root zone and utilised efficiently by the crop. The small gap between the functions will represent primarily spray losses due to evaporation and wind drift. However, as irrigation applications increase, the two functions will diverge.
>
> This divergence is due to spray losses, surface runoff, deep percolation and increased evaporation from wet surfaces. The horisontal spread between the gross water use function and the ET function, can be viewed as a measure of the inefficiency of the irrigation system.

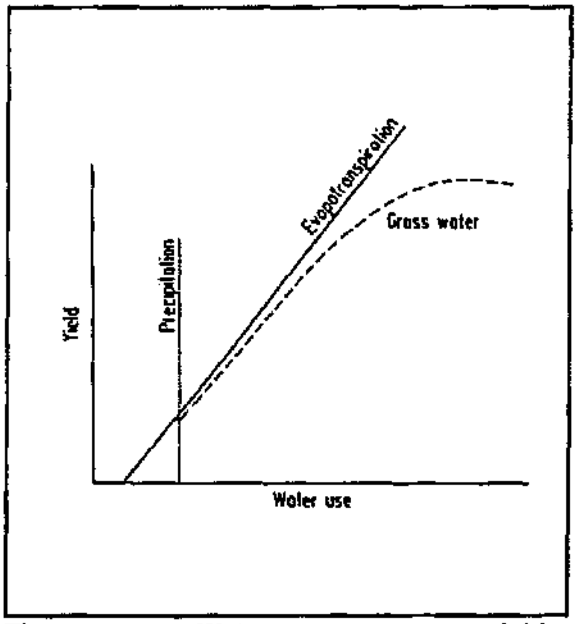


Figure 12-1 Water use versus crop yield

> Overall irrigation efficiency declines rapidly as the yield-maximising level is approached. To achieve maximum yields, it is necessary to irrigate more frequently and to over-irrigate some areas of the field in order to gain the last increment of attainable yield in other areas of the field. This combination of heavier and more frequent irrigations tends to increase water losses, i.e. irrigation efficiency decreases as yields approach the maximum attainable level.

It is important to keep in mind that the water production function shown in the figure is not unique. While relationships between ET and yield that are more or less constant for a given crop, can be derived, the shape of the gross water use curve will vary. Differences in soil characteristics, changes in irrigation systems, variations in irrigation management practices and changing weather patterns will result in widely varying efficiencies.

To understand the practical implications, suppose, for example, that it were possible to determine the average depletion in a field, and that an irrigation system delivered exactly that amount of water to the field. Even if the amount supplied was exact and applied at a low enough rate to avoid runoff, the variability of soil moisture conditions and the non-uniformity of application would cause a part of the applied water to be lost to deep percolation. Figure 12-2 illustrates the problem. Here 105 mm is applied to a field with an average depletion of 110 mm. Although the calculated efficiency would exceed 100%, only 90% of the applied water is useful to the crop.

When irrigation water use is less than the maximum crop water requirement, the existing approximations for application efficiency are too conservative. The model, **IEM** (Irrigation Efficiency Model), developed by English et al (1986), can make an important contribution to establishing realistic values for application efficiencies. This would enable the extending of FAO 24, FAO 33, **CROPWAT** and **BEWAB** to include the conversion from nett to gross irrigation requirement. **IEM** is still not fully operational as a computer program, but when finally released could be an important tool in the RSA, where more attention should be paid to limited and deficit irrigation.

12-2 ESTIMATING APPLICATION EFFICIENCY

As an interim measure, present estimates can be improved by applying a statistical approach developed by Clemmens (1992). All irrigation methods are inherently non-uniform in their application of water and if an abundant supply of water is available and pumping costs reasonable, the usual approach is to apply more water than is needed on average, thus ensuring that all parts of the field receive an adequate amount. Where water is more scarce or pumping costs are considerable, a reduced amount of water is applied. This implies that some portions of the land may receive less water than the amount stipulated by the nett crop water requirement calculations. The farm manager is faced with a trade-off between the amount of water applied and the amount of deficit.

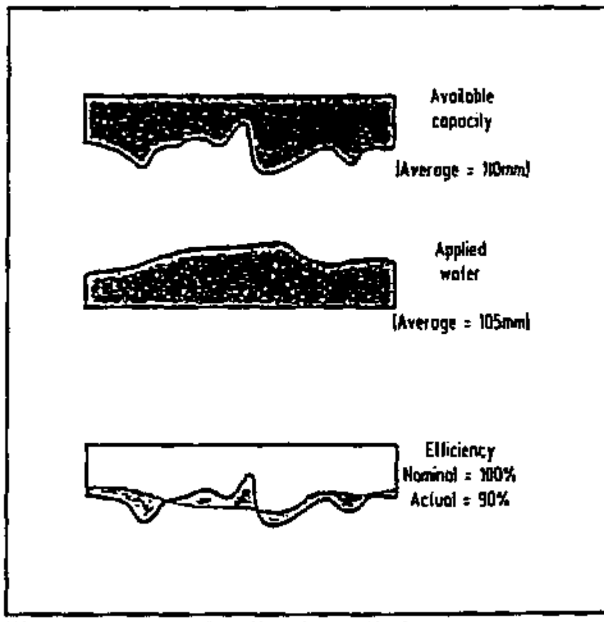


Figure 12-2 Application efficiency

This can be expressed as irrigation adequacy (IA), which is the percentage of the total land area which is refilled to field capacity during an irrigation. If the water applied is approximately equal to the nett irrigation requirement, then half the land area will receive more water than is required, while the other half will receive less. The irrigation adequacy will thus be 50%.

In the over-irrigated areas water will be lost to deep percolation, and this quantity essentially determines application efficiency. The profile will receive the full target amount of water, so that the storage efficiency will be 100%.

In the dry parts there will be no deep percolation (boosting application efficiency) but the profile will store less than the target amount of water, resulting in reduced storage efficiency and consequently a reduction in yield.

Where near maximum yield is the objective, a 50% irrigation adequacy is not considered acceptable. The SCS in the USA specify that the driest 25% of the field should receive an average application equal to the nominal crop water requirement. This implies that 87.5% of the land will receive the full water requirement, or more, while only 12.5% will be under-irrigated. Irrigation adequacy is then 87,5% and storage efficiency will be almost 100%, ensuring near maximum yield. Unfortunately, there will be considerable water lost to deep percolation and thus a low application efficiency.

In RSA practice, for all but flood irrigation, the coefficient of uniformity (CU) of the irrigation system is not taken into consideration. The assumption is that CU is reasonable, and irrigation adequacy is approximately 50%. This is now being considered good practice in the USA, as water savings far outweigh yield losses. Typically, when irrigation adequacy is increased from 50% to 90%, application efficiency drops from 92% to 73%, while storage efficiency improves from 92% to virtually 100%. ***In practical terms this means that the sacrifice of 8% yield can mean a saving of 20% in irrigation.***

Thus, as a consequence of the design approach adopted in the RSA, where 50% irrigation adequacy is approximated, it follows that a limited degree of deficit irrigation is, in fact, standard practice.

12-3 FROM NETT TO GROSS

The application efficiencies used for converting from nett to gross values usually follow the standard recommendations for specific areas and irrigation methods. Efficiencies specified by Lategan (1992) for the Western Cape and those recently published in the USA (ASAE 1990) are as in table 12-1. The local values appear to be well within range for design purposes, bearing in mind that in the USA higher irrigation adequacies are assumed. We have seen that the assumption of high application efficiencies carries a relatively low irrigation storage efficiency penalty, in fact English et al (1990) maintain that if high application efficiencies are assumed, they are in fact achieved.

At this stage, there is merit in accepting the "standard" application efficiencies for routine design, but

Type of Irrigation	Lategan	USA
Drip	85%	65-90%
Micro, Permanent set sprinkle & Pivot	80%	60-85%
Siderolls & Semi-permanent sprinkle	70%	60-80%
Flood	60%	50-80%

Table 12-1 Application efficiencies for various types of irrigation schemes.

there are circumstances where this can be counter-productive. The special case where crop water use is less than nominal crop water requirement, is discussed elsewhere. In order to assist planners and designers to develop a better feel for irrigation adequacy, application efficiency and storage efficiency, a computer program **GROSS** based on Clemmens (1991), has been developed. Inputs are the coefficient of variation (CV), estimated wind and runoff losses and type of irrigation employed. Output is in the form of a table which provides application efficiency and storage deficiency for a range of irrigation adequacies. This program is suitable for all irrigation methods except flood and one of its main uses is the evaluation of "standard" recommended values. It helps to answer questions such as whether the recommended value for application efficiency is in line with known spray losses; if it represents a low CU value or very variable soils and what irrigation adequacy has been tacitly assumed. Default values for the coefficient of variation (CV) values are provided and can be edited. The routine incorporates a method for estimating spray losses under pivots based on Van der Ryst (1991).

12-3-1 Example outputs and editing

The following are screens from the program **GROSS**. Editing of default Cd and wind loss values is possible.

Type Irrig.		Cd(%)	Wind loss(%)
1.	Sprinkle	25	15
2.	Pivot	20	10
3.	Micro	18	5
4.	Drip	15	0
5.	Other	0	0

Enter a number for type of irrigation or <E> to edit values

GROSS Screen 1: Input

Type of irrigation : Sprinkle

Coefficient of Variation : 0.25 Wind Losses : 0.15

Fraction adequately irrigated area:	Application Efficiency:	Storage Deficiency:
0.50	0.77	0.100
0.55	0.75	0.087
0.60	0.74	0.076
0.65	0.72	0.065
0.70	0.70	0.055
0.75	0.68	0.045
0.80	0.65	0.035
0.85	0.61	0.026
0.90	0.57	0.017

<Enter> to continue <Q> to quit

GROSS Screen 2: Output

12-4 SPRAY AND RELATED LOSSES

The direct losses, other than deep percolation, that must be taken into account when estimating application efficiency, include spray losses, runoff and interception. Van der Ryst (1991) came to the conclusion that in the case of pivots over-all spray losses were in the order of 10%, half evaporation losses and half spray drift. Losses could be estimated by the following regression equation:

$$\text{Percentage spray loss} = 2[8{,}34 + 0{,}1066S - 0{,}2182A]$$

where

S = Wind speed in m/s

A = Individual application in mm

Losses with conventional sprinkler systems were higher. The generally accepted USA nomographs tend to underestimate losses for centre pivots.

Runoff presents a problem, in that it is assumed that rate of application is such that there will be no runoff. This may or may not be true in practice, where severe crusting can account for significant reduction in application efficiency and under-irrigation of the crop at peak periods. Design and planning assumptions normally neglect runoff, although water balance calculations disclose it where there is excessive irrigation resulting from a fixed irrigation regime, or when the soil profile cannot absorb surplus precipitation.

One controversial aspect is whether interception should be regarded as a loss. Kanemasu et al (1982) reported on research done on pivots in Kansas:

> If the evaporation rate from an unwetted canopy is defined as being 100% efficient, then evaporation from a wetted canopy at a higher rate can be regarded as inefficient. Any water which evaporates from a sprinkled canopy at a rate greater than that which would occur for an unwetted canopy, can be defined as a nett plant interception loss.
>
> Sprinkling a well-watered, healthy, transpiring corn crop will have a minimal effect on ET rates and little additional water will be lost compared to an unsprinkled crop. The warmer the temperature, the less the difference in ET for wetted and dry canopies.
>
> Nighttime irrigation has often been recommended, because it reduces spray losses, but adopting this practice could result in nett plant interception losses of as high as 6% of the pumped water. Only about 2% of pumped water may be a nett interception loss under daytime conditions.

12-5 DISTRIBUTION LOSSES

There is a tendency to brush aside as inevitable the losses that occur between the water source and the side of the land. These losses can make a mockery of the attention given to the nett irrigation requirements of crops in the planning and design of irrigation schemes. In a classic ICID World-wide study, Bos and Nugteren (1982) revealed the complexity of the factors that influence overall project water use efficiency. Interestingly enough, in the areas broadly similar to the RSA, average application efficiency for border (flood) irrigation was 57% and for sprinkler of all types 68%. Presumably the irrigation adequacy was quite realistic.

Irrigation system efficiency, that is the combined effect of losses in canals and on-farm distribution, but excluding application losses, was related amongst other factors to the size of the irrigation scheme. The optimum size lay between 3 000 and 4 000 hectares, where system efficiency averaged 70% with an upper limit of 80%. The overall project efficiency is the product of system efficiency and application efficiency. A typical scheme with overhead irrigation and optimum size would, therefore, have a project efficiency of:

$$66 \times 70 = 47.6\%$$

Irrigation system efficiency drops away significantly with both a reduction and increase in scheme size, an average value of 50% is found on both 400 and 25 000 hectare schemes. It is a sobering thought that for sprinkler irrigation, scheme efficiency would now be only :

$$66 \times 50 = 34\%$$

The importance of management is stressed in the study. The smaller schemes cannot afford effective management, while on the large schemes communication between farmers and officials suffers. This is food for thought when one reflects on the idea of transfering irrigation schemes to irrigation boards.

The universally accepted practice of "bulking up" nett irrigation requirements by means of efficiency factors is unfortunate. More accurate figures could result if actual losses could be estimated for the conditions experienced and applied on an additive basis. In the case of reduced quotas it would seem that application efficiencies will improve, but it is unknown what would happen to distribution efficiencies.

CHAPTER 13

PEAK WATER REQUIREMENTS

13-1 INTRODUCTION

Remarkably little has been published about estimating peak water demands. In practice, designers base system capacity on the average daily ET for the month with the greatest demand in the growing season. In the drier areas, rain is normally ignored when estimating system capacity.

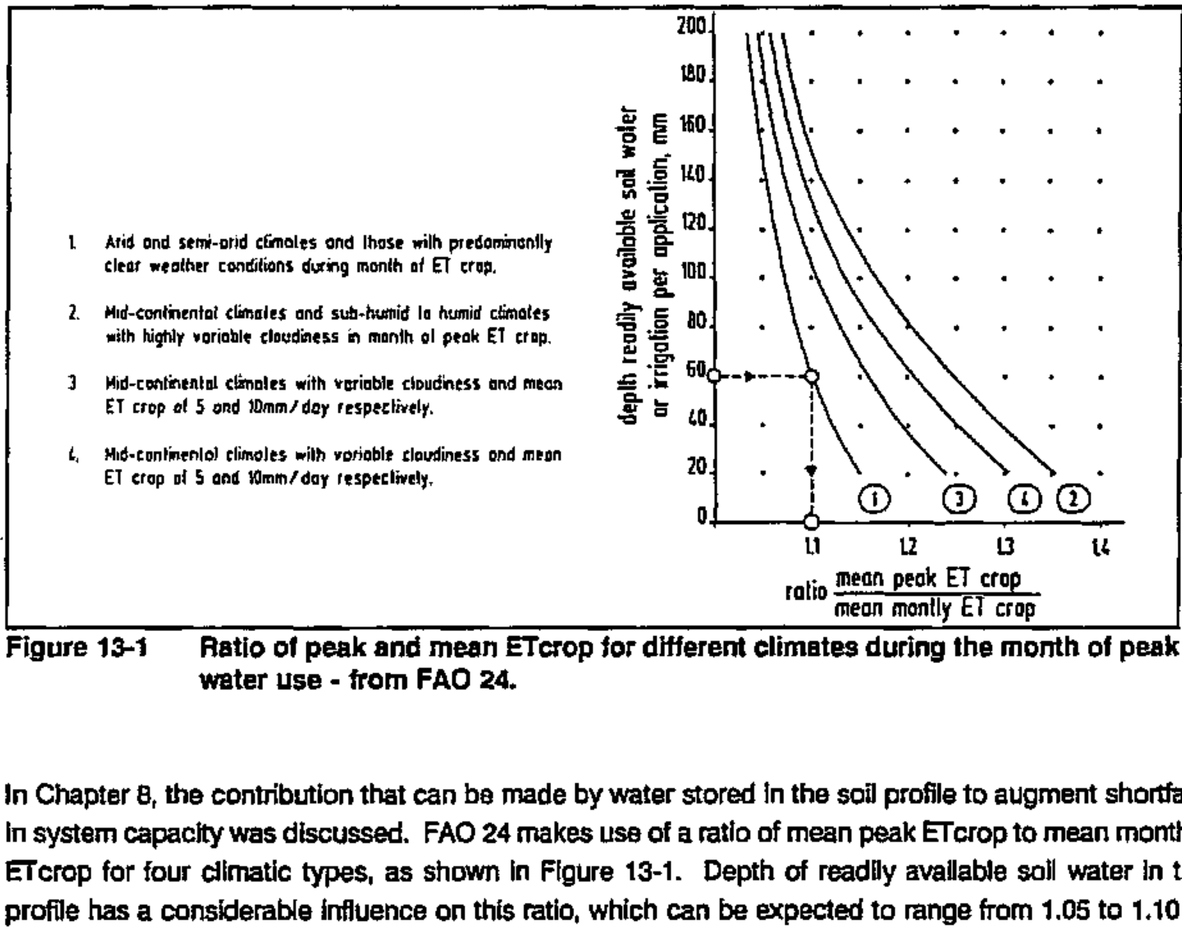


Figure 13-1 Ratio of peak and mean ETcrop for different climates during the month of peak water use - from FAO 24.

In Chapter 8, the contribution that can be made by water stored in the soil profile to augment shortfalls in system capacity was discussed. FAO 24 makes use of a ratio of mean peak ETcrop to mean monthly ETcrop for four climatic types, as shown in Figure 13-1. Depth of readily available soil water in the profile has a considerable influence on this ratio, which can be expected to range from 1.05 to 1.10 in a dry region. In an area with highly variable cloudiness in the month of peak ETcrop, the ratio can range from 1.1 to 1.3 at which point the values become significant.

13-2 PRACTICAL EXAMPLES FROM Southern-Orange Free State.

The practical data developed by Bennie et al (1988), is of value in assessing the realities of the situation. The bulk of this work was done during 1985 and 1986 at the height of the drought, when conditions along the Orange River at Ramah were severe, both for summer and winter crops.

An examination of the Ramah data provides interesting insights. In the case of maize on plot M99, a yield of 11½ ton/ha was achieved with a nett irrigation level of just over 6 mm per day. At times, in peak periods, the measured ET reached 9 mm per day for short periods, but the water available in the soil profile was able to provide the shortfall. In the case of a second plot (M100), where a yield of 15½ ton/ha was achieved, the average ET was just under 12 mm per day over a 47 day period, the height of the season, while the average irrigation rate was just under 10 mm per day. Here again, some water was extracted from the soil profile. To a degree, the soil water use during peak ET periods is self-regulating. If some stress occurs, then with the closing of the stoma a balance is achieved at the expense of yield.

In the case of wheat, at one plot (W13) an average daily irrigation rate of about 3½ mm was enough to cope with short peaks rising to 9 mm per day ET, with the A-pan-evaporation being in the order of 10 mm per day. The duration of these peaks is normally in the order of 4 to 5 days. A second field, Plot W30, had a nett irrigation rate of approximately 5 mm per day, but there were 3 to 4 day peaks running up to 8 and 9 mm per day.

The peaks predicted by the 1985 Green Book are undoubtedly achieved in practice (within the limitations of the validity of the crop factors utilised and the tendency for the A-pan to exaggerate peaks), but there are clear indications that the plant can cope with relatively short peak periods, and thus there is no need to go to a higher system capacity.

13-3 MANAGEMENT CONSIDERATIONS

Du Rand (1991) stresses that the practical management situation must be considered. He points out that there are a number of factors that need to be taken into account and which will vary with the requirements of the particular farmer and the situation in which he is operating. The number of hours per week that it is planned to irrigate and the safety factor which is built in to cater for power interruptions and the utilisation of labour, has an important influence. Should a crisis arise due to exceptionally high atmospheric demand or low soil water resources, then irrigating additional hours would enable this exceptional peak to be successfully surmounted.

In addition, crop rotations and crop combinations can be planned to spread peak requirements, as has been done for many years at Vaalharts. The deficit in peak capacity created by the canal systems can be overcome by intelligent combinations of crops, so that peaks do not coincide. A further variable is the efficiency of the irrigation system and the way in which it is managed, while the effective utilisation of soil water can also reduce peak demand. Du Rand (1991) maintains that in the light of the variations that can arise in terms of these factors, it can be an unproductive exercise to try and accurately predict the likely peaks as part of design. What is desireable, is that the overall factor of safety built into the design be adequate to cater for exceptional circumstances.

This appears to be sound comment and **SAPWAT** does not cater specifically for peak requirements. By selecting the 90^{th} percentile option, however, a dry year can be used to assess system capacity. The extreme climatic conditions experienced in 1992 have drawn attention to a possible weakness in assuming that calculations can be based on "average" evaporative atmospheric demand and that it is only precipitation that varies greatly.

Apparent lack of capacity of irrigation systems is frequently a management problem in that effective soil depth may be inadequate, due to a compaction layer or crusting that may have drastically reduced infiltration rate and the quantity of water that can be applied during an application. The deeper reaches of the soil profile may in fact never have been replenished.

CHAPTER 14

NETT WATER SUPPLY LESS THAN ATMOSPHERIC EVAPORATIVE DEMAND

14-1 INTRODUCTION

The decision support system approach, **SAPWAT**, in common with most methods of estimating irrigation requirements, is based on meeting atmospheric evaporative demand. At this stage **SAPWAT** does not cater for the situation which arises when the full irrigation amount is not applied. This situation can occur either because there is a shortage of water, or because some form of deficit irrigation is practised.

Deficit irrigation comes into its own when irrigable land is not the limiting factor and it is possible to increase total production by utilising the available water over a larger area. The implication is that the percentage decrease in yield is significantly less than the percentage water deficit.

In Chapter 10 it was shown that by designing for 50% irrigation adequacy, it was possible to reduce planned water requirements by up to 25% with a yield reduction penalty of only 10% .

There is, in addition, the relationship between ET and yield, which is approximately linear. For effective deficit irrigation, relative yield should decrease at a slower rate than relative water use. This varies from one crop to another.

14-2 THE BASIC PRINCIPLES

FAO 33 utilises the yield response factor (Ky) which relates relative yield decrease (1 - Ya/Ymax; where Ya=actual yield and Ymax=maximum yield) to relative evapotranspiration deficit (1 - ETa/ETmax; where ETa=actual evapotranspiration and ETmax=maximum evapotranspiration).

Water deficit of a given magnitude may either occur continuously over the total growing period of the crop, or it may occur during any one of the individual growth periods. Application of Ky for planning, design and operation of irrigation projects allows quantification of water supply and water use in terms of crop yield and total production for the project area. Under conditions of limited water distributed equally over the total growing season, involving crops with different Ky values, the crop with the higher Ky value will suffer a greater yield loss than the crop with a lower Ky value. Both the likely losses in yield and the adjustments required in water supply to minimise such losses, can be quantified. Similarly, such a quantification is possible when the likely yield losses arise from differences in the Ky of individual growth periods.

FAO 33 includes valuable manual routines for planning irrigation schedules and calculating scheme water requirements, but these have not come into general use, certainly not in the RSA. This is probably because the procedures can be tedious and require some effort to master. FAO 33 appeals more to the scientist and specialist than the practitioner and in this respect has lagged behind FAO 24.

FAO 33 procedures have been included in **CROPWAT** (FAO 46) and it would be similarly desireable to extend the scope of **SAPWAT** by incorporating freely available FAO 33 data and routines. It is appreciated that **ACRU** and **PUTU** have a greater capability, but for the practitioner, the self contained simplicity of SAPWAT is applicable in this context. SAPWAT already embodies BEWAB, which has an element of deficit irrigation in that it incorporates the principle of "target yields" which may have lower than maximum irrigation requirements.

14-3 DEFICIT IRRIGATION

English et al (1990), states that deficit irrigation is an optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and consequently experience stress and a reduction in yield. An alternative and descriptive name for the practice is partial irrigation. In other words, irrigation is applied, but not to the level where water ceases to be the limiting factor in production. Production will be reduced by this partial irrigation, because water is the limiting factor. To some extent this is the position under rain-fed crop production. Normally the inputs such as seed and fertiliser will be scaled down proportionately, in comparison with fully irrigated crop production. In the extreme situation limited irrigation may amount to "assuring normal rainfall".

Deficit irrigation is widely practiced, particularly in areas that regularly experience water shortages. In India, which has over one hundred million hectares of regularly drought affected land, major irrigation projects are designed for extensive irrigation where available water is spread over a larger area than would normally be the case for full irrigation. The objective is "protective irrigation" in which the water supply is used to augment yields and protect crops from complete failure, rather than to meet full crop water requirements.

The intention is to distribute the benefits of irrigation to a large number of farmers. One example is where the water allowance is only 12 l/min/ha, only 25% of the full irrigation requirement. Smaller scale systems operate on the same principle. Runoff from seasonal rains is collected in small dams which provide a reserve capacity for an area of a few hectare, supplying only 20% of the seasonal water requirements but sustaining the crop at critical times. The position in Pakistan is similar, where it is estimated that overall crop water use is 35% below full crop water requirements.

Deficit irrigation is widely practiced in the Great Plains of the USA, a semi-arid region characterised by limited and declining water supplies. It is common practice to irrigate roughly double the nominal area with a given amount of water, and some farmers have tripled the area. The USA Soil Conservation Service has accepted a reduction to 35% of system capacity for subsidy purposes.

The combined effect of improving application efficiency and a reduction in nett water availability is difficult to quantify. It is here that the model IEM (English - presently being programmed) can make an international contribution. If, however, one makes the assumption that conditions are such that application efficiency can be ignored, the impact of reducing nett water supply can be assessed using the methods established by FAO 33.

In developing zone and regional guidelines, it will be important to assess deficit irrigation in the light of area specific circumstances and to provide the necessary assistance in the form of data and recommendations based on sound practice and a clear understanding of all the factors involved.

CHAPTER 15

CROP GROWTH MODELS

15-1 INTRODUCTION

All irrigation farming is, to a greater or lesser extent, non-standard. Bennie (1992) stresses that the decision-making criteria developed by successful irrigation farmers as a result of years of past experience and intimate contact with crop, soil and climate, are mostly applicable to one set of farming circumstances only.

The process of researching the development of a decision support system for the estimation of crop water requirements has gone through several stages and the end is not yet in sight. What has become clear, however, is that crop growth models can play an important part in developing irrigation guidelines for specific areas and situations. It cannot be left to planners or designers alone to use these models, it is indeed surprising to find how little crop growth models have been used in irrigation. Outside of the inner research circle, they are not very well understood.

It should not be the task of the modeller or the researcher to utilise the crop growth models, because their interests and abilities should be concentrated on developing and calibrating better models. It is important that there be practitioners from a variety of disciplines who are crop growth model literate. In essence these models summarise the state of the art and define the relationships between inter-related factors. Most models promote interdisciplinary co-operation and a better understanding of the fundamentals. It is a bonus if a model is so highly developed and calibrated that it can accurately simulate "correct" answers. It would be valuable if the use of these models could become part of the stock-in-trade of a new breed of irrigation specialist.

15-2 THE ROLE OF CROP GROWTH MODELS

Textbooks, scientific reviews and professional papers deal with isolated aspects of irrigation. Models of the crop growth type force integration and co-ordination and one has the assurance that the best available information developed by research has been incorporated in such a model and that it has stood up to the scrutiny of specialists in their specific fields. The model integrates and quantifies a mass of inter-related information and the final output may be based on numerous individual relationships and equations that are dovetailed into a comprehensive whole.

Models of this nature are effective in enabling one to understand basic principles and to undertake "what if" exercises, where one can vary inputs and assess the corresponding outputs. Such excercises can be an important adjunct to decision making. It is not necessary to confine oneself to RSA examples only, it is possible to use overseas simulations which are validated by field experiments. One is then reasonably certain that there is the correct balance between the inputs and that the outputs reflect a realistic simulation of what will happen when alternative strategies are applied. It is dangerous to mix local and overseas *inputs* in a model, unless calibration against local experimental results is available. There is no implication that South African models are inferior. In the long term, local models could provide more appropriate data, specifically validated under local conditions. However, it would be unreasonable to ignore the possibilities of using international models to explore principles in the interim period until RSA models become freely available.

15-3 APPLYING CROP GROWTH MODELS

In the process of this investigation, a number of simulations (**CERES** or other crops conforming to the **DSSAT** system) have been performed because they are available, relatively easy to use and the case studies provided with the standard software are in themselves valuable tools, being based on well documented field experiments. The objective was to establish general principles and procedures and not to attempt to arrive at specific yield or water-use predictions for South African conditions. In the future, **PUTU** will be a more appropriate model applied for the purpose.

Typical examples of the principles that can be illustrated, are:

a) the influence of management factors such as fertilisation and plant population on water-use and yield,

b) permissible water-extraction from soil (PAWC),

c) plant stress under deficit irrigation conditions,

d) the effectiveness of precipitation in the irrigation scheduling context,

e) the risks involved in supplementary or limited irrigation,

f) the influence of various irrigation scheduling regimes under specific circumstances.

The type of crop growth model which is particularly applicable, is sophisticated in construction, but useable by any PC operator. The basic principles are well explained by Jones and Ritchie (1990), and the following explanation has been derived from their publication:

> Several research groups are developing "user-orientated" crop growth models. Generally, these user-orientated crop growth models can be operated with data readily-available to the user, are well documented and widely available, and have been tested over a range of conditions. These models have components that are based on plant physiology. They include processes that describe the development of reproductive structures, photo-synthesis, respiration and biomass growth, partitioning, and tissue senescence.
>
> The soil component part of the models vary in degree of detail from those with only one state variable (total soil water in a root zone) to those that have state variables for soil water content in each of several layers of soil or even in two or three dimensional elements of soil. The soil component is normally divided into several layers and input information on the soil comes from standard soil classification data. The water contents of each layer in the soil component are changed through time by the processes of infiltration, re-distribution, drainage, evaporation, and root water extraction for transpiration. Some models also include soil nitrogen state variables and processes that move, transform, and remove nitrogen from the soil profile.
>
> The type and frequency of weather data inputs to crop models have also varied. Weather input frequency is usually hourly or daily. Since user-orientated crop models require readily available data, most have been developed to use daily weather data as

input. Such models are also usually "daily incrementing", that is, state variables are updated once every day and use rational empiricisms to compute daily rates of the processes which are actually instantaneous.

The irrigation management components of crop models allow users to specify different strategies for managing the crop, or to input specific dates and amounts of irrigation for comparison purposes and the selection of the best strategies. User-orientated crop models allow users to easily change the irrigation strategy, make one or more runs and then compare the results.

Some models allow users to define irrigation strategies that will automatically cause irrigation events to be simulated when soil water conditions reach a certain level. This is done by selecting values for a depth of soil to be considered for the irrigation decision (management zone), a threshold level soil water content for the zone, and an irrigation amount to apply when an irrigation event is simulated. These management variables can be varied with crop growth stage. Users can also specify particular calendar date irrigation events for comparison purposes.

15-4 EXAMPLE OF MODEL APPLICATIONS

This imaginary case study is located in a dry part of the country with a rainfall pattern similar to Christiana. A scheme is being considered on good soils, 1 500mm deep and with a profile capacity between upper limit and lower limit of 200mm of water. The intention is to plant maize on Nov 15 and to ensure that the profile is full at planting, by applying a pre-irrigation if early season rain is inadequate.

There are a number of management variations that are explored:

a) Pre-irrigation plus a full irrigation, with a "normal" plant population of 66 000 plants/hectare and matching fertiliser.

b) Pre-irrigation, but otherwise a dry-land situation, with a plant population of 20 000 plants/hectare and reduced fertiliser inputs.

c) As in (b) but the crop receives a 100mm irrigation on the 15th of January.

A simulation was run for the eight years 1983/84 to 1990/91 for all three cases. As stressed above, not too much attention should be given to the absolute values obtained from the simulations. Crop water use seems low, probably due to the method of calculating reference evaporation.

a) With full irrigation, the average yield over the 8 years was 9737 kg/hectare.

b) The dry-land situation resulted in complete crop failure in five out of the eight seasons, despite the pre-irrigation to field capacity.

c) The mid-January application of 100mm of irrigation to boost the early season full profile, resulted in an average crop of 3252 kg/ha and no year with a complete crop failure.

Under rain only conditions, crop failures resulted from stress during the grain filling stage and consequent premature crop maturity, because of slowed grain filling. There are indications that if irrigation is applied in January, the water savings will be marginal as compared to full irrigation.

However, full irrigation requires high inputs in seed, fertiliser and management, which may not be technically attainable, while the approach of applying 100mm irrigation in January is really only an extension of established dry-land technology. The question that remains is the cost and practicability of this single irrigation, but at least the specialist has a "feel" for the factors involved and has improved inputs for economic analyses.

The approach of trying various management options with the various inputs can become a viable tool in the decision making process, but it does require a degree of "model literacy" and knowledge of the practical farming situation.

CHAPTER 16

PACKAGING REGIONAL IRRIGATION GUIDELINES

16-1 INTRODUCTION

A computerised procedure for estimating the irrigation requirements of crops such as SAPWAT, can be a valuable aid, but it must be recognised that there are limitations. All irrigation farming is, to a greater or lesser extent, non-standard. Bennie (1992) stresses that the decision-making criteria developed by successful irrigation farmers as a result of years of past experience and intimate contact with crop, soil and climate, are mostly applicable to one set of farming circumstances only.

The estimation of the irrigation requirements of crops, should be supplemented by practical guidelines developed on a multidisciplinary basis by a group dedicated to irrigation and the farmers' needs. Bennie (1992) makes the valid point that, presently, each irrigator has the unenviable task of having to decide whether to adopt or reject recommended approaches and practices, taking into account his own specific circumstances and the possible hidden interests of the advisors or researchers. There should be guidelines available that at least ensure that this "hidden interests" factor is eliminated and that the concentration is on the actual circumstances that determine the success of irrigation in the region.

The Soil Conservation Service (SCS) in the USA have addressed the problem by developing State guidelines. This task is undertaken by the multidisciplinary teams located at the regional technical service centres. A typical State Irrigation Guide, which considers Irrigation zones in detail, has these chapter headings:

Climate and water supply
Soils
Crops
Irrigation water requirements
Irrigation method selection
Irrigation system components
Soil conservation
Irrigation energy use
Irrigation economic evaluation
Irrigation method design
Irrigation water management

These guides expand on the estimation of crop water requirements and draw on natural resource information, research results and practical experience. They place the emphasis on the specific needs of the area being served. Similar regional guidelines would provide the background information to supplement the **SAPWAT** procedure. This would enable practitioners to make realistic decisions applicable to specific farmer needs.

Guidelines of this nature can be "packaged" and made available in the form of a PC program that can not only provide a data base, but can lead the user through a logical, well structured procedure which will help ensure that important aspects are not overlooked. Regrettably, many designers and suppliers of irrigation equipment are better informed on the mechanical and hydraulic aspects of irrigation than the agricultural. Guidelines can go a long way towards compensating for this situation.

16-2 GUIDELINE ELEMENTS

It is not the intention that the guidelines should deal with all aspects of crop production under irrigation, this would be impractical, but rather to concentrate on the main factors influencing irrigation planning. Soils and their relationship to crops and irrigation are a typical example.

There is a tendency, in practice, to concentrate on arriving at an appropriate design application. The Green Book (1985) sets out the normal procedure followed.

> The complete set of information needed to select the appropriate design application is:
>
> (i) the water holding capacity of the soil (example: 100 mm/m);
> (ii) the soil depth (example: 0.9 m);
> (iii) the potential rooting depth of the crop after which the shallower of (a) the rooting depth (example: 1.2 m) and (b) the soil depth can be termed the useful soil depth (thus: 0.9 m);
> (iv) the permissible level of available soil water depletion (example: 50%), when the crop is in the most actively transpiring stage.
>
> *The design application is obtained by multiplying the total available soil water per unit depth with the useful soil depth and taking that percentage of the product which represents the permissible depletion.*

Green Book assumptions for rooting depths are 900mm for maize and wheat and 1000mm for cotton. The equivelent values tabulated in FAO 24 and FAO 46 are 1000-1700mm for maize and cotton and 1000-1500mm for wheat. In all cases, a depletion percentage in the order of 50% is indicated.

It can be assumed that RSA designers will utilise the Green Book recommendations. How would these differ from guideline values that could be developed for the Southern Free State utilising the data contained in Bennie et al (1988). Measured rooting depth of wheat ranged from 900mm to 2100mm and extractable water (PAWC) from 45mm to 211mm, as compared with the 60mm that would have been estimated using the Green Book procedure. Depending on soil, one would assume that guideline values could be a rooting depth of 1700mm and extractable soil water values at least double those that would normally be accepted. Much the same values would apply to maize and cotton. Interestingly the rooting depths are in line with the upper limits suggested in FAO 24.

The predominance of light sandy soils has resulted in the general use of centre pivot irrigation, which leads to further soil related considerations. Surface sealing tends to be a major consideration and where lands slope, runoff is a major problem, very often limiting individual applications to 12mm despite the significant water holding capacity of the profile. The high atmospheric demand may make daily irrigation essential under these circumstances, unless special measures are taken in system design.

BEWAB, Bennie et al (1988), was developed to provide a PC computer based aid to irrigation management and planning in this region and incorporated the principle of utilising water stored in the profile to reduce the applications required at peak season.

While soils are important, such elements as feasible crop rotations, incidence of untimely cold and heat, especially if accompanied by high winds, and the influence of topography on climate must all be taken into consideration.

The establishment of irrigation water requirements is not a major problem if water is not a restraint. If, however, it becomes necessary to cater for periodic droughts, or the application of limited or deficit irrigation, the development of effective strategies is complex. Crop growth models can be a valuable aid to developing regional strategies under these circumstances.

The SCS guide cited earlier, deals with a wide range of aspects and is a valuable and authoritative publication. It also has 12 chapters and more than a hundred pages.

16-3 PACKAGING GUIDELINES

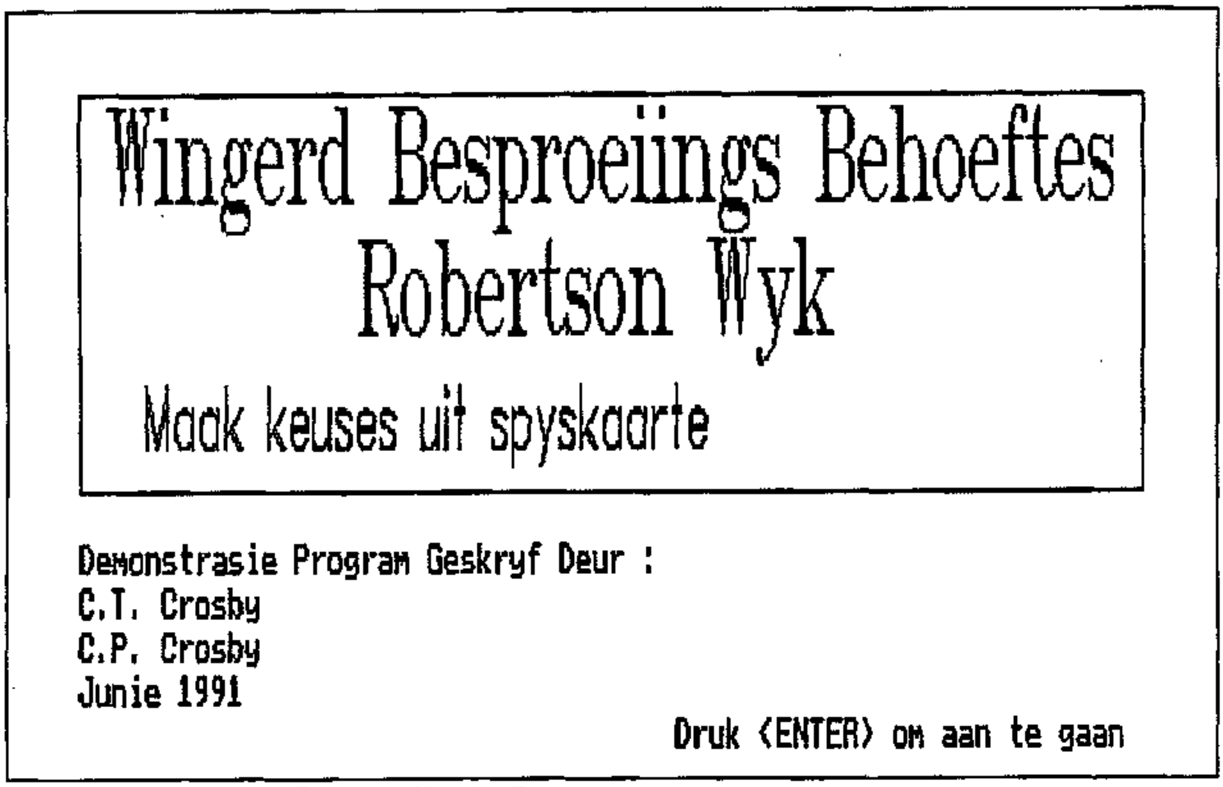
Computers provide an effective method of presenting essential information in a usable form and can help guide the practitioner through a relatively unfamiliar subject. A program **ROBERTS** was developed to assess the possibilities of this approach and seems to have promise. The program provides guidelines for the irrigation requirements of vineyard in the Robertson area. This is a well researched crop, so that the program can be regarded as being based on valid information. The emphasis is on irrigation water requirements, but it would not be difficult to extend the program to cover various other aspects of irrigation management.

In common with **SAPWAT**, the program is written in Turbo Pascal and makes use of menus and graphics in order to make it simple to install and operate. The user is presented with a menu listing the six areas comprising the Robertson area. It is possible that a designer may not be aware that there are six areas with differing climatic and other circumstances warranting differentiation.

On selecting Breerivier Vallei, the user is asked to specify the details of up to 8 vineyards in a block. He enters the area, in hectares, of each vineyard and follows this up with further details. He is confronted with a list of the soils found in the area, the common local name is used, e.g. Diep Brakgrond, Harde Karoo etc., not the soil form or series. Once again, he may, or may not, be aware of these soil differences and their implications, but the program forces him to make the identifications, either by observation or by asking!

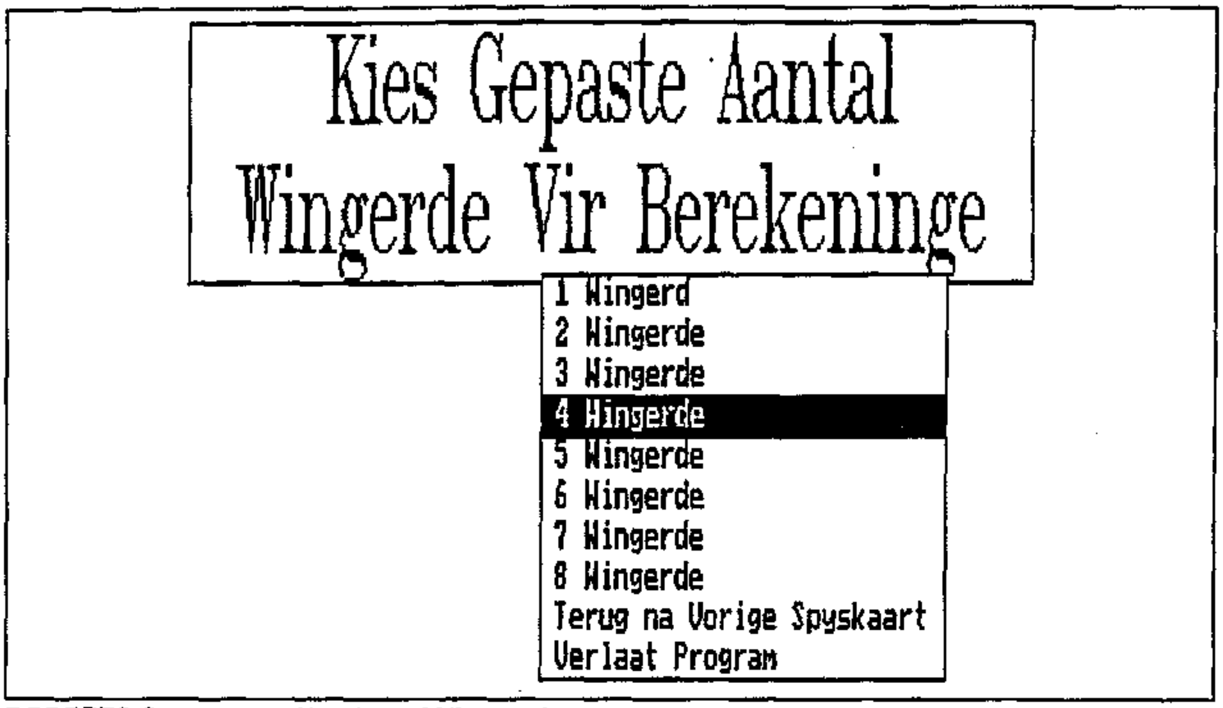
The next screen provides him with descriptions of the soils commonly covered by the popular name. The recommended cultivars are listed with an indication as to whether they are early, normal or late varieties and the yields that can be expected if they are managed for maximum production or high quality. He selects the cultivar planted in the vineyard and the desired production level. The long term average yield achieved under each of four irrigation methods comes up on screen and he is asked to make his selection. This choice may not be based on yield alone, but at least the designer will be aware of the yields achieved in practice. These may differ significantly from farmer claims and influence economic viability studies.

The program now presents a summary of the inputs and results for each of the vineyards and for the block as a whole. Irrigation requirements for each vineyard are tabulated in mm of water per month, while the consolidated block requirements are provided in cubic metres of water, also per month. The results are presented graphically if selected.

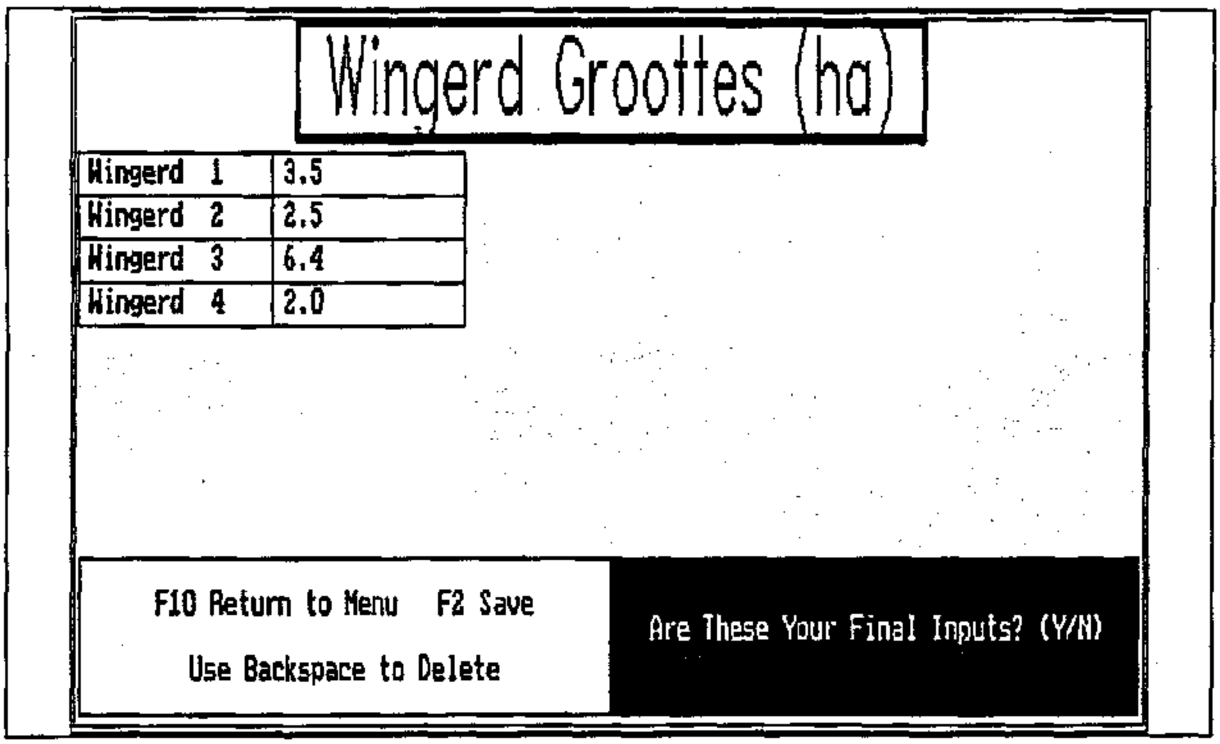


ROBERTS Screen 1: Program Header Screen

ROBERTS Screen 2 : Production Region Selection

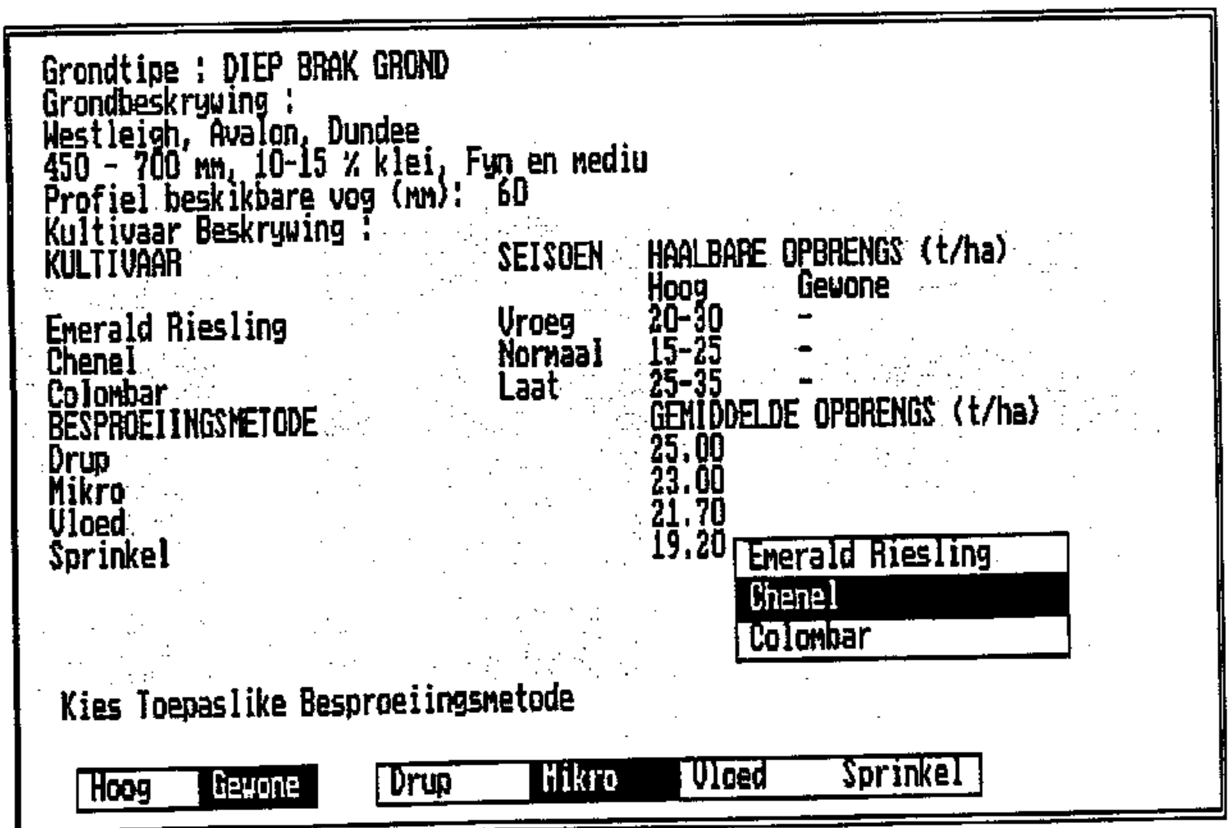


ROBERTS Screen 3 : Number of Vineyards

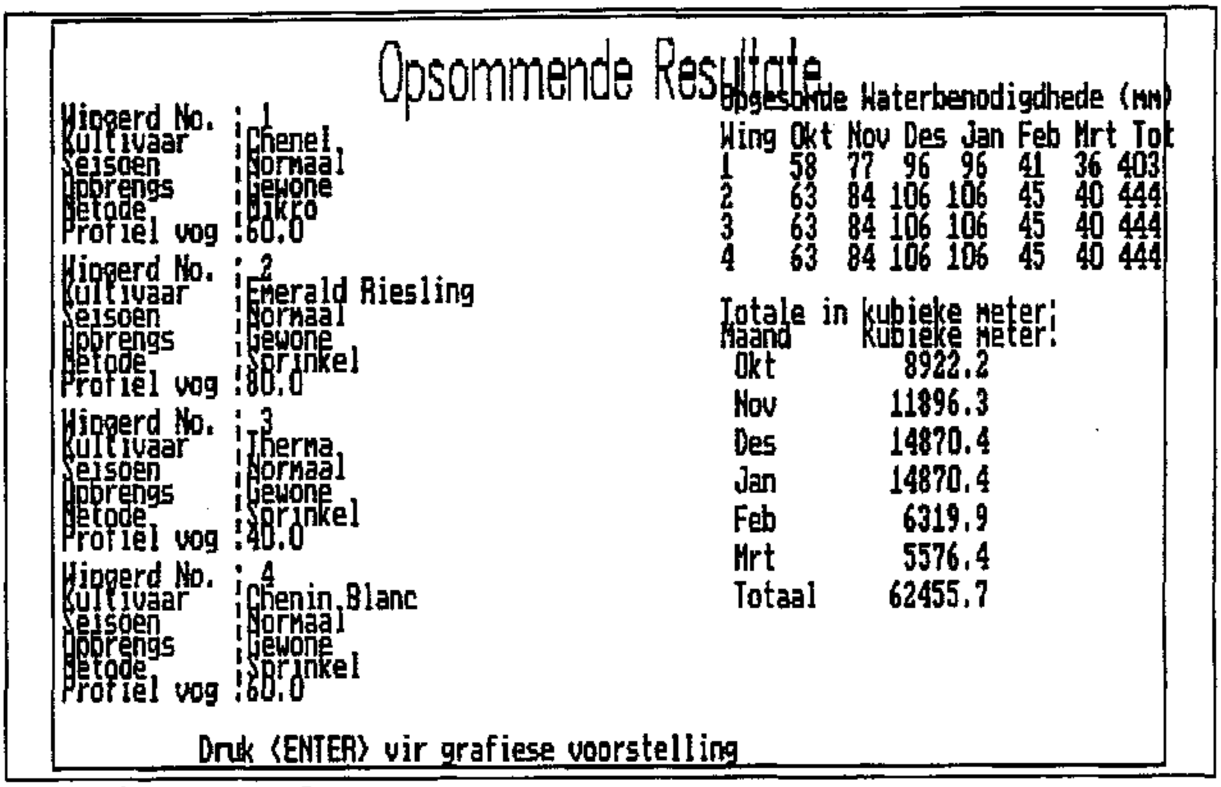


ROBERTS Screen 4 : Vineyard Size

ROBERTS Screen 5 : Soil Type



ROBERTS Screen 6 : Information, Cultivar and Irrigation Selection



Opsommende Resultate

Wingerd No. : 1
Kultivaar : Chenel
Seisoen : Normaal
Opbrengs : Gewone
Metode : Mikro
Profiel vog : 60.0

Wingerd No. : 2
Kultivaar : Emerald Riesling
Seisoen : Normaal
Opbrengs : Gewone
Metode : Sprinkel
Profiel vog : 80.0

Wingerd No. : 3
Kultivaar : Therma
Seisoen : Normaal
Opbrengs : Gewone
Metode : Sprinkel
Profiel vog : 40.0

Wingerd No. : 4
Kultivaar : Chenin Blanc
Seisoen : Normaal
Opbrengs : Gewone
Metode : Sprinkel
Profiel vog : 60.0

Opgesomde Waterbenodigdhede (mm)

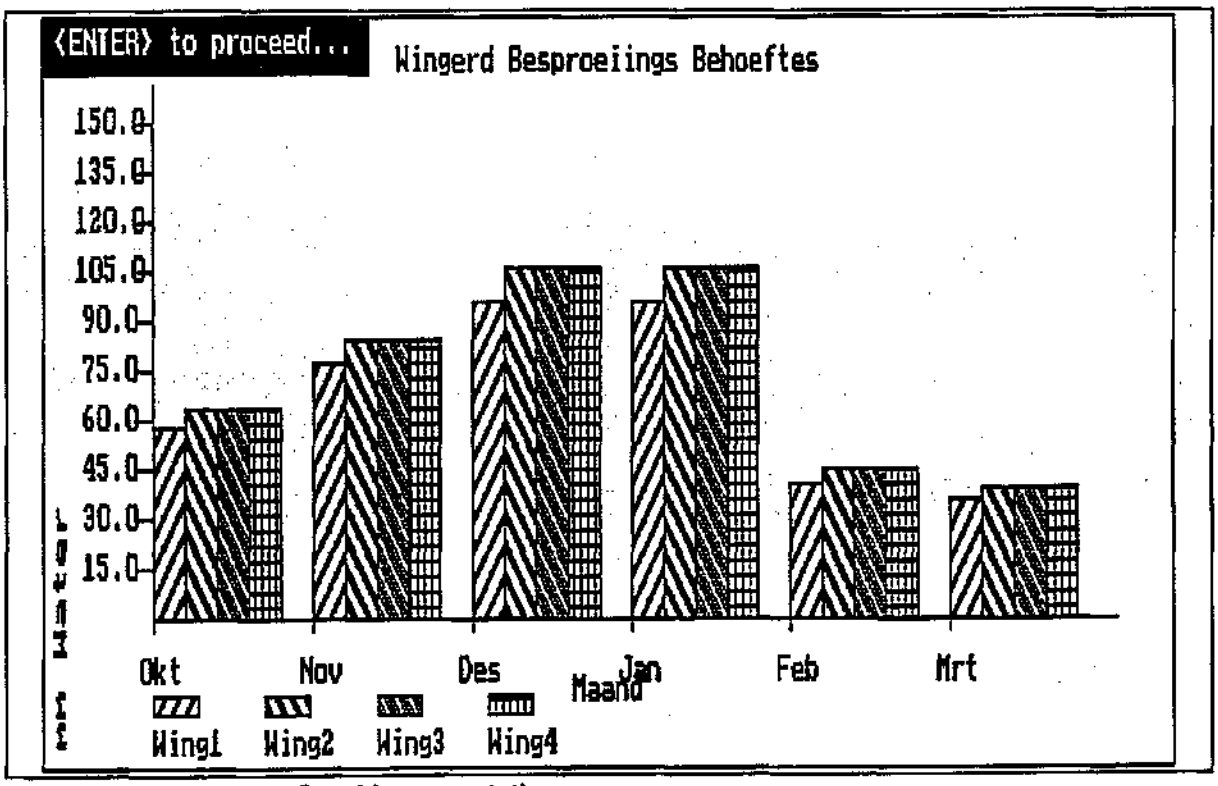
Wing	Okt	Nov	Des	Jan	Feb	Mrt	Tot
1	58	77	96	96	41	36	403
2	63	84	106	106	45	40	444
3	63	84	106	106	45	40	444
4	63	84	106	106	45	40	444

Totale in kubieke meter:

Maand	Kubieke meter:
Okt	8922.2
Nov	11896.3
Des	14870.4
Jan	14870.4
Feb	6319.9
Mrt	5576.4
Totaal	62455.7

Druk <ENTER> vir grafiese voorstelling

ROBERTS Screen 7 : Output



ROBERTS Screen 8 : Graphic presentation

CHAPTER 17

CONCLUSIONS AND RECOMMENDATIONS

17-1 CONCLUSIONS

SAPWAT, in its current form, completes the pilot phase of a project which had the following objectives:

* to assess the feasibility of establishing a computer-based decision making procedure for the estimation of crop water requirements, that was
* suitable for use by practitioners with limited experience and training, and in line with current international practice, and
* incorporates both interpreted research results and the practical experience of specialists.

The objectives of the pilot phase have been met. **SAPWAT** is still in demonstration form, but has confirmed that it is feasible to establish an appropriate computer-based procedure conforming to the original objectives of the project. Limited exposure to specialists and practitioners has evinced favourable reaction and comments have been constructive. There is every indication that **SAPWAT** can be developed to the stage where it can be accepted as the standard procedure for estimating the irrigation requirements of crops in Southern Africa. Modifications are, however, necessary to some component programs, the data bases need further expansion and refinement and overall program packaging is necessary before distribution.

There is a demand for the extension of the scope of **SAPWAT** to cater for the planning and strategy development of deficit and limited irrigation, when either water or management inputs are a restraint. This is particularly appropriate in the case of development intended to support emerging farmers.

There is a pressing need for practical zonal irrigation guidelines, developed on a multidisciplinary basis and incorporating functional management factors that can augment irrigation water requirement estimating procedures.

17-2 RECOMMENDATIONS

This is a pilot project and recommendations are, in the first instance, focused on what needs to be done in order to develop a final product that can be released for general use. The next aspect considered is how the program can be introduced, distributed and maintained if it is to serve as a standard approach to the estimation of irrigation water requirements. Finally, recommendations are made on the actions required to expand **SAPWAT** to cater for the various "water deficit" situations. Zonal irrigation guidelines are considered as a separate issue.

17-2-1 Evaluation of SAPWAT

It is recommended that a workshop be held to evaluate **SAPWAT**, with representation from the South African Irrigation Institute (SABI), the South African Institution of Agricultural Engineers (SAIAE), the Directorate of Irrigation Engineering, scientists engaged in irrigation research, and personnel at

Technicon and University departments concerned with irrigation. A demonstration of **SAPWAT** and the software developed during the pilot project, should be followed by open discussions aimed at achieving consensus on the format and scope of a computerised procedure for the estimation of crop water requirements for irrigation planning and design.

17-2-2 The generation of estimated irrigation requirements by ACRU

The pilot project made use of the irrigation requirements as estimated by Dent et al (1988) as a primary input to the interactive computer program for irrigation planning and design. The basic concepts that were developed in the pilot phase should be expanded and refined in cooperation with, inter alia, the Department of Agricultural Engineering, University of Natal. Cooperation should focus on the generation of estimated irrigation requirements by the **ACRU** model. These new estimates will replace those of Dent et al (1988). Developments in the **ACRU** model, the climatic data base and related estimators of climatic input, (for example, reference evaporation), along with technological changes, have made such adaptations desirable, necessary and feasible.

Apart from the advances that have been made in the interim, mentioned above, the tabulated estimates made by Dent et al (1988) (**PMBWAT**) are restricted by the assumptions which were made at the time of their generation. Whilst remaining with the concept of a DOS based system which is to be operated on personal computers, the proposed new enhancements will incorporate a procedure for developing the irrigation requirement information in a fashion which is far more tailored to the specific needs and assumptions desired by the client, for example, different scheduling strategies. The Department of Agricultural Engineering, University of Natal, can make use of the considerable advances which they have made in:

* the data base of information on the 712 homogeneous climate zones, and

* the techniques to automate much of the input information which is required by the **ACRU** model.

It is envisaged that by using a suite of programs that could be developed in cooperation with the Computing Centre for Water Research (CCWR), it would be possible to provide a relatively seamless operation between the PC-based program and the **ACRU** model running on the CCWR computer. Such operation would only be for the duration of the generation of the client specific set of irrigation requirement information. The consultant who is preparing **SAPWAT** diskettes for a client would disconnect from the CCWR and operate in stand alone mode on the PC only. As such, the system would be fully portable from that point onwards, until a change was required in the base set of irrigation requirement information, whereupon the connection would again be made with the CCWR to run **ACRU**. Several sets of base information for specific clients could be stored on diskettes by the consultant.

The advantages of this mode of operation are numerous, since all the past, present and future advances made by researchers will be available as they occur and these will be transparent to the user. An example of this is the possible inclusion in future **ACRU** versions of relevant developments from the **PUTU** models developed at the University of the Orange Free State. This means that the consultant will be deriving the benefit of the latest research, without being concerned with the underlying complexity of the modeling processes. This would make a significant contribution to technology transfer. In addition, since many of the routines and much of the input data and information is being used by numerous researchers on a regular basis, the chances are good that these inputs will contain very few errors.

17-2-3 The further refinement and development of SAPWAT

On the assumption that **SAPWAT** is found to be satisfactory, after the incorporation of the workshop recommendations, it is anticipated that the following should be undertaken:

- liaison with the Department of Agricultural Engineering, University of Natal, and the development of a program, equivalent to **NATAL**, to link the proposed **ACRU** run outputs to **SAPWAT**. (See 17-2-2)

- the updating of the monthly precipation input to **RAIN**, to include the most recent data from the 712 climatic zone data base.

- the expansion of the range of crops for which default values of the crop co-efficients are available, to include the bulk of crops and varieties in South Africa and the incorporation of the revised crop factors under development for **PUTU**.

- the provision of a soils data base to facilitate PAWC estimations.

- the extension of **GROSS** to make provision for the influence of irrigation methods on irrigation requirements.

- the further development of **SCHEME**, a procedure to facilitate the estimation of monthly water requirements on a scheme, where the mix of crops, areas planted and planting dates can be varied.

- the general editing of the **SAPWAT** component programs to ensure uniformity and coherence.

- the preparation of a user's manual for **SAPWAT**.

17-2-4 Implementation

It is recommended that in the next phase of the project the **SAPWAT** procedure be implemented and evaluated at one regional centre. Thereafter the implementation of **SAPWAT** could be achieved by establishing regional consultants, equipped to obtain updated data from the CCWR and prepare **SAPWAT** diskettes tailored to the climatic circumstances of regional users. Tours of each region would have to be undertaken to introduce **SAPWAT** and the relevant regional centre to potential users. Users should be made aware of the inherent inability of **SAPWAT** to cater for non-standard situations, and the proposed extension to the program to cater for these situations discussed with potential users. During this phase, tailored diskettes will be developed for all regions.

17-2-5 The "water deficit" situation.

It is recommended that in a later phase, attention be given to estimating yield reduction as a consequence of water constraints. FAO 33 and **CROPWAT** (FAO 46) make provision for applying the yield response factor (Ky). Versions of **PUTU** utilise the same approach, which could also be applied to **SAPWAT**. It is possible that with the recommended direct linking with **ACRU** on the CCWR computer, the impact of less than maximum water availability will be a "carry over" from **ACRU** developments.

17-2-6 Zonal irrigation guidelines

It is recommended that guidelines of the nature discussed in this report be developed on an on-going basis. In the RSA context this would require interdisciplinary action and could involve a number of organisations and funding sources. It is recommended that a workshop be held to consider the matter further.

CHAPTER 18

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