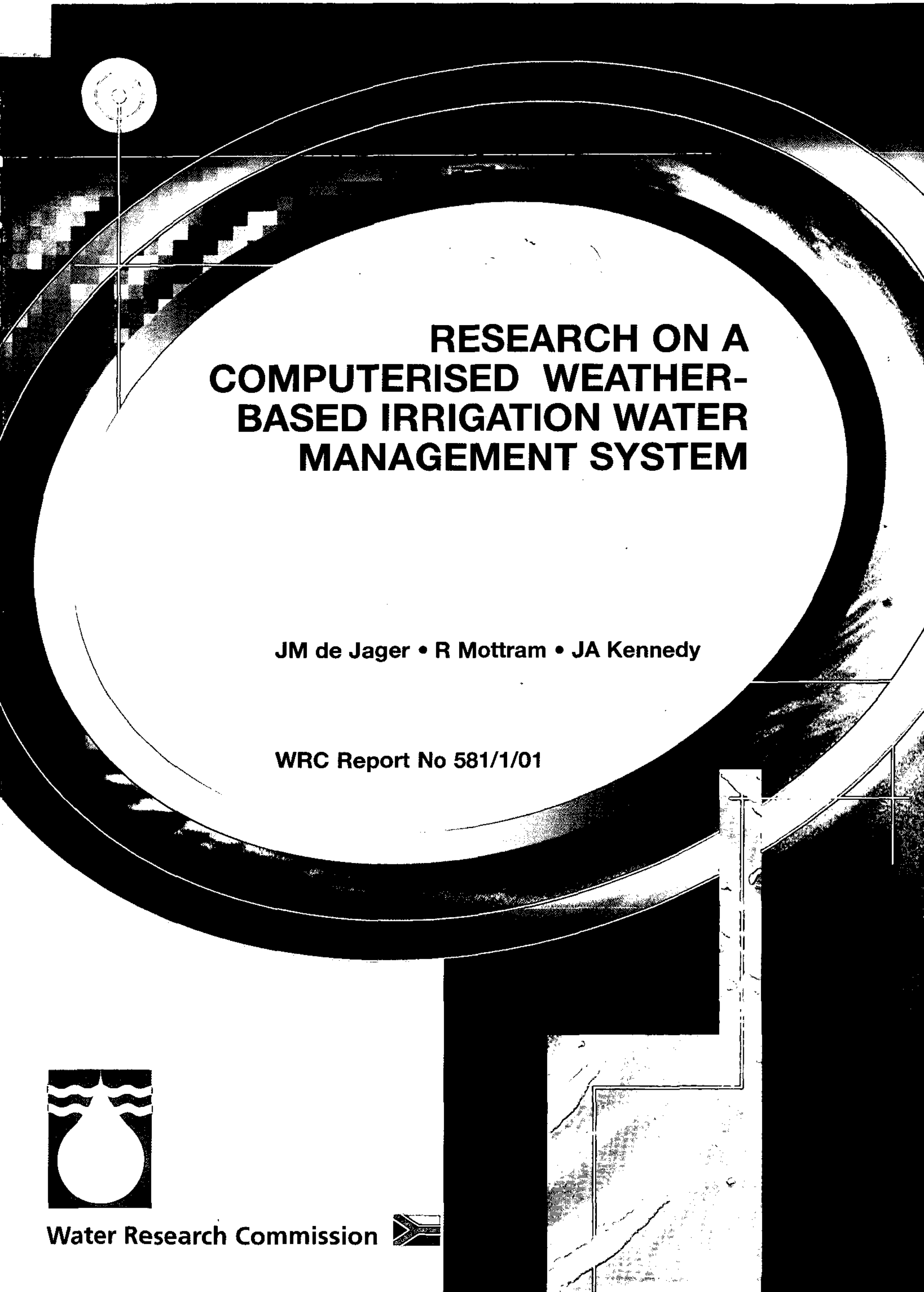

RESEARCH ON A COMPUTERISED WEATHER-BASED IRRIGATION WATER MANAGEMENT SYSTEM

JM de Jager • R Mottram • JA Kennedy

WRC Report No 581/1/01

Water Research Commission

RESEARCH ON A COMPUTERISED WEATHER-BASED IRRIGATION WATER MANAGEMENT SYSTEM

Report to the Water Research Commission

By

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EXECUTIVE SUMMARY

RATIONALE

Use of automatic weather stations (AWS) and crop growth models (CGM) have been shown to be a successful method for management of efficient irrigation scheduling. Irrigation boards and/or individual farmers are prepared to purchase their own automatic weather stations for this purpose. Apart from scheduling irrigation, the climatic data collected may be used, for example, for climate surveys and decision support for pest control and frost protection. In addition, the weather data can be accessed at any time. Similar networks and decision support systems have been developed overseas and are functioning effectively. This project was aimed at adapting and developing such technology for southern Africa, but housed within a telecommunications network capable of serving farms and irrigation schemes located in various provinces and countries.

In previous WRC research projects conducted by the Department of Agrometeorology, UOFS methods for maximizing irrigation efficiency using AWS and CGM and the Putu computerised procedures in differing climate-soil-crop scenarios had been formulated. This project collated these procedures and demonstrated the technology transfer thereof to irrigation practitioners.

Opening markets in the UK and Europe now provide opportunities for the export of high income crops such as potatoes, asparagus, runner beans, tulip bulbs, baby vegetables and fresh flowers etc. In order to be successful in both the existing as well as these new export markets, technology enabling and simplifying irrigation of such crops needed to be developed.

A Successfully operated Irrigation Decision Support System (IDSS) serves as an excellent demonstration of computerised technology transfer. Timeous irrigation decisions based on scientific principles, demonstrate to farming co-operatives, irrigators and/or consultants, who previously had no such information, the advantages of IDSS and create an awareness of the benefits of scheduling and judicious management of limited water resources.

Managers of small to moderate sized farms cannot devote the necessary time to irrigation scheduling without reducing their other farming activities and are in urgent need of time-saving real-time irrigation schedules.

Preliminary feasibility studies had indicated that considerable water savings could be attained in comparison to scheduling based upon Class A pan evaporation. Furthermore, since the introduction of variable ESCOM tariffs could provide opportunities for immense savings in electricity as irrigators are now permitted to choose low tariff periods during which to operate. Such strategies will also assist ESCOM to regulate peak loads and consequently reduce electricity costs to the consumer countrywide.

Computerised scheduling programmes and water management will improve water use and distribution efficiencies which will not only benefit optimum crop production, but will also save water particularly during times of drought and when restrictions are applied.

OBJECTIVES

Taking into consideration the rationale for the study, the overall aims of this research project were the design, development and establishment of an effective automatic weather station network and computerised irrigation decision support system (IDSS). Essentially this entailed establishing a computer aided system for the provision of information upon which to base decisions related to irrigation planning, scheduling and water distribution management.

The specific objectives of the research were:

Network development

Determine which type of telecommunications network system, involving radio links if necessary, is best for the different situations found in southern Africa. Thereafter establish such a network to serve estates/farms, groups of farms and irrigation schemes and test and improve the data retrieval system.

Data management

Develop data management procedures which make possible the efficient use of water on numerous irrigation plots.

Irrigation scheduling and water-use efficiency maximisation

Create a computerised Irrigation Decision Support System (IDSS) resident in research centres at Pietermaritzburg and Bloemfontein, from which scientific irrigation advice may be provided to water managers to enable them to :

- schedule irrigation on individual lands for a variety of crops for maximum water use efficiency,
- derive the most efficient seasonal water use strategies for given water supply-climate-soil-crop scenarios and apportion limited water, fairly and sparingly, between numerous clients with differing crops and land areas,
- extract information from a database with respect to atmospheric evaporative demand which may be used together with information on given dam, catchment or river water supplies (hydrological resources), so as to determine, for example, the feasibility of irrigated agriculture in a specific area.

Regarding the apportionment of limited water between clients and crops, a theory and a computerised optimisation procedure were developed. Unfortunately, the latter failed to function satisfactorily and hence this aspect and the management of water distribution to numerous farms will not be reported on in this document. Details of the theory however, are included in the complete report.

Information disemination

Devise, by surveys and trial and error how client requests may be received and processed and recommendations may be rapidly disseminated.

Documentation of procedures

Provide a thorough description of the system and detailed instructions on how to operate it.

RESULTS

A survey of selected literature covering the research topics was undertaken. From this the research was planned and guided and the results of the work will now be described.

A telecommunication network for southern Africa

It was shown that efficient scheduling of irrigation can be achieved using the Putu-IDSS based upon automatic weather station data and crop growth models. Water-saving irrigation scheduling advice was transmitted from central computing centres linked by telecom-munication network to distant AW's and farm managers located in other provinces and countries.

Automatic weather stations were connected in a computerised network. Weather data were collected and used in mathematical models to compute crop water-use and recommended irrigation amounts. This information was then disseminated in sufficient time to allow irrigators to act before crop water stress with concomitant yield reductions were induced.

The technology devised, is suited to extensive commercial as well as low-input small-scale operations and the major advantage of the system stens from the use of data from a single weather station and its application to numerous neighbouring farms. This has significant cost and logistic benefits.

The installation and maintenance of AWS's were investigated and applied. The most necessary precautions are detailed in the report. While Putu-IDSS does advocate a standardised format for information dissemination, this was however not always found to be desirable, because of varying client facilities and requirements. Radio, short-haul modem, direct cable and telephonic links all proved successful for the interchange of data and irrigation depth and timing recommendations.

Increasing numbers of clients expressed the desire to schedule irrigation for themselves and several needed only values of reference evaporation. Groups of farmers who purchase an AWS wish also to be able to sell weather data. Furthermore, the use of weather data to calculate disease indexes has become a necessity.

Theory and user instructions

The computational and mathematical procedures and mathematical equations required in the IDSS are outlined in the report. Innovations include algorithms for the numerical solution of the non-linear equation indicating the onset of water stress in plants, the introduction of default values of critical leaf water potential, a method for transforming calendar dates into thermal period from sowing date, and a streamlined software package for creating input data files and irrigation recommendations. Instructions on how to run the computer programs are outlined. The use of thermal period means the crop phenology established in one particular locality may be used elsewhere.

Detailed descriptions on how to estimate certain crop parameters and the soil water characteristic are given. The standard form of the Penman-Monteith equation recommended by the Food and Agriculture Organisation was tested and an appropriate version included in the Putu-IDSS.

An example of a pro-forma contract between irrigation agent and water manager is included.

ACHIEVEMENTS

The irrigation decision support system was comprised of irrigation advisors in Bloemfontein and Pietermaritzburg who were telephonically and/or computer linked to various participants. The telecommunication network grew steadily and included operations in Zimbabwe and Swaziland, with a service planned for Tanzania. Approximately 125 clients and 1900 plots of land were irrigated from centres at the Department of Agrometeorology, UOFS, Bloemfontein and in Pietermaritzburg. Similar operations run by three farming Cooperatives and the Free State Department of Agriculture which also used Putu, but were not part of this project, are included in these numbers. In excess of 34 AWS's, purchased by private entrepreneurs, were involved in the operation.

Apart from pastures, maize, soyabeans, wheat, peas, dry beans, potatoes, runner beans, sugarcane, barley, cotton and vegetable crops; the Putu-IDSS was adapted to handle high income crops such as apples, asparagus, tulip bulbs, tomatoes, onions, seed maize and mange tout peas. Envisaged expansion includes: the eastern Free State (asparagus, apples, cherries), Zimbabwe (potatoes), Komatipoort, Mpumalanga (plantations), Delmonte, Cameroon (bananas) and Tanzania (diverse).

Two agents set up independent commercial undertakings which proved financially viable. This may be taken as an indication that farmers are prepared to pay for this type of irrigation decision support.

It was found that two levels of decision support made available in the Putu-IDSS are useful in practice. These are:

High level – where the irrigation simulation model simulates field conditions from weather data and computed reference evaporation and enables recommendations regarding the depth and timing of the next irrigation.

Intermediate level – where managers are provided with daily values of reference evaporation and simply irrigate an equal amount of water, or some empirical fraction thereof. Of the abovementioned plots, 295 were serviced at intermediate level.

This approach makes the Putu-IDSS highly suitable for both commercial and small farm enterprises.

FUTURE RESEARCH

Software needs to be developed which will make the Putu-IDSS available on Internet and a Website. This will make it readily accessible to a large number of irrigation farmers.

The sparse canopy and partial cover routines in the irrigation simulation model require refinement and validation.

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Dr R Mottram and Mr James Kennedy for successfully handling the difficult task of venturing into the field of technology transfer. The manner in which the project expanded bears testimony to their dedication and ability.

Prof. Sue Walker for setting aside facilities and personnel to prepare the final report.
Belmarié Langeveldt for undertaking the arduous task of typing the final report in her inimitable, enthusiastic, competent and cheerful manner.

The Steering Committee for the project was constituted of the following persons:

Dr. P. MacRobert Reid	Water Research Commission (Chairman 1993-95)
Dr. G.R. Backeberg	Water Research Commission (Chairman 1995-98)
Mr. D.S. van der Merwe	Water Research Commission
Prof. J.G. Annandale	University of Pretoria
Mr. P.S. van Heerden	Department of Agriculture, Free State Province
Prof. A.T.P. Bennie	University of the Free State
Mr. C.T. Crosby	MBB Consulting Engineers Inc.
Mr. D.J. du Rand	Department of Agriculture, Free State Province
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LIST OF ABBREVIATIONS

AWS	Automatic Weather Station
CCWR	Computing Centre for Water Research
CGM	Crop Growth Model
CIMIS	California Irrigation Management Information System
DSSAT	Decision Support System for Agrotechnology Transfer
DST	Decision Support Technology
FAO	Food and Agriculture Organisation of the United Nations
FS	Free State Province
GSM	Global Systems for Mobile Communication
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICID	International Commission on Irrigation and Drainage
IDSS	Irrigation Decision Support System
IPS	Integrated Power Supply
ISU	Irrigation Scheduling Unit of the University of the Orange Free State
PC	Personal Computer
PME	Penman-Monteith Equation
PTE	Priestley-Taylor Equation
SWC	Soil Water Characteristic
USAID	United States Aid for International Development
WMDSS	Water Management Decision Support System
WRC	Water Research Commission

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PREFACE

THE STRUCTURE OF THE REPORT

The work of the project may be classified into four themes. The report will be presented in four sections each one addressing a specific theme, viz.

I ***Introduction***

The rationale and objectives of this work and a relevant literature survey.

II ***Network Development and Data Management***

The development of a telecommunication network for irrigation decision support

III ***Putu Modelling System***

The refinement and description of the theory of the Putu modelling system, with suggestions of how to obtain some of the model input

IV ***Irrigation Decision Support and Technology Transfer***

The description of how to apply the modelling system for technology transfer and some practical results

MODUS OPERANDI

In the main, project conceptualisation, theory and model development (particularly Chapters 1, 3, 7, 10, 11 and 12) were carried out by Prof. Jimmy de Jager.

Dr. Roy Mottram undertook the survey of selected literature and was responsible for installing and monitoring automatic weather stations and the successful electronic transmission of data and technology transfer (see Chapters 3, 4 and 6). From these operations it was possible to refine the Putu irrigation model and establish some of the required crop parameters and guidelines for advisors (Chapters 8, 9, 13 and 15).

The preliminary electronic data management reported in Chapter 5 was organised by James Kennedy, who was also responsible for the field tests on the Penman-Monteith Equation, levels of technology transfer and effectiveness of irrigation scheduling by means of weather data and computer models (Chapters 11, 12 and 14).

Computer coding for the optimisation of managing limited water resources and profit maximisation was undertaken by Mr. Louis de Lange. Coding of the Putu shell was done by numerous students, but Mr. Phillip Nel in particular.

SECTION I INTRODUCTION

CHAPTER 1

RATIONALE AND OBJECTIVES

RATIONALE

Water use for agriculture in southern Africa is at present under critical scrutiny. Industry and household use are agriculture's biggest competitors in this regard. Recently severe restrictions have been imposed upon irrigators by the Water Act. For example, stored water on farms in certain controlled areas has been reduced to 50000m^3 and abstraction rates from rivers to 25 l s^{-1}. The Water Rights Law in the RSA is being re-formulated.

With the regional and local irrigation boards possibly assuming water management responsibilities from the Department of Water Affairs, it is imperative that efficient use be made of water (see for example Crosby, 1996). A suitable computerised system will greatly assist such operations and eliminate inconsistencies.

Use of automatic weather stations (AWS) and crop growth models (CGM) have been shown (De Jager, Van Zyl, Kelbe and Singels, 1987, De Jager, Van Zyl, Bristow and van Rooyen, 1982; and Mottram and De Jager, 1994) to be a successful method for water-use efficient irrigation scheduling. Water Boards, irrigation communities and/or individual farmers are prepared to purchase their own automatic weather stations. Prior to 1990 ten AWS had been purchased by the private sector for this purpose. Apart from scheduling irrigation, the data collected may also be used, for example, for climate surveys and decision support for pest control and frost protection. In addition the weather data can be accessed at any time. To-date, real-time weather data collected by the Weather Bureau has been difficult to access for various logistic reasons. Hence AWS and CGM offer a practical solution to the problem of irrigation planning and scheduling. Similar networks and decision support systems have been developed overseas and are functioning effectively (Phene, 1991; CIMIS, 1985 and the SIRAGCROP computer-based crop management system for irrigated wheat and summer crops of Maarten Stapper and Wayne Meyer in Australia).

The majority of irrigators have no access to real time values of daily reference crop evaporation and consequently are unable to schedule their irrigation (Mottram and De Jager, 1994) accurately. This project aims to remedy such shortcomings.

Different irrigation communities require system scheduling programmes which have been drawn up for their particular sets of circumstances. In previous WRC research projects conducted by the Department of Agricultural Meteorology, UOFS, (De Jager et. al, 1982, 1987, and Mottram and De Jager, 1994) methods on how to maximise irrigation project efficiency using AWS's and computerised procedures in differing climate-soil-crop scenarios have been formulated. All these procedures need to be collated and the technology transferred to irrigation practitioners.

Following the return of South Africa to the international community, overseas markets are providing opportunities for export. Markets for crops such as potatoes, asparagus, runner beans, tulip bulbs, baby vegetables and fresh flowers have been found in the UK and Europe. There are few, if any comprehensive irrigation programmes for these crops under our conditions. Thus, in order to be successful in both existing and new export markets, new irrigation strategies need to be developed and applied to these new crops.

The creation of an AWS network will provide irrigated areas in southern Africa with near-real-time weather data which will serve as an example of how to schedule irrigations and promote efficient water-use and management. Timeous decisions based on scientific principles, need to be demonstrated. Tested data collection and technology transfer systems, could make available irrigation advice to co-operatives, irrigators and/or consultants who previously had no such information, or to whom the information was not instantaneously available. Such technology should create the desired awareness of scheduling and judicious management of limited water resources.

Most small to moderate size farms are owned and operated by the grower/irrigator who must manage all aspects of his farming and thus cannot devote the necessary time to irrigation scheduling without reducing his other farming activities. The proposed system will be designed to provide these irrigators with time-saving real-time irrigation schedules.

Preliminary feasibility studies indicated that expected water savings brought about by a computerised decision support system above the use of Class A pan evaporation could exceed 20 x 10^6 m^3 per annum of water on sugar estates irrigating say 10 000 ha.

Savings in electricity could also be immense. For example Mottram and De Jager (1994) have found that electricity savings using the proposed scheduling methods on irrigated pasture in the Karkloof amounted to some 50%. The introduction of the new variable ESCOM tariffs, which permit irrigators to choose periods in which to irrigate will allow optimisation of pumping costs. Such decisions will also assist ESCOM to regulate peak loads which could consequently reduce electricity costs to the consumer countrywide.

Employing computerised scheduling programmes and water management will improve water use and distribution efficiencies. This is not only beneficial to optimum crop production, but saves water particularly during times of drought and when water restrictions are applied.

OBJECTIVES

The overall aims of this research project were the design, development and establishment of an effective automatic weather station (AWS) network and computerised irrigation decision support system (IDSS). Essentially this entails establishing a computer aided system for the provision of information upon which to base decisions related to irrigation planning, scheduling and water distribution management.

The methodologies and programmes developed in the previous research on the maximisation of Irrigation Project Efficiency (IPE) (Mottram and De Jager, 1994) will be combined in a single comprehensive IDSS. The IDSS should be geared for use by regional and local irrigation boards, irrigation communities, extension services, agricultural consultants and co-operatives.
The system should be linked via a telecommunications network throughout southern Africa to the CCWR and research project offices. Implementation and advisories will emanate from research offices in Howick and Bloemfontein.

One of the aims will be to establish an economically viable agency to demonstrate the capability of providing irrigators and the irrigation industry with a complete service in matters of scheduling and managing irrigation water. The demonstration unit will operate within the Department of Agrometeorology at the University of the Orange Free State and will be known as the Irrigation Scheduling Unit (ISU).

A set of operational guidelines which should ensure continuity irrespective of personnel changes, and which allow for upgrading of the system, will be drawn up.

The specific objectives of the research are:

Network development

Determine which types of network system, involving telecommunications and radio links if necessary, that will be best for different situations in southern Africa.

Establish such a network to serve an estate/farm, a group of farms and irrigation schemes and where necessary, test and improve, the data retrieval system.

Establish procedures and computer programs for the collection and collation of the data and the application thereof to irrigation scheduling.

Data management

These data must be made available in a form promoting efficient use of water on numerous irrigation plots.

Irrigation scheduling and water-use efficiency maximisation

Create a computerised Irrigation Decision Support System (IDSS) resident at the CCWR, and in the research centres at Howick and Bloemfontein, from which scientific irrigation advisories may be provided to irrigation boards, extension officers and farm managers to enable them to:

> schedule irrigations on individual lands for a variety of crops for maximum water use efficiency
>
> derive the most efficient seasonal water use strategies for given water supply - climatic - soil - crop scenarios
>
> apportion limited water, fairly and sparingly, between numerous clients with differing crop and land areas
>
> extract information from a database with respect to atmospheric evaporative demand (AED) which may be used together with information on given dam, catchment or river water supply (hydrological resources), so as to determine, for example, the feasibility of irrigated agriculture in a specific area
>
> efficiently manage water distribution to numerous farms through a limited capacity conveyance system using the software developed at the Rand Afrikaans University.

All the procedures to be used in the above (except the last) were developed in the IPE project. As it becomes necessary, models for new crops, such as export potatoes, baby vegetables, bulbs and flowers will be developed, and where possible, verified.

Regarding the apportionment of limited water between clients and crops, a theory and a computerised optimisation procedure were developed. Unfortunately, the latter failed to function satisfactorily and hence this aspect and the management of water distribution to numerous farms will not be reported on in this document. The theory is found in Appendix IV.

Information dissemination

A major problem with the proposed type of decision support system is transfer of advice to the client and how best to utilise the expertise of scientific advisors. The research will devise, by surveys and by trial and error, how best client requests may be received and processed, and how solutions and recommendations may rapidly be disseminated. A system, efficiently utilising the expertise of scientific advisors, technical assistants and available equipment, will be developed.

Documentation of procedures

It is imperative that a thorough description of the system, and detailed instructions on how to operate it, be provided to ensure the system's preservation for the future. A complete manual, including system operation procedures for prospective scientific advisors, will be prepared.

CHAPTER 2
LITERATURE SURVEY

INTRODUCTION

Automatic weather stations are being installed in increasing numbers in southern Africa. Resultant weather station networks provide real time data for use in verified crop growth simulation models such as Putu and CERES and agrohydrological models such as ACRU which facilitate irrigation planning and scheduling. Problems experienced by regional and local irrigation boards with the management of water can be simplified by providing suitable information aimed at ensuring sound decisions by irrigation managers. These data include the pre-season selection of suitable crops given, pre-season water supply, gross margins and or how to manage situations where water allocation become restricted during the season.

Crop production depends entirely on an adequate supply of resources such as water, nutrients and solar radiation. In many areas of the world, and especially in southern Africa, water is a major factor limiting crop production. Water for crop production can come from either precipitation or irrigation. Where economically viable, irrigation can be used to supplement natural rainfall. In the many semi-arid regions, agricultural production is wholly dependent upon irrigation as a source of water. In this case, in particular, it is necessary to achieve maximum production from the water applied.

At present, competition for limited water supplies is increasing. The agricultural, municipal and industrial sectors compete for water. Burman *et al.* (1983) reported that this situation is being aggravated by the rapidly developing energy industry. The water used to generate energy is thus actually indirectly routed to both the municipal and industrial sectors.

Approximately 50 per cent of surface water resources are allocated to irrigation in South Africa. Of this, up to 30 per cent is lost before reaching the edge of the cropped surface (Bang, 1989). Improving on-farm irrigation efficiencies is thus imperative if more water is to be made available for other purposes. This could even have a positive effect on groundwater degradation. The California Department of Water Resources (Hawkins and Craddock, 1985) defined water supply savings as the reduction of water flowing into a sink where it would be rendered unusable for further beneficial use. In southern Africa this is seen primarily in river flow into the ocean.

Burman *et al.* (1983) stated that according to Western USA water right laws, the crop consumptive use is the limit of water that could be transferred from agriculture to industry.

This background emphasises the need for responsible, thrifty management of all aspects of water distribution on irrigation projects. Water could be saved during conveyance to farms and cropped areas, distribution between farms, physical application to crops, and irrigation scheduling.

The objectives of the literature survey were mainly to review selected scientific literature on:

a) the estimation of crop water requirements;

b) approaches to models and soil-crop water relations; and

c) methods of water supply management.

Throughout an attempt will be made to highlight subjects relevant and important to the objectives of the project.

ESTIMATING IRRIGATION WATER REQUIREMENTS

Current Support Technology

Personal computers have become readily available and inexpensive. Increasingly, farmers utilise personal computers for recording and managing farm operations. Computers can also be usefully applied in on-farm irrigation water management. The majority of the calculations involved in estimating irrigation water requirements are repetitive and protracted and, thus, the personal computer is ideally suited to the task.

Microprocessors, apart from being utilised in personal computers, are used in other applications such as data loggers. Perhaps the most frequent use is found in accumulating and processing climatic data needed for estimating irrigation water requirements. Automatic weather stations which collect, store, process and display values of climatic variables are being used in many situations. In southern Africa, apart from universities, the Weather Bureau and Department of Agriculture have converted to use of automatic weather stations.

Definitions Relevant to Estimating Water Requirements

Precise definitions of the terms and concepts required for estimating crop evaporation are imperative (Burman *et al*, 1983).

Total Evaporation (E). Monteith (1985) suggested that when describing the water vapour exchange at natural surfaces the term total evaporation be used. De Jager and Van Zyl (1989) defined (crop) total evaporation using:

$$E = E_v + E_s \qquad (2.1)$$

where,

E = total evaporation rate from a natural vegetative surface

E_v = evaporation of water from the plant, and
E_s = evaporation of water from the soil surface

Total evaporation is the total process of water transfer into the atmosphere from vegetated land surfaces.

Potential Total Evaporation (E_p). Rosenberg, Blad and Vermes (1983) defined potential total evaporation as the evaporation from an extended surface of crop cover which fully shades the ground, exerts negligible resistance to the flow of water, and for which the soil surrounding the roots is maintained at field capacity.

Reference Crop Evaporation (E_o). Doorenbos and Pruitt (1977) defined reference crop evaporation as the rate of evaporation from an extensive surface of 80 to 150 mm tall green grass cover, uniform in height, actively growing, completely shading the ground, and not short of water or soil nutrients.

Atmospheric Evaporative Demand (AED). De Jager and van Zyl (1989) defined atmospheric evaporative demand as the water vapour transfer to the atmosphere required to maintain the energy balance at a given vegetative surface (crop) in its present growth stage, when the water status of its root zone permits unhindered plant evaporation and the water status of the top 150 mm of soil equals its current value.

Efficiency. In order to bring about water savings, an analysis of water-use efficiency is required. Numerous significant definitions pertain. Svehlik (1957) lists some ICID definitions relevant to this study. These will be modified to suit the project and accommodate South African perceptions (Reinders, 1994).

Application efficiency η_a, is the ratio of quantity of water placed in the root zone to the total quantity of water applied to the field.

$$\eta_a = (AED - R_e)/V_a = V_n/V_a \qquad (2.2)$$

where

R_e effective rainfall (rainfall stored in the root-zone)
V_n net irrigation requirement
V_a field application over the cropped area

Thus net irrigation requirement $V_n = AED - R_e$ (2.3)

Farm Ditch Efficiency, η_b, is the ratio of field water application to the water supplied to a farm or group of farms, V_f

$$\eta_b = V_a / V_f \qquad (2.4)$$

Water Conveyance Efficiency, η_c, is the ratio of water supplied to a farm or group of farms to the water supplied to the irrigation area, V_t (2.5)

$$\eta_c = V_f/V_t$$

Overall Project Efficiency, η_p, is the ratio of net irrigation requirement to water supplied to the irrigation area. Thus

$$\eta_p = V_n/V_t = \eta_a \eta_b \eta_c \qquad (2.6)$$

Irrigation Efficiency, η_i, Seeking to reflect a measure of managerial skill in utilizing rainfall, soil characteristic and plant genetic properties, De Jager and Mottram (1995) defined irrigation efficiency as the ratio of marketable yield harvested per unit water received (i.e. irrigation (I) plus rainfall (R)).

$$\eta_i = Y/(I + R) \qquad (\mathrm{kg\ m^{-3}}) \qquad (2.7)$$

Deficit irrigation, is the scheduling method applied under a restricted water supply, where irrigation does not fully cover the water requirements of the crop and where certain stress conditions are allowed. (Itier, Maraux, Ruelle and Deumier, 1996).

Estimation of atmospheric evaporative demand

De Jager and van Zyl (1989) showed that evaporation from a vegetated surface must be considered in terms of two components, namely, soil evaporation and plant evaporation. They suggested that since both plant and soil water evaporation bear differing relationships to soil surface wetness it is incorrect to utilise a single crop coefficient. Two crop evaporation coefficients, k_v and k_s, are required, where:

$$k_c = k_s + k_v \qquad (2.8)$$

with k_c crop evaporation coefficient, the ratio of AED to reference evaporation - often >1

k_v vegetation (plant) evaporation coefficient, the ratio of plant water evaporation to reference evaporation

with,

k_s evaporation for soil water coefficient, the ratio of evaporation from the soil surface to reference evaporation.

Thus,

$$\mathrm{AED} = k_c \,.\, E_o \qquad (2.9)$$

The method whereby AED is estimated as illustrated in Fig. 2.1.

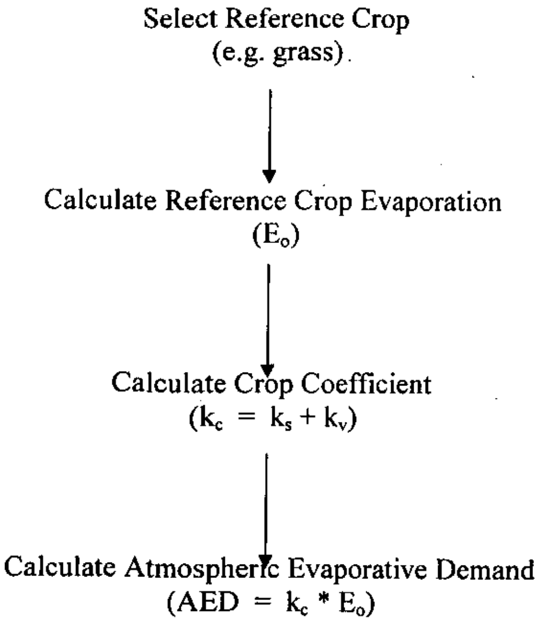


Fig. 2.1: Flow chart for estimating atmospheric evaporative demand

Eqn. 2.8 and 2.9 emphasise the importance of evaporation from the soil surface in reducing irrigation efficiency. A matter also addressed by Ceulemans, Laker and Van Asche (1988).

Estimation of Reference Evaporation

Penman (1948) introduced the Penman evaporation equation some 49 years ago and with rapid changes in electronic technology and extensive research it has been refined into the Penman-Monteith equation (see Monteith, 1985), a most accurate (Jensen and Allen, 1990) equation for estimating reference crop evaporation with real-time data collected from automatic weather stations. Penman (1948) measured water loss from large tanks containing bare soil, grass, and water. His original equation was based on monthly evaporation of water from these tanks, but the equation is now used for daily or hourly estimations. The initial definition of potential evaporation and experimental procedure implied an upper limit of evaporation determined by weather conditions in the atmosphere. Rosenberg *et al* (1983) stated that potential evaporation probably should not exceed free water evaporation under the same weather conditions.

Where routine weather data are available, a good estimate of E_o for 24-hour periods is obtainable from the daily Penman-Monteith equation. Following work by Burman *et al.* (1983) and Doorenbos and Kassam (1979), a version of the Penman-Monteith equation (PME) acceptable to the FAO panel of experts (Smith, 1992) was formulated by Allen, Smith, Perier and Pereira (1994). The Putu IDSS uses both the hourly and daily versions of this (see Section III).

Using the PME, reference evaporation may be estimated, for either an 80 to 150 mm grass cover (Doorenbos and Pruitt, 1977) or a 300 to 500 mm tall crop of lucerne (*Medicago sativa L.*) (Jensen and Allen, 1990). Parameters such as the aerodynamic resistance are specific for a given crop height and must strictly be accounted for when calculating reference evaporation.

Much controversy surrounds calculation of daily mean values of vapour pressure, incoming solar radiation, slope of the vapour pressure temperature curve and the psychrometric constant. The method of calculation adopted markedly affects the final estimate of reference evaporation. Once again the methods suggested by Allen *et al* (1994) are to be recommended.

Should vapour pressure and wind measurements not be available, an alternative estimate of Eo may be obtained using the **Priestley-Taylor** equation (Priestley and Taylor, 1972):

$$E_o = \alpha.EE \qquad (2.10)$$

where EE, defined as equilibrium evaporation is given by:

$EE = [s/(s+\gamma)](Rn - G)$, and Rn and G are not radiation and soil heat flud respectively.

α is an empirical coefficient equal to 1.26 for free water surfaces (Priestley and Taylor, 1972), 1.35 for perennial ryegrass (Mottram, 1975), and 1.42 for lucerne (Jury and Tanner, 1975). The latter also developed a version which included vapour pressure deficit. The empirical coefficient, α, approximates the aerodynamic contribution in the Penman evaporation.

When (Rn - G) is set equal to 0.65 of incoming solar radiant flux density, De Jager (1990) and Meiring (1989) found by calibration that daily E_o estimates are improved by making α a function of temperature, viz. for daily maximum temperature, T_{max}, between 20°C and 30°C:

$$\alpha = 1.28 + 0.08\,(T_{max} - 20) \qquad (2.11)$$

Meyer *et al.* (1979) also found that using maximum daily temperature above a base level to adjust α, produced a very satisfactory simulation of crop evaporation from well-watered spring wheat.

The value $\alpha = 1.3$ provides accurate estimation of hourly values of E_o

The **Goff-Gratch** (List, 1958; Goff and Gratch, 1995) and modified **Clausius-Clayperon** formulae (Allen *et al*, 1994) express saturated vapour pressure (SVP) in terms of air temperature in degrees Celsius (T). More convenient to use are the equations of Tetens (1930) and Murray (1967). The latter is used in Putu and is reproduced here.

$$SVP = 0.611 * EXP[17.27*T / (T + 237.3)] \text{ (kPa)} \qquad (2.13)$$

MODELLING

Passioura (1973) cautioned against making crop growth models (CGM) too complex. Model parameters should be few, all should be directly or indirectly measurable, and suggested that only verified models should be used.

There are several models for estimating soil water deficits using weather inputs (Penman, 1948; Ritchie *et al.*, 1976; Francis and Pidgeon, 1982; Walley and Hussein, 1982; and de Jager *et al.*, 1987). The majority of these were designed to provide estimates of soil water deficits for irrigators and some are very specific with respect to local climate, soil and crop phenology.

Since 1978, the Meteorological Office in Great Britain has used a meteorological model, MORECS, to provide weekly area estimates of evaporation, soil water deficit and hydrologically effective rainfall. Gardiner and Field (1983) investigated the accuracy of the soil water deficit estimation in this model and reported decided overestimation in most years, except during dry summers when underestimation was found. Reasons for these errors were non-representative meteorological data, especially effective rainfall. De Jager *et al.*, (1981) developed and Singels (1984) refined a wheat growth simulation model, Putu 6. Given weather input data, this model simulates the soil water balance by extracting daily transpiration losses from the water present in each soil layer. De Jager Van Zyl, Kelbe and Singels (1987) improved upon the accuracy of the simulation of soil water content by including better mathematical equations for hydraulic conductance and an iterative routine for modelling water stress situations. Cultivar differences were also accommodated in the latest wheat version, Putu9-89 (Singels, De Jager and Manley, 1989).

Burt *et al.*, (1981) cautioned that water-use modelling should always be kept in perspective. Empirical models are essentially regressions of evaporation on weather variables. Irrigation scheduling models are numerous (see Bennie, Coetzee, Van Antwerpen, Van Rensburg and Burger, 1988; Annandale, Van der Westhuizen and Olivier, 1996). Complex, mechanistic, dynamic models employ partial differential equations, governing the exchange processes of energy and mass in the soil-plant-atmosphere system.

Allen and Brockway (1983) developed equations and statistical relationships which relate annual operation and maintenance costs to water-use and the physical characteristics of given irrigation project systems.

Jameison *et al.*, (1984) used four different models to explain how three sowing dates and six irrigation treatments caused growth and water-use to vary in pea production and to analyse their transpiration efficiency and response to drought. These four models described water-use, crop growth, water-use efficiency and response to drought.

Riestra-Diaz (1985) used a water balance simulation model which provided reasonable estimates of crop evaporation and soil profile water content. Allen (1986) developed a mathematical model that formulates guidelines for allocation of irrigation water during a season and for sizing irrigation components. This model linearises evaporation and application rate relationships. Sprinkler system costs and efficiencies, pumping costs, piping costs, canal system costs and conveyance efficiencies are then optimised. The model presents design and management strategies for the average year case. Results obtained were realistic and usable for irrigation system planning and sensitivity analyses.

Place and Brown (1987) developed a simulation model, SIMCOY, to simulate maize yields for different soil water regimes. This model used daily climatic data, crop and soil parameters. Sensitivity of model output (viz. yields, phenological phases and stress days) to change in plant population, soil type, maximum evaporation limit and water-use efficiency was tested. Estimates of phenological phases were early, but accurate to within three days. Transpiration was slightly overestimated during dry spells. Yields were over-estimated especially under dry-land conditions. A similar model, much used today is EPIC of Williams, Jones and Dyke (1984).

IRRIGATION WATER SUPPLY AND MANAGEMENT

Doorenbos and Kassam (1979) pointed out that, "The upper limit of crop production is set by the climatic conditions and the genetic potential of the crop. The extent to which this limit can be reached will always depend on how finely the engineering aspects of water supply are in tune with the biological needs for water in crop production. Therefore, efficient use of water in crop production can only be attained when the planning, design and operation of the water supply and distribution system is geared toward meeting in quantity and time, including the periods of water shortages, the crop water needs required for optimum growth and high yields." This statement reflects much of the objective of the project.

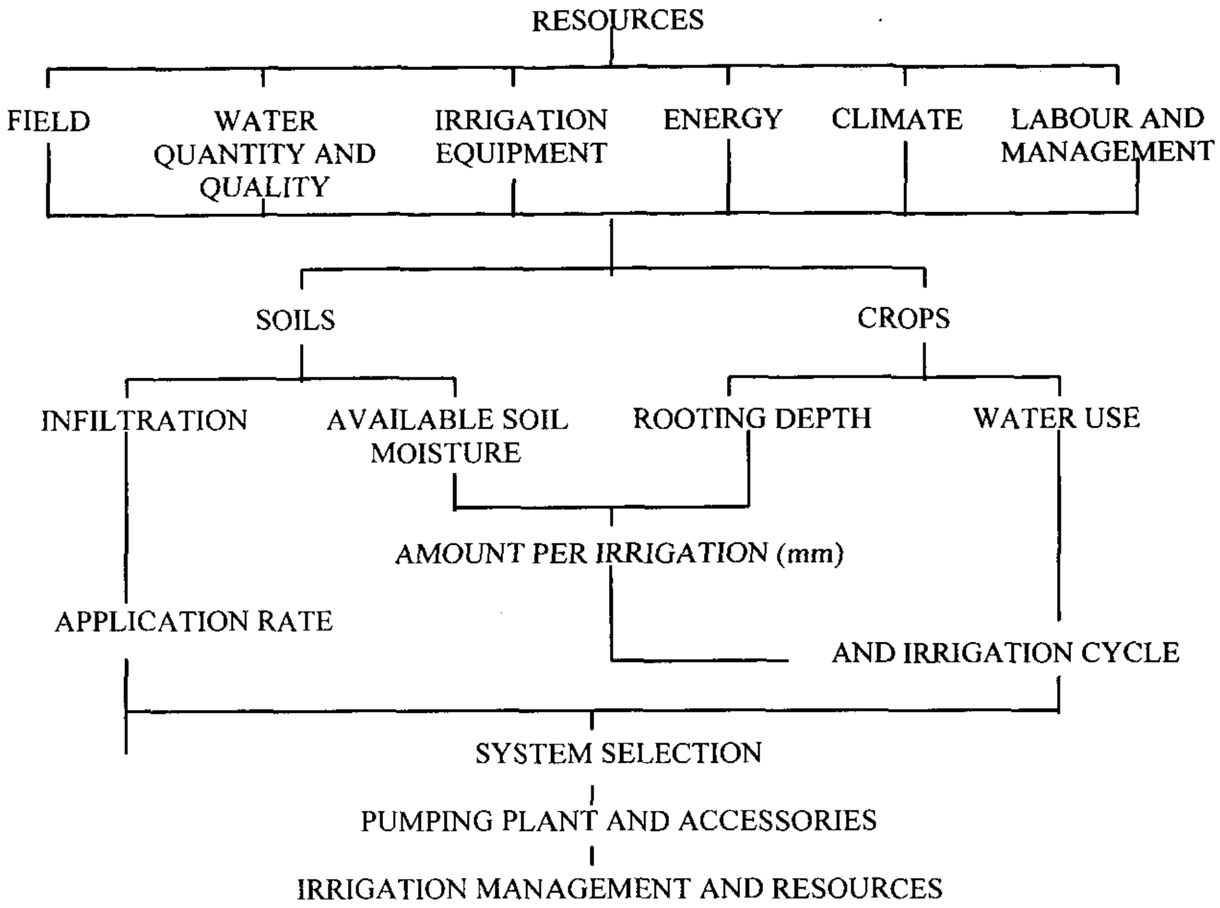


Fig. 2.2: Flow chart illustrating factors considered in irrigation system selection and management

When planning, designing and operating irrigation projects, production objectives must be related to existing physical resources, in order that required crop yields may be achieved. Furthermore, technical, economic and organisational factors must be manipulated in order to ensure a technically sound, manageable and financially viable project. The flow chart in Fig. 2.2 illustrates the major issues which should be considered in this process (Mottram, 1997 *pers. comm.*).

In 1983, Steinberg *et al.*, (1983), reviewed USAID irrigation projects and concluded that lack of good planning and management are the principal reasons that most irrigation projects fail to attain their potential. Although irrigation normally improves yields, it is not a simple matter to ensure worthwhile financial returns and alleviate food shortages. Encouraging farmers to plan carefully undoubtedly improves management. Existing irrigation boards should be encouraged in this regard. Steinberg *et al.* (1983) found that irrigation project planning is subject to a series of pressures which induce hurried decisions. Lack of success includes failure to consider adequately such facilities as farmers' needs, host country commitment, agronomic realities, social context, past performance, intrusion into fragile environments and inefficient markets, etc.

Skogerboe *et al.*, (1982) attempted to improve on-farm water management in irrigation schemes in developing countries by considering two themes, viz. a) an interdisciplinary approach and b) a farmer-client involvement. Agriculturists and social scientists must co-operate with farmers to overcome constraints and increase agricultural productivity.

Bergmann and Boussard (1976) and OECD (1985) proposed an interdisciplinary approach for management of water projects which integrates economic, financial, social and environmental aspects. The inadequacy of methods, attitudes and practices in management constitutes a major obstacle to efficient management of water. Dielman (1984) suggested that, instead of funding irrigation projects, existing management institutions and evaluation procedures should be improved.

Manig (1984) reported that the type of irrigation technology applied in developing countries is critical. Only very rarely do technical factors call for capital-intensive large-scale projects. Manig (1984) maintains that in large irrigation schemes, organisational water distribution problems lead to an underutilisation of production potential. He recommended small, individually or commonly organised schemes which strengthen private land ownership and contribute towards a higher water-use efficiency via diversification of land use.

Lynch (1984) found in his review of small-scale irrigation experiences that participation in irrigation activities takes different forms and occurs in association with one or more project phases, including initiation and planning, construction, system operation and repair. The physical environment, community social structure, regional and national economic and political structures have a pronounced impact on levels of participation. Local organisations must have accountability to their constituents and the ability to interact with development agencies. The agency role in irrigation project development is found to be a critical factor in the success, or failure, of local organisations (irrigation boards).

As the demand for water increases, the efficient conveyance of agricultural water in canal systems becomes a priority. In Southern Africa there is a tendency toward a higher water demand per unit area. Reid, Davidson, and Kotze, (1986) and Reid, Davidson, and Grift (1987) pointed out that increasing canal capacities to meet these higher demands is often extremely costly. They suggested that decreasing water losses from existing canal systems is perhaps the only way, as additional water is not readily available to agriculture. Also, in order to decrease losses from existing canal systems, a detailed knowledge of every loss causing factor is required initially. Once these have been defined and quantified, a meaningful decision can be taken regarding the most efficient remedial action. Reid *et al.*, (1987) provided successful methods of defining and quantifying conveyance losses, and, proposed remedial methods which had been tested successfully.

Studies in the United Kingdom (Howarth and Benn, 1986) on water management in small-holding irrigation schemes have shown that the supply of water to farmers is both unreliable and unquotable. The causes for this rest both in the main supply system and farm level management. Improving the efficiency of the main system is a prerequisite to tackling the other problems. Howarth and Benn (1986) developed a computer model to simulate the operation of such projects. This model is designed to give the project manager reliable information on the status of the system, and to assist in optimising irrigation schedules. The rationale of this model is that the project manager should provide reliable and timely water supplies to blocks of farmers. Management within these blocks remains the responsibility of the farmers themselves.

Clemmens and Dedrick (1984) found that on-farm water use is affected by delivery flexibility and uniformity of water deliveries. Upgrading of farm irrigation systems may require improvements in delivery flexibility and uniformity. However, increasing the delivery flexibility may result in less uniform deliveries, which may also reduce the operational capacity of the delivery system unless the system were upgraded. Improving the overall water use within an existing project will also require improvements in farm water management, delivery control and canal system management.

Irrigation boards can be a vehicle for promoting and enhancing water development and improved water distribution and use in Southern Africa. Anderson (1984) found little interaction or co-ordination of the public sector with private sector efforts and parallel systems of water management and delivery.

The traditional concept of an irrigation project has changed. Purely from a physical structure for storage, conveyance and distribution of water, it is now regarded as a more complex system. This implies improved management in all phases from dam operation to farm management, i.e. from "operation and maintenance" to "operation, maintenance and management". Perreira (1988) showed how research through modelling can be orientated towards improved management, regarding the conveyance and distribution systems, as well as the on-farm systems. Together with the technical problems which need solving, the involvement and participation of the farmers must be improved at all levels of management.

An important element determining crop production under irrigation is balancing available and required water supply over time and area. When the available water supply is adequate and fully meets crop water requirements, the production is maximum and the supply depends upon the crop selected, the length of the growing season, and the area irrigated. When available water supply is limited, production is determined by the extent to which the full water requirements can be met by the available water supply over each phase of the total growing season.

To accommodate these aspects, Doorenbos and Kassam (1979) proposed that when planning, designing, supplying and distributing water for an irrigation project one should consider:

a) selection of crops and crop rotations;
b) peak supply requirements (weekly to monthly); and
c) the scheduling of irrigation water supply over the growing season.

When water supply is limited, selection of crop and irrigated area should be based on ensuring crop water requirements are met by the available water supply over the entire growing season. With stress sensitive crops, scheduling of the water supply must be based on meeting full crop water requirements. With less sensitive crops, scheduling can be based on minimising water deficits during the most sensitive growth stages.

Benadé (1993) and Benadé, Annandale and Van Zijl (1996) have developed a computerised database for administering and managing water distribution on irrigation schemes where demand irrigation is practised. The programs are designed to manage water distribution to clients. Outputs from this project will be aimed at providing decision support useful to such database particularly regarding optimal water requests in times of water restriction.

CROP WATER-USE EFFICIENCY

Taylor *et al.* (1983) summarised the relationships between crop water use and crop production. Although many specific relationships between dry matter production and crop water-use have been proposed, much uncertainty still exists in quantifying the relationships for many crops, soils and climates.

Howell and Musich (1985) pointed out that dry matter production is closely related to crop evaporation and light interception. Ritchie (1983) suggested that the relationship between crop evaporation and dry matter production may be indirectly due to various management practices such as fertility, plant population, etc.

Research aimed at highlighting this relationship has been guided by various notions of what constitutes a "desirable" level of water use. Vaux and Pruitt (1983) identified three general definitions of desirable level, viz.

a) Establishing the levels of water input necessary to achieve maximum yield per unit area (i.e. AED).

b) Maximum crop water-use efficiency which exists when the crop yield per unit of water input is maximised.

c) Economists argue that water applied should be increased up to the point where the price of the last unit of water applied is just equal to the revenue resulting from its application.

De Jager *et al.* (1987), and Vaux and Pruitt (1983), argued that these various goals are inconsistent with each other. With all other variables held constant, yield (Y) is a function of water (W);

$$Y = f(W) \tag{2.14}$$

This relationship is called the crop-water function. Then, the average physical product (APP), sometimes termed crop water-use efficiency, is the total output divided by the total input,

$$APP = Y/W \tag{2.15}$$

and, the marginal physical product (MPP) the change in yield, or output, associated with additional applied water,

$$MPP = \Delta Y/\Delta W \tag{2.16}$$

Vaux and Pruitt (1983) stated that the yield is maximised when the MPP is equal to zero and APP is maximised where MPP is equal to APP. Consequently, maximum water-use efficiency (APP) and maximum yield could only coincide if Y is a linear function of W. Although some authors (see for example Crosby, (1996) report straight line relationships, linear functions can only be offered as a rough first approximation.

De Jager *et al.* (1987) were able to maximise profit with respect to water application. For maximum profit the following must be true:

$$MPP = Pw/Py \tag{2.17}$$

where,

Pw = price per unit variable input,

Py = price per unit output.

Hexem and Heady (1978) showed that water is applied efficiently when the value of the marginal product (MPP times crop selling price) is equal to the cost of the water. They also showed that profits, can only be maximised when APP>MPP and MPP>0. Vaux and Pruitt (1983) stated that economic efficient production can only be coincident with maximum physical production when water does not cost anything.

Ayer *et al.*, (1980) suggested that optimum irrigations could occur when water limits yield. This implies that carefully managed water deficits might reduce the use of water for irrigation without necessarily unduly paralysing yield and profits. Such strategy can only be adopted if precise management is practised. For this complete and comprehensive information on the consequences of differing levels and timing of water application on yield must be available. De Jager *et al.* (1987), described how a CGM might be applied to achieve this.

Profitt *et al.* (1985) found that high frequency irrigation of spring wheat caused the development of a shallow rooting system by comparison to plants subjected to low frequency irrigation. Low frequency irrigation developed deeper roots and efficient extraction of soil water, but total water uptake was insufficient to ensure transpiration at the potential rate. Thus, high yields and good water-use efficiency were obtained with high frequency irrigations, provided no water stress occurred during any stage.

Marais (1985) found that irrigation, when the soil plant available water had been depleted by 73-75 per cent, did not significantly reduce wheat yields and that water-use efficiency, and utilisation of water from deeper soil layers was increased.

Meyer *et al.*, (1987), in comparing measured and estimated water used by irrigated wheat, found that the upward flux from a water table between 1.2 and 2.1m below the surface could contribute up to 30 per cent of daily evaporation. Such upward flux will need to be taken into account if efficient use of irrigation water is a goal.

Botes (1994) used a CGM to show that the most important information a farmer could be provided with a view to maximising the utility of an irrigation system is a forecast of soil water content.

Bennie and Botha (1986), in comparing the effects of conventional tillage with those of controlled traffic during seedbed preparation of a sandy soil, which included deep-ripping the subsoil, found a significant increase in both water-use efficiency and the yield of irrigated maize (30%) and wheat (18%), with controlled traffic.

Eck (1986) stated that, although profile modification of a clay loam, under conditions of limited water, increased water-use efficiency of grain sorghum and lucerne, this was not the case with wheat. Henggeler (1988) found that frequent irrigations maintaining a high soil water depletion level with trickle irrigation increased average lint cotton yields from 685 to 868 kg ha^{-1} and irrigation water-use efficiency from approximately 10 to 15 kg m^{-3}.

Vaux and Pruitt (1983), concluded in their review that crop-water production functions (relationship between yield and applied water) have not been studied sufficiently, and surmised that this relationship could be curvilinear. Such relationships are relevant to irrigators, as applied water, and not crop evaporation, is under the control of the irrigator. As long as water remains relatively inexpensive, irrigators have little incentive to economise on water-use by for example permitting water deficits which limit production. A general conclusion was that water would be used more efficiently if it were priced according to its true scarcity value.

WEATHER STATION NETWORKS

Recent developments in electronics have found application in estimating irrigation requirements at both the research and field application levels. Electronic datalogging has enabled researchers to compute accurate, reliable estimates of real time values of reference evaporation from hourly weather data (Snyder *et al.*, 1985).

The California Irrigation Management Information System (CIMIS) is the major irrigation management programme of the California Department of Water Resources (Hawkins and Craddock, 1985). CIMIS provides Californian farmers with daily reference evaporation estimates, based on hourly computations using a combination equation. Automatic weather stations (AWS) are used in CIMIS because they speed up the data gathering process, eliminate loss of data due to human error and allow for the calculation of crop evaporation from hourly weather data.

In the past automatic weather stations have been powered by solar energy independent of any telecommunication system. Data were then usually stored on magnetic tapes until the station is serviced. The tapes may be down-loaded by tape readers onto computers. At present power is generally available, data and operating commands can be transmitted via modems and telecommunications networks enabling access to remote sites.

A typical AWS is one configured to monitor wind speed and direction, incoming solar radiation, rainfall amount and intensity, temperature (air and/or soil) and relative humidity. The sensors used to monitor these climatic variables are installed (Hawkins and Craddock, 1985) as follows:

Incoming solar radiation (2m above grass)
Temperature (air - 1.5m above grass, soil - 150mm below soil surface)
Relative humidity (1.5m above grass)
Wind speed and direction (2m above grass)
Rainfall (1 m above grass)

The AWS maintenance manual in the CIMIS programme Hawkins and Craddock (1985) requires site visits every two weeks during the growing season and sensor calibration twice per annum. Visits entail mowing the grass, cleaning the sensors and checking their operation. Hawkins and Craddock (1985) noted that this maintenance programme resulted in 43 AWS being operated with less than 2% down-time. The net radiometer provided the most problems. Their plastic domes break down in sunlight. The humidity sensor (capacitance type) was also prone to failure mainly as a result of dust, chemicals and salt in the air.

Choosing an ideal site is important but not always possible. A large well-maintained pasture with the weather station in the middle is required. It should be representative of the surroundings, but also convenient for maintenance. Furthermore, once operators are educated as to how valuable are the outputs of these stations, the AWS could well be placed in more appropriate but less accessible sites.

The CIMIS network collected daily data by computer via telecommunications network and modems Beginning midnight each day, the computer would automatically interrogate weather stations in turn and download hourly weather values. However, CIMIS did experience problems with line failures which caused delays. A similar, however, not insurmountable problem, is envisaged in South Africa, especially with the smaller country exchanges which are not yet automatic.

Dissemination of CIMIS information is achieved by:

a) direct access 24 h a day via computer and modems;

b) printed form - monthly summaries of daily means;

c) monthly newsletters (CIMIS Update) which also contain tables of current, normal and previous year's evapotranspiration values and rainfall; and

d) the press, television and radio;

In South Africa, the Weather Bureau and Agriculture Research Council hold and update climate data and, with the now expanding automatic weather station network real-time data should hopefully become readily available. Weather data are also stored at the Computing Centre for Water Research (CCWR) at the University of Natal, Pietermaritzburg.

IRRIGATION SCHEDULING

The factors influencing the decision when to irrigate are all encompassing. They involve water supply, crop type, crop development stage and water requirements, irrigation system, soil data, weather data, price relationships of inputs versus outputs, irrigator risk aversion, electricity supply, salinity control, quality of the harvest, and labour.

Doorenbos and Kassam (1979) report that the distribution of a limited water supply must be correctly apportioned over the different crop growth stages. Irrigation scheduling should be aimed at minimising water deficits during most stress sensitive growth stages. For most crops these are the initiation, flowering and yield formation stages. When water supply is limited, but fully controlled (e.g. supply from a dam), the irrigated area at that time is primarily determined by the amount of water available. When water supply is limited, but uncontrolled (e.g. supply from a river), the irrigated area at that time is primarily determined by the available supply at the time of maximum atmospheric demand.

Of many methods, the soil water budget technique has been identified as the one most likely to be adopted by irrigators with a view to improving irrigation scheduling (Coord. Comm. Irrig. Res., 1982; De Jager *et al.*, 1982; Hawkins and Craddock, 1985; and, De Jager, van Zyl, Kelbe and Singels, 1987).

California has numerous private irrigation scheduling services. The pre-CIMIS survey (CIMIS, 1985) indicated that the majority of growers were hesitant to employ these services. Mainly moderately large farm operators, unable to afford the services of a full-time irrigation specialist, who recognise the importance of irrigation management, employed private agencies. Large operators employ their own specialists, while the smaller farmers developed their own techniques. One of the main purposes of the CIMIS project was to make it profitable for private scheduling services to add small farming operations to their clientele thereby increasing the number of farmers practising sound irrigation scheduling.

Bennie *et al* (1988) developed a computer model for generating pre-season fixed irrigation schedules, using historical means of crop water evaporation.

Computer owners seek to make full use of their investment and hence it is likely that irrigation scheduling, using inexpensive user friendly software and crop evaporation information, will become popular. Hindering the expansion of irrigation scheduling in this manner, is the extra time required to manipulate real-time data which leads to a reduction in other farm activities. For such situations a pre-season schedule, based upon historical means of crop evaporation (Green, 1982; CIMIS, 1985; Bennie *et al*, 1988; Crosby 1996) offers a viable alternative. All irrigation scheduling program seem to be difficult to apply arid require to be preceeded by an instructional course.

SOME GENERAL CONCLUSIONS

Current computer technology has significantly simplified and expedited estimation of crop water requirements. Suitable data bases are available, and reliable and accurate monitoring of weather data a reality. Energy budget equations can be used in the field to estimate crop evaporation and contribute towards the optimization of water distribution on irrigation projects.

In Southern Africa, automatic weather stations are being installed in increasing numbers. Weather station networks provide real-time weather data for use in irrigation planning and scheduling. Validated crop growth models are available for these purposes. Furthermore databases for research and advisory bodies are developing rapidly. On-farm water-use and economic efficiency, are promoted by collecting weather data using automatic weather stations and applying them together with the necessary soils and crop data together with price of products and variable cost of water applied.

It appears that potential exists for applying a central computer and the methods described to particular water supply and irrigation situations in order to attempt to determine the most efficient distribution of water. Irrigation boards are currently using simple water allocation methods (Mottram and De Jager, 1994) which, in times of water shortages, could lead to dissatisfaction and dissent within its community. Such problems would be solved by supplying the necessary real-time data and provide water managers with computerised IDSS.

It is evident that irrigation boards would be greatly assisted in their decision making by:

a) estimates of the amount of water needed to be allocated to each registered area in order to maximise profits for the individual and the group,

b) a water allocation strategy which takes between-crop and within-crop growth stage sensitivity to water stress into account, when water restrictions apply as a result of drought and crop-water requirements cannot fully be met.

SECTION II NETWORK DEVELOPMENT

CHAPTER 3

A NETWORK FOR SOUTHERN AFRICA

INTRODUCTION AND OBJECTIVES

Introduction

In developed and developing countries, irrigation is scheduled using different levels of expertise. These range from small, low-input endeavours to sophisticated extensive commercial operations. Irrigation managers and advisors can be university graduates, or virtually untrained irrigators at farm level. Accurate, disciplined irrigation scheduling technology is required offering exciting opportunities for saving water. The desired scheduling methods need to be inexpensive, simple and convenient to apply; must conserve water and accommodate numerous clients.

Initially a network was established to obtain experience in this type of enterprise. The group which undertook the work of scheduling on the network was named the Irrigation Scheduling Unit (ISU). It was operated by two advisors supported by a varying contingent of assistants.

Objectives

The objectives of this section were to:

i) Determine which type of network would be best suited for Southern Africa.

ii) Establish a network which includes numerous types and size of farm, and

iii) Improve the data network system where necessary.

Comment The network and data transfer technology developed and established under objective (ii) was shown to function most efficiently. It is thus not necessary to report on item (iii)

DESCRIPTION OF THE NETWORK

The best way of serving a large number of irrigation farmers was found to be the use of crop growth models, CGM, and data from automatic weather stations, AWS.. The latter should be placed centrally in different groups of farmers. Given uneven topography it was found that macro-weather data from a single AWS were representative of an area bounded with a radius of 50 km. The decision support technology (DST) software package, Putu, was used. It is described in Section III. A system meeting the objectives described above, was developed by participative research and management and leaned heavily upon experience gained over the past sixteen years by the Department of Agrometeorology in previous WRC Projects (De Jager *et al*, 1982, 1987 and Mottram and De Jager, 1994).

The weather variables monitored were those required by the Penman-Monteith equation, PME, viz. solar radiation, air temperature, relative humidity and wind speed. Data for estimating the onset of diseases and pests, thermal period, soil temperature and soil water content were also measured.

Hourly weather data were collected and daily summaries compiled at two central computing centres in Bloemfontein or Pietermaritzburg. The hours 04:00 to 06:00 proved to be most convenient for data transfer. To avoid congestion, each weather station was allocated a 15 minute time slot during which telephonic links could be established. Where possible, scheduling advisories were distributed on Monday \mornings.

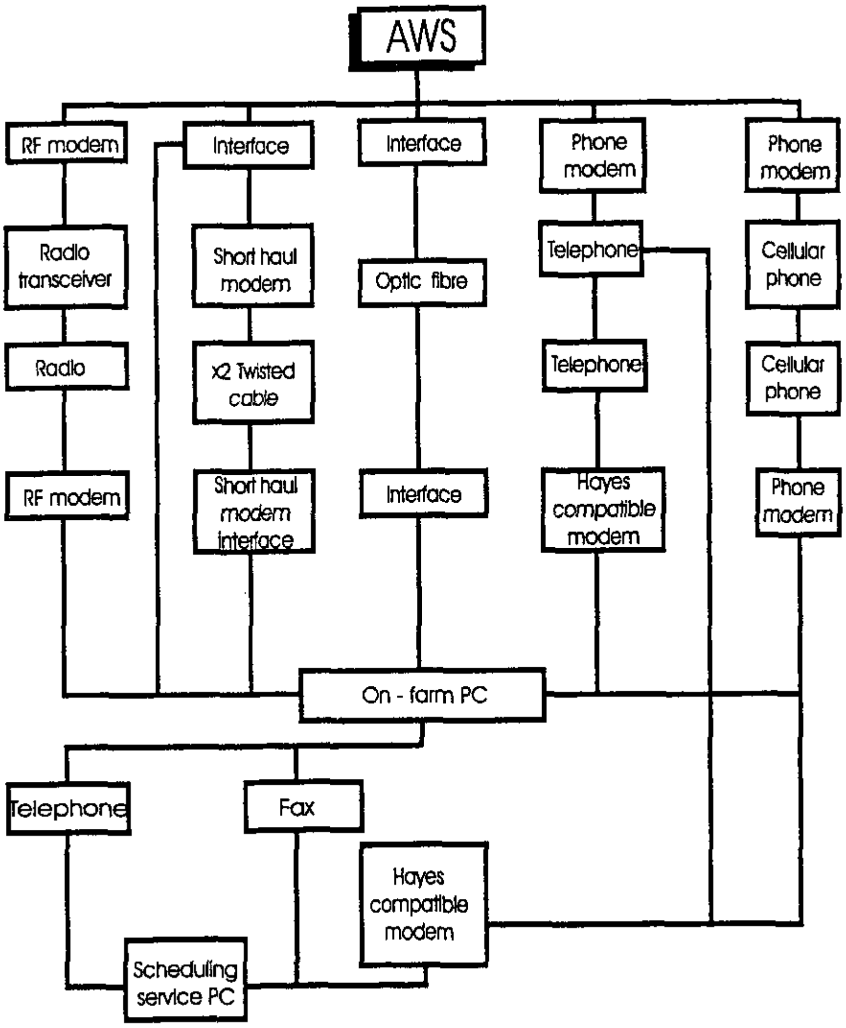


Fig. 3.1: Electronic information flow options for AWS-based irrigation scheduling at high and intermediate DST levels.

Each client was expected to return daily records of irrigation amounts and rainfall accrued on each plot of land. Such data were usually collected each Monday for appending to the relevant computer files.

Electronic data transfer

According to the financial resources available, and the level of technology required by individual participants, data were transfered electronically by various means. These are illustrated in Figure 3.1 and include data transfer by audio tape, direct cable link to on-farm PC, radiotelemetry, direct telephone line (see Chapter 4). Future developments could see cellular telephone and satellite being introduced.

Computer procedures

Full details on how computations are carried out in Putu are given by De Jager and Mottram (1995). In brief, daily reference crop evaporation, E_o, is computed using the Penman-Monteith equation (PME) in the form recommended by the FAO panel of experts (Allen, Smith, Perrier and Pereira, 1994), and hourly AWS data. Thereafter, daily crop evaporation, E_v, and soil evaporation, E_s, are calculated for different crops and plots using E_o and appropriate crop evaporation coefficients. The crop coefficients are calculated from values of fractional radiation interception. Such interception values for a large number of different crops are already available, or can easily be estimated. Even inexperienced managers quite accurately estimate the percentage of foliage ground cover at midday using sunlight rays and these provide sufficiently accurate estimates of fractional interception. Nine values of fractional interception corresponding to nine different growth stages are required. Files containing texture and water holding information for each soil layer are also necessary for each plot of land. Because it is not site specific, thermal time (growing day-degrees) is the most convenient measure of crop age. However the option to use days after planting could also be made available.

System refinement

The Putu models were run and farm managers advised, on a continuous basis, how much and when to apply irrigation water. The performance of the models and data transfer system was continuously evaluated and the most effective data transfer and information dissemination systems developed. Particular aspects addressed were reliability, capability, scheduling criteria, service and backup, and costs of operations, maintenance and equipment.

Information transfer

Specially designed forms for rapid transfer of data and irrigation advice back to farmers have been developed.

Each day, the advisor is presented with a computer update of plant and soil water status for the preceding seven days as well as a forecast for the ensuing seven days. Having scrutinized these, the advisor decides upon the amount of water to be applied and an approximate irrigation date. Forecasts are based on average long term crop evaporation rates, the water holding capacity of the relevant soil type and the stage of development of the crop. Advisories are transmitted to the farmer per telecommunications network, or on hard copy via telefacsimile.

Fig. 3.2: Distribution in southern Africa of AWS sites at which irrgation scheduling advice is provided from Bloemfontein and Pietermaritzburg.

Extent of the irrigation scheduling system

The system developed, consists of irrigation advisors in Bloemfontein and Pietermaritzburg who are telephonically linked to various participants. The telecommunication network has grown steadily. Its present size is illustrated in Figure 3.2, with a service planned for Tanzania. Approximately 125 clients and 1900 plots of land (295 intermediate) were irrigated from centres at Bloemfontein and Pietermaritzburg. Similar operations run by three farming cooperatives and the Free State Department of Agriculture are included in these numbers, but were not part of this project. In this project, some 34 AWS were in operation for scheduling irrigation.

Examples of locations and crops on which the ISU provides irrigation information are:

Karkloof, KwaZulu-Natal : irrigated pastures
Winterton, KwaZulu-Natal : maize, soyabeans, wheat, peas, dry beans, potatoes and pastures
Sheridan, eastern Free State Province : potatoes, apples and asparagus
Reitz, eastern Free State Province : potatoes, runner beans, tulip bulbs and peas
Simunye, Swaziland : sugarcane
Mooketsi, Northern Province : tomatoes and onions
Taung, North West Province : wheat, barley, cotton, maize
Molatedi, North West Province : wheat, peas and beans
IYSIS, Swaziland : citrus and other sub-tropical fruit
Harrismith, eastern Free State Province : seed maize, mange tout peas
Merton Park, Zimbabwe : maize, wheat and vegetable crops

Envisaged expansion includes:

Tambankulu, Swaziland : sugarcane, citrus
Big Bend, Swaziland : sugarcane, citrus
Kransfontein, eastern Free State Province : potatoes, asparagus
Clarens, eastern Free State Province : apples, cherries, beans, potatoes
Harare, Zimbabwe : potatoes
Komatipoort, Mpumalanga : citrus, plantations, and other sub tropical fruit
Delmonte, Cameroon : Bananas
Tanzania : diverse

Levels of DST and their computation

As the investigation proceeded, it became evident that in order to meet the needs of both low-input and commercial farmers two levels of DST were required. viz. intermediate level DST for low-input situations and high level DST for commercial operations. Computational procedures capable of meeting the demands of both levels had to be devised. They are depicted in Figure 3.3, and a brief description of the different levels of DST and conventional practice follows.

HIGH LEVEL DST

- Clients purchase, install and maintain AWS. Weather and irrigation data are transferred electronically to advice centres.
- The Putu model is run on near real time weather data up to the present date and then on forecasted weather data for the ensuing week. Soil water deficit and plant water stress index are predicted.
- The advisor proposes future irrigation based upon the computed predictions.
- Information on how much and when to irrigate is disseminated by telephone, facsimele or e-mail.

INTERMEDIATE DST

- Daily Eo is computed using the PME and weather data from a centrally sited AWS.
- Daily and cumulative Eo is displayed on notice boards or disseminated telephonically.
- Farm managers simply irrigate sufficient water to replace Eo.
- Some enterprising irrigators use appropriate crop coefficients.

These two procedures differ from conventional practices.

CONVENTIONAL PRACTICE

- Feel the wetness of soil samples, and/or
- Apply constant amounts of irrigation at fixed intervals.

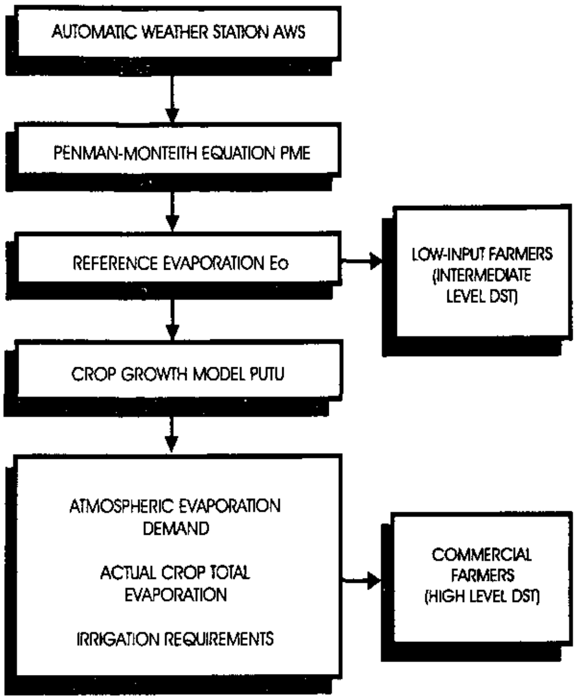


Fig. 3.3: Computational procedure accommodating both high and low level irrigation scheduling DST

CONCLUSIONS

It has been shown that efficient scheduling of irrigation can be achieved using the Putu IDSS based upon automatic weather station data and crop growth models. Water-saving irrigation scheduling advice has been transmitted from central computing centres linked by a telecommunication network to distant AWS's and farm managers.

Automatic weather stations enabled a computerised weather network to be established which collected water data and disseminated crop water-use values and irrigation amounts in sufficient time to enable irrigators to react before crop water stress prevailed with concommitant yield reductions.

Suitable software and hardcopy forms, etc. as required by the technology have been designed and are in use.

The technology is suited to extensive commercial as well as low-input small-scale operations. The major advantage of the system results from the fact that data from a single weather station may be applied to numerous neighbouring farms. This has significant cost and logistic benefits.

CHAPTER 4

INFORMATION AND TECHNOLOGY TRANSFER

INSTALLATION AND MAINTENANCE OF AUTOMATIC WEATHER STATIONS

The installation of the automatic weather stations is relatively simple, provided the person carrying out the installation is fully conversant with the programming procedures of the dataloggers and the specifications of the sensors involved.

Locally manufactured sensors have caused problems in data collection and require more maintenance and checking. Having continually to check the accuracy of sensors detracts somewhat from the benefits of remotely positioned automatic weather stations.

When operating with a large number of automatic weather stations, regular calibration of sensors imposes both time and technical problems. The calibration of a single automatic weather station situated close to a scientific/research institution is far easier than that of a remotely situated automatic weather station. What is necessary is to decide upon acceptable calibration frequencies, procedures and parameters. These parameters must include levels/bounds of accuracy that are acceptable to both the researcher and the operator in the field.

Regular checks are made by viewing the hourly outputs of the remote automatic weather station and significant differences are identified. Should these occur, it is imperative that the problems are rectified as soon as possible (within days). Surrogate data generated from reliable relevant long-term averages is used to substitute for missing data.

Maintenance of remote automatic weather stations is simple in that all that is required is regular cutting of the grass surrounds, replacement of insect repellents inside the tipping bucket rain gauge and cleaning of pyranometers. Where wet bulb thermometers are installed, the wicks need to be changed regularly, because accumulated dust causes inaccuracies.

INFORMATION RETRIEVAL AND DISSEMINATION

At the outset of the project it was deemed efficient and acceptable that all input and output data would be standardised, both in format and manner of retrieval and distribution. After some three months of providing a service, it became apparent that use of a standardised format was not always desirable or practical. The main reasons for this being:

- clients posess varying facilities (fax, computer, radio link, telephone)
- varying client requirements

- when a service is supplied at a fee, the service rendered is determined largely by the client.

Brief descriptions of the telecommunication links mentioned in Chapter 3 follow.

Radio link

Use is made of an RF modem and a low powered (5W) transceiver at the remote site and a similar transceiver connected to a PC via a base station modem. Up to 255 stations can be interrogated over a single UHF or VHF frequency. Any station may serve as a repeater to extend the line-of-sight transmission of the base station. Although the manufacturers claim line-of-sight transmissions of up to 45 km, only distances of up to 15 km have been attained locally. This could be as a result of frequency allocation and antennae compatibility. The Campbell (1991) radiotelemetry system was utilized. Radio links are very costly, but are excellent in their resistance to lightning damage.

Short haul modem link

These modems provide a local communication between the datalogger and a PC with an RS 232 serial port. Manufacturers claim sucessful data transmission over 11 km via two twisted pair cables. Surge protectors on both ends are recommended. These have been used over 2 km distances locally but are subject to lightning damage, even with surge protectors. Buried cable is also susceptible to damage, especially under agricultural conditions. Suspending the cable overhead renders it very susceptible to lightning damage.

Direct cable link

Using four-wire screen cable connections from an RS 232 interface at either end has proved successful over distances of up to 1 km of buried line. The majority of our links are of this kind, with recommendations that the PC end be disconnected when not in use. This link is susceptible to lightning damage when connected. Damage is usually to the interface and the PC's serial port.

Optic fibre link

Using optic fibre links with an interface at either end has proved very successful in linking the automatic weather stations to a PC. Communication distances have not been established to date.

Telecommunications link

(a) *Normal telephone link* - using a battery powered (12V DC) modem at the datalogger end and a Hayes compatible modem at the PC end, gives a good fast retrieval of data at any time. However, the link is extremely sensitive/susceptible to lightning damage especially at the remote site.

(b) *Cellular telephone link* - cellular communication requires subscription to a cellular network with coverage at the automatic weather station site. It is a convenient alternative for mobile applications, or for locations where ordinary telephone lines are not available and are too costly to implement. Cellular communication is advantageous over RF links/systems because it does not require allocated frequencies and on-farm PC's. It is also not as susceptible to lightning as the other links, besides RF. As southern African cellular communication is a totally digital network, modifications at the data logger end of the link will need to be made and are currently being tested. A PCMCIA adaptor is used at the PC end with a suitable cellular phone.

Retrieval of data

Data are retrieved from the automatic weather station in an ASCII format using PC208 software either daily, twice or three times a week, or weekly. Where on-farm PC's are used, a communications package (PC Anywhere) is used to access the on-farm PC, download the data from the automatic weather station and then transmit it to the service PC. All data from the automatic weather station is collected in a standardised format. Other on-site data such as irrigation amounts per block, rainfall amounts per block, soil-water data, penological data, canopy measurements etc., are sent either via modem, facsimile or telephone to the service base. This data is retrieved in various formats depending upon the client's management and administration system.

Dissemination of data

The Putu system displays current soil and plant water status and a forecast of when the next irrigation becomes imminent and prompts the operator to make a recommendation for each irrigation plot. This recommendation is then disseminated in the desired format, via differing communication links, to respective clients.

CHAPTER 5

ELECTRONIC DATA MANAGEMENT AND DISSEMINATION

MOTIVATION

Experiences with the Putu system and irrigation scheduling resulted in the evolution of a computer system whereby data are collected, stored and utilised for scheduling irrigation. The methods evolved differ slightly from what was originally intended, but the logistics associated with the use of the system brought about the modifications. Major reasons for the changed procedures were as follows:

1. An increasing number of clients expressed the desire to schedule irrigation by themselves and many needed only daily E_O values.

2. Where groups of participants purchased weather stations, they were keen to undertake the fair sale and distribution of weather data. The additional sale of weather data *per se* for generating additional funds from clients outside the group also became an objective.

3. The need to record and apportion an appropriate tariff according to frequency of access and time.

4. The introduction of disease indexes derived from weather data and the sale thereof, are highly desirable.

5. The provision of data under 4 so as to ensure effective response by managers to combat sickness and disease requires data to be readily available and distributed rapidly (if required).

6. The establishment of a single central data source for the management, sale and dissemination of data to clients.

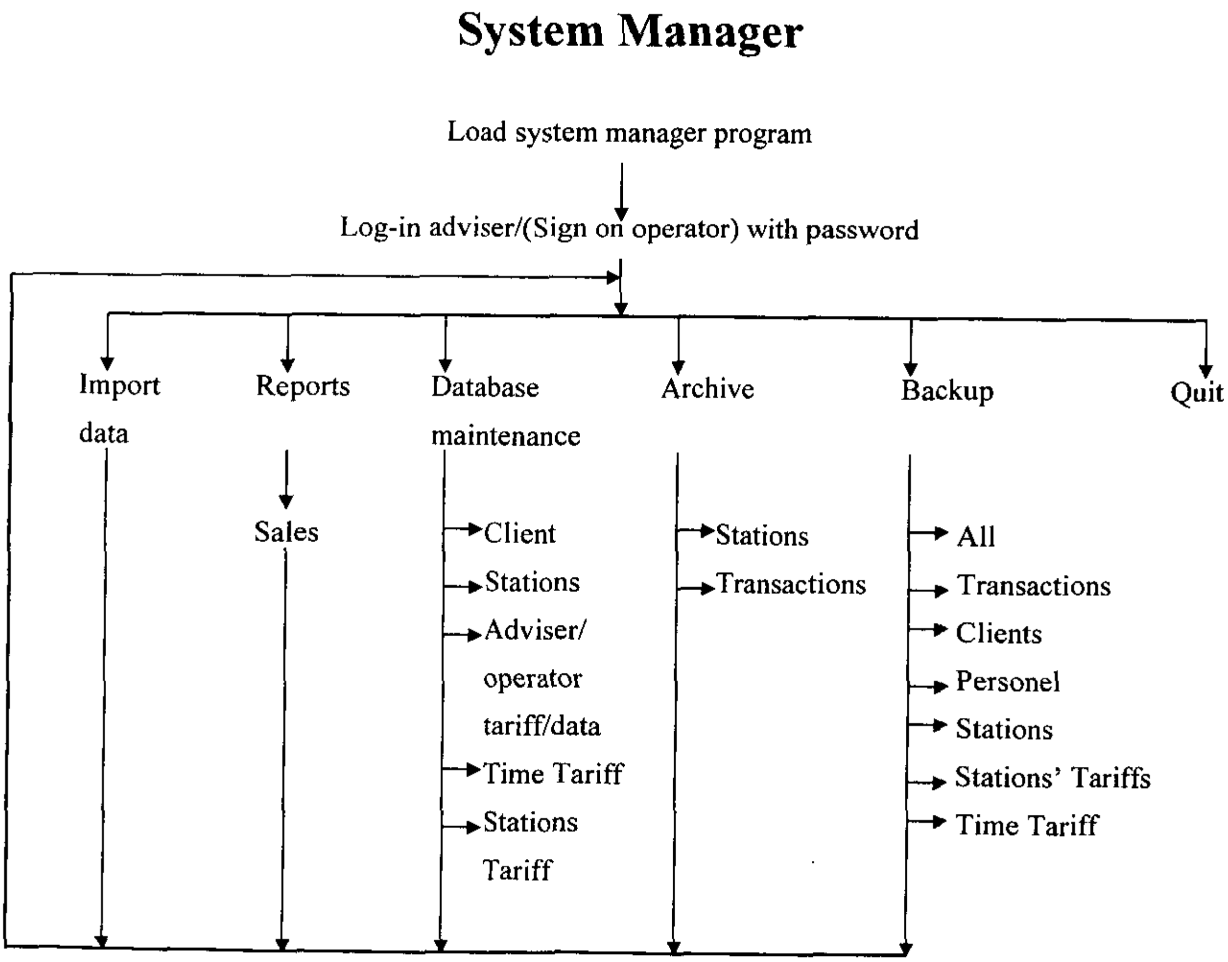
7. The need to record the names of personnel working on the system and their time allocated.

SYSTEM DEVELOPMENT COSTS

Kennedy Irrigation Consultants, at own expense commissioned Prof. Messerschmidt, of the Department of Computer Science of the University of the Orange Free State, to develop the system. The latter's fee at that stage, was beyond the means of Kennedy Irrigation. As a result a profit sharing agreement between the two parties was negotiated. This met with the approval of the owners of the weather stations, especially as the system was also to provide an automatic check on sales other than those undertaken by Kennedy Irrigation. This system is thus the property of Kennedy Irrigation and Prof. Messerschmidt.

SYSTEM DESCRIPTION

As a natural evolution out of this WRC project, and an example of present trends, a short description of the electronic data management is included by kind permission of its owners. The system consists of two main parts. The Database Manager and the System Manager. The latter manages the dissemination of data and controls sales and registration of clients. The second, the Database Manager, handles the compilation of raw data in ASCII format and its conversion to binary format. The flow diagram for the Data Base Manager part of the system is given in Figure 5.2, which schematically illustrates the manner in which data are collected and processed. It is evident that clients must register each time before accessing the programme. The latter then delivers whatever information is requested and automatically computes the cost thereof.



System Manager

Fig. 5.1: **System management options.**

The operator has three choices.

1. To log-out of the system

2. To register a new client, or
3. To permit an existing client to access data.

A new client is registered on a prompt from the programme, requesting the normal details expected, viz. the client's name and weather station password. To access weather data, the client enters any station number and the dates for which data are required. The requested data are then displayed on the computer screen. The client may request averages, totals, or maximum and minimum values for the relevant data series. The compiled data may then be transferred to the client either telephonically, or per telefacsimile. The client's job is then automatically logged, together with the time.

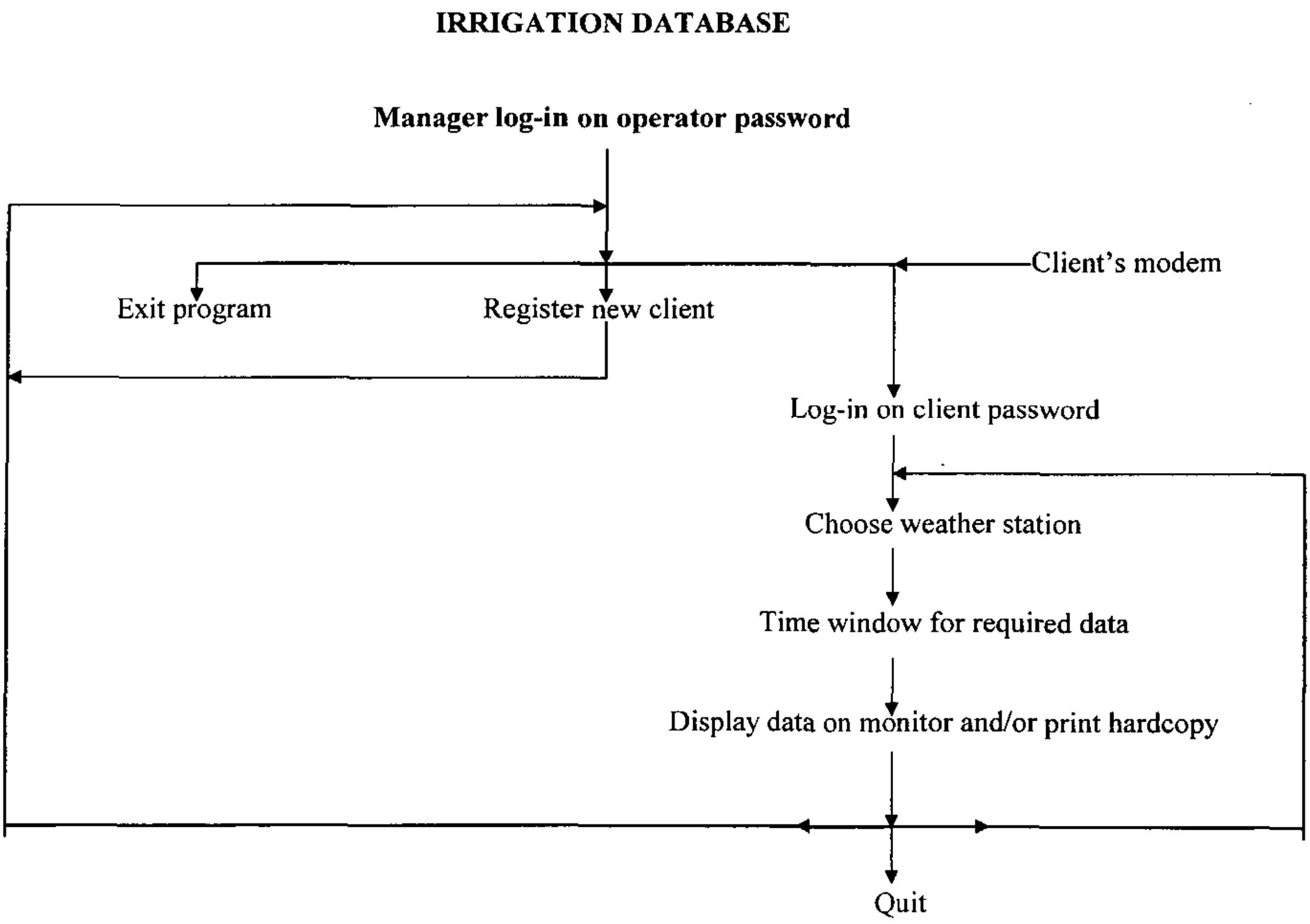


Fig. 5.2: **Flow diagram of the operations possible in the database manager.**

The System Manager allows the advisor, to access data from different weather stations may choose to transform data from ASCII to binary format. This is carried out by the command **IMPORT**. The second choice available is to view the sales report which lists transactions conducted by the various clients within any selected date window, or for any of the weather stations or clients. The relevant tariffs for data will be specified in the next section. The third option concerns client details listing station detail, personnel detail, tariff for operator or personnel time and station tariff, etc. and applicable tariff. The adviser may also at this stage, change any of this information. The tariff for each station may be adjusted each month to permit discounts for large volume data transfers. Obviously a fixed charge for transfer of a standard amount of data is possible.

The **time tariff** permits application of a price per unit time applicable to a given client. The **archive option** contains station and transaction data for compilation and storage. The **backup option** simply backs up the relevant data on stiffies or floppy diskettes. Both the Database and the System Manager can access the same database.

Advantages of the system

The ability to adjust the tariffs for weather data is a big advantage. It permits one to work within a given budget for a given month.

Future developments

At present the system is being modified to permit access from a modem and a network. The programme was developed for networking so that the databases may be available to several users simultaneously. An additional advantage of the use of modems, is the possibility that clients may access data without human intervention. A facillity whereby clients may off-load data files automatically via the modem onto their own computer was an urgent necessity.

DATA SALES THROUGH THE AGRIHUB SYSTEM

The implementation of Database and System Manager brought about a few problems:

1. According to Prof. Messerschmidt the creation of the necessary software for individual clients is an extremely expensive operation.

2. More than one telephone line will be required to meet the needs of all clients and this escalates expenses.

3. Multi-tasking of this nature can only be conducted through an expensive server system with a sorting capacity which will cost approximately R50 000.

An agreement has been undertaken between Kennedy Irrigation and Agrihub permitting Kennedy Irrigation to place data on the Agrihub National Electronic Telecommunication and Sales System. The Agrihub system has already developed the necessary software for the individual clients and already sells data and information to agricultural lists.

The advantages of the agreement are as follows.

1. Clients can now buy Kennedy Irrigation data. The number of Agrihub clients exceeds 300 at present.

2. Agrihub will provide Kennedy Irrigation with a "logfile" listing which keeps a record of clients' weather stations and the duration of access to the data files.

3. Agrihub has the capacity to exclude bad debt clients.

4. The appearance of Kennedy Irrigation on Agrihub will serve as an exciting promotion of the technology developed by WRC research and Kennedy Irrigation System.

5. The data sales through Prof. Messerschmidt's system serves as a backup for the Agrihub system and for clients without computers.

Additional Information

Together with the above-mentioned options, Kennedy Irrigation provides a description of a simple scheduling method which clients may use to schedule irrigation themselves. The option of utilising the specialist services of Kennedy Irrigation is also available, as is the option for clients using the specialist Kennedy Irrigation Putu system themselves.

The future work entails the development of a highly simple user-friendly method utilising only E_O as an input. In this approach, the client may schedule irrigation himself and need only purchase E_O values from Agrihub. The E_O values are computed by Kennedy Irrigation and the access programme developed by Prof. Messerschmidt.

CHAPTER 6

INSTALLATION AND MAINTENANCE OF AUTOMATIC WEATHER STATIONS

INSTRUMENTS AND CALIBRATION

For this project, Campbell Scientific Inc. CR10 data loggers are being used in all automatic weather stations (AWS) with both locally produced and imported weather sensors. The locally manufactured wind sensors repeatedly suffered bearing problems entailing lengthy repair delays. The wind monitors or wind sentry sets produced by R M Young are now being used and have worked satisfactorily to-date.

The radiation sensors (Li-Cor 200X) have operated successfully, but require routine re-calibration.

The temperature sensors, both local and imported, have performed satisfactorily and spot checks have indicated insignificant calibration variations.

Relative humidity sensors have in some instances tended to lose accuracy and develope hysteresis problems. Scientific P207 sensors have recently been successfully employed. In order to maintain accuracy, it is recommended that the sensor micro-chip be replaced on a yearly basis.

Calibration of the AWS and its sensors, although critically necessary, is time-consuming and consequently expensive. The maintenance of acceptable standards by researchers and consultants is an urgent requirement. At present there are several precision instruments which could act as calibration standards.

INSTALLATION

Where practically possible, all AWS are positioned in representative areas, with all obstacles/structures distant from the AWS at least ten times their height .

The sensors are installed in their respective enclosures at the following heights above uniformly growing grass cover:

Wind speed - 3 metres
Wind direction - 3 metres
Incoming solar radiation - 2 metres
Temperature and relative humidity
in either Stevenson or Gill plate screens - 1.3 to 2 metres
Rain gauge - 1.2 metres

In practice, it is difficult to obtain unobstructed fetch for anemometers (wind speed sensors). It was therefore decided to install anemometers as high as practicable because wind speed increases logarithmically with height and higher measurement points will tend to decrease errors.

The radiation sensors are positioned such that no other instrument or structure will cast a shadow across them at any time of the day.

The data logger, power supply and communication and recording systems are installed in a weather-proof enclosure. It is imperative that an insect repellant be placed in the automatic rain gauge and the weather-proof enclosure.

Correct earthing of all the sensors, data logging and communication equipment is essential. Earthing with copper strapping of thick wire and copper earth rods is recommended. With the exception of the terminal connectors, all other electrical connections should be soldered.

Where a direct cable link is employed, lightning arrestors should be installed at either end of the cable. Earth loops must be avoided. To date, this precaution has protected the AWS from lightning, but not the serial ports of the computer. It is recommended that, where practical, the cable is disconnected from the computer's serial port when not in use, or when electric storms are predicted.

Voltage surges tend to damage serial ports in computers. Integrated power supplies (IPS) have helped to protect against voltage surges. It must be noted that an IPS does not provide lightning protection.

The use of radio-telemetry has proved successful in avoiding damage due to lightning. Whereas direct cable links are considerably less costly than radio links, they are limited by distance. The maximum direct cable link used successfully to date is approximately 1 000 metres. The use of short haul modems at either end of the cable significantly increases the length of cable that might be used (manufacturers claim up to 5 km and more). They are susceptible to lightning damage however.

With the advent of global systems for mobile communication (GSM) and the availability of cellular telephone networks, the use of the latter is being investigated for communication with remote AWS and the transmission of data.

MAINTENANCE

The external maintenance of the AWS and their sites involve the following:

- regular cutting of grass surrounds
- cleaning radiation sensors with a fine brush and alcohol

- cleaning the rain gauge orifice especially during dry spells)
- replacement of contaminated (salt build-up) or dirty wet-bulb temperature probe coverings
- checking for and rectification of rust on the tripod/stand
- painting or refurbishing wooden Stevenson screens
- checking and rectifying if necessary, of earth and other relevant electrical connections for corrosion

LOCATION OF SOME OF THE AWS

Some of the AWS sites established include:

Station 4	Situated on J. Venning’s Swiss Valley Farm, Harrismith, Free State
Station 5	Situated on SAPPI nursery, Kwambonambi, Kwazulu-Natal on coordinates 32°04’E and 28°36’E
Station 6	Situated on G. Osler’s Lone Tree Farms, Sheridan, eastern Free State on coordinates 28°14’E and 28°38’S
Station 7	Situated on SAPPI research station, Tweedie, Kwazulu-Natal on coordinates 30°14’E and 29°28’S
Station 8	Situated on H. Saaiman’s Moedershuis farm, Reitz, eastern Free State on coordinates 28°26’E and 27°47’S
Station 9	Situated on Hancock Farms, Karkloof, Kwazulu-Natal on coordinates 30°14’E and 29°23’S
Station 10	Situated on D.B.A. Sclanders’ Clydesdale farm, Winterton, Kwazulu Natal on coordinates 30°14’E and 28°50’S
Station 11	Situated on R. Tratschler’s Rooidraai farm, Winterton, Kwazulu-Natal on coordinates 29°32’E and 28°50’S
Station 12	Situated on M. O’Brien’s Mary Pebbles farm, Winterton, Kwazulu Natal on coordinates 29°37’E and 29°06’S
Station 23	Situated in the Meteorological site, UOFS, Bloemfontein on coordinates

	26°07'E and 29°06'S
Station 31	Situated on the Mlaula Section of the Royal Swaziland Sugar Corporation estate at Simunye on coordinates 31°56'E and 26°13'S
Station 41	Situated on the ZZ2 Estate, Mooketsi, Northern Province on coordinates 30°10'E and 23°42'S
Station 48	Situated on the ZZ2 Estate, Dikgale, Northern Province
Station 50	Situated on Merton Park, Norton, Zimbabwe on coordinates 31°02'E and 17°48'E

These stations are all linked via telemetry to the research offices in Pietermaritzburg and the Dept of Agricultural Meteorology, UOFS, Bloemfontein.

Stations 4, 5, 7, 9, 10, 11, 12, 31, 41, 48 and 50 are linked directly via cable to on-farm PC's which in turn are connected to telephone modems. Station 23 is linked via a remotely controlled telephone modem to the office's PC. Station 6 and 8 are linked via radio-telemetry to on farm PC's which in turn are connected to telephone modems.

Direct links via cable and remotely controlled telephone modems are all sensitive to lightning. There is little or no protection available at this stage for remotely controlled telephone modems, whereas there exists reasonable protection for direct cable links. The cables must be buried and have lightning protection at either end immediately before the datalogger and PC respectively. To-date no lightning damage has been experienced with the links via radio.

The instruments connected to the AWS are exposed to a harsh environment and need regular calibration.

To collect the weather data from each remote station, the following procedure was followed:

a. Dial the remote PC via a telephone modem using PCAnywhere software.
b. Initiate a manual download of the data from the datalogger to the remote PC via a cable or radio telemetry using TELCOM software.
c. Transfer the data file from the remote PC to the central PC using PCAnywhere.
d. Any editor (Word, etc.) can be used to append the new data to an existence weather file.

e. The Putu IDSS has a routine for carrying out d) and transforming the data from datalogger format to a standard 14 column format which is compatible with the Putu irrigation model. It is called the IBSNAT file because it is identical to files used by the International Benchmark for Agro-technology transfer used in DSSAT (The Decision Support System for Agro-technological Transfer.

SECTION III PUTU MODELLING SYSTEM

CHAPTER 7

THE THEORY OF PUTU

In this chapter, the theory of Putu will be dealt with as follows:

(a) An introduction outlining the purpose and origins of the Putu model, its modular structure and listing of the symbols used in describing its theory.

(b) Descriptions of the theoretical basis for the various operations carried out by the program. Where appropriate, hints on how to introduce input data into the system are included.

1. INTRODUCTION

1.1 *General*

The crop growth process basically consists of the conversion of carbon dioxide to carbohydrate by solar radiation. All conversion processes are characterised by an efficiency. As the agriculturist's major objective is to increase production efficiency, the examination of the manner in which the environmental elements control this efficiency is most useful.

Broadly, the growth simulation model Putu, for each day of the growing season, describes the proportionate limitation on growth due to each of the climatic variables (see De Jager, 1976). Such an exercise permits the explanation and estimation of the expected yield from weather data; the definition of when adverse conditions occur, the determination of which environmental element was mainly responsible for retarding growth during a given period, and the degree to which a given element reduces the growth efficiency. Thus, Putu may be used for crop management decision making during the growing season; yield forecasting; multi-year climate risk analyses for efficient planning and policy making; and, for identifying research needs. It is particularly relevant for scheduling irrigation. The version to be described here is a modified form of Putu-Irrigate (De Jager, 1992) and is primarily adapted for this purpose.

Here follows a description of the mathematical equations and procedures included in the latest version of Putu-Irrigate as modified in 1997. The theory is described mainly by presenting the relevant defining equations, because these explain both the physical laws involved and assumptions made. Only artificial boundary conditions have been stipulated. The literature sources of the equations and concepts are given should the reader require further details.

In different parts of the program, integration of differential equations was carried out using Eulers's (1^{st} order) method, or the finite differences method. Errors for both over day iterations are usually small enough to be negligible.

1.2 *Modular Structure*

The basic structure of Putu was designed by De Jager and King (1974) and De Jager (1974). The basic modules are depicted in Fig. 7.1. The model was written in Quick Basic and a version in language C is now also available. A major advantage of the Putu Model is its subroutine structure. Each of the operations carried out by the model is undertaken in an independent subroutine. This offers great modelling flexibility as modellers may now alter any subroutine, or even introduce routines from a foreign model and test them without influencing the other operations. The Putu operations tree is shown in Fig. 7.2. It is evident that it encompasses the essential processes common to virtually all crop growth models. Hence interchange with and linking to other models is simple.

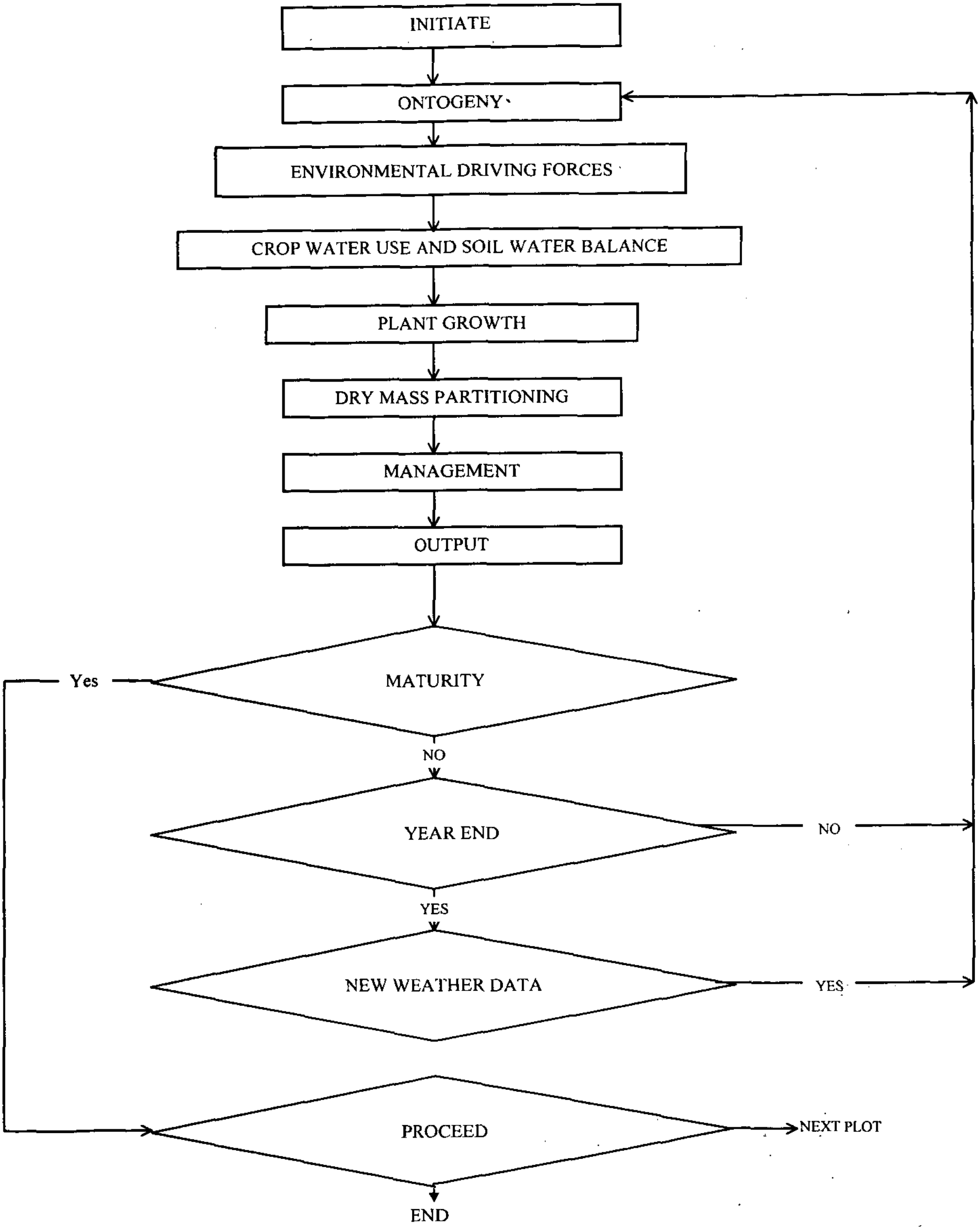


Fig. 7.1 Schematic diagram outlining the modules in Putu, a programme for computing the seasonal water use, growth and development of different crops.

Fig. 7.2 The Putu operations tree - each operation is carried out by one of the subroutines listed

THE PUTU OPERATIONS TREE

INITIATE
- Mechanistic functions
- Initial Conditions
  - Experiment Manager
  - Soil
  - Initial Soil Water
  - File names
  - Input within season Data Adjustments
- Edit
  - Heading
  - Titlepage
  - Tableheading
  - Computation
  - OPENoutputfiles
  - ZERO
  - Calendar

PARAMETERS AND WEATHER DATA INPUT
- Cultivar Characteristics

DRIVING FORCES
- Evironmental Variables
- Weather Data Input
- Input
- Daylength
- Potential Crop Evaporation

WATER BALANCE
- RootDevelopment
- SoilWaterPot
- SoilRootCond
- ReWetSoil

ONTOGENY
- Trigger Stage1
- Trigger Stage2
- Trigger Stage3
- Trigger Stage4
- Trigger Stage5
- Trigger Stage6
- Trigger Stage7
- Trigger Stage8
- Trigger Stage9

PLANT GROWTH
- Leaf area development
- Partitioning

MANAGEMENT
- Schedule Irrigation
- In-season adjustments

OUTPUT
- Totals
- Means
- Record season
- Write Result
- Update
- Mean D
- Summary

ZERO
- Close end

1.3 *Symbols*

Note, where symbols used to develop theory, differ from the symbols which appear on the computer screen, both are given, eg. f_g and F_g. Conventional usage of mm for rainfall or irrigation volume in fact implies mm per m^2 of ground surface. Thus both units mm d^{-1} and mm d^{-1} m^{-2} will be quoted in the text. Furthermore, mm = mm $m^{-2} = 10^{-3}$ m^3 = litres. For volumetric soil water content, also mm m^{-1} implies mm m^{-3}.

The symbols used to describe the theory of Putu are defined as follows:

AED	atmospheric evaporative demand	(mm d^{-1})
AW	plant available water	(mm)
C	crop growth rate	(kg ha^{-1} d^{-1})
C_m	maximum crop growth rate	(kg ha^{-1} d^{-1})
C_p	specific heat at constant pressure	(J kg^{-1} $°C^{-1}$)
$DRAIN_n$	drainage out of soil layer n	(mm)
DOG	days of growth since sowing	(d)
$e_a (T)$	saturation vapour pressure at temperature T	(kPa)
e_d	atmospheric vapor pressure	(kPa)
E_o	reference evaporation rate	(mm d^{-1})
E_s	soil evaporation rate	(mm d^{-1})
E_v	vegetation evaporation rate	(mm d^{-1})
E_{vo}	potential vegetation evaporation rate	(mm d^{-1})
E_w	evaporation from wet soil surface	(mm d^{-1})
E_d	evaporation from soil surface not wetted by irrigation	(mm d^{-1})
f	fraction of a given entity	( )
f	fraction of incoming solar radiation intercepted by the vegetation,i.e. fractional solar radiation interception	( )
F	the rate of a given process relative to its potential, or maximum rate, also termed, relative rate	( )
F_s	surface dry-down factor. The fraction of potential soil evaporation rate permitted during drying of top 150 mm of soil	
F_h	fraction of total dry mass yield which is harvested (Harvest Index)	( )
f_g	fraction of potential plant evaporation (assumed equal to the fraction of ground surface covered by the vertical projection of green leaves i.e. $f_g = FI_g$)	
FI_g	observed fraction of ground surface covered by vertical projection of green leaves in canopy	( )

$\overline{FI}$	observed fraction of ground surface covered by vertical projection of all leaves in canopy	( )
f_c	fraction of ground surface covered by vertical projection of the canopy outline	( )
f_w	fraction of ground surface area wetted during irrigation	
f_r	fraction of ground surface area beneath which roots extract water	
f_{sen}	fractional interception by senesced leaf material	
F_v	relative (to potential) vegetation evaporation rate (Ev / Evo)	( )
F_{ro}	fraction of rain lost as surface run-off	
G	soil heat flux	(W m^{-2})
g	soil-root water conductance	(mm d^{-1} kPa^{-1})
G_l	lateral water conductance in soil	( )
G_0	maximum soil-root water conductance per unit volume of soil	(mm d^{-1} kPa^{-1} m^{-1})
Inf	infiltration through the soil surface	(mm d^{-1})
Irr	daily irrigation	(mm d^{-1})
K	canopy extinction coefficient	( )
K_g	rate coefficient for evaporation from green leaves	( )
k_b	relative plant evaporation with a dry soil surface (screen symbol)	( )
k_c	whole crop evaporation coefficient (includes contribution from soil)	( )
k_s	soil evaporation coefficient	( )
k_v	vegetation evaporation coefficient	( )
k_{vo}	vegetation evaporation coefficient for crops with complete cover and no water stress	( )
k_{so}	maximum soil evaporation coefficient	( )
k_y	relative yield decrement per unit relative vegetation evaporation decrement, i.e. yield-water stress ratio	( )
L	leaf area index	( )
L_g	leaf area index of green leaves	( )
LAR	leaf area ratio (green leaf area per unit total plant dry mass)	(m^2 kg^{-1})
δ	slope of the saturation vapour pressure vs. temperature curve	(kPa $°C^{-1}$)
α	empirical constant of proportionality for reference evaporation on temperature	($°C^{-1}$)
γ_{20}	number of leaves appearing per day at 20 °C	(d^{-1})
DOY	day of the year counted from January 1 = 1	(d)
F_{nos}	expected proportion of total dry matter in plant organ n at the end of each growth stage	( )

g_{on}	maximum soil-root conductance per unit ground area of the nth layer	(mm d^{-1} kPa^{-1})
L_n	leaf area index in plant age category (n)	( )
n/N	fraction of daylight hours with direct unclouded solar radiation incident upon earth surface	( )
R_a	the solar constant (Angot value) of solar radiation flux density incident at the upper limit of the atmosphere	(MJ m^{-2} d^{-1})
R_b	net long-wave radiant flux density	(W m^{-2})
R_{ns}	net short-wave radiant flux density	(W m^{-2})
T_{kn}	daily minimum absolute temperature	(K)
T_{kx}	daily maximum absolute temperature	(K)
ω_s	angle of sun's rays at sunset	(rad)
ϕ	latitude taken as negative in the southern hemisphere	(rad)
λ	latent heat of evaporation	(MJ kg^{-1})
γ^*	psychrometric constant	(kPa $^{\circ}C^{-1}$)
γ	psychrometric constant adjusted for crop canopy and aerodynamic resistance	(kPa $^{\circ}C^{-1}$)
ζ	leaf quantum yield	(kg MJ^{-1})
ρ	density	(kg m^{-3})
ρ_r	fraction of total root mass in a given soil layer	( )
P_s	soil bulk density	(kg m^{-3})
ρ_{ro}	fraction of mature root mass present on a given day	( )
θ, V	volumetric soil water content	(mm m^{-1})
θ_p	porosity, the proportion of air space in a volume of soil	(mm m^{-1})
Θ	soil water content in non-irrigated soil	(mm m^{-1})
ψ_o	upper limit soil water potential	(kPa)
ψ_{se}	effective soil water potential of the entire root zone	(kPa)
ψ_{vcrit}	leaf water potential at the onset of water stress	(kPa)
ψ_v	leaf water potential	(kPa)
p	partitioning factor, i.e. fraction of standing biomass in a given plant organ	( )
p_e	fraction of total dry mass growth partitioned to new leaf expansion	( )
PPAW	percentage plant available water	(%)
r_a	aerodynamic resistance	(s m^{-1})
RAIN	daily rainfall	(mm d^{-1})
r_c	crop canopy resistance	(s m^{-1})

$\overline{RH}$	atmospheric relative humidity	(%)
R_m	maximum leaf relative growth rate	(d^{-1})
R_n	net radiation	(W m^{-2})
R_s	solar radiant flux density	(W m^{-2})
s	specific leaf area (green leaf area per unit total leaf mass)	(m^{2} kg^{-1})
SWC	soil water characteristic	
θ_0, ***SWUL***	upper limit of volumetric soil water content	(mm m^{-1})
AW	plant available water	(mm)
TAW	total plant available water	(mm)
t_b	lost time, the time for crop total growth rate to reach it's maximum value	(d)
t	time measured in sidereal days	(d)
t_g,***DOG***	vegetation growth time. Sidereal days since plant emergence	(d)
T_e	effective temperature for crop growth and development	(°C)
t_p	physiological age in days of 12 hours at 20°C.	(d)
DUL	drained upper limit of soil water retention	(mm m^{-1})
FRACdrain, ***VCON***	fraction of water drained from a soil layer per day	(d^{-1})
W	soil water depth per unit ground area	(mm m^{-2})
W	total above ground standing dry mass i.e. total dry weight	(kg ha^{-1})
Y	harvestable yield	(kg ha^{-1})
Y_d	total above ground standing biomass	(kg ha^{-1})
Y_o	potential harvestable yield	(kg ha^{-1})
Z	current effective rooting depth	(m)
z	soil depth	(m)
Z_o	maximum effective rooting depth	(m)
ψ_v	leaf water potential	(kPa)
υ	conversion coefficient	
υ_s	total dry mass produced per unit solar radiation intercepted, i.e. biomass / radiation coefficient	(kg MJ^{-1})
υ_w	total dry mass produced per unit water transpired at an atmospheric saturation deficit of 1 kPa, i.e. biomass / evaporation coefficient (the Kieselbach coefficient)	(kg kPa ha^{-1} mm^{-1})
ν	factor adjusting the vegetation evaporation coefficient for climate variation	( )

2. *CROP WATER USE*

2.1 *Atmospheric evaporative demand*

All Putu models utilise the same crop water use and soil water balance routines. This entails estimating crop total evaporation $E = E_v + E_s$ and atmospheric evaporative demand (***AED***) from reference evaporation (E_o) using the evaporation coefficient concept. De Jager and Van Zyl, (1989), defined atmospheric demand as follows :

> *Atmospheric evaporative demand is the rate of water evaporated from a crop experiencing no water stress in it's root zone plus the rate of water evaporated from the top 150mm of soil at the existing soil water content. It represents the upper limit of evaporation as determined by atmospheric conditions, the degree of vegetation cover and the water content of the soil surface and quantifies the water necessary to ensure maximum yield.*

Reference evaporation, as defined by Allen *et al* (1994) (see Section 8), is the upper limit of evaporation from a specified short grass surface and is determined entirely by atmospheric conditions.

Reference evaporation is calculated using the Penman-Monteith equation (PME). It was developed by Monteith (1965) and is fully described in Section 8 of this Chapter 7, thus,

$$\lambda Eo = \frac{\delta}{\delta + \gamma^*}(Rn - G) + \frac{\rho Cp}{\delta + \gamma^*}\frac{\left(e_a(T) - e_d\right)}{r_a}$$

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right)$$

where, the bulk canopy resistance to water exchange

r_c = 70 s m^{-1} for 24 hour, or longer, mean values of weather data

When the full set of weather data required for the Penman-Monteith equation are not available, the temperature adjusted Priestley-Taylor equation (PTE) Priestley and Taylor (1972) is used.

$$E_o = \frac{\delta}{\delta + \gamma}(1.28 + \alpha)\left[\frac{Rn - G}{2450 * 1000}\right]$$

α = 0.08 (***Tmax*** -20)

Where, the empirical constant α was found by calibration (see De Jager, 1987 and Meiring 1989) and is constrained for daily data to $0 \leq \alpha \leq 0.6$ and, furthermore

$$\frac{\delta(Rn - G)}{\delta Rs} = 0.5$$

Evaporation coefficient theory (de Jager and van Zyl, 1989) prescribes that:

$$\frac{\delta AED}{\delta Eo} = k_c$$

In which,

$$k_c = k_v + k_s$$

The soil, via the crop, strives to conduct water at the upper limit of crop total evaporation rate ***AED*** which consists of a vegetation and soil component viz. E_v and E_S.

2.2 ***Soil water evaporation***

Evaporation through the soil surface, E_s, is calculated, applying the evaporation coefficient concept (De Jager and Van Zyl, 1989) from

$$\frac{\delta Es}{\delta Eo} = k_S \qquad E_S = k_S E_O$$

With $k_s = k_{so} F_s (1 - f)$

f is the fractional interception of green plus senesced foliage, given by

$f = 1 - \exp(-KL)$ and

k_{so} is the maximum value of k_s, and is a crop and growth stage specific parameter, and

F_s, the soil surface dry-down factor, for most soils defined as

$$F_s = exp^{-0.4t_e}$$

where, t_e is the time elapsed since a wetting event, or alternatively for loam and sandy soils

$$F_S = exp^{-0.03(\theta_O - \theta_1)}$$

where $(\theta_O - \theta_1)$ denotes soil water depletion for the top soil layer (De Jager *et al*, 1987).

Soil evaporation needed to be adjusted not only for sparse canopies, but also for senescing canopies. It was found in practice that towards the end of the growing season senesced leaves from which evaporation does not take place, intercepted solar radiation thereby shading the soil as well as inhibiting water vapour transport to the atmosphere. Both effects seriously reduced soil evaporation which, when not accounted for, caused over-irrigation in the latter part of the season. Use of the equation $k_s = k_{so} F_s (1-f)$, thus accounted for these effects. Thus, total leaf area index L and corresponding extinction coefficient, K, are used for calculating fractional interception above a soil surface.

2.3 *Evaporation through the plant and partially wet surfaces*

Plant evaporation, E_v, is also described using the evaporation coefficient concept (De Jager and Van Zyl, 1989)

$$\frac{\delta E_V}{\delta E_O} = k_V$$

$$E_V = k_V E_O$$

Where potential vegetation evaporation is given by $E_{VO} = k_{VO} E_O$, and

The plant evaporation coefficient is given by ;

$$K_v = v\, k_{vo}\, E_o f_g\, F_v$$

$$f_g = 1 - e^{-K_g L_g}$$

Where, for given crops, v is a factor reflecting the climatic dependence of the evaporation coefficient (Van Zyl and De Jager, 1992), k_{vo} is the plant evaporation coefficient for a full canopy; subscript g denotes green vegetation; L_g green leaf area index, K_g, is the transient coefficient governing the rate at which plant evaporation rate approaches its maximum (potential) rate attainable when a complete cover of green leaves exists (i.e. E_{vo}) (see Section 2.2 for values) and f_g, the fraction of potential plant evaporation taking place through green leaf canopy. How f_g is dealt with in practice is described in the next paragraph on sparse canopies. Although the maximum plant evaporation coefficient, k_{vo} should be crop and growth stage specific; up to now a constant value for a given crop has been used throughout the growing season. In practice k_{vo} may be assumed equal to the maximum crop coefficient (k_c) found in Doorenbos and Kassam (1979). In practice (see De Jager, 1994) f and f_g are assumed equal to the observed fraction of ground surface covered by the vertical projection of all leaves (FI) and green leaves (FI_g) respectively. FI_g is equivalent to the basal cover evaporation coefficient of Wright (1985). It is defined as follows: Plant evaporation relative when the soil surface is dry, i.e. $F_g \approx 0$. In the Putu shell on screen it is denoted k_b.

Furthermore, the relative plant evaporation, permitted by plant water status (stress) F_v, is defined

$$F_v = \frac{1}{\left[[1 + e^{-0,002\ (\psi_{vcrit} - \psi_v)}\right]}$$

in which, the decay constant -0.002, was obtained by calibration (De Jager *et al*,1989). Canopy mean leaf water potential and its critical value are denoted ψ_v and ψ_{vcrit} respectively.

The relative plant evaporation , F_v, is the fraction of E_{vo} permitted by crop physiology and water status. It is a function of a critical leaf water potential ψ_{vcrit}, and the existing soil water status ψ_s. Here, ψ_{vcrit} is defined as the crop specific critical xylem water potential at which plant water stress symptoms, such as stomatal closure appear, with concomitant reduction in E_v, CO_2 assimilation and yield.

Canopy mean leaf water potential, Ψ_v, is calculated using the numerical iteration procedure described in Chapter 7, Section 3 and Section 2.4 (Leaf Water Potential). Drought hardening (decreased sensitivity to water stress i.e. decreasing ψ_{vcrit} with physiological age) is taken to be a linear function of time.

The climate dependence coefficient, v, accommodates changes in the crop evaporation coefficients (k_{vo}) reported by Doorenbos and Kassam (1979) due to climate. A default value of unity is used for crops other than maize or potato (see Van Zyl and De Jager, 1992)

Sparse canopies (trees) and partial wetting

F_v is determined by the plant water transfer mechanism (Chapter 7, Section 2.6) and, since it is not *per se* a function of cover, or surface wetness, it need not be altered for sparse canopies as is the case for f_g.

Initially (De Jager, 1994), f_g was assumed equal to fractional radiation interception f. It is logical, however, to expect that $f_g \neq f$ particularly for a senescing canopy. Values accommodating senescence, are now made available from the cultivar characteristic file as a function of time (see Chapter 7, Section 9).

Ritchie (1983) found (using our notation where we substitute L_g for L) that relative transpiration rate could be expressed

$$f_g = 1 - \exp\left(-K_g L_g\right)$$

where, the rate of change coefficient K_g varied between 0.4 for a wet soil surface and 0.9 for a dry soil surface. It was here assumed that the rate of change in K_g between the two states should parallel the drying rate of the soil surface (i.e. the rate predicted by F_s in Section 2.2). Hence, K_g was described

$$K_g = 0.9 - 0.5\exp\left(-0.03(\theta_0 - \theta_1)\right)$$

Green leaf area index L_g is computed in the Level 3 version of Putu, using the expolinear routing to be explained in Chapter 7, Section 6. For Level 1 and 2 observed values of canopy outline vertical projection, t_c, and observed vertical projection of green leaves FI_g are required. The Ritchie (1983) equation was transformed to yield

$L_g = -\ln(1 - f_g) / K_g$ with further

$$F_g = FI_g / f_w \quad \text{for} \quad f_w \geq f_c$$
$$F_s = FI_s \quad \text{for} \quad f_w \leq f_c$$

When the soil surface is only partially wetted by the irrigation system (eg micro-jet or furrow), some adjustment to this relationship is required. The simplifying assumption was made that K_g could be estimated by this equation when the fraction of ground surface wetted, exceeded $f_w \geq 0.6$, or else, for a dry situation (i.e. $f_w < 0.6$), K_g was set equal to $K_g = 0.9$.

Furthermore, the simulation of crop total evaporation from a sparse crop canopy from a soil surface which is only partially wetted during irrigation, must account for :

a) plant evaporation from only the soil reached by the root system and not the entire soil volume;

b) soil evaporation from only the wetted soil surface area after irrigation and the entire ground surface after rain.

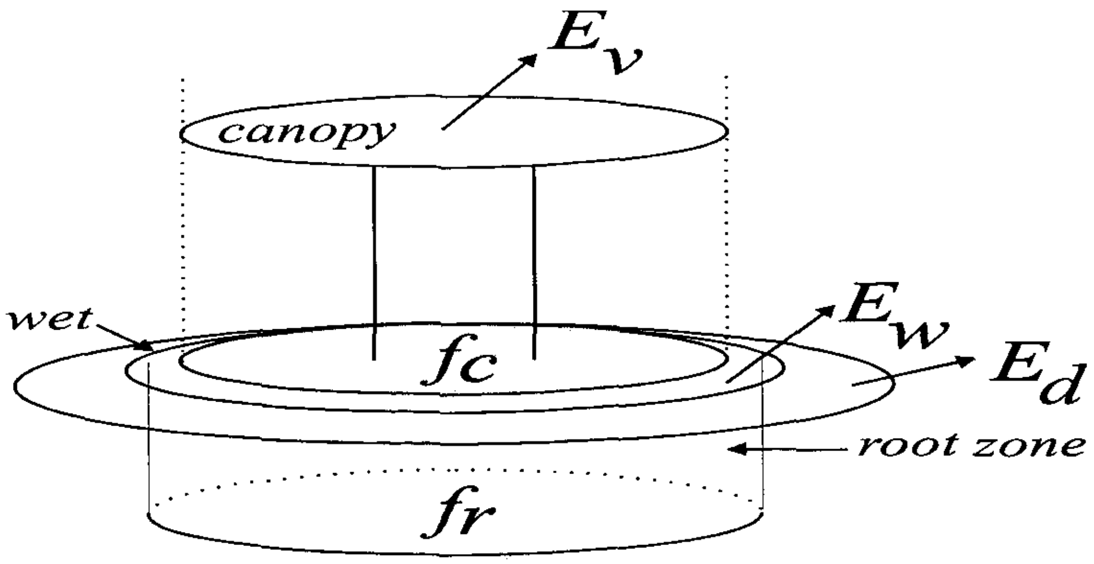


Fig 7.3 Model of the partial wetted surface, sparse canopy situation.

The schematic diagram for this model is given in Fig. 7.3 and the ensuing discussion will utilise the following notation:

f_w	fraction of ground surface wetted by irrigation	
f_c	*fraction of ground surface covered by vertical projection of the outline of the canopy*	
f_r	fraction of ground surface area beneath which roots extract water (not necessarily equal to f_c)	
f_g	vertical projection of green leaf cover assumed equal to FI_g	
E_v	plant evaporation	(mm d^{-1} m^{-2})
E_w	evaporation from wet soil surface area	(mm d^{-1} m^{-2})
E_d	evaporation from soil surface areas which have not been wetted by irrigation	(mm d^{-1} m^{-2})

Plant evaporation extracts water from the rooted soil volume found beneath a fraction of ground surface area denoted f_r. Evaporation rate per unit ground surface area is computed using evaporation coefficient theory (see Chapter 7, Section 2.3). However, since transpired water is extracted only from soil found beneath the projection of the area reached by roots (fraction f_r of total surface area), the amount of water removed from the wetted zone is given by E_v/f_r.. As a first approximation it was assumed that $f_r = f_c. = f_w$.

Soil evaporation - Wetted surface area evaporation, E_{sw}, is computed by applying the equations of Chapter 7, Section 2.2, but substituting observed leaf projections (eg. $f_g = FI_g$). It was assumed that evaporation takes place uniformly from the entire wetted soil surface.

Also from Section 2.2:

$$F_s = \exp[-0.03(\theta_0 - \theta)_1] \qquad \text{for } \theta < \theta_0, \text{ or else } \theta = \theta_0$$

and $$K_g = 0.9 - 0.4\,\mathrm{F_s}$$

$$K_g = 0.9 - 0.4\,F_s$$

The wetted area weighted mean value of (θ_0 - θ_l) was used.

Soil evaporation - non-wetted area (denoted E_{sd}) evaporates independently of the wetted surface and also according to the equations of Section 2.2, but calculated volumetric volumetric soil water contents (Θ)were used.

Soil water extraction and redistribution. In order to compute the soil water balance in a partially wetted soil, certain ***assumptions*** are required.

First, the soil was divided into a wetted (irrigation) zone and a non-wetted zone.

Second, the water in a given layer in the root section was assumed equally available to all the roots in a layer. This is equivalent to spreading irrigated water evenly throughout a layer.

Third, the two fractions evaporate and re-distribute water independently of one another.

Fourth, lateral water movement between the two zones (see Fig. 7.3) is restricted to horizontal flow within soil layers at a rate proportional to the difference in water content between non-wetted soil water content (Θ_n say) and wetted soil water content (θ_n say). The lateral water conductance per unit soil depth denoted G_l, was guestimated equal to -0.5 It is obviously a function of f_r and soil type and requires refinement in the future.

Following these assumptions, the water balance equations for layer n were formulated as follows:

The wetted zone

$$\theta_n = \theta_{in} - E_{vn} / f_w + (DRAIN_{w(n-1)} - DRAIN_{wn}) / \Delta z_n + G_l(\theta_n - \Theta_n)$$

The non-wetted zone

$$\Theta_n = \Theta_{in} + (DRAIN_{w(n-1)} - DRAIN_{wn}) / \Delta z_n - G_l(\theta_n - \Theta_n)$$

Where Θ_n denotes soil water content in the non-wetted portion. G_l is defined as the volume of water flowing laterally from unit area through unit soil depth per unit gradient in soil water content (non-wet to wet soil). G_l is a dimensionless constant. For the nth layer, soil water content (mm m^{-1}) is denoted θ_n; its daily initial value, θ_{in}, is computed at midnight (00h00); and drainage out of the layer, $\boldsymbol{DRAIN_{wn}}$ The last term on the right-hand side represents the water removed laterally from non-wetted soil.

It is important to note that the actual amount of irrigation applied is reduced because of the small wetting zone. Only $f_w I_{rr}$ (mm), or $f_w I_{rr} 10^{-3}$ (m^3) need be applied.

For the top (surface) layer, rain and irrigation are added and soil evaporation subtracted, thus

$$\theta_1 = \theta_{i1} - E_{v1} / f_w - E_{sw} + (RAIN + I_{rr} - DRAIN_{wn}) / \Delta z_n + G_l(\theta_n - \Theta_n)$$

The non-wetted zone

$$\Theta_1 = \Theta_{i1} - (1 - f_w) E_{sd} + (RAIN - DRAIN_{wn}) / \Delta z_n - G_l(\theta_n - \Theta_n)$$

Soil water content per layer in m^3 was computed

$f_w \theta_n \Delta z_n 10^{-3}$ for the wetted zone of the nth soil layer

and $(1 - f_w)\Theta_n \Delta z_n 10^{-3}$, for the non-wetted zone

The value of G_l is one of the parameters entered in the 'Cultivar Characteristics' menu. It is evident that with little modification, this model could be adapted to inter-cropping situations. Van Zyl and De Jager (1997) have shown that for sparse canopies, evaporation coefficient theory produces simulations of crop evaporation which compare favourably with simulations using more sophisticated methods.

Summary

The model in Fig. 7.3 may be used to compute the various components of E after rain and after irrigation in essence using the equation

$$E = E_v + E_{sw} + E_{sd}$$

Irrigation is, of course, scheduled according to the water balance in the rooted area. At this stage the partial wetting/sparse canopy model should be adapted for the specific needs of irrigation managers, by the authors.

2.4 *Leaf water potential*

The soil water potential which the plant in effect senses, Ψ_{se}, is defined as the weighted mean soil water potential. It is computed by weighting soil layer water potential according to the root density in each layer. The model is described schematically in Fig. 7.4.

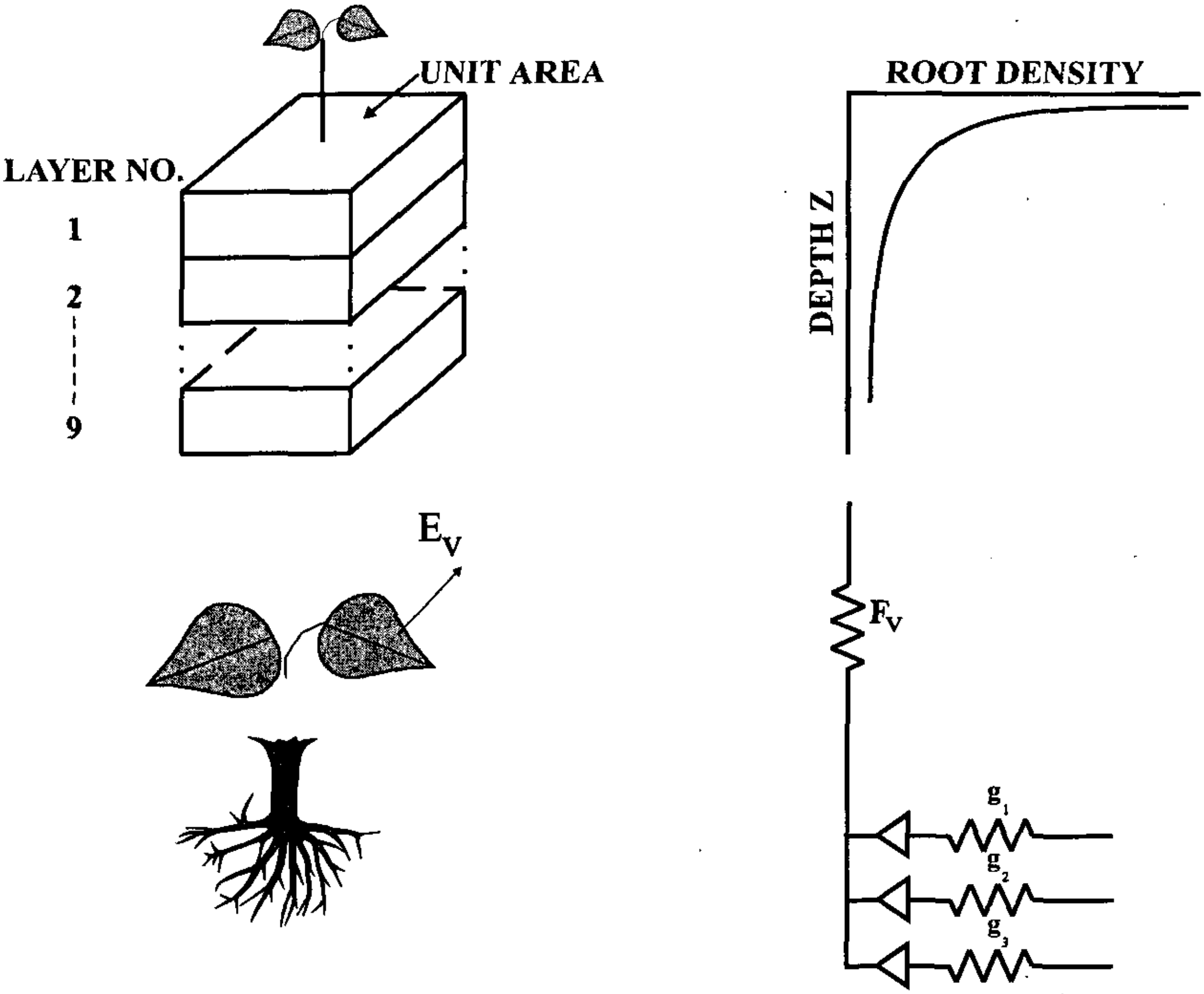


Fig 7.4 Schematic diagram of the multi-layered soil modelled in Putu.

De Jager *et al* (1987) accepted that leaf water potential is a function of atmospheric demand, E_{vo}, effective soil water potential, Ψ_{se} , and a critical crop water potential Ψ_{vcrit}, the hydraulic conductance of the soil-root system (g) and the soil water characteristic (*SWC*). By analogy with Ohm's law:

$$\psi_v = \psi_{se} - \frac{E_v}{g}$$

When, $\bar{E}_v$ takes units of mm d^{-1}, the units for g for unit ground area are mm d^{-1} kPa^{-1} and the contributions from the different soil layers are simulated (see de Jager *et al*, 1987) by expressing

$$\psi_{se} = \sum_n g_n \frac{\psi_{sn}}{g}$$

The soil-root conductance for unit ground area of the entire root zone, is given by

$$g = \sum_n g_n$$

Both g and g_n have negative values and g represents the maximum conductance (capacity of unit volume of soil to supply water) of the soil root system. The equation developed by Botha (1983) and refined by Bennie and Botha (1985) for soil-root conductance was normalised and expressed in terms of:

a maximum conductance:

(g_{on}), the fraction of roots in the layer, and

a normalised expression for soil water content (θ_n)

For the n^th layer soil root conductance is given by:

$$g_n = g_{on} \left(\rho_{rn}\right)^{0.5} \frac{\ln\left[\dfrac{\theta_n}{\theta_{1600\,n}}\right]}{\ln\left[\dfrac{\theta_{10\,n}}{\theta_{1600\,n}}\right]}$$

where, the maximum water conductance of the n^th soil layer, g_{on} is given by

$$g_{on} = G_0 \Delta z_n$$

G_o is the maximum conductance of the soil-root interface per unit depth, where by calibration it was found that for most crops

G_o = -0.02 mm(H_2O)(d kPa m (soil))$^{-1}$

Values obtained by calibration are :

G_o = -0.02 mm (d kPa m)$^{-1}$ for wheat, or any crop, and

G_o = -0.03 mm (d kPa m)$^{-1}$ for maize

These values compare well with the -0.036 mm (d kPa m)$^{-1}$ quoted by Campbell (1985). Symbols θ, θ_{10n} and θ_{1600n} denote the current value of layer soil water content, and values at -10 kPa and -1600 kPa respectively. The theoretical value for θ_{1600} is used so as to prevent computer memory overflow.

A value of G_0 = -0.02 mm (d kPa m)$^{-1}$ is equivalent to -0.02 mm (d kPa m^3)$^{-1}$ and expresses the physical capacity of 1 m^3 of rooted soil to provide 20 mm d^{-1} of water for transpiration through a soil water potential gradiant (soil-root-leaf) of 1000 kPa.

Two distribution patterns for computing the fraction of root mass in a given soil layer are available, viz

$$\rho_{rn} = \rho_{ro} \int_{zn-1}^{zn} e^{-az} dz$$ - Exponential rooting distribution (De Jager *et al*, 1987), or

$$\rho_{rn} = \rho_{ro} \int_{zn-1}^{zn} (b + (z_o - z)\tan c)dz$$ - Conical rooting distribution (see De Jager and Hensley, 1988)

These yield the expressions for calculating the fraction ρ_{rn} of total root mass per unit ground area per unit soil depth in the nth layer:

$$\rho_{rn} = \rho_{ro}\left[e^{-az_{n-1}} - e^{-az_n}\right]$$

,or, for a rooting base width b and cone angle c when

$$\rho_{rn} = \rho_{ro}[\Delta Z_n\{b + (Z_o - Z_n)tanc + 0.5\Delta. \ _n\}]/Z_o(b + .5tanc)$$

(*for maize* b = 0.02 *m and* c = 10°)

where the daily fraction of mature total root mass density per unit ground area ρ_{ro} is given by

$$\rho_{ro} = \frac{1}{\left[1 + e^{-0.6(DOG - 50)}\right]}$$

and a is given by

$$a = Z\left[\frac{-\ln(0.03)}{0.97}\right]$$

Roots are assumed to advance downwards linearly with time (in days) to the maximum effective rooting depth (Z_o) at rates of 0.0182 m d^{-1} for wheat and 0.012 m d^{-1} for maize, or any crop where,

Z = 0.0182 DOG for wheat say, with

z depth in the root zone (m)

Z current effective rooting depth (m)

Z_o maximum effective rooting depth (m)

DOG days of growth since sowing (d)

The constant a in the exponential equation defining root distribution is calculated by assuming that 2.7% of the total roots are found beneath a rooting depth equal to 0,97 Z. It is thus a function of crop growth stage (De Jager *et al*, 1987) and is computed each day.

2.5 *Soil water potential*

Initially, in Putu-grass, a logarithmic multiple spline function was used to simulate the soil water release curve. This was later modified to the Gompertz formula and finally a two-paramater exponential formula.

Originally, values of soil water potential had been calculated using the Gompertz formula

$$\psi = -e^{ae^{-b\theta}}$$

The constants a and b in this equation were obtained by a process of linearization. Now, the soil water characteristic is given by a two-parameter exponential expression (see Chapter 10), viz.

$$\psi_s = -1500\left(\frac{\theta}{\theta_{1500}}\right)^b$$

where, the two parameters are θ_{1500} the soil water content at 1500 kPa and **b** the soil type specific exponent of this log-log expression.

2.6 *Water transfer mechanism*

Vegetation may be water stressed, or water non-stressed. Applying evaporation coefficient theory (De Jager and Van Zyl, 1989), the two conditions may be simulated by :

Water non-limiting

$$E_v = E_{vo} = vk_{vo} f_g E_o$$

because $F_v = 1$

Water limiting

Here, $E_v < E_{vo}$ and from Section 2.3

$$E_v = \frac{vk_{vo} f_g E_o}{\left[1 + e^{-0.002\left(\psi_{vcrit} - \psi_v\right)}\right]}$$

Given the condition $\psi_v = \psi_{se} - \frac{E_v}{g}$

This is a non-linear equation for which ψ_v can only be solved by numerical iteration. The iteration technique is described in Section 2.5. Briefly, a test value for ψ_v is substituted in $F_v = \frac{1}{\left[1 + e^{-0.002\left(\psi_{vcrit} - \psi_v\right)}\right]}$ in order to estimate E_v .This value of E_v is then substituted in $\psi_v = \psi_s - \frac{E_v}{g}$. Should the resulting ψ_v value agree to within 5 kPa of the test value; the value of ψ_v so obtained is used to calculate E_{vn} for each individual soil layer, substituting the values of g_n obtained as in Section 2.4, and using

$$E_{vn} = -g_n\left(\psi_v - \psi_n\right), \text{ from which}$$

$$E_v = \sum_n E_{vn}$$

Each layer's water use , E_{vn}, is then extracted from the water held in the nth layer.

3. *DAILY LAYERED SOIL WATER EXTRACTION*

The water content in each layer at midnight W_{in} , was calculated for each day as follows:

the water content at the start of each day W_{in}, was set equal to the W_n at midnight of the previous day and $DRAIN_n$ is the drainage cascaded from the layer above. Then, layer soil water balance reads,

$$\bar{W}_n = \bar{W}_{in} - \bar{E}_{vn} + DRAIN_n$$

W_n is restricted by the iteration technique to a water content between the soil water lower limit (θ_{1500n}) derived and the soil water upper limit ($SWUL_n$).

In the top soil layer (n=1) $W_1 = W_1 - E_{v1} - E_s + Irr + RAIN$

Given volumetric soil water content ,θ, then soil water depth W, wascalculated from :

$$W_n = \theta_n \Delta z$$

plant available water content (AW_n) from $AW_n = W_n - W_{1500n}$,

total plant available water content from $TAW = \sum_n AW_n$,

and percentage plant available water from

$$PPAW = 100 \sum_n AW_n / \sum_n [SWUL_n - \theta_{1500\,n}] \Delta z_n$$

The denominator equals the total plant available water in the entire root zone, i.e. total of layers up to the rooting depth Z_o.

The computation of $SWUL_n$ and θ_{1500} is dealt with in Chapter 10.

4. *INFILTRATION AND PERCOLATION THROUGH THE SOIL*

For computing the fraction of rainfall infiltrated through the soil surface, ***Inf***, the US curve number method was tested but found unreliable. Hence, the original empirical method, which estimates the fraction of rain lost as surface run-off, F_{ro}, has been retained, viz

$F_{ro} = 0.2$	for $RAIN > 50$ mm d^{-1}	
$F_{ro} = 0.1$	for $50 > RAIN > 25$	(mm d^{-1})
$F_{ro} = 0.05$	for $25 > RAIN > 15$	(mm d^{-1})
$F_{ro} = 0$	for $15 > RAIN > 0$	(mm d^{-1})

where, F_{ro} is the fraction of rain lost as surface run-off. This simple model has been used satisfactorily since 1983. It has the advantage of having more points of inflection than a similar model reported by Supit *et al* (1994).

Infiltration of water through the surface is given by:

$$Inf = (1 - F_{ro})(Rain + Irr)$$

The fraction of excess water drained vertically in one day to a next lower layer denoted (*VCON*) is assumed equal to the ratio of the amount of water which could possibly be held between the drained upper limit of the soil (***DUL***) and its porosity value (θ_p). Thus,

$$VCON = \frac{\theta_p - DUL}{\theta_p}$$

where, θ_p is the soil porosity expressed as

$$\theta_p = \left(1 - \frac{\rho_s}{2650}\right)1000$$

for a soil bulk density ρ_s given in kg m^{-3}.

Drained upper limit, ***DUL***, is defined as soil water content after 60 days of free drainage under gravity with zero evaporation.

Daily drainage (mm d^{-1}) from the nth soil layer, $DRAIN_n$, is thus given by:

$$DRAIN_n = VCON_n(\theta_{pn} - DUL_n)\Delta z_n$$

Drainage occurs subject to the following constraints

(a) For drainage to take place θ must be greater than ***DUL***

(a) If percolation from the layer above was less than $(SWUL_n - \theta_n)\Delta z_n$ then θ_n is first updated by adding $DRAIN_{n-1}\Delta z$ before drainage out of layer n , calculated using the drainage equation, is allowed. No drainage out of the layer is permitted i.e $DRAIN = 0$ if $\theta_n < DUL$.

(c) If percolation from the layer above was greater than $(SWUL_n - \theta_n)\Delta z_n$ then θ_n is first updated to $\theta_n = SWUL_n$, before drainage is calculated using the drainage equation. Any excess water above $SWUL_n$ is immediately cascaded together with the drainage.

Note: Putu-grass differs in that it permits use of an empirical guestimate (not one derived from θ_p) of *VCON* the fraction of excess water to drain per day from a soil layer. Such procedure has been found to work well in practice.

5. *THE ITERATION TECHNIQUE*

An iteration technique is used to solve the non-linear equation which balances ψ_v and ψ_{se} under the water limiting condition. The problem is to solve

$$E_v = vk_{vo}\, fF_v E_o \qquad \text{(State 1)}$$

where,

$$F_v = \frac{1}{\left[1 + e^{-0.002\left(\psi_{vcrit} - \psi_v\right)}\right]} \qquad \text{(State 2)}$$

subject to the limitation that E_v must equal the capacity of the soil and root system to supply water, i.e.

$$E_v = g\left(\psi_{vcrit} - \psi_v\right) \qquad \text{(State 3)}$$

While the Newton-Raphson method may be employed to solve the problem, a simple numerical method is used in Putu. The five steps used are as follows:

I Guess a value for ψ_v using $\psi_v = \frac{HI + LO}{2}$. Where high (***HI***) and low (***LO***) values of ψ_v are made to converge upon a value which makes state (1), (2) and (3) true. This is carried out by successive adjustment of either ***HI*** and ***LO***. For the first iteration,

$$HI = -4500 \text{ and } LO = 0\text{, i.e. } \psi_v = \frac{4500 + 0}{2} = 2250$$

II Calculate E_v using state (1) by substituting state (2) with the guessed value of ψ_v.

III Test whether the value guessed for ψ_v is within ± 0,5 kPa of the value of ψ_v required to make state (3) true. This is equivalent to testing whether the value of E_v obtained using ψ_v is within approximately 0.025 mm d^{-1} (i.e. -0.05 (0.5)) of the maximum rate which the soil can supply.

IV Should the guessed value of ψ_v fail this test (Step III), guess a new value for ψ_v, which is closer to the ultimate solution, by the following method:

(a) Should the guessed value of ψ_v be too high, we know the solution must lie between the guessed value and the present value of ***LO***.

(b) Guess a new value of ψ_v = (ψ_v previous guess + ***L0***)/2 and make ***HI*** = ψ_v previous guess. Should the guessed value be too low guess a value of ψ_v = (ψ_v previous guess + ***HI***)/2 and make ***LO*** = ψ_v previous.

V Return to step II and repeat the procedure using the newly guessed value of ψ_v. Repeat until the test criterion is satisfied. Should the case arise where soil is so dry that a solution is impossible, the run stops and the message "ultra-stress" appears on the screen. A solution can only then be obtained by inputting a higher soil water content.

The onset of water stress is difficult to simulate. Ritchie *et al* (1983) made the degree of stress strictly dependent upon soil water depletion below a threshold value. Slabbers (1980) made this threshold soil water content a function of ***AED***. The ***NEWSWB*** model of Campbell, (see Annandale, Van Der Westhuizen and Olivier, 1996) is an improved version of the original described by Campbell and Diaz (1988). It employs a normalised dimensionless relationship which obviates the need for iteration. It is interesting to note that this relationship has a sigmoid shape similar to the equation for F_v, and in fact, offers an empirical approximation to iteration. High speed personal computers rapidly perform the daily iteration procedure in Putu, which in any event, is only needed during times of plant water stress. Hence this procedure has been retained.

6. *LEAF AREA DEVELOPMENT*

The fraction of incident radiation intercepted by a green leafed vegetative canopy (f) is described by Beer's function;

$$f = 1 - \exp(-KL)$$

where, L is the leaf area index here asumed entirely green leaves and K is the light extinction coefficient which depends on the shapes and arrangement of the leaves and their orientation in relation to solar radiation.

Goudriaan and Monteith (1990) assumed that total crop growth rate (C) is directly related to fractional light interception. Thus, since the time (t) rate of change may be expressed

$$C = \frac{\delta W}{\delta t}$$

then

$$\frac{\delta W}{\delta t} = fC_m = [1 - \exp(-kL)]C_m$$

Here, C_m is the maximum crop growth rate achieved when all incident light is intercepted ($f \approx 1$).

Now, if the fraction of increase in total dry matter allocated to new leaves is p_l and the specific leaf area of these leaves is s, then, by definition,

$$\frac{\delta L}{\delta t} = p_l s \frac{\delta W}{\delta t}$$

Substituting for $\frac{\delta W}{\delta t}$ in this equation yields

$$\frac{\delta L}{\delta t} = [1 - \exp(-KL)]C_m p_l s$$

Goudriaan and Monteith (1990), as well as Fernandino (1989) independently, integrated this equation to derive the ***expolinear function for leaf area index development***, viz;

$$L = \frac{1}{K} \ln \left\{1 + [\exp(L_i) - 1]\exp\left(\int_o^t R_m t\right)\right.$$

where maximum leaf relative growth rate (R_m) is given by

$$R_m = KC_m p_l s$$

Now denote and L_i as the initial leaf area index at time t=0. Then by denoting initial leaf area per plant and plant density by L_{pi} and N_p respectively, the former is given by

$$L_{pi} = \frac{L_i}{N_p}$$

Where, leaf area ratio ***LAR*** is assumed equal to $p_l s$.

While ***KL*** is very small (<0.1 say), then

$$\frac{dL}{L} = R_m t \text{ , and}$$

$$L = L_i \exp\left(R_m t\right)$$

Putu requires a value of *Li* from which to simulate total dry mass and leaf area development. Hence, the following equation will be used.

$$L_i = L \exp\left(- R_m t\right)$$

7. *BIOMASS GROWTH*

The genetic potential dry mass growth rate can be limited either by solar and thermal energy input, or by water. The simulation of plant growth in Putu was undertaken in two states, either energy limted, or water limited.

7.1 *Energy limited growth.*

Goudriaan and Monteith (1990) substituted the expolinear expression for *L* derived above into the expression for $\frac{\delta W}{\delta t}$ to produce the differential equation from which crop total growth rate may be computed, viz.

$$\frac{\delta W}{\delta t} = C_m \frac{\left[\exp\left(KL_i\right) - 1\right]\exp\left(\int_o^t kR_m t\right)}{1 + \left[\exp\left(KL_i\right) - 1\right]\exp\left(\int_o^t kR_m t\right)}$$

Integration of this equation yielded the ***expolinear crop growth function***;

$$W = \left(\frac{C_m}{R_m}\right) \ln\left[1 + \exp\left(R_m\left(t - t_b\right)\right)\right]$$

The expolinear function describes a crop total dry mass vs time growth curve (see Fig 7.5) with an initial exponential growth rate, which gradually decays into a constant maximum growth rate (C_m). From Fig 7.5, the concept 'lost time' (t_b) (see also Squire, 1990) may be introduced. Lost time is the interception of the linear portion of the expolinear growth function on the time axis.

Transposing the fractional interception equation for *L* yields :

$$L = \frac{- \ln\left(1 - f\right)}{K}$$

substitution of which into the equation for *Li* yields;

$$L_i = -\ln(1 - f)\exp(-R_m t)$$

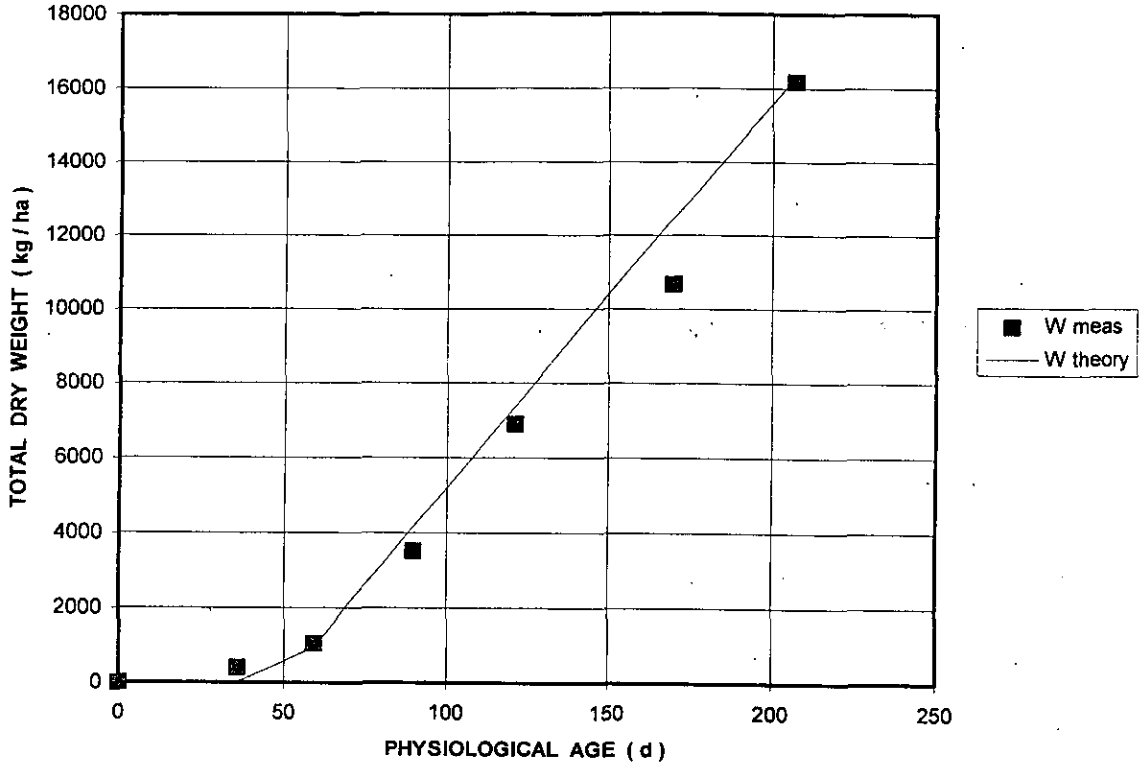


Figure 7.5 Fit of theoretical values of the expolinear growth function to measured data for potato. $C_m = 155$ kg ha^{-1} d^{-1} $t_b = 60$ d K = .65

This equation may be used, in practice, as an alternative method (given *f*) to determine ***Li***. By observing *f* early in the growing season ***Li*** may be determined given $R_m = KC_m p_l s$. Once L_i is known, leaf area development may be simulated using the expolinear function for ***L***

In practice, lost time, t_b, may be computed from;

$$t_b = \frac{-\ln\left\{\dfrac{f_i}{1 - f_i}\right\}}{R_m}$$

In the expolinear function C_m is the slope of the linear portion of the total dry weight versus time curve and t_b the interception of the linear portion of the expolinear function on the time-axis. The term, f_i is the fractional light interception at the initiation of growth. Initially this value is very small, therefore it follows that the divisor $(1 - f_i)$can be omitted and

$$f_i = \frac{\exp\left[-R_m t_b\right]}{1 + \exp\left[-R_m t_b\right]}$$

In practice, it is simple to determine t_b and C_m from serial harvest results plotted on a figure similar to Fig 7.5.

7.2 *Determination of crop parameters for the expolinear growth function.*

The input parameters required to evaluate the expolinear equations are :

N_p, K, LAR, L_{pi}, t_b and C_m.

The strength of the expolinear approach lies in the power of L_{pi} and t_b to account for sparse crop canopies. It is precisely during this growth stage that water may be saved by limiting soil evaporation. Hence accurate estimation of t_b is important.

The first three parameters and C_m can usually be obtained from the literature, or by experimentation. There are then two ways in which L_{pi} and t_b may be found.

Serial harvest method :

From previous experimental data

- Plot serial harvest results of W vs physiological age as in Fig 7.5 and extract C_m and t_b.
- Find f_i by substituting experimental R_m (= $K.LAR.C_m$) and t_b into the equation

$$f_i = \frac{\exp\left[-R_m t_b\right]}{1 + \exp\left[-R_m t_b\right]}$$

- Find L_i and eventually L_{pi} by substitution of f_i into $L = \frac{-\left(1 - \ln(f_i)\right)}{K}$

from which $L_{pi} = \frac{L_i}{N_p}$

Fractional interception method :

A simple device developed by Cackett (1964) for measuring canopy cover was used to estimate fractional interception. This instrument is based upon the common point quadrant used for botanical analysis. Measurements are made by sighting leaf cover through holes in two vertically aligned 1.5 meter long bars suspended above the canopy. The number of leaf “strikes” are counted. The number of strikes divided by the number of sets of holes gives the fraction of ground cover covered by the vertical projection of leaf cover, ***FI***. The designer claims an accuracy of within ±2%. Alternatively the percentage of shade on the ground surface when the sun is at its zenith may be observed.

- Observe f early (t=20 days say) in the growing season.
- Use given values of C_m , K and LAR to calculate R_m from $R_m = K.LAR.C_m$
- Calculate L from $L = \frac{-(1 - ln(f))}{K}$
- Calculate L_i from $L_i = Lexp(-R_m t)$ and $L_{pi} = \frac{L_i}{N_p}$.

7.3 *Water limited.*

Crop total (biomass) growth rate (C) is proportional to plant evaporation rate (E_v) and inversely proportional to atmospheric saturation vapour deficit (D). Hence (see Kieselbach, 1916 and Monteith, 1990) C is directly proportional to the ratio E_v / D, viz.

$$C = \upsilon_w E_v/D$$

We will denote the constant of proportionality υ_w and name it the Kieselbach biomass production - evaporation coefficient. It is a crop specific parameter.

We will ***assume***, that even in a water stress situation, saturation vapour deficit, D, does not differ appreciably from the non-water limited condition. Furthermore, the Kieselbach coefficient υ_w is a crop specific parameter and not-influenced by climate. Thus, just at the onset of water stress, energy limited crop growth rate C_o, is given by

$$C_o = \upsilon_w E_{vo}/D$$

Hence the ratio of water limited to energy limited growth is,

$$C = C_o E_v/E_{vo} \text{ , and}$$

Now relative evaporation is given by the ratio of actual to potential plant evaporation, F_v,

Hence $F_v = E_v/E_{vo}$
i.e. $C = F_v C_o$

which effectively means that water limited growth rate equals the product of relative plant evaporation and the crop growth rate compared by say the expolinear equation.

7.4 *Harvestable yield-biomass relationship.*

In Putu, potential dry biomass is calculated using the expolinear function derived by Goudriaan and Monteith (1990) (see Section 7.1) and harvestable yield is simulated using the k_y parameters reported by Doorenbos and Kassam (1979) and also included in CROPWAT (Smith 1992).

The Stewart *et al* (1977) model for expressing the influence of water stress in a growth stage upon final harvestable crop yield may be written:

$$\frac{(Y_0 - Y)}{Y_0} = k_{yi}\frac{(E_{voi} - E_{vi})}{E_{voi}}$$

where, Y_o is potential final harvestable yield. Y is final harvestable yield, and k_{yi} is a constant of proportionality.

This, relationship may be formulated as follows:
The relative final crop yield deficit ascribable to water stress in a given growth stage (i) is proportional to the relative plant evaporation deficit due to plant water stress in the i^{th} growth stage. The constant of proportionality (k_{yi}) is termed the yield - water stress response factor.

It is logical to expect water stress effects occuring during consequential growth stages to have a multiplicative effect upon final crop yield. For example, should biomass production be limited to 80 % in growth stage i. It is reasonable to assume that a further limitation of 50 % in the i + 1 stage will result in overall biomass production being limited to 50 % of 80 % i.e. 40 % of potential. The problem with multiplicative combination laws is that zero yield is never attained theoretically. Therefore, in seasons with severe stress in different growth stages the model can be expected to underestimate yield reduction.

While Doorenbos and Kassam (1979) applied the yield equation on ***AED*** and crop total evaporation, De Jager (1994) showed, in wheat, that use of plant evaporation and a multi- stage analysis combining growth stage deficits multiplicatively to be most accurate. The final equation for harvestable yields thus reads

$$Y = Y_0 \left\{ \underset{i}{\pi} \left(1 - k_{yi} \frac{E_{voi} - E_{vo}}{E_{voi}} \right) \right\}$$

7.5 *The Cultivar Characteristics*

The crop input parameters required for the computations are extracted from the 'Cultivar Charcteristics' file completed by the operator prior to simulation. Required input parameters are :

LEVEL1 elementary irrigation scheduling

LEVEL2 irrigation scheduling which develops ontogeny as season progresses

LEVEL3 complete crop model using the Expolinear function

B_o, T_b	base temperature below which phenological activity ceases (computer screen uses one or other symbol in different places)	(°C)
k_{vo}	maximum evaporation coefficient for a complete crop canopy E_v / E_{vo}	( )
k_{so}	maximum evaporation coefficient for a soil surface E_s / Es_o	( )
Y_o	experimental potential crop yield	(kg ha^{-1})
$T_{max,e}$	daily maximum temperature beyond which phenological activity increases no further	(°C)
$t_{anthesis}$	thermal period from emergence to anthesis	(d °C)
t_{mature}	thermal period from emergence to crop maturity	(d °C)
f_c	fraction of soil surface covered by the vertical projection of the canopy	( )
f_w	fraction of soil surface wetted during irrigation	( )
f_r	fraction of ground surface area beneath which roots extract water	( )
K	light extinction coefficient for green leafed canopy	( )
Rootbase	width of the soil water extraction pattern	(m)
Rootangle	angle of the cone describing the soil water extraction pattern	(°)
LAR	leaf area ratio	(m^2 g^{-1})
G_o	maximum conductance of the root-soil zone	(mm d^{-1} kPa^{-1} m^{-1})
G_e	conductance of water laterally from outside the wet zone	( )
C_m	maximum crop growth rate	(kg ha^{-1} d^{-1})
t_b	lost time	(d)

8 RADIATION AND EVAPORATION EQUATIONS

Introduction

Possibly the most important computation necessary for simulating crop growth and irrigation scheduling in South Africa is the determination of atmospheric evaporative demand. Putu uses the evaporation coefficient concept (see Section 2.2 and 2.3 of Chapter 7) to estimate ***AED*** from reference evaporation (E_o).

Since 1983 (De Jager *et al* 1987), the ***PME*** has been used in Putu to calculate E_o, and potential crop evaporation (E_p). In the ***PME***, an empirical equation for R_n in terms of measured R_s (described by De Jager *et al* 1987) was adopted, as well as a logarithmic wind profile for estimating aerodynamic resistance (r_a). Canopy resistance (r_c) was held constant at 33 s m^{-1} (see De Jager 1984, Russel 1980, Van Zyl and De Jager, 1987 and Van Zyl, De Jager and Maree, 1989). The value of r_c has been changed to 70 sm^{-1} due to this project.

Reference Evaporation

Reference evaporation (E_o) is defined as the rate of evaporation from a hypothetical crop with an assumed crop height of 12 cm, a fixed given canopy resistance and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water.

Reference evaporation (E_o) was computed using ***PME***, the Penman-Monteith Equation (Monteith, 1965). It reads:

$$\lambda E_0 = \frac{(R_n - G) + \rho Cp\,(e_a - e_d)\,/\,r_a}{\delta + \gamma * (1 + r_c\,/\,r_a)}$$

where:

λE_0	latent heat flux of evaporation (kJ m^{-2} s^{-1})
R_n	net radiation flux at surface (kJ m^{-2} s^{-1})
G	soil heat flux (kJ m^{-2} s^{-1})
ρ	atmospheric density (kg m^{-3})
C_p	specific heat of moist air (kJ kg^{-1} °C)
C_p	<1.013 (kJ kg^{-} °C^{-1})
$(e_a - e_d)$	vapour pressure deficit (kPa)
r_c	crop canopy resistance (s m^{-1})

r_a	aerodynamic resistance to gaseous exchange with the atmosphere (s m^{-1})
δ	slope of the vapour pressure curve (kPa °C^{-1})
γ	psychrometric constant (kPa °C^{-1})
λ	latent heat of vapourisation (MJ kg^{-1})

Logarithmic wind profile Both the hourly and the 24-hour versions use transformations of r_a based upon the logarithmic wind profile, where aerodynamic resistance (r_a) is described by

$$r_a = \frac{ln\frac{z_m - d}{z_{om}} ln\frac{z_h - d}{z_{oh}}}{k^2 U_z}$$

r_a	aerodynamic resistance (s m^{-1})
z_m	height of the windspeed measurements (m)
z_h	height of temperature and humidity measurements (m)
k	Von Karman constant = 0.41 ()
U_z	windspeed measurement at height z (m s^{-1})
d	zero-plane displacement for the wind profile (m)

For psychrometer, temperature and wind measurements at 2 m height this may be transformed given crop (grass) height(h_c), from the definition of E_o

h_c = 0.12, then $d = 0.667\, h_c$ and

z_{om} = $0.123 h_c$ and $z_{oh} = 0.0123 h_c$, which makes possible estimation of r_a, since

$$208 = ln[\frac{Z_{om} - d}{d}]\ \ln[\frac{Z_{oh} - d}{d}]/k^2 \quad \text{then}$$

$$r_a = \frac{208}{U_2}$$

This expression for r_a is then substituted in the aerodynamic term of the ***PME***.

Daytime wind U_d may be obtained from 24-hour wind using

$$U_d = 1.33U$$

Wind at height z is converted to wind at 2 m height using

$$U_2 = Uz \frac{\ln(\frac{z_2 - d}{z_{om}})}{\ln(\frac{z_m - d}{z_{om}})}$$

Saturated vapour pressure at temperature T *(°C)* is given by **e(T)** = 0.611 exp {17.27 $T/(T + 237.3)$}
Slope of the **saturated vapour pressure** is given by

$$\delta = \frac{4099}{(T + 237.2)^{2}}$$

Psychrometric measurements (dry and wet bulb thermometers) are based upon the psychometric equation

$$e_d = e_{a}(T_{wet}) - \gamma_{asp}(T_{dry} - T_{wet})P$$

where,

γ_{asp} = 0.00066 for Assman aspiration at 5 ms^{-1}

γ_{asp} = 0.0008 for natural ventilation at 1 ms^{-1}

γ_{asp} = 0.0012 for indoor ventilation at 0 ms^{-1}

T_{dry} dry bulb temperature (°C)

T_{wet} wet bulb temperature (°C)

P atmospheric pressure (*kPa*)

$e_{a(Twet)}$ saturation vapour pressure at wet bulb temperature (*kPa*)

Daily mean vapour pressures are taken as the artithmetic mean of the maximum and minimum values measured at approximately 0800 and 1400 hrs.

Atmospheric pressure is either the long-term average for the locality, or

$$P = 101.3\left[\frac{293 - 0.0065z}{293}\right]^{5.26}$$

Z height of station above mean sea level (m)

24-Hour Periods. For estimates of reference evaporation, E$_0$, based upon 24-hour mean temperature, psychrometer and wind measurements made at 2 m height; the version of the ***PME*** devised by the FAO Panel of Experts, as reported by Allen *et al*(1994) was used, viz.

$$E_o = \frac{0.408\delta(R_n - G) + \gamma\frac{900}{T + 273}U_2(e_a - e_d)}{\delta + \gamma(1 + 0.34U_2)}$$

where:

E_0 reference crop evaporation (mm d^{-1})

R_n	net radiation at crop surface (MJ m^{-2} d^{-1})
G	soil heat flux (MJ m^{-2} d^{-1})
T	average temperature (°C)
U_2	average windspeed measured at 2m height (m s^{-1})
$(e_a - e_d)$	vapour pressure deficit slower measured at 2 m height (kPa)
δ	slope vapour pressure curve (kPa °C^{-1})
γ	psychrometric constant (kPa °C^{-1})
900	conversion factor

Hourly Periods. For hourly estimates the ***PME*** becomes (Allen *et al*, 1994):

$$E_o = \frac{0.408\delta(R_n - G) + \gamma \frac{37}{T+273} U_2(e_a - e_d)}{\delta + \gamma(1 + 0.34U_2)}$$

The Modified Psychrometric constant, γ^*, is defined as

$$\gamma^* = 1 + \frac{r_c}{r_a}$$

For observations made at 2 m height γ^* is replaced by

$$\gamma^* = \gamma(1 + 0.34\ U_2)$$

The effect of instrument measurement height upon the constants 900 (24 hour expression) and 37 (hourly expression) is evident from the following:

z_m	z_h	u_z	24 hour	hourly	γ^* r_c=33	γ^* r_c=70
2	2	2	902	38	.077	.098
2	1.5	2	942	39	.078	.099
3	1.5	2	867	36	.076	.096
2	2	6			.114	.176
2	1.5	6			.117	.181
3	1.5	6			.112	.172

It is evident that the value of r_c, viz. r_c = 33, or r_c = 70 s m^{-1} will have a marked influence on the constant 0.34 in the expression for γ^*. Following the conclusions from Chapter 11 and the work of Allen *et al* (1994) it was decided to standardise on r_c = 70 sm^{-1}.

Net radiation in Putu is estimated from measured hourly solar radiation (R_S) using the empirical equation from De Jager *et al* (1987), viz.

$$(Rn - G) = 0.75\,R_s - 72 \qquad (W\,m^{-2})$$

For general purposes, when only sunshine and humidity data are available; daily net short-wave radiation (R_{ns}) was estimated according to an Ångstrom type equation, thus

$$R_{ns} \quad = \quad 0.77 \ \ (0.25 + 0.50 \frac{n}{N}) \, R_a$$

and net thermal long wave radiation, R_b, can be estimated by the following equation:

$$R_b \quad = \quad -2.45 \times 10^{-9} \, [0.9 \frac{n}{N} + 0.1] \ \ [0.34 - 0.14 \sqrt{e_d}\,] \, \sigma (T^4_{kx} + T^4_{kn})/2$$

R_b Net long wave radiation (MJ m^{-2} d^{-1})

σ Stefan Boltzmann constant (Jm^{-2} K^{-4} d^{-1}) = 4.903 10^{-9} (MJm^{-2} d^{-1})

T_{kx} Maximum day absolute temperature (K)

T_{kn} Minimum day absolute temperature (K)

Then

$$R_n \quad = \quad R_{ns} \quad + \quad R_b$$

Ephemeris of the sun is computed as follows:

ϕ latitude, taken as - ve in the southern hemishpere

Given the number of the month (***M***) and the day of the month (***D***); the day of the year, counted from January 1, ***DOY***, may be calculated using the following algorithms

$$DOY = integer \ (275 \frac{M}{9} - 30 + D) - 2$$

The adjustment for leap years is made using the algorithms:

If (M<3) Then $DOY = DOY + 2$

If (year mod 4) and M>2 Then $DOY = DOY + 1$

Where distance from sun to earth is denoted ***Dist***, then

$$Dist \quad = \quad 10 + 0.033 \cos (0.0172 \, DOY)$$

Now, the solar declination (δ) may be found from

$$\delta \quad = \quad 0.409 \sin(0.0172 \, DOY - 1.39) \qquad \text{(rad)}$$

For 24-hour periods the solar constant, R_a, is

$$Ra \quad = \quad 37.6 \, Dist \, (\omega_s \ \sin\phi \ \sin\delta + \cos\phi \ \cos\delta \ \sin\omega_s)$$

ω_s sunset angle of the sun (rad)

given by ω_s = arcos (-tan ϕ tanδ)

, or

$$\omega_s = \frac{\Pi}{2} + \arctan\{\tan\left[\frac{-\tan\phi\tan\delta}{(1-\tan^2\phi\tan^2\delta)^{.5}}\right]\}$$

The maximum number of sunshine hours in a day is

$$N = 7.64\omega_s$$

Priestley-Taylor equation. The form of the Priestley-Taylor (1972) formula used reads:

$$\boldsymbol{E_o} = \frac{\delta}{\delta+\gamma}\,(1.28+\alpha)\,(\boldsymbol{R_n} - \boldsymbol{G})\,/\,2.45$$

where,

$$\boldsymbol{R_n} - \boldsymbol{G} = 0.65\,\boldsymbol{R_S} \text{ and}$$

$$\alpha = 0{,}08\,(\boldsymbol{T_{max}} - 20)$$

where, α is constrained as follows $0 \leq \alpha \leq 0{,}6$.

For hourly estimates; α equals unity and

$$\boldsymbol{E_o} = \frac{\delta}{\delta+\gamma}(\boldsymbol{R_n} - \boldsymbol{G})\,/\,2.45$$

Conclusion

For the purposes of conformity, the version of the ***PME*** recommended by the FAO Panel of Experts (Allen *et al*, 1994) has been adopted in Putu with the exception that Putu uses the empirical equation given above for net radiation and a value of $\boldsymbol{r_c} = 70$ s m^{-1}. When only sunshine hours are available $\boldsymbol{R_n}$ is estimated as prescribed above by Allen *et al* (1994)

9. PARTITIONING OF DRY MASS

Putu-Irrigate utilises an empirical linear dry matter partitioning procedure which also makes it simple for operators to complete the 'Partitioning' parameter file. This input parameter file is found under 'Cultivar Characteristics', but only for 4 stages out of the possible 9, appears as in Fig. 7.6. Operators need only to enter $\boldsymbol{F_{nos}}$, the expected proportion of total dry matter in plant organ n at the end of each growth stage (*s*). This is done for each plant organ. The above ground standing dry mass is divided into storage organs (***STORE***), leaves (***LEAF***), stems (***STEM***) and harvestable yield (***YIELD***). The latter could be grain or fruit. For sugar cane stems, and, for grassland leaves plus stems must be added to yield by the operator.

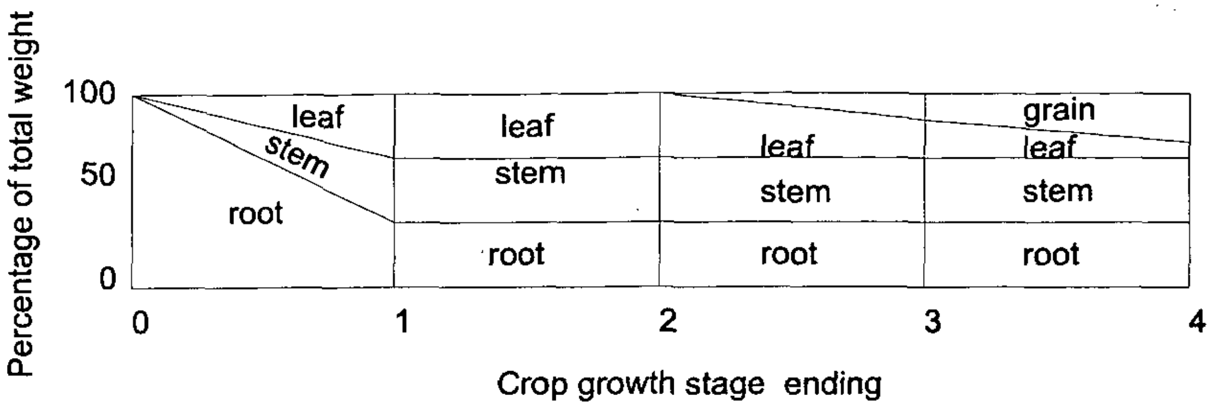


Fig 7.6 Diagram illustrating partitioning of energy limited dry mass for crop cultivar charracteristics.

The theory was derived from Squire (1990) and Supit *et al* (1994) who defined partioning factors, p_n, *as the fraction of dry mass growth partitioned to individual plant organ n. This is the empirical* approach described by Thornley and Johnston (1990), but is also a form of teleonomic partitioning since the crop strives to attain a genetically preferred organ composition at the end of each growth stage. The input parameter file provides F_{nis} and F_{nos}, the fraction of standing dry mass in plant organ n, at the beginning (i) and end (o) of stage s respectively.

The proportion of standing dry mass in the n^th^ plant organ at time t may be calculated using

$$F_{ns} \quad = \quad F_{nsi} + \frac{\delta F_{ns}}{\delta t}\Delta t$$

where $\frac{\delta F_{ns}}{\delta t} = \left(\frac{F_{nos}-F_{nis}}{t_{os}-t_{is}}\right)$

and p_{ns}, the fraction of dry matter growth partitioned to new growth in the nth plant organ during stage s as defined by Squire (1990) and Supit *et al* (1994) is given by $p_{ns} = \frac{\delta F_{ns}}{\delta t}\Delta t$.

An above ground dry mass balance is maintained. Hence, at all times,

$$\Sigma F_n = 100$$

and $$\Sigma p_n = 100$$

The canopy development file

The operator enters observed fractional radiation interception of the total leaf canopy (***FI***) and the *percentage of standing leaf dry matter produced which is green (**GREEN**) and which is trash* (***TRASH***). From this the leaf canopy composition is computed each day, as follows:

$$f \quad = \quad FI$$

$f_g \quad = \quad [GREEN/100]\ FI$

Fractional interception by senesced material is given by

$f_{sen} \quad = \quad [1 - GREEN/100]\ FI$

By definition, relative total production (***PROD***) is given by

$$PROD = GREEN + SENESCED + TRASH$$

$$= 100 + TRASH\text{, and}$$

the percentages (of total biomass produced) of green, senesced and trash dry material, by:

$$F_{green} = [GREEN/PROD]100$$

$$F_{senesced} = [(100 - GREEN)/PROD]100$$

$$F_{trash} = [TRASH/PROD]/100$$

Estimates of fractional interception (*FI*) are taken equal to the vertical projection of leaf cover on a horizontal plane obtained by the method of Cackett (1964), or simply from the percentage shaded ground. The values for f and f_g computed in this manner are used to calculate evaporation coefficients k_c, k_v and k_s. Critical for this, is the estimate of k_{vo}, which is, say the maximum k_c from Doorenbos and Kassam (1979). The method has the advantage that it permits the operator to adjust evaporation coefficients throughout the season if necessary and that it takes sparse canopies into account.

10. *ONTOGENY*

Effective daily temperature

The biological clock for vegetation is driven by heat. Heat is measured by temperature. Where vegetation is concerned, the daily temperature effective in crop growth and development (T_e) is defined (see Supit, Hooijer and Van Diepen, 1994) as follows :

$$T = (T_{\max} + T_{\min})/2$$

$$T_e = 0 \qquad T \le T_b$$

$$T_e = T - T_b \qquad T_b \le T \le T_{max,e}$$

$$T_e = T_{max,e} \qquad T > T_{max,e}$$

T (average)daily temperature

T_b base temperature below which phenological development ceases (°C)

$T_{max,e}$ maximum temperature beyond which phenological activity does not increase (°C)

For tropical crops approximately, $9 \leq T_b \leq 14$°C (Angus *et al* 1981) and for temperate crops $0 \leq T_b \leq 3$°C

Physiological age

In order to facilitate extrapolation of the expolinear growth function and crop parameters to any locality; growth rates were expressed in terms of physiological age. A physiological day is defined as a 24-hour period having an effective growth temperature of 20°C. Essentially it amounts to the linear normalisation of sidereal time to days all having a temperature of 20°C and which will produce the same degree of aging in a given growth process as would be the case at naturally occuring other temperatures.

The concept is similar to that defined by of Galhagher (1979). We derived the relationship for physiological age and between physiological time and sidereal time as follows:
Physiological age is assumed inversely proportional to the heat accumulated by vegetation in one day (J d).

Thus, for a daily effective growth temperature of T_e

$$Qv = \rho_a Cp(T_e - T_b)$$

where,

Qv the daily heat above crop growth base temperature (T_b) in 1 m^3 of air (J m^{-3})
ρ_a density of air (kg m^{-3})

By definition t_p is directly proportional to $\Sigma Q_v = \rho_a Cp \, \Sigma(T_e - T_b)$

Given the above a priori assumption, it is evident that physiological aging per unit sidereal day is the ratio of Q_v at temperature T_e to Q_v at 20°C, or

$$(T_e - T_b) / (20 - T_b)$$

Hence, $$t_p = (DAYLENGTH / 12) \, \Sigma_t [(T_e - T_b) / (20 - T_b)])$$

Since thermal time, t_t, is defined as the summation of effective daily temperature above a given base temperature, T_b, or

$$t_t = \sum_t (T_e - T_b)$$

The relationship between physiological age and thermal time after t_o days, is given by

$$t_p = [DAYLENGTH / 12t_o (20 - T_b)] \, \Sigma_{to} (T_e - T_b)$$

giving $$t_t = 12t_o (20 - T_b) \, t_p / DAYLENGTH$$

Simulation of phenological processes

Thermal period is used to simulate the termination of phenological stages through the growing season. From the previous paragraph it is evident that this is equivalent to using physiological age. A data field for critical thermal periods for a growing season divided into 9 different growth stages is provided. The critical thermal period terminating each stage is entered by the operator in the "Calendar" file under Cultivar Characteristics on the menu for Level 2 simulation. The operator must obtain values of critical thermal period from the literature, or determine them as the season progresses using the facility in Level 1. In Elementary Level 1 the operator simply enters the days on which the phenological change are observed and gives the stage a name, either his own, or one of those provided in the pull-down menu. Putu then proceeds to calculate the appropriate thermal period and completes the crop calendar. The major advantage of this method is that users can now determine thermal time as the season progresses. Since thermal time and physiological age are independent of climate these values will apply in other localities.

11. SENESCENCE

The senescence model of Johnson and Thornley (1983) was adopted. Here canopy leaf area is divided into categories, or stages. Each stage contains leaves of a certain age described as follows:

1. Expanding leaves
2. Fully mature leaves (First leaf)
3. Second and older, green leaves (Second leaf)
4. Senesced leaves

As the canopy ages and leaves develop, the amount of dry mass in each leaf stage varies. In effect, mass flows (translocates) from one category to the next.

Leaf mass appears in a given category at a rate, which is proportional to the mass in the source (donor) category and physiological time. The rate of leaf appearance at 20°C in a given category, termed γ_{20} by Johnson and Thornley (1983), was adopted, viz.

$$\gamma_{20} = 0.15 \text{ d}^{-1}.$$

Data and results reported by De Jager, Howard and Snyman (1997) have shown the value to be accurate for grassland. The relevant defining equations are as follows:

$$\frac{\delta W_n}{\delta t_p} = \gamma_{20} \qquad \text{for age categories n, where } 1 \leq n \leq 4.$$

L_n, the leaf area index in age category (n) is given by $L_n = p_i s \ W_n.$

CHAPTER 8

MODIFICATIONS REQUIRED AND BROUGHT ABOUT AND APPLIED TO THE 1992 PUTU-IRRIGATE IRRIGATION SCHEDULING MODEL

Irrigation scheduling using the Putu-Irrigate Model (De Jager, 1992) has been operating successfully in the commercial field for seven years. During this period, several modifications and updates to the system became evident. Listed below are some of the difficulties encountered and improvements undertaken or suggested.

Use of Screen Output as well as hardcopy

Originally it had been necessary to print each model run for each irrigation block. This was altered to allow the user to view output, create output files, or print whatever information is required for scheduling irrigation.

Type of Decision Support Information

To assist advisors a list of the simulated values for the last seven days and a prognosis for the next seven days based upon long-term climate are provided. Graphical presentations of this on any time frame in the lead-up period are now possible.

Vinit and In-season Files

Users experienced difficulty in creating initial (i.e. at the time of planting) soil water content files. This has been rectified by including an appropriate procedure in the main menu. The desire to modify simulated soil water content during the season became evident and such facility has also been included in the main menu.

A Sequence of Years

Growing periods for crops such as sugar-cane and maize, extend from one calendar year to the next. In such cases the previous year's irrigation dates and amounts were carried forward to the following year. The simulation of crops, be they annual or perennial, planted within fourteen days of the end of a year, caused print-out for fourteen days from each year. This too has been rectified.

With perennial crops such as citrus, apples, avocados and other orchard crops, the crop evaporation coefficient files had to be modified. Simulation of perennial crops had to be re-started each year and the canopy cover factor had to be maintained at unity in the crop coefficient file all of which was inconvenient and time consuming. A new crop cultivar file has been created which extends up to ten years.

Ultra Stress

Certain crops such as potatoes are planted in extremely dry soil. When such initial conditions exist at crop establishment, the simulation defaults to ultra-stress. The practical solution is artificially to increase the available water to a value minimally above the lower limit of soil water thereby avoiding the ultra-stress condition. A function requires to be included which ignores ultra-stress in the first two weeks of the growing season.

Upper and Lower Limits of Soil Water Content

Measured values of soil water content at drained upper limit (DUL) and lower limit (LL) are seldom available and therefore have to be estimated. This complicated problem is addressed in Chapter 10. The model was altered so that the operator now, needs initially to enter θ_{1500}, θ_{10} and DUL in the soil data file.

Actual Soil Water Content

During the season, the actual soil water contents of the various soil layers, if expressed as mm of water, may differ from those determined by the model and stored in the output (i.e. *.VAR) files. Although the values may differ, the percentage of available soil water between DUL and LL will be accurate. The soil water content should therefore be expressed as a percentage. Clients are encouraged to take gravimetric samples throughout the season to monitor the real situation, and compare it to model results, thereby gaining confidence in the system. The In-season file may be used to make adjustments to soil water content and LAI.

Input Files

The creation of rainfall and irrigation files for individual plots is a welcome improvement over the old method which required various IBSNAT files to be created.

The identification code of the irrigation files and control files are limited to 8 digits. The eight character limitation is a feature of the computer operating system, but is easily overcome by creating a new series of files, when large numbers of blocks are involved.

An attempt was made to standardise input files from clients, but proved unsuccessful. Clients record irrigation and associated data differently, using different software programmes. The advisor, however, should be prescriptive in this regard and ensure that input to the system is uniform. Thereby saving himself much time.

Scheduling Procedures

It is noted that some advisors are loathe to use the forecast irrigation dates and the reasons for this should be ascertained.

Continuous Calibration

It was found that canopy cover (fractional radiation interception) is a concept easily visualised and measured by both client and consultant. Operators may now enter fractional interception in the cultivar file at different crop growth stages.

VARYING METHODS OF TECHNOLOGY TRANSFER FOR DIFFERENT SYSTEMS

Experience showed that different irrigation systems require different scheduling procedures because of the nature of their design, eg.

(i) Centre pivot system - can operate on a daily basis but usually set to complete 1 cycle in 3-4 days. Thus the advice provided must include a forecast for 3-4 days.

(ii) Dragline system - usually operates on a 7 day cycle thus advice provided must include a forecast of 7 days. Within the 7 days, if the crop is say winter pastures, the crop growth stages may change significantly when a grazing/harvesting event occurs. This can either be accommodated by the irrigator, or by the advisor.

(iii) Drip or microjet system - usually operates on a 1-3 day cycle, and advice provided varies from near real-time to forecasting 3 days ahead.

Appendix II illustrates the types of recommendation possible with Putu for these different systems.

Modifications required on the Putu system

The Putu system shell functioned adequately for most applications. The need to streamline and expedite operations particularly where large numbers of irrigation plots are involved, often requiring scheduling on a daily basis, became evident. Listed below are some of these

(i) Redevelop the system as a Windows-based system. Printing can be handled by the Windows Print Manager, while the computer is released for further computing.

Data manipulation is done using Word Perfect for Windows, and the recommendations can be done using Quattro Pro for Windows. With a Windows based system, these operations (including the running of the model) can continue simultaneously in separate windows.

(ii) Generate a flexible output file for each run of the model (includes all the irrigation blocks), in the format preferred by the client. This file can then be used to generate a skeleton recommendation file in Quattro Pro and the only data requiring to be filled in manually are the actual recommendations, dates and irrigation amounts.

(iii) Automate generation of the weather file. Once the weather data has been downloaded via telemetry, the weather file can be automatically generated, producing an error message if necessary. This automatic generation will have to account for the different size data files (ie. daily, 3day, 7day).

(iv) Streamline input of the irrigation data. Most users submit their irrigation data either via telephone, facsimile or in spreadsheet form on their PC's. Once received, this data has manually to be entered into the model. It should be considered providing clients with a program with which he can add or change irrigation data to a format compatible with the model. These data can then be read directly into the model.

(v) Introduce the critical soil water depletion levels for each crop growth stage into the evaporation co-efficient file. Allowance will also have to be made for the irrigation system should it have a direct effect on this depletion level. eg. the majority of centre pivot systems can only apply a net amount of 5 mm per day. This application is insufficient in the periods when atmospheric evaporative demand easily exceeds this amount. A soil water depletion level of 75% was recommended for all crops being produced under centre pivot systems. For at least 2 months, this method was adopted successfully, eg. with onions produced at ZZ2, Dikgale under centre pivot irrigation. The determination of the "forecast irrigation date" (FID) must be modified to accommodate varying depletion levels.

(vi) The Putu irrigation model accounts for a water table. This unfortunately seems to be limited in the model to a minimum depth of 900mm. Soils with a restrictive layer shallower than this could be encountered and the model must be able to account for this.

Conclusions

The Putu-IDSS worked well in the commercial environment with increased irrigation efficiency and better quality yields being experienced. Appendix II illustrates the type of information that is sent to clients initially.

State telecommunications have improved in an increasing number of areas and this promoted the efficient transfer of information.

Comment

The Putu IDSS was re-programmed into a Delphi shell run through Windows and most of the problems mentioned have been solved.

CHAPTER 9

MODEL PARAMETERS FOR PUTU-IRRIGATE

INTRODUCTION

In practice, as irrigation managers become familiar with the Putu scheduling software they should be able to adjust the model input parameters in the cultivar file to suit the crops and cultivars for which the irrigation is being scheduled. Such skills are easily developed with practice. Useful information is also available in the literature. The most important parameters are the soil water characteristic, fractional interception by green leaves (*FI_g*), the yield reduction – water stress response factor (*k_y*) and the leaf water potential at which water stress commence (ψ_{vcrit}). The first is discussed in Chapter 10 and values of the others for some 20 crops are here tabulated to assist managers to get started.

At a first approximation it may be assumed that *FI_g* is equal to the fractional vertical projection of green leaf cover on the ground surface. The data listed were obtained from Mottram Associates (pers. comm.) and Doorenbos and Kassam (1979).

Table 9.1a CROP COEFFICIENTS FOR POTATOES

GROWTH	AILSA/BP/13/MORENE VARIETIES			BP/1/MONDIAL VARIETY		
STAGE	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	2	0.30	0.20
DEVELOP	7	0.40	0.30	7	0.40	0.30
MID	14	0.70	0.45	14	0.70	0.45
FLOWER	28	1.00	0.80	28	1.00	0.80
GRAIN	50	1.00	0.70	50	1.00	0.70
RIPE	70	1.00	0.70	70	1.00	0.70
REST	90	1.00	0.70	120	1.00	0.70

Table 9.1b CROP COEFFICIENTS FOR WHEAT

GROWTH STAGE	WINTER			SUMMER		
	Day of Growth	Ground Cover (FI$_g$)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI$_g$)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	2	0.30	0.20
DEVELOP	14	0.35	0.20	7	0.40	0.30
MID	60	0.55	0.30	28	0.70	0.40
FLOWER	105	1.00	0.65	56	1.00	1.10
GRAIN	115	0.90	0.55	84	1.00	0.80
RIPE	150	0.45	0.00	94	1.00	0.80
REST	165	0.20	0.00	185	1.00	0.80

Table 9.1c CROP COEFFICIENTS FOR APPLES AND MAIZE

GROWTH STAGE	APPLES			MAIZE		
	Day of Growth	Ground Cover (FI$_g$)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI$_g$)	Yield reduction factor (ky)
REST	0	0.25	0.00	0	0.00	0.00
SOW	62	0.30	0.00	1	0.00	0.00
ESTABLISH	94	0.40	0.00	2	0.30	0.20
DEVELOP	125	0.45	0.00	7	0.30	0.20
MID	157	0.50	0.00	27	0.60	0.30
FLOWER	189	0.50	0.00	59	1.00	0.65
GRAIN	200	0.50	0.00	73	1.00	0.55
RIPE	232	0.40	0.00	0.80	0.00	
REST	365	0.20	0.00	0.60	0.00	

Table 9.1d CROP COEFFICIENTS FOR SOYA BEANS AND SUGAR CANE

GROWTH STAGE	SOYA BEANS Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	SUGAR CANE (April planting) Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	2	0.20	0.75
DEVELOP	14	0.35	0.20	35	0.40	0.75
MID	60	0.55	0.30	70	0.55	0.75
FLOWER	105	1.00	0.65	105	0.72	0.75
GRAIN	115	0.90	0.55	126	0.85	0.50
RIPE	150	0.45	0.00	140	1.00	0.50
REST	165	0.20	0.00	366	1.00	1.00

Table 9.1e CROP COEFFICIENTS FOR SUGAR CANE

GROWTH STAGE	JUNE PLANTING Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	JULY PLANTING Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.20	0.75	2	0.20	0.75
DEVELOP	35	0.56	0.75	35	0.45	0.75
MID	70	0.66	0.75	49	0.60	0.75
FLOWER	84	0.80	0.75	56	0.70	0.75
GRAIN	105	0.90	0.50	70	0.80	0.50
RIPE	126	1.00	0.50	84	1.00	0.50
REST	366	1.00	1.00	366	1.00	1.00

Table 9.1f CROP COEFFICIENTS FOR SUGAR CANE AND RYEGRASS

GROWTH STAGE	SUGAR CANE (Aug-Oct planting)			RYEGRASS		
	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.25	0.00
ESTABLISH	2	0.25	0.75	7	0.50	0.00
DEVELOP	28	0.40	0.75	14	0.70	0.00
MID	35	0.56	0.75	21	0.90	0.00
FLOWER	49	0.70	0.75	22	0.90	0.00
GRAIN	63	0.80	0.50	23	0.90	0.00
RIPE	84	1.00	0.50	25	0.90	0.00
REST	366	1.00	1.00	85	0.90	0.00

Table 9.1g CROP COEFFICIENTS FOR CABBAGES AND ONIONS

GROWTH STAGE	CABBAGES			ONIONS (early March)		
	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.20	0.20	2	0.30	0.20
DEVELOP	15	0.30	0.20	7	0.40	0.30
MID	30	0.40	0.20	14	0.60	0.40
FLOWER	55	0.60	0.30	28	0.80	0.50
GRAIN	75	0.80	0.30	50	1.00	0.80
RIPE	90	1.00	0.45	70	1.00	0.80
REST	120	1.00	0.60	115	1.00	0.30

Table 9.1h CROP COEFFICIENTS FOR ERNESTOLZE AND BP 13

GROWTH STAGE	ERNESTOLZE Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	BP 13 Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	2	0.10	0.20
DEVELOP	7	0.40	0.30	7	0.30	0.30
MID	14	0.70	0.45	14	0.60	0.45
FLOWER	28	1.00	0.80	25	0.90	0.80
GRAIN	60	0.90	0.70	50	1.00	0.70
RIPE	70	0.60	0.70	70	1.00	0.70
REST	115	0.50	0.60	170	0.60	0.70
SHORT POTATO						

Table 9.1I CROP COEFFICIENTS FOR TOMATO - FLORIDADE AND CARROTS

GROWTH STAGE	TOMATO - FLORIDADE Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	CARROTS Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	4	0.10	0.10
DEVELOP	7	0.40	0.30	7	0.30	0.30
MID	28	0.70	0.40	28	0.40	0.50
FLOWER	56	1.00	1.10	53	0.50	0.50
GRAIN	84	1.00	0.80	75	0.60	0.50
RIPE	94	1.00	0.80	86	0.60	0.30
REST	200	1.00	0.80	230	0.70	0.30
OTHER MEDIUM						

Table 9.1j CROP COEFFICIENTS FOR POTATOES AND PEAS

GROWTH STAGE	POTATO - MONDIAL			PEAS - MANGETOUT		
	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)	Day of Growth	Ground Cover (FI_g)	Yield reduction factor (ky)
REST	0	0.00	0.00	0	0.00	0.00
SOW	1	0.00	0.00	1	0.00	0.00
ESTABLISH	2	0.30	0.20	4	0.10	0.10
DEVELOP	7	0.40	0.30	7	0.30	0.30
MID	14	0.70	0.45	28	0.50	0.50
FLOWER	28	1.00	0.80	53	0.80	0.80
GRAIN	50	1.00	0.70	68	0.80	0.80
RIPE	70	1.00	0.70	86	0.30	0.30
REST	120	1.00	0.70	180	0.00	0.00
OTHER MEDIUM						

DEFAULT VALUES OF CRITICAL LEAF WATER POTENTIAL

To simplify setting up input files, default values of critical leaf water potential (ψ_{vcrit}) for 21 crops are included in Putu. When the operator selects a crop type the appropriate values of ψ_{vcrit} from Table 9.2 are automatically defaulted into the model.

The model default values given in Table 9.2, which represent the critical leaf water potential at which evaporation starts being impaired by plant water stress, were taken from values compiled and reported by Schulze (1995b) from numerous authors.

Table 9.2 Critical leaf water potential ψ_{vcrit} at which evaporation from the plant starts to decrease (after Doorenbos and Kassam, 1979; Slabbers, 1980; Martin, Stegman and Fereres, 1990, as reported by Schulze, 1995b)

CROP	CRITICAL LEAF WATER POTENTIAL ψ_{vcrit} (kPa)		
Bananas	-600	to	-800
Beans	-800	to	-1000
Cabbage	-600	to	-800
Citrus	-900	to	-1200
Cotton	-1000	to	-1400
Grapes	-1000	to	-1400
Grass	-1000	to	-1400
Groundnuts	-900	to	-1200
Lucerne (Alfalfa)	-800	to	-1200
Maize	-1200	to	-1700
Onion	-400	to	-600
Pea	-600	to	-800
Pepper	-400	to	-600
Potato	-400	to	-600
Soybean	-1000	to	-1500
Sorghum	-1200	to	-1400
Sunflower	-1000	to	-1200
Sugarbeet	-500	to	-1400
Tobacco	-900	to	-1300
Tomato	-600	to	-1000
Wheat	-900	to	-1400

CHAPTER 10

THE SOIL WATER CHARACTERISTIC

DEFINITIONS

The Soil Water Characteristic (SWC). The curve and equation describing the relationship between soil matric potential (***kPa***) versus soil water content (mm m^{-1}).

The Upper Limit of Soil Water (SWUL). The soil water potential (ψ_{so}) and soil water content (θ_o) associated with the condition reached immediately after a soil wetting event, without evaporation and after the initial excess water has rapidly drained away (percolated). The water remaining usually almost (80% of θ_p) fills the soil pore space. At this phase deep drainage commences with an exponential decay rate. The subscript $_o$ denotes upper limit, or reference level.

Plant Available Water (PAW). Soil water content (mm m^{-1}) held between ***SWUL*** and θ_{1500}.

Percentage Plant Available Water (PPAW). The percentage of ***PAW*** in a volume of soil.

Porosity θ_p. The proportion (mm m^{-1}) of soil volume which is pore space.

Drained Upper Limit DUL. The soil water content (mm m^{-1}) after, say 60 days when exponential decay in deep drainage has caused all free water to have drained through the soil and the water remaining is held by capillary forces great enough to resist gravity and evaporation is prevented by plastic cover.

SYMBOL	***DEFINITION***
FRACsand	Fraction off soil matrix which is sand ()
FRACsilt	Fraction of soil matrix which is silt ()
FRACclay	Fraction of soil matrix which is clay ()
DIAMpart	Average diameter of soil particles (mm)
DIAMclay	Average diameter of clay particles (= .001 mm)
DIAMsilt	Average diameter of silt particles (= .026 mm)
DIAMsand	Average diameter of sand particles (= 1.025 mm)
θ_p	Porosity percentage air space in the soil matrix (%)
ρ_s	Dry bulk density of the soil matrix (kg m^{-3})
DUL	The drained upper limit - volume of water retained in unit volume of soil matrix after 60 days of drainage by gravity (mm m^{-1})

LL	The lower limit of plant extractable water - volume of water retained per unit volume of soil matrix after the roots of a specific crop have extracted as much water as they possibly can (death) (mm m^{-1})
θ_o, V_o	Volumetric water content of the soil at SWUL (mm m^{-1})
V_{10}	Volumetric water content at -10kPa soil water potential (mm m^{-1})
V_{1500}	Volumetric water content at a soil matric potential of -1500 kPa (mm m^{-1})
V	Volumetric soil water content (mm m^{-1})
Ψ_s	Soil water potential i.e. suction pressure on water held in a soil matrix (***kPa***)
Ψ_{so}	Suction pressure on water in a soil in which soil water content is at ***SWUL*** (***kPa***)
$COND_{so}$	Hydraulic conductivity in a saturated soil matrix
FRACdrain, and ***VCON***	Fraction of water held in soil above ***DUL*** which drains to the next lower level (d^{-1})
b	Empirical constant in the two - or one - parameter exponential soil water release equation.

THE PROBLEM

Simulation of the onset of plant water stress requires a relationship expressing soil water potential in terms of soil water content named the soil water retention characteristic (*SWC*), or soil water release curve.

Scheduling irrigation using crop growth models (CGM) over the past fifteen years has shown that correctly describing this curve is critical and fraught with practical problems. Putu-irrigation (De Jager 1992) utilized the theory of Campbell (1985) to estimate ***SWUL***, but found that in practice ***SWUL*** values required trial and error calibration so as to ensure simulated values of soil water content (θ) lay between field measurements of (***SWUL***) and θ_{1500}. This trial and error approach is not always realised by operators (eg. Botes and Oosthuizen, 1992) and was difficult to explain to users. It is important to note that, while measured absolute values of θ may not necessarily agree with modelled values in Putu, it is actually the soil water depletion which is critical in the simulation of the value of ψ_s and the onset of stress, resulting in accurate simulation nonetheless.

In practice, in each soil layer, when soil water suction reaches approximately -200 ***kPa*** (and ***PPAW*** drops to approximately 50%) water flow to the plant becomes restricted. Remember that in the top layer soil evaporation can deplete θ to well below -1500 ***kPa***. A sound model for soil water release should therefore compute accurate values of θ especially around ψ_s = -200 ***kPa***. Effective practical irrigation scheduling using a CGM entails being able to:

1. Find a convenient expeditious method for establishing a soil water release curve which is representative of the relevant soil layer. The two-parameter exponential law is now used in Putu.

2. Make sporadic checks of simulated soil water content against observed values and adjust the former at any time during the season. The In-season subroutine in Putu undertakes this.

Upper Limit of Soil Water

Operators in the field experience difficulty accurately calibrating ***SWUL*** so that simulated values of soil water content, V or θ, occur between ***SWUL*** and -1 500 ***kPa*** (θ_{1500}). The model has now been modified making it necessary for the operator to enter θ_{1500}, θ_o and ψ_{so} in the soil parameter file.

Porosity, θ_p, could be used as an indicator for estimating the soil water content at which the drainage phase commences (***SWUL***). It could for example be assumed that ***SWUL*** was a fraction (80% say) of porosity θ_p. Porosity can be determined from bulk density.

POSSIBLE MODELS

The Two-parameter Exponential Law

Over the years different versions of Putu have used different equations for expressing the ***SWC*** - an exponential spline fit in Putu 2 for grassland (Booysen, 1983); the Hutson (1984) empirical equations in Putu 6 (De Jager *et al,* 1981); Gompertz equation in Putu 9 (De Jager *et al,* 1987) and Putu 12 (De Jager, 1990) and in Putu-irrigate (1992) the two-parameter exponential law (Williams, Prebble, Williams, Hignett, (1983) and Bennie, Coetzee, Van Antwerpen, Van Rensburg and Burger, 1988).

It was decided to utilize empirical equations for the ***SWC*** of the type developed by Williams, Prebble, Williams and Hignett (1983) on 78 horizons in 17 profiles representing 12 Australian soil groups and Bennie, Coetzee, Van Antwerpen, Van Rensburg and Burger (1988) on relatively coarse textured irrigation soils in the central RSA. Model application requires knowledge of any two points on the soil water characteristic. While advisers in this project did have a soil neutron probe at their disposal, it seems, pressure of the routine scheduling on many fields made the initial determination of two reference points, θ_0 and θ_{1500} say, impracticable.

The two-parameter equation for describing the soil water characteristic is written:

$$\psi_s \quad = \quad \psi_{so}(\theta/\theta_o)^b \qquad (10.1)$$

The soil input parameter file of Putu was therefore modified so as to allow ψ_{so}, θ_o and θ_{1500} to be entered for each of nine soil layers. An EXCEL spreadsheet permitting calculation of these by five different methods given soil, clay and silt percentages and bulk density for non-structured soils was constructed.

Furthermore, laboratory determinations of θ_{1500} abound and facilitate empirical estimation (see Bennie *et al*, 1988 and Hutson, 1984). θ_{1500} was adopted as a reference point, because this characteristic is determined to a large extent by particle size. Note: a problem with these is that they have often been done on disturbed samples - but one can only use what is available.

The exponential law then takes the form

$$\psi_s = -1500(\theta/\theta_{1500})^{-b} \tag{10.2}$$

The value of exponent b in Eqn. 10.1 was calculated from

$$b = \ln(\psi_s/\psi_{so})/\ln(\theta/\theta_o) \tag{10.3}$$

The One-Parameter Exponential Law

The option of using a one-parameter exponential equation, which is extremely convenient to apply in practice, was investigated. For this, only one point on the soil water characteristic is needed. Gregson, Hector and McGowan (1987) found an extremely strong linear relationship (r > -0.992) between ψ_o and b in eqn 10.1 for a wide range of soils in England, Wales, Scotland and Australia. Hence, there is good reason to expect that this relationship will hold true for soils of the RSA. By introducing the derived linear relationship into eqn 10.1, Gregson *et al* (1987) derived the one-parameter exponential equation for describing the soil water release curve, viz.

$$\psi_s = -0.375\,(0.01795\,\theta)^b \tag{10.4}$$

where θ is expressed as a percentage and ψ is expressed in units of ***M Pa***. The option of using this equation in Putu is now also available.

Eqn 10.5 was used to calculate b in Eqn 10.4.

$$b = (\ln\psi_s + 7.89)\,/\,(\ln\theta - 4.02) \tag{10.5}$$

Testing of the accuracy of the one-parameter equation proceeds.

Estimation of parameter b

The exponent ***b*** in both Eqn. 10.2 and 10.4 may be calculated from measured, or estimated values of ψ and θ (eg. from the equations of Hutson (1948) and Bennie *et al* (1988) for non-structured soils and Mottram (1995) for heavy clay soils).

The elementary model (Level 1) of Putu defaults to a selected ***SWC***. Here, the operator simply needs only to specify the texture of each soil layer approximately. Putu then defaults the soil water characteristic to the values shown in Table 10.1, which were decided upon by discussion with Malcolm Hensley (1997).

Table 10.1 Default values of the soil physical properties for seven different categories of soil and the parameter *b* for the two-parameter soil water characteristic determined using the equations of Bennie *et al* (1988) and Hutson (1984) for non-structured soils.

Soil Type	ρ_s	**Clay**	**Silt**	θ_{10}	**DUL**	θ_{1500}	ψ_{so}	**b**
	(Mg m^{-3})	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**		
Sand	1.60	8	3	15	12	6	-5	-5.03
Loamy sand	1.60	10	5	18	15	7	-6	-5.39
Sandy loam	1.55	15	10	25	21	11	-7	-6.13
Loam	1.50	20	35	37	32	19	-8	-7.40
Sandy clay loam	1.45	27	15	28	25	15	-8.5	-7.90
Sandy clay	1.45	40	15	33	29	19	-9	-9.21
Clay	1.40	50	20	39	35	24	-10	-10.27

The equations used in the spreadsheet for determining the soil water characteristic are as follows:

NON-STRUCTURED (SILT + CLAY > 27%)

Hutson (1984)

$$\theta_{10} = 0.0558 + 0.00365C + 0.00554S + 0.0303\rho_s \qquad r^2 = 0.681$$

$$\theta_{1500} = 0.0602 + 0.00322C + 0.00308S - 0.0260\,\rho_s \qquad r^2 = 0.785$$

or (Hutson, 1984) when only clay content is available

$\theta_{10} = 0.1387 + 0.00416C$

$\theta_{1500} = 0.0344 + 0.00381C$

NON-STRUCTURED (SILT + CLAY < 27%)

Bennie, *et al* (1988)

$\theta_{10} = 0.0345\,(S + C)^{0.611} \qquad r^2 = 0.76$

$\theta_{1500} = 0.00385\,(S + C) + 0.013 \qquad r^2 = 0.70$

Here regessions were determined for silt and clay particle size approximating 0.05 mm examined in 30 cm soil layers. The number of data pairs exceeded 120.

Alternatively, only clay content is required for the equations for non-structured (silt and clay < 27%) soils of Hutson (1984), viz.

$\theta_{1500} = 0.01616 + 0.0052C + 0.00222S$

Comment

It is noteworthy that the estimates of θ_{1500}, θ_{500}, θ_{100}, θ_{30} and θ_{10} obtained from the Hutson equations, in no way whatsoever fit the two-parameter exponential law. The one- and two-parameter theoretical values agree reasonably well with one another.

CAMPBELL MODEL

The equations in the Campbell model for USA soils were found not to fit South Africa soils well. For completeness, they and the required assumptions are listed.

$FRACsand = 1 - FRACsilt - FRACclay$ (10.6)

$DIAMpart = EXP\,(FRACclay \,.\, DIAMclay + FRACsilt \,.\, DIAMsilt + FRACsand \,.\, DIAMsand)$ (10.7)

$COND_{so} = 2 \times 10^{-3} \times EXP\,(-4.26 \times FRACsilt + FRACclay)$ (10.8)

$\Psi_{sat} = (-0.5 * PART\ DIAMpart)^{-5}$ (10.9)

$\theta_p = (1 - \rho_s\ 12.65)1000$ (10.10)

Assumptions which have been used in the past, include

$V_o = 0.5 * (\theta_p - DUL) + DUL$ (10.11)

$V_{10} = DUL + .5 * (V_0 - DUL)$ (10.12)

$FRACdrain = (\theta_p - DUL)/\theta_p$ (10.13)

ESTIMATION OF THE SOIL WATER CHARACTERISTIC (θ_{1500}, θ_0, ψ_{so}).

The need for accurate evaluation of ***SWUL***, is brought about by the rapid change in θ for a small change in ψ_s near ***SWUL*** (see Hillel, 1982) This could induce large errors in values of θ calculated from the soil water characteristic using an estimated value of ψ_{so} which is in error, albeit by only a small amount.

Given the present state of knowledge; irrigation scheduling using a ***CGM*** when the soil water characteristic, θ_{1500}, θ_o and ψ_{so} are unknown and need to be estimated, is best surmounted by either:

a) An approach, which measures θ_{1500} in the laboratory, or from an empirical equation. The value of ψ_{so} is then estimated between -5***kPa*** for clay soils and -10***kPa*** for sand soils. Since θ_{1500} is determined by particle size, it can be accurately estimated using empirical formulae. On the other end of the scale however, θ_0 is determined by soil structure, which is very variable and amongst other things a function of management. Fortunately, error in calculated ψ_s at high θ, when no stress occurs, will not cause drastic error in model output.

b) Calibration by estimating θ_{1500}, θ_o and ψ_{so} from empirical equations and then running the model and comparing spot measurements and simulations of θ, particularly on days after thorough wetting and when the soil is very dry. θ_o, ψ_{so} and θ_{1500} are then adjusted so as to ensure computed θ agree reasonably with field values.

For irrigation scheduling, soil water upper limit (***SWUL***) as defined in this project, is an important reference level. So, it is advisable to apply eqn 10.3 and use the values obtained for ***SWUL*** denoted ψ_{so} and θ_0, rather than some other reference point. Van Rensburg and Bennie (1997) suggested that for clay $\psi_{so} \approx -10$ ***kPa*** and for sand $\psi_{so} \approx -5$ ***kPa***. Malcolm Hensley (1997) suggests that a reasonable first approximation value of ***DUL*** for non-structured freely drained soil layers is the value of θ corresponding to a soil water suction of -30 ***kPa***. Until such time as experimental values of ***SWUL*** and ***DUL*** become readily available, these approximations will have to be used.

There are five possible methods (I to V) whereby the relationship Eqn. 10.3 between soil water potential and soil water content for a given soil may be determined. An EXCEL spreadsheet has been created whereby these different methods may be tested.

The five methods are:

METHOD	**GIVEN VALUES**	**ASSUMPTIONS REQUIRED**
I	θ_{1500}	One-parameter exponential law
II	θ_{1500}, θ_0	ψ_{so} = -5 ***kPa*** for sand, or ψ_{so} = -10 ***kPa*** for clay and estimate intermediate values. Two-Parameter Law
III	θ_{1500}, θ_o, ψ_{so}	Two-parameter exponential law
IV	θ_{1500}, ***DUL***	Soil water potential at ***DUL*** = -30 ***kPa*** and use two-parameter exponential law
V	Soil particle distribution θ_{1500}, ρ_s	The theory of Campbell (1985) using soil textural composition.

Values for given entities must either be measured (in the field, or the laboratory); estimated from empirical equations; calibrated by trial and error using cursory field observations while scheduling irrigation; or just plain guessed from subjective knowledge and experience of the terrain. Possibly the most useful estimates may be had from Table 10.1, which is also included as default in the soil parameter file used at the 'Elementary' level of irrigation scheduling. Method I, II and III are now available in Level 1 and Level 2 of Putu-Irrigate. The Basic program SOILWCHR.BAS (see Appendix IV) carries out the necessary computations.

The form of the two-parameter law in eqn. 10.2 is used in Putu, because the soil water characteristic needs to be accurate at the dry end of the range where stressed conditions occur. Thus a value of V_{1500} is always required as input to the model. This may be obtained either by laboratory measurements or, if clay percentages ≥ 27 %, from the equation of Hutson (1984), or else, for clay percentage < 27 %, from the equation of Bennie *et al* (1988). Thereafter, depending upon what data are available, the other parameters may be derived. The most convenient options are the methods II through IV. These have been coded in a Basic program which is accessed from the Putu shell. Details regarding assumptions, input and output for the program SOILWCHR.BAS (Appendix IV) are as follows:

Assumption	**Input**	**Output**
Ψ_{dul} = -30 ***kPa***	θ_{1500} θ_{10} Ψ_{so}	b V_0 ***DUL***
	θ_{1500} θ_0 Ψ_{so}	V_{10} ***DUL***
	V_{1500} b Ψ_{so}	V_0 V_{10} ***DUL***
Ψ_{dul} = -30 ***kPa***	V_{1500} ***DUL*** Ψ_{so}	V_0 V_{10} b

For purposes of clarity and application, symbol definitions for the Basic program and Putu shell are given as follows:

Symbol	Basic	Putu shell
θ_0	$SWUL$content	$SWUL$
θ_{1500}	V_{1500}	V_{1500}
Ψ_{so}	$SWUL$potential	Values defaulted to those given in Table 10.1
θ_{10}	V_{10}	V_{10}
DUL	DUL	DUL

CHAPTER 11

FORM OF THE PENMAN-MONTEITH EQUATION FOR ESTIMATING REFERENCE EVAPORATION

INTRODUCTION

Uncertainty exits regarding exactly which form of the Penman-Monteith equation is most suitable for estimating E_o for South African conditions. Three forms are compared, viz.

Version	*Notation*
Putu	PUTU
FAO panel of experts	FAO
Campbell	CAMP

Mathematical details for the latter two are as reported by Allen *et al* (1994) and Campbell (1989) respectively. Complete details for the Putu and FAO versions are found in Chapter 7. Major differences between the versions are found in the mathematical simulation of canopy resistance r_c, net radiation R_n, and the manner in which daytime or 24-hour values of E_o are computed.

OBJECTIVE

The objective was to test the occuracy of the above three methods for computing E_o against lysimeter measurements.

METHOD

Hourly and bi-hourly measurements of ***Eo*** were made in the lysimeter described by Van Zyl and De Jager (1987). The vegetative cover was of 15 cm high clipped rye grass. The ***Eo*** and weather data were obtained on the West Campus Experimental Site , U.O.F.S. Totals of hourly values for daytime periods and 24-hour periods provided 52 day, or daylight, test data sets. Hourly ***Eo*** was computed using each of the above approaches. Daylight and 24-hour totals of measured and modelled ***Eo*** were compared against lysimeter values using standard regression and correlation procedures from the Quattro software package.

RESULTS

The results are given in Table 11.1 through 11.5. Definitions for ***TOT***, ***DAY*** and the column headings used in the tables are as follows:

ACRONYM	DESCRIPTION
METH	Method used
TOT	Computed and measured values stretching over 24 hours
DAY	Computed and measured values stretching over daytime
R3	Canopy resistance r_c=30 s m^{-1}
R7	Canopy resistance r_c =70 s m^{-1}
R700	r_c=70 s m^{-1} for daytime and 700 s m^{-1} for nighttime
RS	If total solar radiation $R_S * 0.77 < 10$ MJ m^{-2} d^{-1} then R_s=0
EP	If *Eo*-hourly < 0 then *Eo*-hourly = 0
PER	Period for which comparisons were carried out
RSQR	Correlation coefficient squared
SLOPE	Slope of the regression-line
ABS	Absolute value of (slope - 1)
SEOYE	Standard error of the y-estimate
SEOC	Standard error of the intercept

Which of the options ***R3, R7, R700, RS***, and ***EP*** are included in a given statistical test (***METH***) is specified by unity for enable, or zero for disable. Please note that R_s and E_P provide values of E_o totalled through periods delimited by either low radiation R_s, or E_o. The R_s option is at present in use in Putu. ***R700*** provides a 24-hour period estimate totalled over hourly periods over 24 hours.

RESULTS

The results of all the statistical tests undertaken are given in Table 11.1 through 11.5. The results of the tests were sorted in descending orders of accuracy for daytime, 24-hour periods and overall.

Table 11.1 **Correlation and regression parameters for measured versus modelled Eo for PUTU, CAMP and FAO for daytime periods sorted according to descending r-squared.**

METH	R3	R7	R700	RS	EP	PER	SEOYE	RSQR	SLOPE	ABS	SEOC
CAMP	1	0	0	1	0	DAY	1.1	0.62	0.87	0.13	0.02
PUTU	1	0	0	1	0	DAY	1.13	0.61	0.88	0.12	0.02
PUTU	1	0	0	0	1	DAY	1.13	0.61	0.83	0.17	0.02
CAMP	0	1	0	0	1	DAY	1.13	0.6	1.02	0.01	0.001
CAMP	0	1	0	1	0	DAY	1.13	0.6	1.01	0.01	0.03
FAO	1	0	0	1	0	DAY	1.14	0.59	0.71	0.29	0.02
FAO	1	0	0	0	1	DAY	1.14	0.59	0.71	0.29	0.02
PUTU	0	1	0	1	0	DAY	1.16	0.58	1.03	0.03	0.03
CAMP	1	0	0	0	1	DAY	1.1	0.56	0.87	0.13	0.02
PUTU	0	1	0	0	1	DAY	1.22	0.54	0.96	0.04	0.03
CAMP	0	0	1	0	0	DAY	1.21	0.54	1.09	0.09	0.03
FAO	0	1	0	0	1	DAY	1.22	0.53	0.83	0.17	0.02
FAO	0	0	1	0	0	DAY	1.23	0.53	0.83	0.17	0.02
FAO	0	1	0	1	0	DAY	1.22	0.53	0.82	0.18	0.02
PUTU	0	0	1	0	0	DAY	1.25	0.51	1.04	0.04	0.03

Table 11.2 **Correlation and regression parameters for measured versus modelled Eo for PUTU, CAMP and FAO for 24-hour periods sorted according to descending r-squared.**

METH	R3	R7	R700	RS	EP	PER	SEOYE	RSQR	SLOPE	ABS	SEOC
PUTU	1	0	0	0	1	TOT	1.37	0.49	0.97	0.03	0.03
FAO	1	0	0	1	0	TOT	1.39	0.49	0.84	0.16	0.02
FAO	1	0	0	0	1	TOT	1.37	0.49	0.84	0.16	0.02
CAMP	0	1	0	0	1	TOT	1.36	0.49	1.19	0.19	0.03
CAMP	0	1	0	1	0	TOT	1.37	0.49	1.19	0.19	0.03
CAMP	0	0	1	0	0	TOT	1.38	0.49	1.28	0.28	0.04
CAMP	1	0	0	0	1	TOT	1.4	0.48	1.02	0.02	0.03
FAO	0	1	0	1	0	TOT	1.4	0.48	0.97	0.03	0.03
CAMP	1	0	0	1	0	TOT	1.4	0.47	1.02	0.02	0.03
FAO	0	0	1	0	0	TOT	1.4	0.47	0.97	0.03	0.03
PUTU	0	1	0	0	1	TOT	1.4	0.47	1.13	0.13	0.03
FAO	0	1	0	0	1	TOT	1.4	0.47	1.97	0.97	0.03
PUTU	0	1	0	1	0	TOT	1.43	0.45	1.21	0.21	0.04
PUTU	0	0	1	0	0	TOT	1.45	0.44	1.22	0.22	0.04
PUTU	1	0	0	1	0	TOT	1.46	0.43	1.03	0.03	0.03

Table 11.3 **Daytime regressions sorted according to slope closest to the 1:1 line**

METH	R3	R7	R700	RS	EP	PER	SEOYE	RSQR	SLOPE	ABS	SEOC
CAMP	0	1	0	0	1	DAY	1.13	0.6	1.01	0.01	0.001
CAMP	0	1	0	1	0	DAY	1.13	0.6	1.02	0.01	0.03
PUTU	0	1	0	1	0	DAY	1.16	0.58	1.03	0.03	0.03
PUTU	0	0	1	0	0	DAY	1.25	0.51	1.04	0.04	0.03
PUTU	0	1	0	0	1	DAY	1.22	0.54	0.96	0.04	0.03
CAMP	0	0	1	0	0	DAY	1.21	0.54	1.09	0.09	0.03
PUTU	1	0	0	1	0	DAY	1.13	0.61	0.88	0.12	0.02
CAMP	1	0	0	0	1	DAY	1.1	0.56	0.87	0.13	0.02
CAMP	1	0	0	1	0	DAY	1.1	0.62	0.87	0.13	0.02
FAO	0	1	0	0	1	DAY	1.22	0.53	0.83	0.17	0.02
FAO	0	0	1	0	0	DAY	1.23	0.53	0.83	0.17	0.02
PUTU	1	0	0	0	1	DAY	1.13	0.61	0.83	0.17	0.02
FAO	0	1	0	1	0	DAY	1.22	0.53	0.82	0.18	0.02
FAO	1	0	0	1	0	DAY	1.14	0.59	0.71	0.29	0.02
FAO	1	0	0	0	1	DAY	1.14	0.59	0.71	0.29	0.02

Table 11.4 **24-hour regressions sorted according to slope closest to the 1:1 line**

METH	R3	R7	R700	RS	EP	PER	SEOYE	RSQR	SLOPE	ABS1	SEOC
CAMP	1	0	0	1	0	TOT	1.4	0.47	1.02	0.02	0.03
CAMP	1	0	0	0	1	TOT	1.4	0.48	1.02	0.02	0.03
FAO	0	1	0	1	0	TOT	1.4	0.48	0.97	0.03	0.03
FAO	0	0	1	0	0	TOT	1.4	0.47	0.97	0.03	0.03
PUTU	1	0	0	0	1	TOT	1.37	0.49	0.97	0.03	0.03
PUTU	1	0	0	1	0	TOT	1.46	0.43	1.03	0.03	0.03
PUTU	0	1	0	0	1	TOT	1.4	0.47	1.13	0.13	0.03
FAO	1	0	0	0	1	TOT	1.37	0.49	0.84	0.16	0.02
FAO	1	0	0	1	0	TOT	1.39	0.49	0.84	0.16	0.02
CAMP	0	1	0	1	0	TOT	1.37	0.49	1.19	0.19	0.03
CAMP	0	1	0	0	1	TOT	1.36	0.49	1.19	0.19	0.03
PUTU	0	1	0	1	0	TOT	1.43	0.45	1.21	0.21	0.04
PUTU	0	0	1	0	0	TOT	1.45	0.44	1.22	0.22	0.04
CAMP	0	0	1	0	0	TOT	1.38	0.49	1.28	0.28	0.04
FAO	0	1	0	0	1	TOT	1.4	0.47	1.97	0.97	0.03

Table 11.5 Daytime and 24-hour regressions sorted according to slope closest to the 1:1 line

METH	R3	R7	R700	RS	EP	PER	SEOYE	RSQR	SLOPE	ABS	SEOC
CAMP	0	1	0	0	1	DAY	1.13	0.6	1.02	0.01	0.001
CAMP	0	1	0	1	0	DAY	1.13	0.6	1.01	0.01	0.03
CAMP	1	0	0	0	1	TOT	1.4	0.48	1.02	0.02	0.03
CAMP	1	0	0	1	0	TOT	1.4	0.47	1.02	0.02	0.03
FAO	0	1	0	1	0	TOT	1.4	0.48	0.97	0.03	0.03
PUTU	1	0	0	0	1	TOT	1.37	0.49	0.97	0.03	0.03
PUTU	1	0	0	1	0	TOT	1.46	0.43	1.03	0.03	0.03
PUTU	0	1	0	1	0	DAY	1.16	0.58	1.03	0.03	0.03
FAO	0	0	1	0	0	TOT	1.4	0.47	0.97	0.03	0.03
PUTU	0	0	1	0	0	DAY	1.25	0.51	1.04	0.04	0.03
PUTU	0	1	0	0	1	DAY	1.22	0.54	0.96	0.04	0.03
CAMP	0	0	1	0	0	DAY	1.21	0.54	1.09	0.09	0.03
PUTU	1	0	0	1	0	DAY	1.13	0.61	0.88	0.12	0.02
PUTU	0	1	0	0	1	TOT	1.4	0.47	1.13	0.13	0.03
CAMP	1	0	0	1	0	DAY	1.1	0.62	0.87	0.13	0.02
CAMP	1	0	0	0	1	DAY	1.1	0.56	0.87	0.13	0.02
FAO	1	0	0	0	1	TOT	1.37	0.49	0.84	0.16	0.02
FAO	1	0	0	1	0	TOT	1.39	0.49	0.84	0.16	0.02
FAO	0	1	0	0	1	DAY	1.22	0.53	0.83	0.17	0.02
FAO	0	0	1	0	0	DAY	1.23	0.53	0.83	0.17	0.02
PUTU	1	0	0	0	1	DAY	1.13	0.61	0.83	0.17	0.02

DISCUSSION

The performance (accuracy) of the various options was assessed according to how close r-squared values and slopes of the regression line approached unity.

R-squared

Using r-squared as criterion, it is evident that from Table 11.1 and 11.2. that daytime , Putu (r_c = 30 s m^{-1} and r_c = 70 s m^{-1}), Campbell and FAO all performed better than did the 24-hour versions.

For the 24-hour totals Putu (r_c = 30 s m^{-1}) is best, because it underestimated by only 3 percent, but unfortunately, it returned a poor r-squared of 0.49. The next best 24-hour method is that of FAO which underestimated measured values by 16 percent.

Slope

From the daytime results in Tabel 11.3, Campbell and Putu are within 4% of the 1:1. The best *Campbell method in this evaluation is the method originally used by Campbell namely rc*=70 s m^{-1}. The three methods of Putu follow closely on Campbell. They also use r_c = 70 s m^{-1}. Thus, for modelling ***Eo*** during daytime, a value of r_c = 70 s m^{-1} seems most accurate.

For the 24-hour results, two versions of each method came within 3% of measured values. Both Campbell and Putu methods use r_c = 30 s m^{-1}. The one FAO method uses r_c = 70 s m^{-1} and the other method uses r_c = 70 s m^{-1} during the daytime and r_c = 700 s m^{-1} during nighttime. It seems that by using r_c = 30 s m^{-1}, Campbell and Putu correctly simulate daylight conditions and ignore the loss of water during the night. The original Campbell method which uses r_c = 70 s m^{-1} during the day and r_c=700 s m^{-1} during the night compensated poorly for nighttime transpiration and it overestimated measured E_o by 28%.

General

No advantage appears to result from modelling ***Eo*** for 24-hour periods. There is little to choose between Campbell and Putu methods. The problem however, is the apparent loss of water during nighttime. Irrigation scheduling advisors have an immense responsibility on hand and may not ignore nighttime transpiration, should it occur in the magnitudes here reported. A method should therefore be devised accurately to model the total ***Eo*** for the day.

In Putu, the radiative energy available for evaporation ($R_n - G$) is estimated from measured incoming short-wave radiation (R_s) using the empirical relationship given in Section 8.2, viz.:

$$R_n - G = 0.75\, R_s - 72$$

Flowing out of this research, the methods that can be used for this purpose are the first six on Table 11.4, because all have a deviation of less than 3% from the 1:1 line. But the r-squared values are low at approximately 0.49.

CONCLUSION

How to deal with nighttime transpiration presents problems when computing E_o irrespective of the version of ***PME*** selected. More research is required to determine whether agronomic crops transpire at night and how to deal with its simulation in the ***PME***, especially over 24-hour periods. (see also Smith *et al*, 1996)

The low r-squared values were disappointing, but could be due to lysimeter measuring error. It is suggested that under these circumstances, highest weight be accorded methods closely approaching a 1:1 relationship with measured ***Eo***. Nighttime ***Eo*** is unexplained at this stage. Hence daytime methods should be used where possible. Either of the specific versions of Campbell and Putu at the head of Table 11.3 can be used. For 24-hour estimates the Putu (r_c = 30 s m^{-1}) version seems best see Table 11.2.

Based upon earlier research findings (see Russel, 1980 and De Jager, 1984) and Table 11.1 a version of the PME with $r_c = 30$ s m^{-1} has been used in Putu in the past. Because of the results of this work and the recommendations of Allen et al (1994) it was decided to modify this and $r_c = 70$ s m^{-1} will be used in future.

SECTION IV

INFORMATION DISSEMINATION AND TECHNOLOGY TRANSFER

CHAPTER 12

DIFFERENT LEVELS OF TECHNOLOGY TRANSFER FOR DIFFERENT TYPES OF FARMERS

INTRODUCTION

Decision support for scheduling irrigation on both commercial and small-scale farms entails the transfer of large volumes of data intended for either numerous fields on a single farm, or for numerous small plots. Cutting costs is important to low-input farmers, but not for commercial farmers. Commercial farmers require high quality, scientific information. Low-input farmers prefer simple instructions for specific fields. The dissemination of the many data required to both types of user from a central source does however present logistical problems.

Weather-based irrigation scheduling methods suitable for both types of operation were investigated. ***The specific objectives*** of this chapter were to assess how the most relevant and useful information may be produced and disseminated to large numbers of users.

MATERIALS AND METHODS

Site, climate, crop and soil

The investigation was carried out for location Douglas in the arid irrigation region of the Northern Cape Province, South Africa. The annual normal rainfall and temperature in this area is 315 mm and 24°C respectively. Corresponding normals for the summer and the winter are 236 mm and 29°C and 79 mm and 14°C respectively. The irrigation of spring wheat *Triticum aestivum* Cultivar SST4, planted on 27 July, 1994 on a 1.8 m deep sandy loam was studied. Seasonal saturation vapour deficit was 2.2kPa.

The levels of decision support technology

Water application efficiency was compared for three levels of decision support technology, viz. high, intermediate and minimum. The latter corresponds to present conventional practice.

For high technology, an automatic weather station and the Putu-Irrigation simulation model (De Jager, 1992) which has been shown by De Jager, Van Zyl, Kelbe and Singels (1987) accurately to schedule irrigation, was used. Putu-Irrigation is an irrigation model named after the Zulu word for maize porridge. It was used to simulate daily values of crop transpiration (***Ev***) as the product of reference crop evaporation (***Eo***) and empirical crop specific evaporation coefficients as well as daily soil profile water deficits. The model has been validated by De Jager et al. (1987) and Mottram and de Jager. (1994).

In intermediate technology, cumulative reference crop evaporation is replenished before crop water stress occurs. The most accurate equation for determining reference crop evaporation from a short grass surface (Eo), viz. the Penman-Monteith equation (see Jensen, Burman and Allen, 1990) was used.

Irrigation practices and simulations

In practice two types of irrigation occur in the western Free State, viz. demand-driven center pivot (or sprinkler) or supply-driven flood irrigation. While the former case applies predominantly to commercial farming, the latter is appropriate to small-scale low-input farming. The capacity of center pivot systems limits water application rates to 12 mm d^{-1}. For supply-driven flood or bucket irrigation, individual applications generally exceed 50 mm. The most common fixed interval irrigations practised, are either bi-daily, weekly, or fortnightly with application rates of 12, 80, or 100 mm per application, respectively.

All simulations assumed the soil profile to be at field capacity (10 kPa tension) at the time of planting. This required an initial irrigation of 50 mm to fill the 1.8 m soil rooting zone and is in agreement with common practice; as are the flood schedules, which were tested, appropriate for state river or canal schemes. Deficit irrigation, which replaces a simulated soil water deficit of 60mm with 50 mm of irrigation (cf. method 2 in Table 12.1), was also examined.

The 9 different methods of scheduling irrigation investigated, including the irrigation scheduling decision criteria for each, are described in Table 12.1. The symbol definition used in Table 12.1 is:

I - Irrigation amount (mm).

DEF - Profile soil water deficit below a volumetric soil water content corresponding to -10 ***kPa*** (mm).

Eo - Daily reference crop evaporation for short grass as computed by the Penman-Monteith equation (mm).

Observations

All water applications were as measured by farmer cooperators in 3 or 4 rain gauges installed under each center pivot. The number of plots per farm varied between 1 and 5.

Wheat-grain yields were as delivered at the farm cooperative. The average yield for all farms delivered to the farm cooperative from surrounding farms was 5200 kg/ha (cf. strategy 5, Table 12.1).

Table 12.1. **Measured wheat-grain yields at 7 sites and the farm cooperative together with relevant simulated and field derived application (AE) and water-use (WUE) efficiencies for the 1994 wheat growing season in the western Free State.**

Scheduling Method	Irrigation		AE		WUE	Meas. grain yield
	Simulated	Measured	Simulated	Field	Field	
			Eqn.1	Eqn..2	Eqn..3	
	(mm)	(mm)	(%)	(%)	(kg/m^3)	(kg/ha)
HIGH						
1. Putu modelled		665	81	82	0.90	6100
water use and		640	84	91	1.00	6500
adviser		590	90	95	1.14	6300
expertise		680	79	83	1.14	6300
		722	74	69	1.01	5600
Average		659	82	84	1.16	6160
2. DEF>60mm,I=50mm	700		77			
INTERMEDIATE						
3. I = ΣEo when	800		67			
ΣEo = 50 mm					.60	
4. I=ΣEo, I<12 mm	865	865	62	53	.92	5100
5. I=DEF, I<12mm		870	62	54	.94	5200
Average	833	868	64		.93	5150
MINIMUM						
6. Bi-daily 12mm/d	878		61			
7. Fortnightly I=100 mm	950		57			
8. Weekly I= 80 mm	1570		35			
9. Center pivot conventional practice 12mm/d	1706		32	27	.92	5100
Average	1276		46	27	.92	5100

Flood irrigation: 2, 3, 7, 8

Center pivot: 1, 4, 5, 6, 9

Calculation of irrigation water application efficiencies

Water application efficiencies attained during irrigation were both simulated and derived from field measurements. A modified definition of irrigation application efficiency (*AE*) was adopted.

Since, for a given seasonal saturation vapour pressure deficit, the seasonal crop transpiration (***Ev***) is directly related to biomass production (Kieselbach, 1916), ***Ev*** may be taken to represent the true outcome of an irrigation operation for which the input may be deemed to be the water applied (in mm) by irrigation (***I***) plus rainfall (***R***). Hence, since efficiency is the ratio of outcome to input, application efficiency (*AE*) may be defined:

$$AE = Ev/(I+R) \qquad (13.1)$$

This ***AE*** was expressed as a percentage and computed each day using the cumulative values of modelled ***Ev***, ***R*** and ***I*** and Eqn. 13.1. The seasonal variation in ***AE*** for strategies 1, 4 and 8, representing the three levels of technology transfer are depicted in Figure 12.1. Also, seasonal final values of ***AE*** are listed in Table 12.1.

Furthermore, to make possible the comparison of computed values of ***AE*** with some form of field observation, seasonal ***AE*** values were derived from measured wheat-grain yield using Eqn.. 13.2, cf. Table 12.1. Here the total transpiration required to produce a measured crop yield was calculated using a transpiration equivalent of grain yield of 0.92 kg/ha mm. The latter was derived from the Kieselbach (1916) equation assuming a harvest index for wheat of 0.6; a normalised biomass/transpiration ratio for C_3 plants of 40 kg kPa/mm (Monteith, 1990); and the measured seasonal saturation vapour pressure deficit of D = 2.2 kPa. Thus,

$$AE = 2.2\ Yg/[(0.6 * 40)(I+R)] = 0.092\ Yg/(I+R) \qquad (13.2)$$

where, ***Yg*** is wheat-grain yield (in kg/ha).

Water-use efficiency (***WUE***), is here defined as harvested yield per unit water transpired, cf. Eqn.. 13.3. Values derived from field observations were expressed in kg/m^3 and are given in Table 1 .

$$WUE = 0.1\ Yg / E_v \qquad (13.3)$$

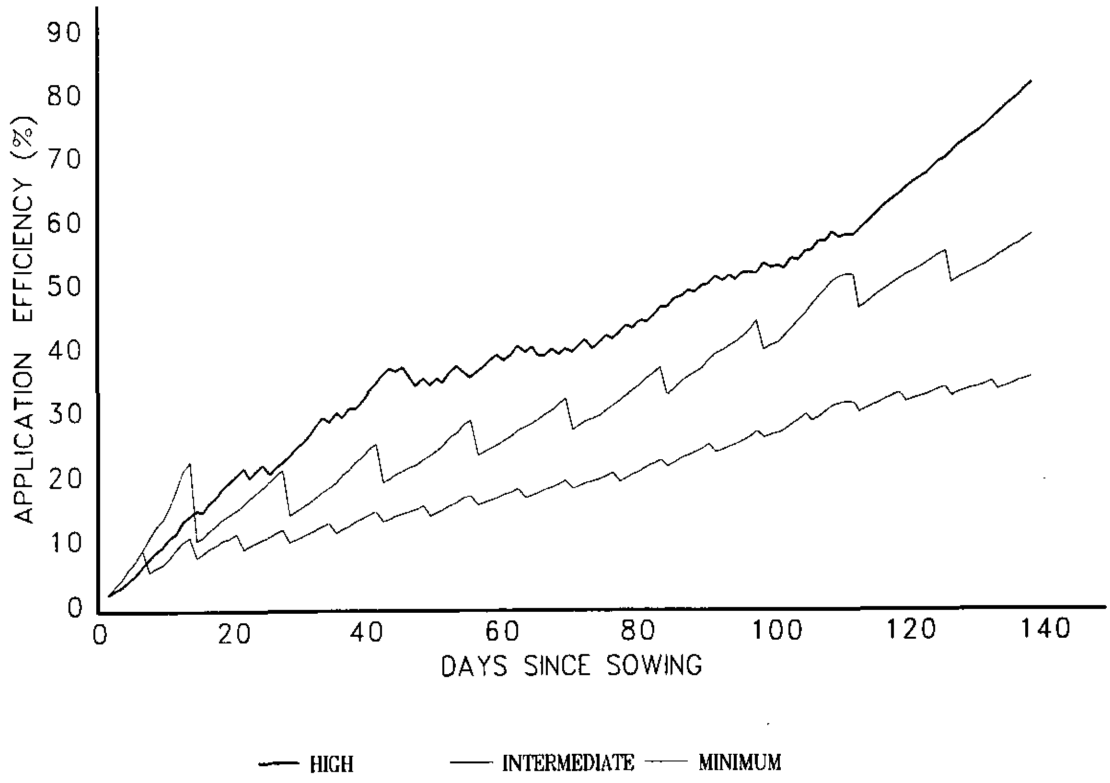


Figure 12.1. Daily values of cumulative application efficiency simulated for a wheat crop in the western Free State for HIGH, INTERMEDIATE and MINIMUM levels of technology transfer.

RESULTS AND DISCUSSION

No water stress was simulated in any of the treatments. Simulated transpiration totalled to E_v = 552 mm in all treatments. In the 1994 wheat growing season, 20 mm of rainfall was recorded. The benefits of adviser expertise in particularly the late season for the high technology application is most evident in Figure 12.1. Table 12.1 shows that the simulated *AE* for high, intermediate and minimum technology may be expected to approximate 82%, 64% and 46% respectively. For minimum technology, the simulated efficiencies ranged between 32 and 61% - the latter could be attained with a sprinkler system. Fortnightly flood irrigation reduces soil evaporation and hence its favourable efficiency of 57% compared to 35% for weekly flood. The simulated average AEs for all three technologies agreed reasonably well with the field derived efficiencies of 84%, 54% and 27% respectively. Strategy 6 may not be considered as a practicable solution for low-input farms, but offers exciting possibilities for commercial farms.

Simulated *AE* for intermediate technology closely followed that of high technology except in the late season, cf. Figure 12.1, but exceeded minimum technology by approximately 8% (Table 12.1). Average seasonal values of *AE* obtained with high technology (82%) were found to be approximately 36% higher than the value of 46% estimated for minimum technology. Intermediate technology has also been found to be popular among farm cooperatives in sub-humid areas (Mottram et al., 1994).

The measured grain yields shown in Table 12.1 suggest that high technology, by reducing the amount of alkaline water applied, and hence the soil alkalinity, improves the efficiency with which nutrient fertilizers are utilised. Furthermore, the high risk of over-irrigation associated with minimum technology methods, apart from wasting water will in addition leach nutrients from the root zone. High alkalinity and over-irrigation could thus partly explain the lower yields of 5100 kg/ha (see Table 12.1) obtained with the minimum technology methods. All in all, this emphasises the need for implementation of more advanced irrigation scheduling techniques, such as a combined use of appropriate models and advice from experts.

Financial returns due to reduced irrigation (@ R0.5 per mm) and improved yields (@ R8 per kg) for high technology were better than returns from intermediate and minimum technology by approximately R700 and R800 respectively per ha.

Technology Transfer methods

Based on the results and discussion above, the following methods for disseminating irrigation scheduling advices may be suggested:

High technology. Soil water deficits are modelled using an appropriate model run on locally measured weather data, plus data from a weekly forecast based upon long term mean weather records. Analysis of these deficits and crop growth stage and the application of personal expertise, enables the local adviser to communicate to farmers per fax, telephone modem or e-mail, how much and when to irrigate.

Intermediate technology. Each week, daily ***Eo*** computed from the Penman-Monteith equation and relevant weather data is displayed on notice boards, or conveyed telephonically to farmers who simply replenish cumulative reference crop evaporation (method 3 or 4 Table 12.1). Enterprising operators and cooperatives apply appropriate crop evaporation coefficients.

Minimum technology. Fixed interval irrigations of given amounts are applied at regular intervals (methods 7 to 9 Table 12.1).

SUMMARY

Effective methods for the rapid dissemination of irrigation information to various farmers were sought. Three levels of technology transfer were examined - high, which is based upon the Putu-Irrigation computer model and weather data; intermediate, which replenishes cumulative daily reference crop evaporation; and minimum (conventional), which applies fixed amounts of water at fixed time intervals.

Irrigation application efficiency (*AE*) was defined as crop transpiration per unit applied water. Wheat-grain yields were measured on 7 and irrigation applied on 6 farms. Irrigation scheduling was simulated using automatic weather station data, the Putu simulation model and 9 different scheduling

strategies. Simulated *AE* obtained with the 2 high technology methods were compared to those obtained with 3 intermediate and 4 conventional scheduling strategies.

For high, intermediate and minimum technology *AE* averaged 82%, 64% and 46% respectively. Intermediate technology transfer could possibly offer an effective, convenient, inexpensive alternative in multi-user situations. Procedures for disseminating the relevant information to many users were developed.

CONCLUSIONS

From the simulations, measurements and computations carried out, it may be concluded that:

(1) Use of high technology transfer could improve seasonal irrigation *AE* by approximately 36% above that attainable with use of conventional methods (i.e. minimum technology)

(2) An intermediate level of technology which replenishes accumulated reference crop evaporation, should improve *AE* by approximately 8% above conventional farming practice.

(3) Both the high and intermediate procedures are considerably better than flood irrigation of 80 mm at weekly intervals for which an *AE* = 35% might be expected. Fortnightly flood irrigations, by reducing simulated soil evaporative losses, could improve *AE* to approximately 57% for this practice.

(4) Applications of 12 mm/d every second day throughout the season appears to be a more efficient conventional practice than flood irrigation for the western Free State.

(5) Convenient methods for disseminating high and intermediate technology information have been developed.

CHAPTER 13

SELECTED CASE STUDIES

BASIC FIELD RESEARCH ON THE NEW CROPS

Some examples of irrigation scheduling undertaken on less well-known crops is now given. ***PPAW*** denotes plant available water (%).

Station 6, Lone Tree Farms - the crops currently being commercially produced under irrigation are chipping and table potatoes, and apples for export.

The production of apples in this area is relatively new and as a result new crop coefficients had to be established. While the trees were small an estimate of crop cover could be attained using the instrument developed by Cackett (1964). Furthermore these trees are grown under hailcloth which has a significant influence on the surrounding microclimate. The ***AWS*** is situated alongside one of the orchards and additional instruments were installed under the netting to monitor the different microclimate.

In the current apple production areas of the Cape it is common practice to impose a water stress on the crop. This is difficult to do in a summer rainfall area. Table 13.1 presents the guidelines for the scheduling of irrigation of apples in the Eastern Free State as provided by a consultant. (Barkhuizen, 1993)

TABLE 13.1 Guidelines for scheduling irrigation of apples in the Eastern Free State (after Barkhuizen, 1993)

GROWTH STAGE	GROWTH	DESCRIPTION	% OF *PPAW* EXTRACTED
Non-bearing trees in first year	I	Leaf fall to commencement of root growth (End of AUG)	80
	II	Commencement of root growth till end of season	50
Non-bearing trees in second year	I	Leaf fall to commencement of root growth (End of AUG)	80
	II	Commencement of root growth till DEC.	50
	III	Beginning of JAN (flower bud development) till cessation of tree development	Extract 100 then fill to 80
	IV	Cessation of tree development till leaf drop	50
Bearing trees from second year	I	Leaf fall to commencement of root growth (End AUG)	80
	II	Commencement of root growth till DEC	50
	III	Beginning of JAN (flower bud development) till cessation of tree development (max 2 weeks)	Extract 100 Fill to 80
	IV	Cessation of tree development till harvest	50
	V	Harvest to leaf fall	50 if growth has ceased 100-80 if growth is continuing

PPAW = Percentage Plant Available Water

These guidelines present a problem to scheduling and water management as:

(i) it is almost impossible to extract 100% of the 'plant available water' because of rain during the month of January

(ii) it is not possible evenly to fill the entire rooting profile evenly to only 80%

The apple orchards have a grass cover crop in between the rows of trees and the scheduling procedure adopted was required also to satisfy this grass cover's demands.

The farmer reported that the apples performed well and that less irrigation water had been used than budgeted for in his pre-season plan.

Station 31, Simunye

The Mlaula section of the Simunye Sugar Estate has ± 3500 ha of sugarcane being produced under dragline irrigation. Two pump stations 5 and 6 were selected in this section and irrigation scheduled using Putu. Four planting periods are conducted on Simunye, viz. April, June, July and August to October. Irrigation scheduling where applied on the estate in the past, had made use of the evaporation pan and the crop factors presented in Table 13.2.

Table 13.2 **Relationships between canopy cover of irrigated sugarcane and crop factors for use with readings from an evaporation pan.**

Canopy Cover (%)	Pan factor
0 to 20	0.40
20 to 45	0.55
45 to 70	0.70
70 to 95	0.85
95 to 100	1.00
Lodged crop	0.70

Canopy covers were monitored monthly for the different varieties ratooned in different months and are used as a guide to select an appropriate canopy cover.

An alternative method employed on the estate is to use standard canopy curves which are based on long term records for Nco 376 ratoon crops. However, crops ratooned from August onwards develop rapidly and one should use more than one crop factor per month. The four different crop evaporation coefficient files illustrated in Chapter 9 were derived from analyses of historical canopy data and current measurements.

Appendix II presents the results obtained on selected fields at Mlaula section, producing sugarcane under irrigation scheduling using the Putu system.

The irrigation management at Simunye is relatively simple but fairly inflexible. There are 3 irrigation sets per day, each 8 hours in duration and there is a choice of either a 3 or 4 day cycle (23 or 32 mm applications). These 3 sets per day involve 3 shifts (different groups of irrigators). In order to accommodate these sets and the two cycles, Putu irrigation scheduling entailed advising managers once the requirement approached either 23 or 32mm.

A group of management specialists convinced the corporation that they could cut down their labour bill substantially by reducing the number of irrigators. Each irrigator's task is only to move a predetermined number of sprinklers irrespective of the time he takes to perform this task. As a result the efficiency of the water management and irrigation suffered. The ISU will continue to present results to management in an attempt to improve the situation.

Station 41, ZZ2 Estate

Approximately 1000 ha tomatoes, 145 ha avocados and 250 ha of onions are produced under irrigation annually on ZZ2 Estates. The majority of the irrigation is drip (tomatoes and avocado) while the Dikgale area irrigate with centre pivots. The Mooketsi estate has a large dam which was empty for 5 years and their water supply came from some 54 boreholes supplying ± 2 250 $l.h^{-1}$

Prior to the ISU being involved, irrigation for the tomatoes was being scheduled using a fork, for examining soil water condition, a Class A evaporation pan and the set of seasonal crop factors for either summer, or winter given in Table 13.3. These crop factors were changed when the relative humidity drops below 30% at midday say, and the mean daily temperature drops below 20°C.

Table 13.3 **Crop factors used in summer (September through March) and winter on the ZZ2 estate**

Weeks of growth	Summer	Winter
0-3	0.3	0.2
3-6	0.4	0.3
6-8	0.7	0.6
8-12	0.8	0.7
12	0.9	0.8

Irrigation used to be applied daily resulting in reasonably good yields, but a high incidence of disease. Thereafter the irrigation management changed to 3 to 4 sets per week in summer and 1 to 2 in winter. However when the class A pan indicated evaporation figures in excess of 8 $mm.d^{-1}$, then the irrigation reverted to daily irrigation.

The ISU became involved in scheduling irrigation on one of their numerous blocks. After about 2 months with the reported saving in water, the number of blocks scheduled was increased as a result. The ISU was requested to schedule all the irrigation of tomatoes and onions on the Mooketsi and Dikgale farms. This amounts to ± 80 blocks per day.

Appendix I includes a Putu irrigation run on tomatoes and an example of a daily recommendation respectively.

Station 8 - Moedershuis, EFS

Approximately 150 ha of table potatoes under drip irrigation alongside the Wilge river were scheduled.

The AWS was connected via radiotelemetry to the Simonsium office and operated successfully over a distance of some 5 kms. It is pertinent to note that this link was not strictly 'line of sight'. Later, upon moving the AWS and radio link to Moedershuis some 20 km away from the base station at Simonsium it became necessary to incorporate a repeater station. This repeater station is situated some 10 km in line of sight from the base station and some 10 km out of direct line of sight from the AWS. Although this did not comply directly with the specifications listed by Campbell Scientific Inc it was possible to establish a link after numerous attempts.

Not unexpectedly, this link did not operate continuously. It worked only when conditions were cool (eg. early morning) and in overcast weather.

This led to intermittent collection and collation of data, untimeous scheduling of irrigation in the potatoes and client dissatisfaction. To compound matters, excessive rain was experienced and due to the situation of the lands and slow draining soils in parts, a significant amount of waterlogging occurred. This drastically affected quality and yield

Station 7 - Laggan Dairy, Howick

Laggan Dairy has a combined Friesland and Jersey herd for retail milk production. 32 ha of irrigated ryegrass pasture provide winter grazing for this herd at a stocking density of ± 200 mature livestock units (*MLU*) per hectare per day. The ISU advised Laggan Dairy on a weekly basis as to how much irrigation to be apply per grazing block per week. This involved 32 irrigation blocks under full production and had to accommodate the grazing cycle where each block is grazed approximately once every 32 days. This meant that the model had to be restarted after each grazing event. This is a problem which deserves attention in the future.

The farmer's input and the ISU's output and recommendation are illustrated in *Appendix II.*

CHAPTER 14

EFFECTIVENESS OF THE SYSTEM

INTRODUCTION

The effectiveness of an IDSS can be assessed by whether it alters decisions and what are the benefits, if any, accrued from its use. These aspects were examined by comparing some field observations with and without Putu and comparing WUE attained with the IDSS and those genetically possible. Such comparisons are always difficult and open to criticism because they rely heavily upon the records of untrained personnel. Simulated and measured soil water contents were also compared.

CROP YIELD COMPARISONS

Examples of comparisons between yields obtained using high level DSS with those obtained from conventional practice on neighbouring plots are presented in Table 14.1. Such comparison provides an indication of how effective is the DSS. The yields listed were measured in semi-arid and sub-humid regions.

In no case did conventional irrigation practice out-yield crop production attained using the AWS-DSS. Improvement in average yields due to the AWS-DSS ranged between 13% and 152% for five different crops. In addition, the marketable proportion of high cost crops such as potato and tomato was increased using AWS-DSS.

Irrigation Efficiency

$$\mathrm{IE} = Y/(I+R)$$

I and R denote irrigation and rainfall respectively. For crop scientists, Doorenbos and Kassam (1979) defined crop water use efficiency as the harvestable yield produced per unit plant evaporation (kg m^3). This approaches the genetic limit of water use. Irrigation managers should strive to attain comparable WUE. The authors report WUE for numerous crops.

Values of IE and WUE obtained on individual plots for eleven crops are reported in Table 14.2. The AWS-DSS values of IE compared well with WUE as defined by Doorenbos and Kassam (1979) for good farming practice. The IE values attained in practice should be lower than the WUE values suggested by Doorenbos and Kassam (1979), but close agreement, when attained, attests to the efficiency of the AWS-IDSS.

Table 14.1 **Crop yields attained with and without high level DST irrigation scheduling**

Crop	Level of DST		Improvement	
	High (kg/ha)	Conventional (kg/ha)	Plot (%)	Mean (%)
Soyabeans	2 950	2 000	48	
	2 700	2 000	35	
	4 400	2 700	63	49
Maize	9 800	7 800	26	26
Wheat	6 100	4 500	36	
	6 500	4 500	44	
	5 300	3 500	51	47
Dry beans	3 154	1 250	152	152
Tomato	76 000	62 500	13	13

Table 14.2 **Range of IE attained with high level DST irrigation scheduling and expected WUE for eleven crops in semi-arid and sub-humid regions**

Crop	Possible WUE	IE attained
	Good Conventional (kg/m^3)	High Level (kg/m^3)
Maize	0.8 - 1.6	1.1 - 1.4
Soyabeans	0.4 - 0.7	0.4 - 0.6
Wheat	0.8 - 1.0	0.8 - 1.0
Dry peas	0.5 - 0.7	0.6 - 1.1
Dry beans	1.5 - 2.0	0.3
Cotton	0.5 - 0.6	1.1
Groundnuts	0.6 - 0.8	0.9
Lupin		0.4
Ryegrass	1.5 - 2.0	0.4
Potato	4.0 - 7.0	9.1 - 10.4
Tomato	10.0 - 12.0	16.0 - 20.0

It was furthermore found that AWS-DST schedules generally applied less irrigation than did, neighbouring conventional practice. However, because of poor records, poor irrigation system calibration and distribution efficiency; accurate quantities of water applied in the neighbouring fields were seldom forthcoming from the experiments. For wheat in semi-arid regions (see Chapter 12) the IE obtained with high level DST was approximately 15% better than that attained by intermediate level

DST which in turn was 16% better than conventional practices using a fixed pre-determined schedule. This demonstrates the value of intermediate DST for low-input operations particularly in semi-arid conditions.

EXPERIMENTS IN THE WESTERN FREE STATE AND NORTHERN CAPE

Introduction

During 1995/96 the Putu-IDSS was tested on eight irrigation farms alongside the Orange River by Kennedy Irrigation Consultants cc. Five weather stations, as indicated in Table 14.3, serving a total of 42 clients were installed.

The objective of the exercise was to test the reliability of the IDSS as a tool for managing irrigation; its potential for providing an irrigation service and its financial viability.

Table 14.3 Weather stations installed in the western Free State during 1996.

Station Id	Closest Village	No. of Clients
835	Niekerkshoop	10
564	Christiana	9
386	Morgenson	1
111	Villiers	12
541	Wonderfontein	10

Method

Hourly averages of windspeed, radiation and dry and wet bulb temperature were logged every 10 seconds and recorded every hour. The Campbell CR10 data loggers proved most reliable. The worst downtime was caused by lighting which caused much damage and inconvenience as spare parts had to be imported from the USA.

The location of the experimental plots is shown in Figure 14.1 and the distance between the Lubbeshoop experimental terrain and the Department of Agrometeorology, UFS is illustrated in Figure 14.2. All data transfer took place via telephone modem.

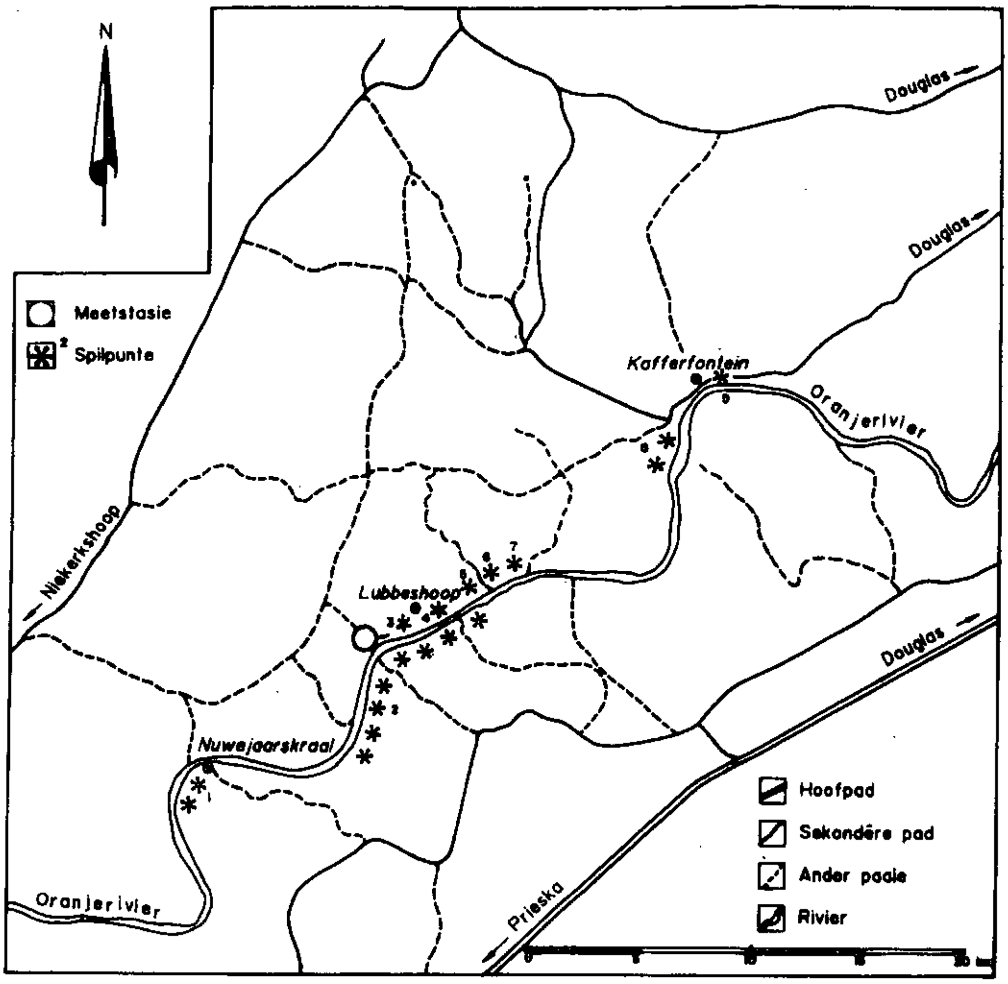


Figure 14.1 Location of measuring sites along the Orange river.

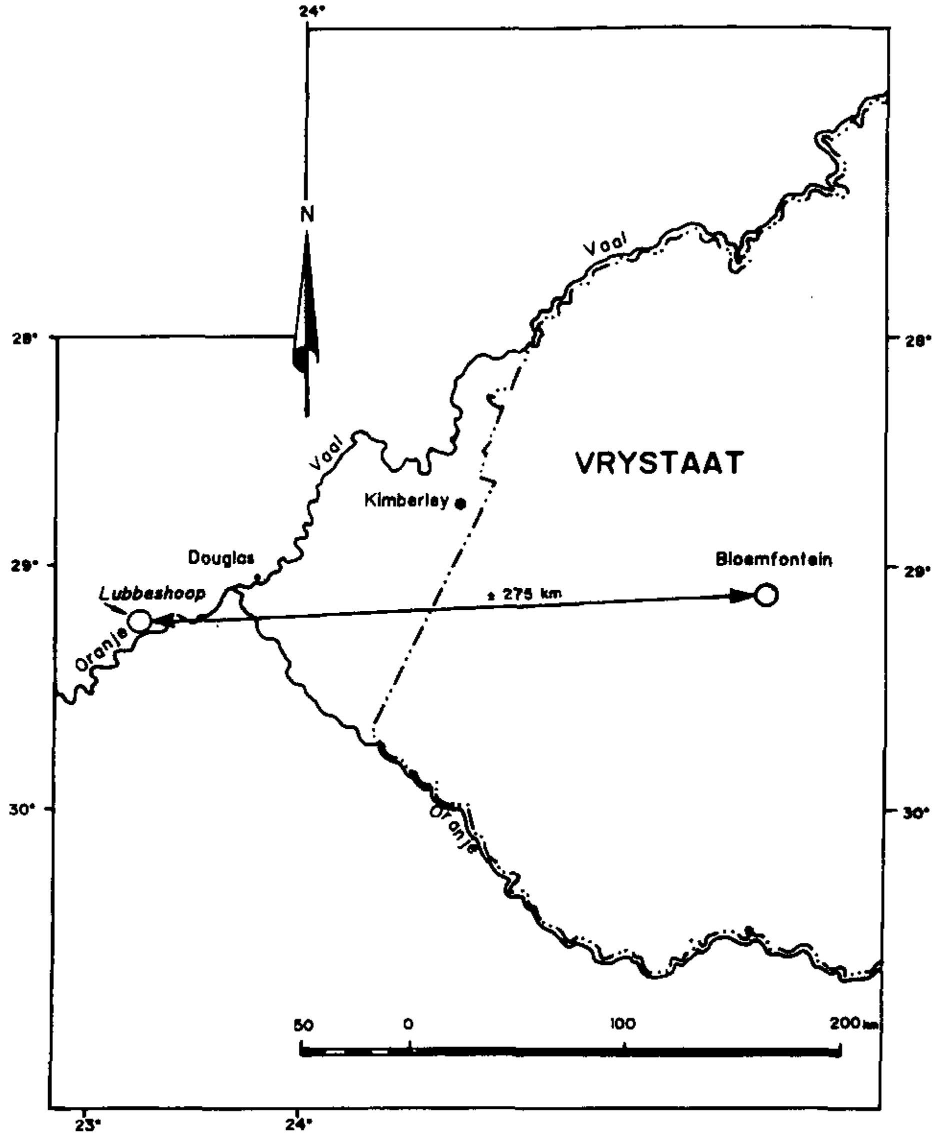


Figure 14.2 Location of the west Free State experimental site relative to the University of the Free State.

Table 14.4 Example of the output provided to western Free State Farms

DAY	TMAX	TIME	TMIN	TIME	E_0	WIND	STRA	RH	CU	T	S1	S2	S3	ST
14 Apr	25.9	14:30	9.4	07:24	2.27	133	9.32	65	-7.75	7.94	6	6	0	12
15 Apr	26.6	14:00	8.8	04:50	3.86	104	17.10	66	-7.40	8.31	8	4	0	12
16 Apr	28.3	14:32	6.7	06:26	4.02	119	17.62	64	-4.90	9.14	8	3	0	11
17 Apr	28.5	14:22	10.9	23:52	5.79	258	18.29	51	-16.25	9.66	2	1	0	3
18 Apr	26.8	14:44	6.3	06:12	5.14	157	20.03	60	-1.70	8.41	11	0	0	11
19 Apr	25.8	16:16	5.8	02:59	4.09	107	18.33	62	1.80	7.90	11	0	0	11
20 Apr	25.7	15:10	4.7	03:51	4.20	98	18.85	61	1.35	7.83	8	0	0	8
Gemid	26.8		7.5		4.20	139	17.08							
Totaal					29.37	976			-34.85	59.19				

DAY	Calendar date
TMAX	Daily maximum air temperature (°C)
TIME	Exact time air temperature maximum occurred
TMIN	Daily minimum temperature (°C)
TIME	Exact time air temperature minimum occurred
Eo	Reference evaporation (in mm per day)
Wind	Total wind (in kilometer per day)
Stra	Total radiation in Megajoules per day
RH	Average humidity for the day (%)
CU	Daily Richardson cold units
t	Thermal time above a base temperature of 10°C (°d)
S1	Disease index one
S2	Disease index two
S3	Disease index three
ST	Disease index total

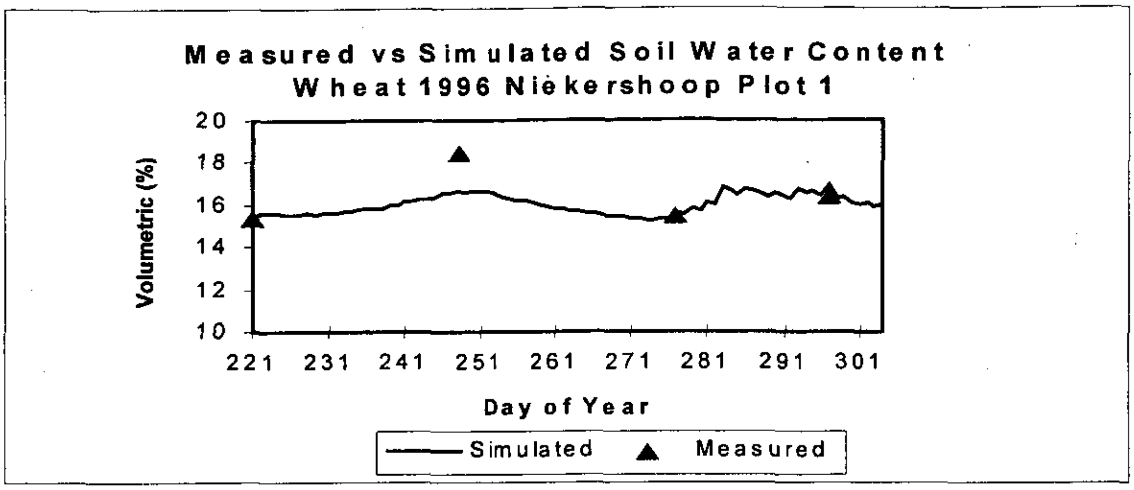
An example of the type of weather data distributed to clients on a weekly basis is given in Table 14.4

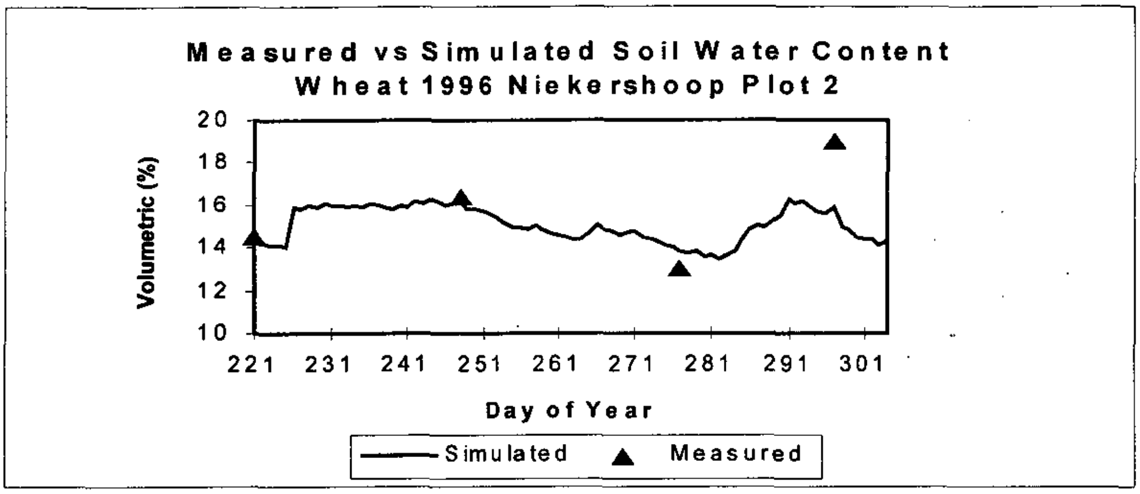
Apart from irrigation scheduling, clients were particularly keen to receive plant disease indicators. Three of the latter plus a combined disease index were provided. The indexes were defined as follows:

S1	the number of hours during the day for which reletive humidity RH > 70% and air temperature (°C), $7 \leq T$
S2	the number of hours during the day for which RH > 70% and $14 \leq T \leq 21$
S3	the number of hours during the day for which RH > 70% and $21 \leq T \leq 28$
ST	total of S1 + S2 + S3

Clients were able to adapt their spray programs according to these indexes.

Sporadic neutron probe measurements were made by an independent observer usually at 4 soil depths. The results are reported in the eight graphs constituting Figure. 14.3a, b and c. A numerical comparison of the measured (θ) and simulated (θ') soil profile water contents on the eight plots is given in Table 14.5.





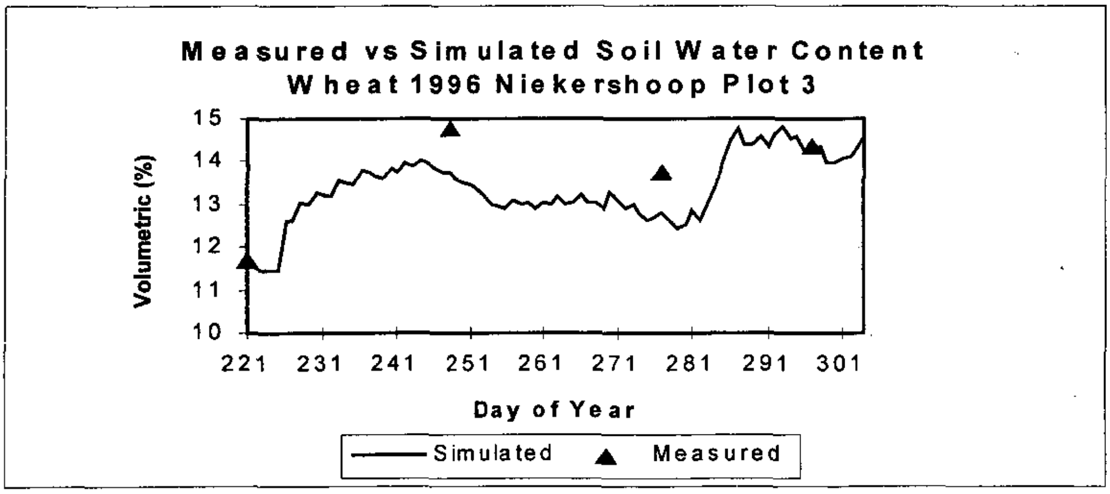


Figure. 14.3a Soil water contents measured and simulated on plots 1, 2, 3, Niekerkshoop.

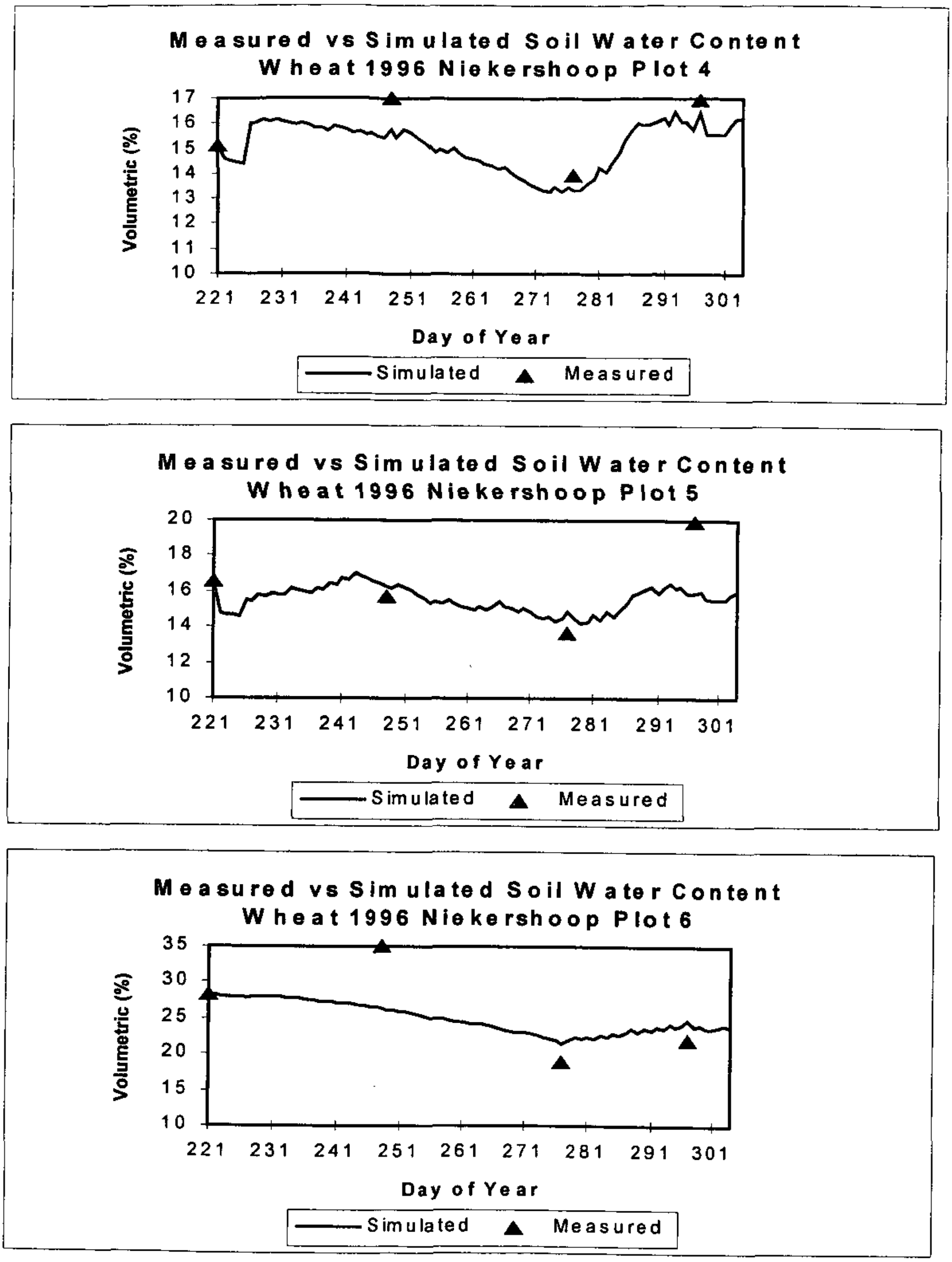
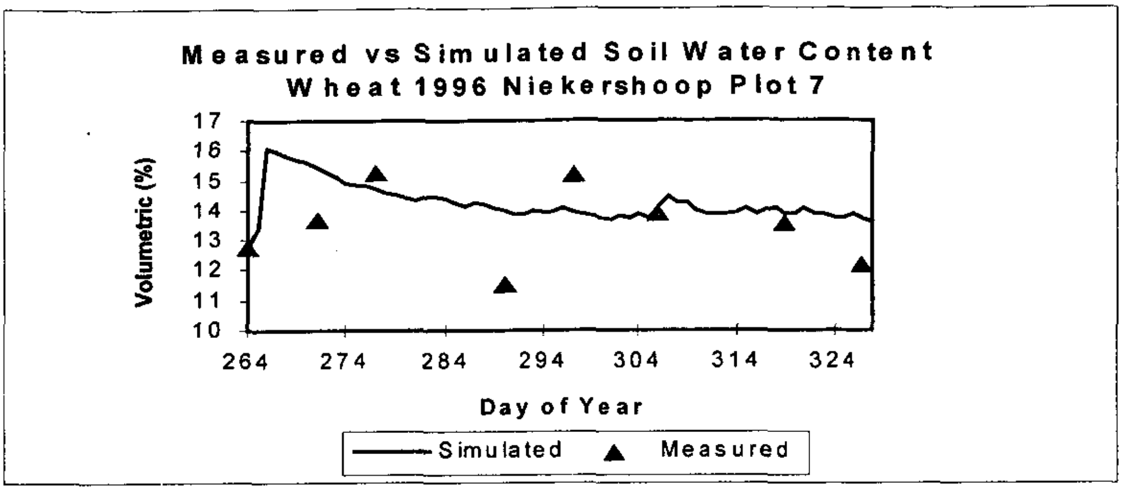


Figure 14.3b Measured and simulated soil water content on plots 4, 5 and 6, Niekerkshoop.



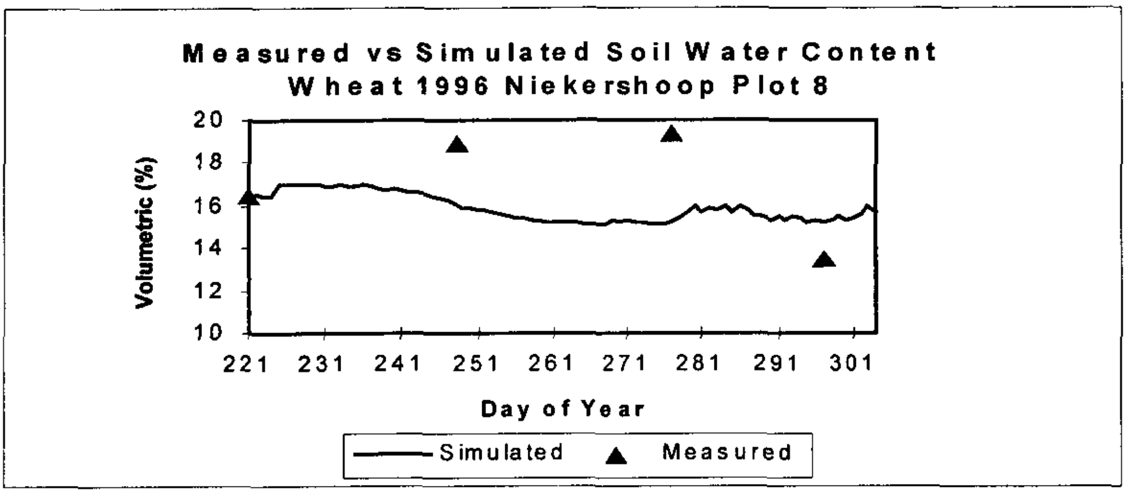


Figure 14.3c Measured and simulated soil water content on plots 7 and 8 Niekerkshoop

Table 14.5 **Comparison of measured (θ) and simulated (θ') soil profile water content made on 8 plots along the Orange River.**

Site	DOY	No. of depths monitored	Simulated θ' (%)	Measured θ (%)	Difference ($\theta' - \theta$) (%)
1	221	4	16	15	0
1	248	4	16	18	-2
1	277	4	14	15	-2
1	297	3	16	16	-0
2	221	3	15	15	0
2	248	3	14	16	-2
2	277	3	13	13	-0
2	297	3	15	19	-4
3	221	3	12	12	0
3	248	3	16	15	1
3	277	3	15	14	1
3	297	3	18	14	3
4	221	3	15	15	0
4	248	3	15	17	-2
4	277	3	12	14	-2
4	297	3	16	17	-1
5	221	3	16	17	-0
5	248	3	16	16	0
5	277	3	14	14	0
5	297	3	17	20	-3
6	221	4	28	28	0
6	248	4	15	35	-20
6	277	3	13	19	-5
6	297	3	16	22	-6
7	264	4	13	13	-0
7	271	4	13	14	-1
7	277	4	13	15	-3
7	290	4	11	12	-0
7	297	4	12	15	-3
7	306	4	12	14	-1
7	319	4	11	14	-2
7	327	4	11	12	-1
8	221	4	17	16	0
8	248	4	12	19	-7
8	277	4	12	19	-8
8	297	3	11	13	-2

Measurements of θ were made at 300 mm intervals commencing at a depth of 150 mm.

Results
Appreciable water saving with concomitant increased yield in comparison to previous normal practice were attained. In the Niekerkshoop area, some of the clients who used Putu-IDSS claimed that their yields increased from 5.1 to 6.2 t ha^{-1}. The average yield recorded at the farming cooperative was 5.2 kg ha^{-1} compared to an average of 5.9 kg ha^{-1} attained by the clients of the adviser. Increased wheat grain yields were ascribable to diminished leaching of soil nitrogen.

Furthermore, one Niekerkshoop client irrigating 178 ha of wheat reported that use of Putu-IDSS caused peak month electricity costs to drop from R25070 to R18915, or a 24.5% decrease.

Clients desire a rapid, effective service. Complaints (two clients actually withdrew from the service) are quick in coming when advisories are delayed. This provides problems because advice is based upon irrigation amounts provided by clients per facsimile and these are not always returned promptly. A complete operation say for 3 blocks involving input of facsimile data; running the CGM; printing the recommendation and disseminating the data per facsimile could occupy up to 20 minutes. Serving 50 clients could thus require some 16 hours. A single computer business would thus require judicious logistical planning to spread data retrieval and advice dissemination over the entire week. The new Putu-IDSS produces electronic files rapidly, which should expedite dissemination.

Measured and simulated volumetric soil water content compared reasonably well (see Figure 14.3) Irrigation scheduling accuracy was assessed using the ***scheduling reliability rate index*** **(SR)** defined as the proportion (%) of neutron measurements of θ occurring between θ_{10} and a soil water depletion of 50% ***PPAW***. The data in Figure 14.3 reflect a success rate of SR = 86%. For practical and logistic reasons, the number of measurements per plot per season was limited. Hence a ***credibility index*** **(CI)** defined as the percentage of days during the growing season on which measurements were carried out was determined. Because of the low measurement frequency; a low CI = 6% could be accorded the experiments.

The differences between measured and simulated θ are given in Table 14.4. Simulation error in profile soil water content was $\leq$ 20 mm/m for 78% of the time. Scrutiny of the Figure 14.4 does however indicate at least 5 outliers which might have been due to inaccurate neutron measurements. There seems to be a particular problem at plot 6.

Financial Aspects for the experimental period expressed in terms of costs as a percentage of turnover were:

Telephone	17%

Travel	17%
Repairs	9%
Wages	6%
Overheads	6%
	51%

Telephone costs include facsimile, telephone and cell phone. Travel covers all costs involving visits to clients; repairs include all AWS and other items not for clients account; and overheads entail salary for a full-time secretary/assistant, office maintenance and stationery. Turnover could be divided into 96% irrigation scheduling and 4% diverse essentially, advice such as, fertilizer recommendations and irrigation system design.

CONCLUSION

The successful, efficient scheduling of irrigation using decision support technology based upon automatic weather station data and crop growth models has been demonstrated. Weather data are applied in crop growth models for the scheduling of irrigation on numerous individual plots.

The technology was shown to improve scheduled yields above neighbouring conventional plots by between 13% and 152% depending upon crop type. Irrigation efficiencies attained with the decision support technology approximated genetic maximum water-use efficiencies expected from good conventional practice.

CHAPTER 15

GUIDELINES FOR ADVISORS

INTRODUCTION

In this chapter some of the main features of the Putu-IDSS will be discussed and some client reaction given, with a view to providing guidelines for the effective application of the IDSS.

IRRIGATION SCHEDULING PROCEDURES

Some of the crops for which irrigation was scheduled using near real-time weather data and the Putu system include:

apples
citrus
mangoes
potatoes
sugar-cane
avocados
maize
onions
runner beans
tomatoes
baby vegetables
mange-tout peas
soyabeans
wheat
pastures

The irrigation systems used to irrigate these crops include:

flood/furrow irrigation
hop-a-long
solid set
drip
dragline
conventional/portable pipe and risers
microjet
centre pivot

The water supply and distribution systems include:

borehole water
river and dam
river/dam and canal
dam
river

Irrigation schedules are provided either daily, or a set number of times per week. The relevant information in a format preferred by the individual clients, is sent either by facsimile, or via telecommunication modems to the individual on-site computers.

The reaction of individual clients to this method of scheduling has, to date, been most positive. Almost every client has offered constructive feedback, especially with respect to estimating soil water conditions. The most common reaction is that they perceive the soil to be "too dry" and request earlier irrigation than recommended by the system. Another contentious issue is the condition of temporary wilt. The clients observe wilt occurring during the hot midday periods and feel that they should be irrigating to prevent this from occurring.

Probably the most beneficial effect of the system has been that the clients/irrigators are now devoting more time to observing crop and soil conditions.

In order to evolve crop coefficients for the different cultivars and crops, selected clients are monitoring canopy development (fractional interception) on at least a weekly basis, especially during the early vegetative growth phases. Certain selected clients are conducted serial harvesting on different potato varieties to determine vegetative and tuber production during the season.

On larger estates where numerous section and area managers are involved, some resistance to the system has been encountered. This has largely been overcome by holding workshops with managers. Some organisations wished to run the model themselves. Certain of these people have attended courses and then commenced to operate the system themselves only to find that it was occupying too much of their managerial time.

It is important that the service backup in all departments of the system must be of a high, professional standard. In the initial stages (at least one whole season) this was very time-consuming and consequently expensive. Once the clients have confidence in the system, they tend to become more involved in operations and in some cases, even offer technical assistance. Examples of the latter are corporations such as Agrelek and research organisations such as the Agricultural Research Trust, Zimbabwe; Agronomy sections of Simunye and Tambankulu sugar estates in Swaziland and the Agronomy Department at the University of Natal.

Consultants in Mocambique and Zimbabwe are promoting use of the Putu-IDSS to their clients. In KwaZulu Natal the system has been illustrated/demonstrated to the extension services in the Department of Agriculture and to local co-operatives and irrigation boards. These boards are usually interested until levels of expenditure on their part became apparent. Individual clients within the boards have, however, accepted the financial implications and shown interest in using the system.

Usually, the client has to be educated in respect of the advantages of using Putu-IDSS in preference to other scheduling methods, as well as be advised regarding the suitability of his resources to meet the requirements of his enterprises. Then briefly, the advisor must:

1. If one is necessary, establish the AWS and appropriate telecommunications links.
2. Assist in the taking of the soil samples necessary for creating the soil files (mechanical analysis) and vinit files (gravimetric determination of initial soil water).
3. Obtain the necessary crop inputs: crop, cultivar, planting/transplanting date, germination date, population, row spacing, orientation etc.
4. Compile the necessary soil, irrigation, cultivar and control files.
5. Download the requisite amount of raw data from the AWS.
6. Run the PUTU Irrigation model and make a suitable recommentdation.

Here follows a brief case study which illustrates the procedure.

Lone Tree Farms - Mr. G. Osler. Land F10.1
Crop - Potato (BP13) planted 15/10/96, germinateed 5/11/96.4 plants/m^2

Soil - SaLm:	ρ_s	**%Clay**	**%Silt**	**SWUL**	θ_{1500}
0-15cm	1.5	20	8	240	136
15-30cm	1.5	17	10	245	123
30-45cm	1.5	21	10	275	140

Similar information is generated for lands F10.2 to F10.6, and 2C1 to 2C8.
The Simulation is started at 50% germination of the field, at which time the gravimetric soil water determination is done for the initial soil water content.
Recommendations in the following format are made every Monday, Wednesday and Friday. As an example, a recommendation for Lone Tree Farm on 18 December, 1996 is given below.

EXAMPLE RECOMMENDATION FOR LONE TREE FARMS FOR 18 DECEMBER 1996

Dear Neal Herewith your recommendation until Friday. Regards

FARM NAME: Lone Tree Farms
DATE OF RECOMMENDATION: 18 December 1996
REFERENCE CROP EVAPORATION: 35.1 mm
RAINFALL: 1 mm since Monday

DOG = Day of Growth
CWU = Crop Water Use
FW = Stress Indicator (0 to 100)
PPAW = Percentage Profile Available Water
TDEF = Total Deficit below Field Capacity
HU = Cumulative Heat Units

LAND NO	DOG	CWU	FW	PPAW	TDEF	CUMUL		HU	RECOMMENDATION
						IRR	RAIN		
F10_1	43	1	76	14	38	7	176	263	11 mm
F10_2	32	5	7	43	20	13	134	156	10 mm
F10_3	34	1	79	23	35	8	134	175	5 mm
F10_4	42	4	27	31	30	15	164	251	12 mm
F10_5	40	3	44	18	34	8	160	232	15 mm
F10_6	30	1	82	7	26	11	79	137	8 mm
F11_1	52	5	1	44	18	18	217	350	12 mm
2C1	56	4	14	47	13	31	252	377	Nil
2C2	56	4	14	48	13	30	252	377	Nil
2C3	57	4	14	47	13	30	252	384	Nil
2C4	57	5	7	58	9	26	252	384	5 mm
2C5	55	5	5	66	7	29	219	372	3 mm
2C6	55	5	4	70	6	33	219	372	2 mm
2C7	49	5	2	68	6	29	199	320	5 mm
2C8	53	5	2	75	5	32	219	359	2 mm

In addition, monthly summaries of daily weather data (radiation, rainfall, reference crop evaporation, crop water use, maximum and minimum temperatures) are collated and presented in both tabular and graphical form.

Follow-up visits are undertaken every 2 months to ensure the client is happy with the service and has confidence in the system. This may require using gravimetric samples to compare against values calculated by the model, and being able to explain away differences between the two methods. It is at this point that the in-season adjustment procedure for correcting simulated soil water content is a great advantage. Fractional interception can also be adjusted in-season if necessary.

DATA MANIPULATION, DISTRIBUTION AND CLIENT USAGE OF INFORMATION

After retrieval, weather and other data can be manipulated using commercially available word processor (eg. WORDPERFECT, MS-WORD) and spreadsheet (eg QUATTRO PRO) packages, and thereafter, the relevant software in the Putu-IDSS.

Resultant data is distributed to the client in a spreadsheet format. Apart from the irrigation information regional weather forecasts and monthly summaries of the relevant daily weather variables are supplied on request to the individual clients both in tabular and graphical format.

Data is distributed either directly to the individual clients, or to a base from which it may be accessed at will. The distribution takes place by:

- facsimile transmission,
- transmission via telemetry, utilising telecommunications modems, personal computers and compatible software, and
- downloading of daily summaries for each station on a monthly basis to the Computing Centre for Water Research in Pietermaritzburg.

The clients utilise the resultant data on a day-to-day basis to manage their irrigation. This includes labour management, scheduling, application of fertiliser, irrigation water management (water orders by bailiffs and irrigators). The data are used for periodic reports to top management with respect to the seasons progress.

Near real-time data is used by individuals for assessing conditions for aerial spraying, ground spraying and management decisions such as pest and disease provention by chemical means. Recently, there has been much interest in utilising these data and relevant models in integrated pest management.

From personal discussions with the clients, reaction at workshops and the improvement in both management and production, it is evident that the data in all the various formats; is of benefit to the client. This is best illustrated by the concern expressed when telecommunication breaks down.

With respect to telecommunications in southern Africa, there are areas which repeatedly create problems. It is in the main "converted/modified" farm, or party lines, during very hot or stormy conditions that communication with these areas is almost impossible. It is for these reasons, together with the direct climate effect on telephone links that cellular and even satellite links should be utilised. Communication via satellite is at present probably too costly.

GENERAL DESCRIPTION OF THE PUTU SYSTEM FOR IRRIGATION MANAGEMENT

Objective

The aim of this section is to describe:

a) briefly the advantages and disadvantages of irrigation scheduling,

b) use of Putu-IDSS for irrigation management, and

Mottram and De Jager (1995) described the Putu-IDSS in detail.

1. *Basics of Irrigation Scheduling*

Irrigation scheduling is the supply of water to plants as needed to achieve optimum yield and quality of a desired plant constituent.

The upper limit of crop production is set by climatic conditions and genetic potential. The extent to which this limit can be reached will always depend upon how finely the engineering aspects of water supply meet the biological needs for water in crop production.

How much water and when to supply it is a question of supply and demand. In context here are the following concepts:

Supply - how much water can a particular soil hold and make available to the plant
Demand - what atmospheric demand is imposed on the crop during its growth

The rate of water application is dependent upon the infiltration rate of the soil, the slope of the land and the soil surface condition.

Methods of Scheduling Irrigation

Various methods of deciding when and how much water to apply exist.

Auger and Feel Method

A soil auger may be used to obtain soil samples at different depths. It can be used to assess water movement in a soil profile after a rain or irrigation. However, it cannot be used directly to quantify water content in a soil. Indirectly it is used to take gravimetric samples from which percentage water contents may be determined.

The "auger and feel" method cannot be recommended, because of it's inherent inaccuracy.

Tensiometers

Tensiometers operate in the wet range of plant available water i.e. 0 to 0.07 Mpa. They need to be carefully installed and require constant in-field servicing. A representative number of instruments are required for each field station, and each instrument needs to be calibrated in situ in order to obtain meaningful readings.

Tensiometers encompass the soil water potential range required for most shallow rooted and quick growing vegetable crops. For deeper rooted and longer season crops, electrical resistance blocks may be required to extend the soil water potential range over which soil water content may be monitored. These resistance blocks also require individual calibration in situ and are inaccurate and unstable. Small range, sampling logistics and specialised maintenance make this method impractical.

Neutron water meter (Neutron probe)

In using the neutron probe to determine soil water content, a source of fast neutrons is lowered down an access tube (normally aluminium) which has been installed in the soil profile. The fast neutrons are slowed down by collisions with nuclei in the soil, particularly those of hydrogen atoms. The intensity of these back scattered slow/thermal neutrons is determined by a scintillation counter mounted just above the fast neutron source. Since water is the main source of hydrogen atoms in soil, the scintillation count is directly proportional to the soil water content.

The advantages of the neutron probe are that it is non-destructive and samples a sphere 15cm in diameter. The same volume of soil is sampled each time which reduces variability.

The disadvantages of using the neutron probe for irrigation scheduling are that numerous access tube sites are required to accommodate various soil types and different areas. Furthermore the time spent monitoring each tube is appreciable (say 10 minutes). This imposes a logistic and time restraint upon its practical usefulness. Furthermore it needs to be calibrated for each soil type/site, the instrument is expensive (>R30 000) and is radioactive. The latter requires continuous safety measures especially in handling and storage.

Evaporation pans

The use of a single climatic variable to estimate reference crop evaporation seems attractive. Extensive use and testing of the evaporation from standardised evaporation pans such as the Class A pan have illustrated, however, that the daily evaporation of the water in the pan is influenced by a range of environmental conditions. These are wind, type of vegetative cover around the pan, painting and maintenance conditions, the need for screens to prevent animals and birds from drinking water, etc.

Doorenbos and Pruit (1977) introduced the pan-factor related to various advective and environmental conditions. Smith (1991), while reporting the guidelines for predicting of crop water requirements, states that the use of the pan evaporation method for estimating reference crop evaporation should be recommended for practical scheduling only if it has been properly calibrated against field measurements of evapotranspiration.

Overestimation of evapotranspiration using the Class A pan was substantiated by van Zyl, de Jager and Maree (1989) for wheat growing in a lysimeter. Furthermore they showed that climate dependent correction factors are necessary. Humdal and Sandhu (1989) found that pan evaporation overestimated both actual and potential crop evaporation from maize over two seasons by between 15 and 90 percent, and 6 and 50 percent respectively. Mottram and De Jager (1990) illustrated the overestimation of reference crop evaporation when using the Class A pan as compared to the Penman-Monteith approach on results from a grass covered weighing lysimeter.

Automatic weather stations

Use of automatic weather stations was discussed in the literature survey. Noteworthy is the 1982, CIMIS (Californian Irrigation Management Information System) initiative in California to achieve greater efficiencies in water use and reduce the projected deficit between water supply and use (Hawkins and Cradock, 1985). CIMIS strategy was to develop a weather station network and dissemination system, develop irrigation scheduling programmes, verify the accuracy and utility of water budget scheduling on-farm, and conduct adaptive research to improve water budget scheduling technologies.

CIMIS provides Californian farmers with daily reference crop evaporation estimates based on hourly computations using a combination equation. Automatic weather stations are used in CIMIS because they speed up the data gathering process and eliminate loss of data due to human error.

In Southern Africa, automatic weather stations have been successfully used in projects of the Water Research Commission (WRC) on maximising irrigation project efficiencies. (Mottram and De Jager, 1994).

Hourly data accumulated by the automatic weather stations are used in the Penman-Monteith equation to estimate reference crop evaporation and AED for use in CGM adapted for irrigation scheduling.

A major advantage of use of automatic weather stations is that the data collected is representative of a relatively large, approximately 50 km radius area. Thus many neighbouring farms may be served by such a system.

Input data for the Putu-IDSS

Briefly, some of the data required for the management of irrigation using Putu-IDSS, includes:

Soil information

For each irrigation block/section the following information is required for each predetermined layer in the rooting/soil profile:

Soil water content at -10 kPa (θ_{10})	mm m^{-1}
Soil water content at -1500 kPa (θ_{1500})	mm m^{-1}
Initial soil water content at planting	mm m^{-1}
Field soil bulk density	g cm^{-3}
Infiltration rate of soil	mm h^{-1}
Depth of the water table	m
Classification - soil description	

Clay and silt percentages can alternatively be used to compute matric contents at -10 kPa and -1500 kPa.

In the event of these data not being available, either default values already in the system of values estimated for the given soil type and form may be utilized. Both produce acceptable results.

Rainfall and irrigation data

Rainfall and irrigation dates and amounts need to be entered manually, on days when they occur. The Putu IDSS provides appropriate files for this. Experienced operators could import electronic files directly into the irrigation files. The greatest source of error in the entire scheduling process is caused by farmers incorrect reporting of amounts and time of application.

Plant information

For each crop and season the following plant information is required:

Crop type and cultivar
Plant population and/or row width and plant spacing
Planting date

Climatic information

Hourly mean values of the following climatic variables are required:

Incoming solar radiation	W m^{-2}
Temperature	°C
Wind speed	m s^{-1}
Relative humidity	%
Rainfall	mm

Computation of water use

The hourly weather data are monitored by the AWS and retrieved by cassette tape which is downloaded to a computer, or by direct link, or by telephone modem, or by radio telemetry to a remote computer. After retrieval these data are checked, sorted up to the most recent 24h period and then merged into data files. The data are then converted into the IBSNAT standard format and used to calculate reference crop evaporation, Eo, using the Penmán-Monteith equation.

Eo is defined and discussed by Allen *et al* (1994) in Section 8 of Chapter 7.

In order to schedule irrigation it is necessary to determine the atmospheric evaporative demand, AED, which is the transfer of water to the atmosphere required to sustain the energy balance of a given vegetative surface, in the present growth stage when the water status of the root zone permits unhindered plant evaporation and the water status of the top 150mm equals its current value (De Jager and Van Zyl, 1989).

It is important to note that the definition of AED not only acknowledges the dominant influence of the atmospheric conditions, but also accounts for crop type, crop growth and soil surface water content. It represents the physical upper limit of actual crop evaporation. (see Mottram and De Jager, 1995)

Putu determines the daily AED (see Mottram and De Jager, 1995) which usually varies between 0 to 15 mm d^{-1}.

The fractional interception f_g is assumed equal to the fraction of ground covered by the vertical projection of green leaves (denoted FI_g in Putu - *IDSS*.)

AED is the upper limit of atmospheric demand from a natural surface on a given day.

$$\text{AED} = k_c.\text{Eo}$$

where,

k_c appropriate crop evaporation coefficient

This crop evaporation coefficient, kc, may be defined as

$$k_c = k_v + k_s$$

where,

k_v = fraction of reference evaporation supplied by plant evaporation

k_s = fraction of reference evaporation supplied by soil evaporation

Maximum values of k_v and k_s exist, namely k_{vo} and k_{so} respectively. These depend upon crop architecture and soil character and are determined empirically. Values of k_c reported for full canopy crops by Doorenbos and Kassam provide good estimates of k_{vo}.

Improvements include accounting for the variation in k_c due to variation in k_s as the soil surface dries, by using the above definitions and an empirical relationship (De Jager *et al*, 1987; also described in Section 2.1, 2.2 and 2.3 of Chapter 7), viz.

k_v = f(leaf area index, crop growth stage)

k_s = f(time since last wetting event), or

= f(soil water deficit in the top layer of soil)

when, $k_v = f_g k_{vo}$ is the fraction of reference evaporation taking place. The maximum plant evaporation coefficient k_{vo} is the ration of full cover crop evaporation to reference evaporation. It equals the crop coefficient for full cover crops given by Doorenbos and Kassam.

Putu computes k_v, k_s and k_c and determines the AED each day in the manner illustrated in Figure 15.1.

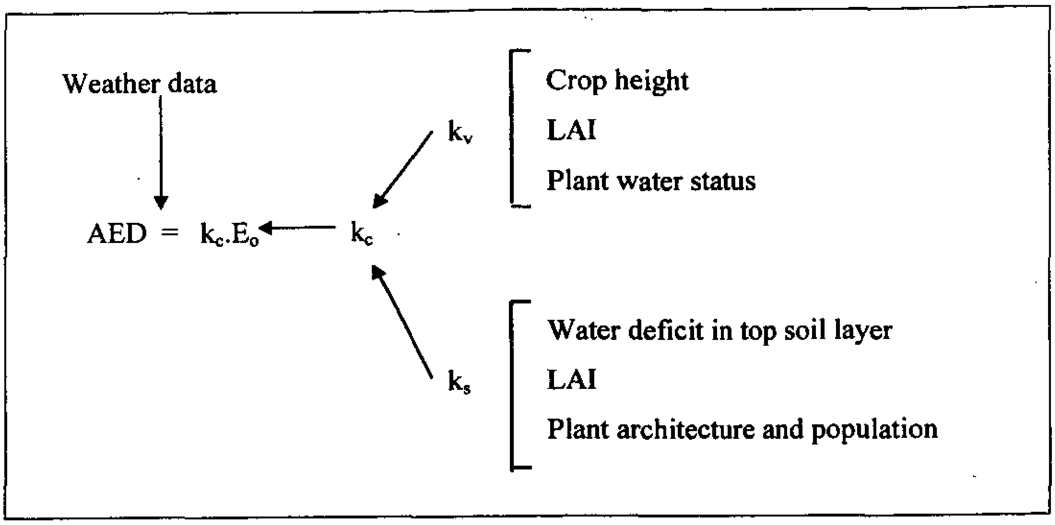


Figure 15.1. **Schematic diagram illustrating the computational procedure for determining AED**

The soil water balance equation as applied in PUTU summarized for the entire root zone is,

$$W = Wo + I_{rr} + Rain - D + \Delta W - AED$$

where,

W = soil water content (mm)

Wo = soil water content at 00h00 (mm), i.e. at end of previous day content

I_{rr} = irrigation amount (mm)

Rain = rainfall (mm)

D = drainage out of the root zone (mm)

ΔW = change in soil water content due to root extension and capillary flow (mm)

AED = atmospheric evaporative demand (mm)

Putu computes the soil water balance for nine soil layers. The thickness of each of these layers (eg. 150mm) is selected by the operator. The programme also accounts for the influence of a water table, or impervious soil layer, surface runoff and percolation through soil layers, should this occur.

It is important to note that this approach (use of AED) strives to reach water non-limited maximum yields. Appropriate management can also be applied where sub-optimal yield strategies are the objective, i.e. deficit irrigation.

GUIDELINES FOR THE USE OF THE OUTPUT VARIABLES OF THE PUTU IRRIGATION MODEL FOR IRRIGATION SCHEDULING

The AWS continuously records near real-time weather data which are retrieved either manually or via telecommunication networks. These data are used in the Putu system of simulation models which transform the data into IBSNAT format and calculate reference crop evaporation, AED and daily plant and soil water status.

Table 15.1. illustrates the output of PUTU-irrigation for tomatoes produced under drip irrigation and fertigation in the Mooketsi, Northern Province, RSA area. It is convenient to tabulate AED and E_o in whole numbers, hence the units mm x 10 and also leaf water potential in Mpa x 100.

Table 15.1. **Daily output of crop growth, water use and water requirements for tomatoes produced by, PUTU-Irrigation, with data from Station 41, Mooketsi, Northern Province, RSA**

ZZ2 - McNaughton C2

PLANT POPULATION
PLANTING DATE
1.2 (/M^2)
25/1/1994

CULTIVAR

MEDIUM

SOIL DESCRIPTION: Sandy Clay Loam

SOIL MOISTURE (mm/m)

MAXIMUM	MINIMUM	INITIAL	EFFECTIVE ROOTING DEPTH
301	193	240	0.6 m

1994 DOY	FW	LAI	IR	RAIN	PERC	PPAW	DEF	PSI		HU	kc	AED	Eo	FID
								ST	L					
	(%)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	(MPa*100)		(DD)	(%)	(mm*10)		(d)
62	1	72	0	0	0	38	41	-15	-145	595	94	38	40	3
63	0	76	11	0	0	35	43	-19	-90	608	90	17	19	5
64	0	80	0	0	0	46	36	-12	-126	621	100	40	40	4
65	0	84	0	12	0	42	39	-14	-115	635	98	31	32	4
66	7	88	0	0	0	51	33	-9	-166	651	100	60	64	3
67	16	91	0	10	0	42	38	-11	-177	668	100	56	65	2
68	0	95	0	0	0	51	33	-9	-133	684	100	45	45	4
69	1	97	7	0	0	44	37	-11	-143	695	100	42	43	4
70	1	99	0	0	0	49	34	-10	-135	706	100	42	43	4
71	2	100	0	0	0	42	39	-11	-149	717	99	41	43	3
72	6	102	0	0	0	36	42	-14	-164	728	96	39	42	2
73	13	103	0	0	0	31	46	-17	-175	739	96	35	42	2
74	24	104	0	0	0	26	49	-21	-182	750	96	31	42	1
75	35	105	0	0	0	22	52	-27	-188	760	96	26	42	0

In this table, daily status variables useful in irrigation scheduling decision taking include:

DOY	day of year
FW	water stress factor (0-100)(%)
LAI	leaf area index (%)
IR	irrigation amount (mm)
RAIN	rainfall amount (mm)
PERC	drainage out of root zone (mm)
PPAW	relative (profile) plant available water (%)
DEF	water deficit below the upper limit (mm)
PSI	ST, stem water potential (M Pa x 100) L, leaf water potential (M Pa x 100)
HU	growing degree days (heat units)
kc	crop evaporation coefficient
AED	atmospheric evaporative demand (water use)(mm)
Eo	reference crop evaporation (mm)
FID	forecasted period to the next day on which irrigation is *required so as to ensure unstressed crop growth*

Each day, the water stress indicator, FW, is determined by an iteration process. It is a function of climate and soil water status. It is expressed as the fraction (%) physiological water stress existing in the crop.

The latest version of Putu also provides a simple graph of AED and water added (I_{rr} + Rain) versus time, which is extremely useful. At a glance the operator can see when AED is approaching, or exceeding water applied, which indicates the need for irrigation is imminent.

The soil profile is seldom filled to field capacity in order to ensure that maximum benefit can be made of rainfall (i.e. leave storage space for rainfall so that it will not be lost by run-off and deep percolation). We term this practice ***deficit irrigation*** Table 15.1 represents one irrigation block. Any number of irrigation blocks can be accounted for in the Putu-IDSS.

The water deficit below the upper limit, DEF, is the amount of water required to replenish the soil profile (rooting zone). Should the irrigator not irrigate on the planned day, water budget calculations continue using near real time data until such time as he is able to do so. The FW value must be considered each day during this delay to avoid imposing undue stress on the crop. Monitoring FW is vital when deficit irrigation is practised.

From Table 15.1 FW, AED, FID, PPAW and DEF are used to decide when and how much irrigation is required for a particular land.

Consider DOY = 67. The following scenario materialises:

FW = 16% -stress indicator is becoming significant

PPAW = 42% -the rooting soil profile is approaching a yield depressing depletion level

DEF = 38mm (38mm is required to bring the rooting soil profile back to field capacity. This gives an indication of how much water could be replaced.)

In addition to the output from Table 15.1, the irrigation advisor must consider the plant's growth stage. The following considerations apply:

- how old is the plant
- is it in a particularly sensitive growth stage with respect to yield being affected by soil water deficits
- what weather conditions are likely to follow in the immediate future
- what plant growth stage is due to be attained in the immediate future
- is there an impervious layer and/or a water table.

Having the output presented in Table 15.1, the irrigation advisor can provide suitable information to the irrigator in order that he might plan ahead and decide when and how much to irrigate.

Table 15.2 illustrates the type of information supplied to the irrigation advisor.

Table 15.2 **Crop water use, crop and soil water status and irrigation recommendations for tomatoes being produced under drip irrigation in the Mooketsi, Northern Province area**

Name of farm : XX
Land no. : Land X

DOY	EO	AED	DOG	STRESS	DEF	RECOMM. IRRIG.	CUMUL. IRRIG.	CUMUL. RAINFALL	FID
	Mm	mm		%	mm	mm	mm	mm	
67	6.5	5.6	42	16	38	11	71	72	2

where DOG = days of growth since planting

The advisor , having examined FW, AED, PPAW, DEF and FID recommended 11mm of irrigation for DOY 67. The irrigator now knows that he must put on at least 11mm in order to maintain the plant in an optimum soil water environment.

Table 15.1 and 15.2 represent one irrigation block. Any number of irrigation blocks can be accounted for in the PUTU system.

LEGAL CONSIDERATIONS

Since there is a danger of participating farmers incurring losses, some sort of legal contract between farmer and agent would be appropriate. A *pro forma* for this is included in Appendix III.

Putu-IDSS MENUS AND WINDOWS

The various computer monitor screens which carry out the operations in the Putu-IDSS are illustrated by Sheet 1 through Sheet 11 given in Appendix I. The menus in most cases are self-explanatory and guide Putu users through the various operations.

CHAPTER 16

THEORY FOR OPTIMIZING LIMITED WATER RESOURCE ALLOCATION

INTRODUCTION

De Jager and Mottram (1995) applied linear programming (LP) to optimise land area cultivated, crop rotation and the irrigation amount for each crop growth stage. This LP approach suffered certain shortcomings. Firstly, it required an unrealistic apportionment of production costs to the different crop growth stages. Secondly, the yield decreases due to water stress in each growth stage needed to be summed, whereas a multiplicative combination of the limitations on growth in individual growth stages should produce a more realistic and reliable model. For these reasons an improved computing procedure was sought.

The software for carrying out the optimisation was developed for inclusion in the Putu Irrigation Decision Support System (IDSS). Unfortunately, the program malfunctioned and was not rectified. Its theory will however be described. The acronym WMDSS, denoting Water Management Decision Support System will be used. A stand-alone version of the WMDSS and its operator's manual are available.

OBJECTIVE

The design and coding of computer software to assist decision making regarding the maximisation and optimisation of:

(i) irrigation applications and timing,
(ii) crop-type selection,
(iii) area cultivated, and
(iv) amount of water distributed to several lands or farms.

Specific objectives were to create a user-friendly computerised **WMDSS** for:

1. Optimising crop type combinations and area cultivated per crop for a given water supply.
2. Computing expected total gross margin from a cropping practice selected by the farmer and limited to a given quota and peak flow rate throughout the year (irrigation scheme situation).
3. Optimising land area and crop type planted to a pump rate which varies with time throughout the year. This scenario applies to a water supply controlled by the stream flow rate where a natural river is used as a water source.

The WMDSS was expected to iterate *daily* weather data (evaporation, rainfall) and apply a *multiplicative combination of water stress effects from different growth stages upon final yield.* This represents an improvement on the De Jager and Mottram (1995) approach. Unfortunately computer speed limited the final WMDSS to week iterations.

REQUIREMENTS FOR THE COMPUTERISED WATER MANAGER

While decision support is most urgent and useful in times of water restrictions, it can also be of great value to calculate water in years when normal quotas apply. Hence, both situations (restricted and normal quota) need to be accommodated.

A solution had to be found for two situations. These are for schemes (or a farm) where water is supplied from either:

A Stream flow from a river which is **uncontrolled** by the water manager, or

B A dam, or borehole, from which water extraction can be **controlled** by the water manager.

In both cases it is assumed that hydrologists or other specialists have predicted the annual water supply, permitting annual water quotas to be allocated ***a priori***.

On-farm, additional situations could pertain, eg. water supply rate is limited to:

C A storage dam with capacity equal to approximately one week's peak crop water requirements, or

D A maximum canal supply rate.

E Furthermore water restrictions could be imposed during the current season calling for modifications to the original strategy.

In attempting to optimise water use, it is assumed that the water manager must distribute the water available from either A or B above, throughout the year amongst several irrigators, or lands. The latter could utilise conveyance methods of either C or D or a combination of C and D. The ideal solution to the problem would thus accommodate any combination of A, or B and C, D and E. Two scenarios have been addressed in the present study, viz. A and C, and B and D

PROPOSED PROCEDURE

1. Use daily weather data to compute weekly individual crop water requirements using the Penman-Monteith equation (PME) using the methods and software described in Chaters 7 and 8.

2. Compute optimal application per plot per week and sum over the entire scheme (farm). This is the information required by the irrigator which will be provided to the water manager.

Assumptions

Resource limitations are a given annual water quota (m^3 ha^{-1} yr^{-1}) for a given scheduled irrigation area (ha). In dry years water supply may be restricted to a percentage of this quota.

1. A given pre-determined annual water quota ranging up to the statutory limit which could for example be 11000 m^3 ha^{-1} yr^{-1}. By applying deficit irrigation individual farmers may irrigate areas larger than these quotas are capable of supporting up to the maximum size as determined by for eg. irrigation equipment , labour and operating capital.
2. Maximise gross margins assuming variable costs and expected market prices of commodoties are given.
3. Each farm manager may propose a set of crop rotations from which the optimal combination is to be estimated.

Objective

The manager must optimise the water allocation for the coming year in terms of the selected crops and areas.

Outcome

Provide a seasonal plan of weekly water deliveries to each farm.

EXISTING WATER PROVISION SCENARIOS

A brief situation survey of the principles which govern water provision on most state water schemes proved useful. Briefly,

State Scheme

- Each farm is granted an annual water quota each year in April or October.
- Quotas are typically 9140 m^3 per listed ha per year, but vary from 5500 to 11000 (and in Upington even 15000m^3/(ha yr)). In the past quotas were 7700 m^3/ha
- Managers order water on a Thursday for the ensuing week. It is available from the coming Monday.
- Peak flow rates are limited by canal size and may not be exceeded. Peak flow application rates vary between 4 and 8 mm/d.
- Water tariffs approximate 3.3 c/m^3 (1994/95) at Vaalharts, but on most other schemes are of the order of 1.5 to 3 c/m^3.

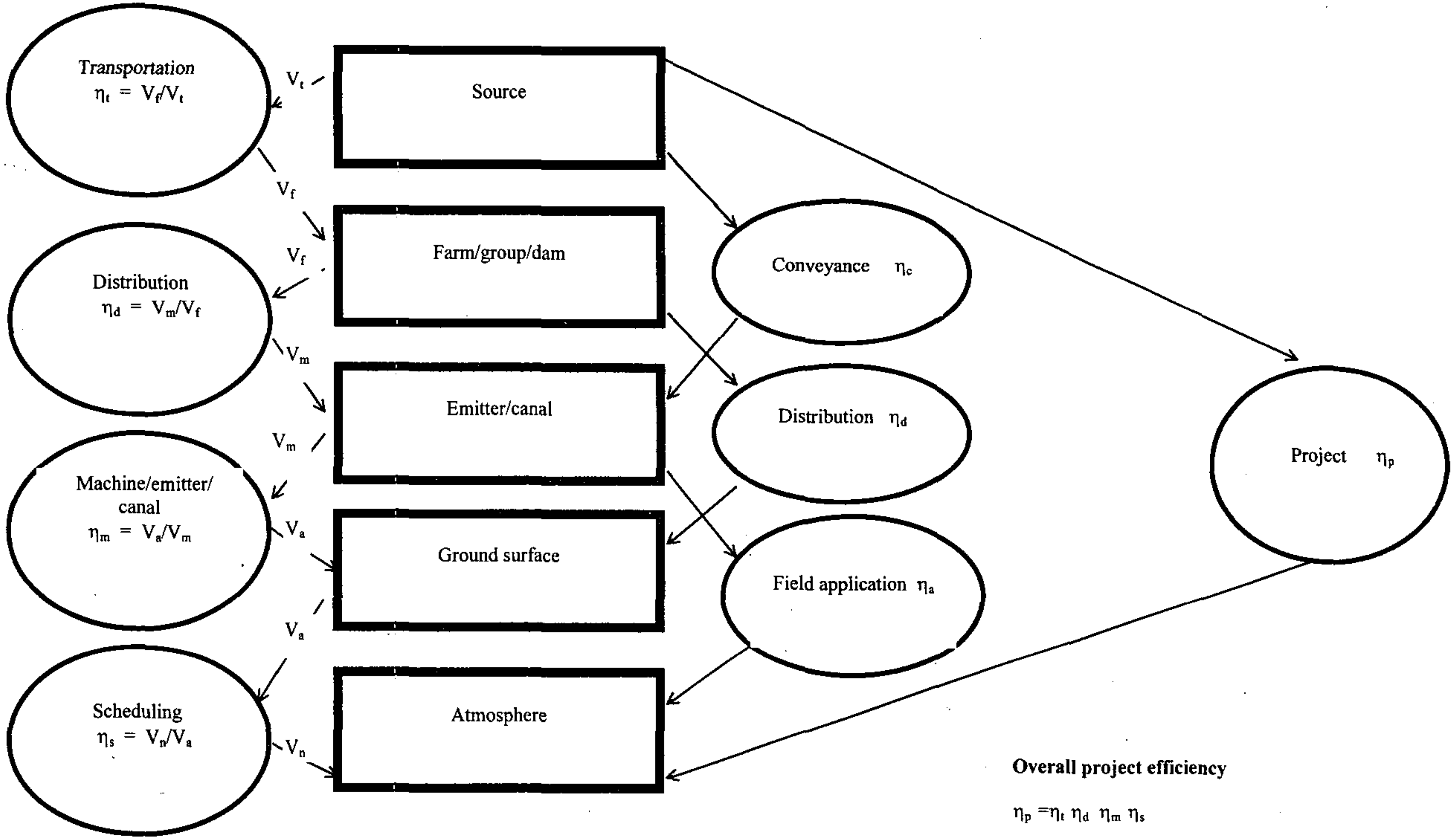
River System

For river systems water supply is determined by the pumping rate (litre/sec) permitted on each farm. The basic principle is that within this framework farmers *may* decide *individually* on what land area to plant what crop.

Efficiency

In the context of irrigation farming in the R.S.A.; water conservation effectively means increasing the efficiency with which irrigation water is used. Potential for improving efficiency is found in the conveyance, distribution and field application operations. In order to assess the efficiency of an irrigation project, it is necessary to define the efficiencies relevant in the different stages of the irrigation project. The efficiencies defined in the literature (see Chapter 2) required some modification to make them applicable to the present study. Atmospheric influence and some slightly changed definitions of the proposals of ICID (Schvelik, 1987), Reinders (1996) and De Jager and Mottram (1995) were introduced. Based upon these new definitions the schematic presentation, Figure 16.1, was prepared.

Fig. 16.1 **Schematic description and definitions of water transfer efficiencies**



☐ Water transfer stage

○ Water transfer branch

V volume of water transferred

η efficiency (output/input)

Overall project efficiency

$\eta_p = \eta_t\ \eta_d\ \eta_m\ \eta_s$

$\eta_c = V_m/V_t = (V_f/V_t)(V_m/V_f) = \eta_t\eta_d$

$\eta_d = V_a/V_f = (V_m/V_f)(V_a/V_m) = \eta_d\eta_m$

Numerous WRC projects have been undertaken with the objective of conserving irrigation water. Each has addressed one, or more, of the efficiencies depicted in Figure 16.1. ACRU (Schulze, 1995a) estimates stream flow given the agro-hydrological characteristics of a catchment. Three computer programmes, based upon the water request mode of operation, were developed by (Benadè, 1993 and Annandale and Van Zijl, 1996). They constitute a computerised system for optimising the water distribution in an irrigation scheme. Briefly,

- WAS/RAUDB, is a computerised water administration/water request system used on irrigation schemes for printing water distribution and water bailiff instruction sheets, accounts
- Procan is an unsteady flow simulation model for simulating water flow in canals and rivers
- Sigma Q, is a water release calculating system, which collates water requests and calculates the amount of water to be released in a canal system, taking losses and flow time into account. Parameters are adjusted in Sigma Q when an incorrect water release, is calculated.

Green (1985), CROPWAT (Smith, 1992) and CLIMWAT (Smith, 1993) SAPWAT (Crosby, (1996) and Dent, Schulze and Angus (1988) offer computerised methods for estimating crop water requirements. Apart from numerous overseas authors; BEWAB (Bennie *et al*, 1988), Putu (De Jager *et al*, 1987) and Annandale, van der Westhuizen and Olivier (1996) in South Africa offer computerised methods of scheduling irrigation involving crop growth models and weather data.

In effect then, the improvement of efficiency relative to the supply of water (η_t), its conveyance and distribution (η_e, η_d) and field applicaton (η_a) have been addressed. This chapter will attempt to contribute towards solving the problem: *given water restrictions, expected crop selling prices and variable costs what will be the most* ***efficient distribution strategy*** *for the available water, relevant crops, area to be irrigated and growth stages in which water should be withheld.* It will thus formulate strategies which optimise water requests that can be used in WAS/RAUDB, Procan and Sigma Q and assist in producing the request cards required by the latter software packages.

THEORY AND PROCEDURE FOR ALLOCATING WATER

The objective function

Biomass production has long been known to be directly related to transpiration (Kieselbach, 1916) (and so approximately water applied), but there is much evidence (Doorenbos and Kassam, 1979 Jensen, 1968; Stewart *et al* 1977) demonstrating the variable influence on final yield of deficit irrigation in different growth stages.

Thus, in a situation of reducing water application, initial water shortfall should particularly (with judiciously timed irrigation management) always reduce final yield less than subsequent water reductions. This infers a diminishing returns, type of crop-water function, (see De Jager, *et al*, 1987) irrespective of what strategy is followed regarding when in the growing season water is witheld.

Considrations such as this, led De Jager and Mottram (1995) to develop a LP program for optimizing area cultivated and crops cultivated under restricted irrigation water supply. Unfortunately, the LP is not user-friendly and takes no account of rain. These shortcomings are rectified here. The coding and program construction was undertaken in Visual Basic by Louis de Lange, Computer Consultant.

Stewart multiplicative theory (Stewart et al, 1977) can be used to estimate the yield of a crop (Y) having a potential yield of Y_o. The equations described by Doorenbos and Kassam (1979) and Smith (1992) in CROPWAT were applied. The final yield equation used (Stewart *et al*, 1977), is described by:

$$Y = Y_o \prod_{s=1}^{s=i} \left[1 - ky_s \left(1 - \frac{E_s}{AED_s} \right) \right] \tag{16.1}$$

where the total growth period is subdivided into i distinct growth stages (s=1 to s=i), and

Y_o	potential yield	(kg ha^{-1})
Y	estimated yield	(kg ha^{-1})
s	given growth stage	
ky	yield stress factor for the growth stage s	
E_s	actual crop evaporation in the growth stage s	(mm/ha)
AED_s	atmospheric evaporative demand in growth stage s for maximum or potential yield	(mm/ha)

With the yield per hectare known, the revenue generated by the crop can be calculated:

$$R = A(Y \times SP - CI - CP) \tag{16.2}$$

where

As a first approximation it was assumed that scheduling efficiency (η_s as applied in Figure10.1) equals unity.

A	Area irrigated	(ha)
SP	Selling price	(R/t)
CI	Irrigation cost	(R/ha)

CP Variable costs (R/ha)

Irrigation cost (CI) is calculated as the cost of irrigation water per mm applied multiplied by the water applied in mm per hectare (CI = (R/mm) (mm/ha)). In practice, current selling prices are used with estimates of irrigation and variable costs.

The gross margin for a combination of crops (c = 1 to c = n) can be calculated by:

$$\sum_{c=1}^{c=n} R_c = \sum_{c=1}^{c=n} A_c\left(Y_c \times SP_c - CI_c - CP_c\right) \tag{16.3}$$

Substituting for Y_c in [Eqn 16.3] from [Eqn 16.1], yields:

$$R_{tot} = \sum_{c=1}^{c=n} R_c = \sum_{c=1}^{c=n} A_c\left\{Y_o \prod_{s=1}^{s=i}\left[1 - ky_{s,c}\left(1 - \frac{E_{s,c}}{AED_{s,c}}\right)\right] SP_c - CI_c - CP_c\right\} \tag{16.4}$$

Eqn 16.4 forms the basis of the procedure employed to search for the optimum application of available irrigation water in order to maximise the value of $\boldsymbol{R}_{tot}$. Eqn 16.4 contains two independent variables, i.e. A_c and $E_{s,c}$. The other variables have defined values for each crop in each growth stage.

By defining a vector containing different, permitted values for A_c and $E_{s,c}$, and substituting these in Eqn 16.4, a value for $\boldsymbol{R}_{tot}$ is calculated. The function must be solved for a number of crops with varying demand and water availability for each week in the year. Effective weekly rainfall is estimated on input.

Selection of an Optimisation Technique

It is important to realise that the accuracy with which the values for the variables A and E must be determined, is not of vital importance. A farmer seldom controls the irrigation applied to within one to two mm, and is unlikely to plant fractions of a hectare because a computer programme produced an answer requiring fractions of a hectare to be planted. If the answer can be determined to the nearest hectare and within one mm from the theoretical optimum, the answer will satisfy the requirements of the program. This implies that discrete, or integer values for A and E, can be used.

Eqn 16.4 is a non-linear equation, which precludes its optimisation using linear programming techniques. With the preceding observations in mind, an optimisation method that will satisfy the following main criteria was sought:

- the method must be simple to apply
- it must be easy to programme
- it must be unconditionally stable in converting to the optimum value

The non-linear optimisation techniques investigated, included gradient methods, generic programming and random substitution methods. The method ultimately selected for use in the program is a random substitution method related to the Monte Carlo method. The major disadvantage of this method is the time required to convert to the final answer. It requires a large number of iterations to obtain a final answer and this can be considerably more time consuming compared to some of the other methods.

Application of the Optimisation Technique in the Program

The program considers two pre-season planning scenarios:

- Controlled water supply (abstraction from a source such as a reservoir where scheduling water abstraction is possible
- Uncontrollable water supply (abstraction from a river with unpredictable and varied flow)

The optimisation technique needed to be adapted for each of these applications, as the constraints on the independent variables are different in each case. In the controlled water supply scenario the total available water supply may not be exceeded at the end of the season. However, in the uncontrolled water supply scenario the water applied in any week of the year may not exceed the volume available in the river or stream for that particular week.

The major difference between the two scenarios from a programming point of view, is the method of testing for valid solutions of $\boldsymbol{R}_{\text{tot}}$. Apart from the validation criteria, the method of obtaining the optimum value for $\boldsymbol{R}_{\text{tot}}$ is identical.

Solving the equation

1. *Calculate or assign a value for $AED_{s,c}$ and $E_{s,c}$ for each week of the year.*

Any plant dates for crops may be chosen, but the area available for irrigation may obviously not be exceeded. Crops are not planted simultaneously and the plant dates and growth stage lengths in terms of weeks are known. This enables a unique value for $AED_{s,c}$ and $E_{s,c}$ to be calculated for each week of the year. If no crop is associated with a specific week of the year, a zero value is assigned. The method is best explained by using an example.

A value for $E_{s,c}$ is assigned by randomly choosing an integer value for $E_{s,c}$ from a set of possible values.

$0,6 <= E_{s,c} <= AED_{s,c}$

In order to curtail computing however, $E_{s,c}$ is chosen from the set of values satisfying:

$0.6\ (AED_{s,c}) <= E_{s,c} <= AED_{s,c}$

The optimation of E (and hence actual irrigation applied) requires that a value for $AED_{s,c}$ must be assigned to each week of the year. Using the Putu irrigation scheduling software package (See Chapters 7 and 8) $\mathrm{AED}_{s,c}$ is calculated for each growth stage for each crop. The quotient of the $AED_{s,c}$ of a particular growth stage and the growth stage length in weeks defines the $AED_{s,c}$ for a particular week of the year. Assume Crop A is planted in the tenth week of the year, the first growth stage has a duration of 2 weeks and the AED for the first growth stage is 300mm. AED for week 10 is calculated as 300/2 = 150mm and the AED for week 11 (the second week of the growth stage) is similarly 150mm. Choosing a value for E between 0 and 150 for each of these weeks ensures that E will not exceed 300mm for the whole growth stage.

Once weekly values have been assigned to $E_{s,c}$ and $AED_{s,c}$ for each of the weeks in the year coinciding with a crop growth stage, the weekly values of $E_{s,c}$ are summed per growth stage to calculate $E_{s,c}$ for the complete growth stage.

If no crop growth stage is associated with a specific week of the year, the values of E and AED are set equal to zero.

The program accounts for irrigation efficiency by dividing E and AED by the irrigation efficiency relevant to each irrigation system.

Weekly effective rainfall needs to be estimated by the operator.

2. *Choose a value for A_c (Area planted)*

A start point for the search is determined by considering the fact that a minimum value for A_c exists. The minimum value for A_c is the number of hectares that can be planted if full irrigation requirements are satisfied with the available water. The available water can be spread over a larger area but there will be no benefit in applying more water over a smaller area. The lower limit for A_c can thus be determined ($A_{c,min}$). The first value selected for program iterations is $A_c = A_{c,min}$, i.e. when $E = AED$ and $A_{c,min}$ = available water supply devided by the product of total AED and irrigation efficiency. Further iterations are done by randomly choosing integer values for A_c subject to:

$A_{c,min}$ <= A_c <= Total area available.

$$\text{where } A_{c.min} = \frac{\text{Water supply available to crop}}{\text{Irrigation Efficiency.Total } AED_c}$$

3. *Calculate a value for* $\boldsymbol{R_{tot}}$ *with the randomly chosen values for E and* A_c.

Substitution of all variables and constants into Eqn 16.4 yields a single value for $\boldsymbol{R}_{tot}$. The result of the preceding steps is a vector containing values for E, Ac and an associated value for $\boldsymbol{R}_{tot}$.

4. *Test whether a particular solution is valid.*

It must be determined if the water constraints are satisfied. In the controlled water supply scenario, the values of $E_{s,c}$ are multiplied with the area planted A_c and the total volume of irrigation water applied over the year is obtained. This volume may not exceed the total available water as specified by the user.

In the uncontrolled water supply scenario, the weekly values of $E_{s,c}$ are multiplied by the area planted A_c and the total volume of irrigation water applied in a particular week is obtained. This volume may not exceed the total available water in the stream for that particular week as specified by the operator.

In both instances, the randomly irrigation efficience total selected value of E is adjusted by adding the effective rain component prior to comparing the total volume to the available water. This ensures that a low value for E may be acceptable when enough rain is available.

If the constraint of total available water is satisfied, the $\boldsymbol{R}_{tot}$ value together with the associated vector of $E_{s,c}$ and A_c values is retained.

5. *Repeat the previous steps.*

Ten thousand iterations are done and the best value of $\boldsymbol{R}_{\text{tot}}$, and the associated vector of E and A_c values are retained.

6. *Narrow the search region for values of E and A_c yielding the highest $\boldsymbol{R}_{\text{tot}}$ values.*

After every ten thousand iterations, the search region is progressively narrowed around the optimum values of E and A_c. A total of 100 000 iterations are done.

7. *Print the values of E and A_c yielding the highest $\boldsymbol{R}_{\text{tot}}$ values.*

SOME THOUGHTS ON GUIDELINES FOR EQUIBLE WATER ALLOCATION

Given the scarcity of, and conflict for, water among different sectors of the community (eg. agricultural, industrial, domestic); any regulations controlling the allocation of irrigation water should strive to achieve the highest possible utilization efficiency.

Proposed guidelines

Some assumptions will have to be made regarding guidelines for acceptable levels of irrigation efficiencies aimed at ensuring equity between the needs of the different water consumers.

All irrigation systems operate at efficiencies below 100 %, but at the present time it would seem reasonable to expect, state and irrigation boards to seek designs operating at $\eta_m > 80$ %, conveyancing systems with $\eta_t > 95\%$, and encourage farming where $\eta_d > 80\%$ and $\eta_s > 80\%$. Assuming these four criteria would yield a $\eta_p = 49$ %.

The proposed guidelines offer water managers ample scope in practice. The whole farm / scheme situation should however always be taken into account when making decisions.

Advantages

The proposed guidelines could ensure that all water for irrigation will be allocated, subject to the expectation that it will be used above a minimum efficiency.

Commercial and small-scale farms will be given equal rights, because the concepts apply to both.

The advantages of the approach here proposed rest in its mathematical procedures which provide for consistent and scientific long-term planning as well as short term calculation and optimisation a.o. of the following:

a) The water quota necessary to attain a desired level of production
b) Given a water quota; the minimum irrigated area required and expected production for given crops.

It is evident that the proposed guidelines apply equally to each of commercial, subsistence or small-scale farms.

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APPENDIX I

OPERATOR'S MANUAL FOR THE PUTU-IRRIGATION DECISION SUPPORT SYSTEM

INTRODUCTION

This appendix provides a brief description of how to operate the Putu-IDSS.

COMPUTATIONAL PROCEDURE

Computational decisions and procedures for the Putu-IDSS are outlined in the diagrams **Sheetl** through **Sheet 11**. Each operation in the IDSS may be accessed by buttons and the operator is led through the steps of the particular file he has selected by the 'next', or 'previous' buttons. The steps and procedures are self-explanotory, hints are provided at strategic places and the major skill required is deciding which option, or task is to be carried out at a given point.

The first option available on the menu (see **Sheet 1)** entails deciding whether to 'Process weather data', 'Schedule irrigation'. Please note that space has been left in the IDSS shell for future inclusion of an 'Optimise water distribution routine'.

The updating of weather data is explained in **Sheet 3** and the procedure for optimising water allocation in terms of what crop to plant, what size areas to irrigate and to determine weekly water requirement is described in Chapter 16. The sequence of operations for managing irrigation of numerous plots is described on **Sheet 2**. Briefly, once the weather data file has been updated, it becomes necessary to:

Sheet 2

Once-off

Create the input files.
Set-up the experiment (scheduling of numerous plots).

Provide irrigation advice by

Select the plots to be scheduled (by setting up a batch job).
Run simulations for each plot.
Prepare irrigation advice for dissemination.

Sheet 4 Offers a choice of modelling level and creating the experimental file. This, the control file, has a name consisting of any 8 characters. For rapid identification by an operator, it is suggested that the first four be alphameric, describing the site and the second four be numeric consisting of the last two digits of the year in which the crop is to be harvested followed by two digits for identifying the plot.

Sheets 5 to 8 each describe how to carry out certain procedures.

Sheet 5	Create the control file.
Sheet 6	Create one or more input files.
Sheet 7	Create a batch job and/or run the scheduling simulations.
Sheet 8	View the results of the simulation in the *.VAR file and prepare the files containing the advice to be disseminated.

There are numerous input files requiring to be completed for each crop, viz.

Sheet 9	Cultivar characteristics. Calendar. Ontogeny. Fractional ground cover yield. Water stress parameters (k_y). Canopy development. Partitioning. Crop parameters.
Sheet 10	Data Input, or Management Rainfall Irrigation Initial soil water content.
Sheet 11	Soil Physical Characteristics. In-season adjustment. Long-term climate averages.
Sheet 11a	Is the explanation of the procedure for calculating a SWC.
Sheet 12	Processing weather data.
Sheet 13	Weather data file identification.

Each of these entities may be viewed on customised graphs.

Simulation Levels

Three levels of simulation are available in Putu-Irrigate, viz.

Level 1 Elementary

Level 2 Irrigation scheduling
Level 3 Any crop model

All three produce essentially the same type of output in a *. VAR file.

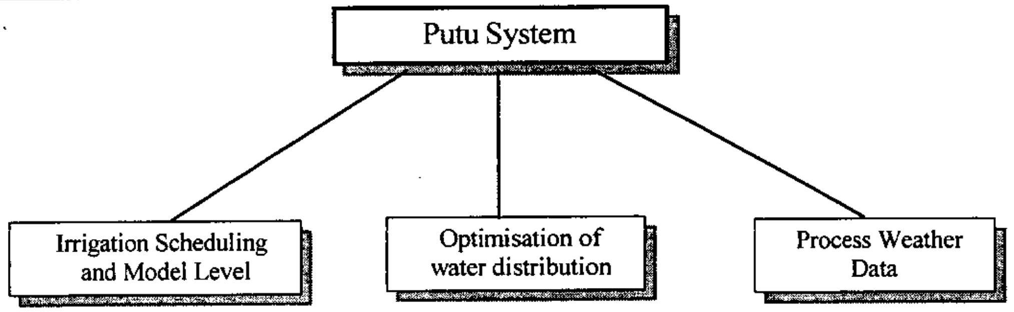
Elementary, Level 1, has two objectives:

1. Introduce and familiarise operators with irrigation scheduling by CGM.
2. Provide a method for converting phenological observations made in terms of sidereal days to thermal time for use in Level 2 and Level 3.

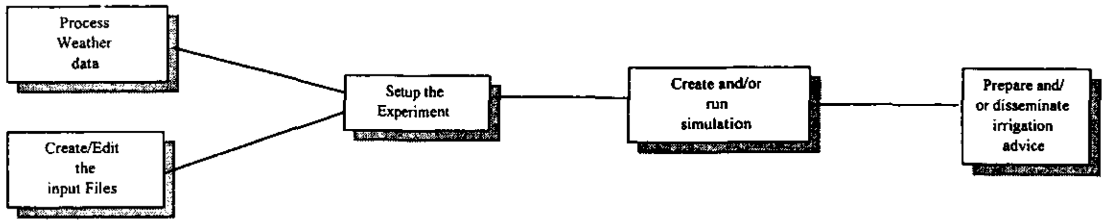
Essentially the operator simply selects a crop and soil type from a given list and all the input parameters are defaulted excepting for ontogeny, canopy development and the experiment manager, or control file. A selection from two or three crops are provided on request when the system is installed.

Irrigation Scheduling, Level 2, allows operators to enter crop and soil parameters obtained in the field. Just as in Elementary, it is basically aimed at simulating crop water status and providing indicators as to when the next irrigation is expected and how much water to apply. Yield is simply computed from estimated harvestable yield potential and the Stewart *et al* (1977) relative evaporation deficit formula.

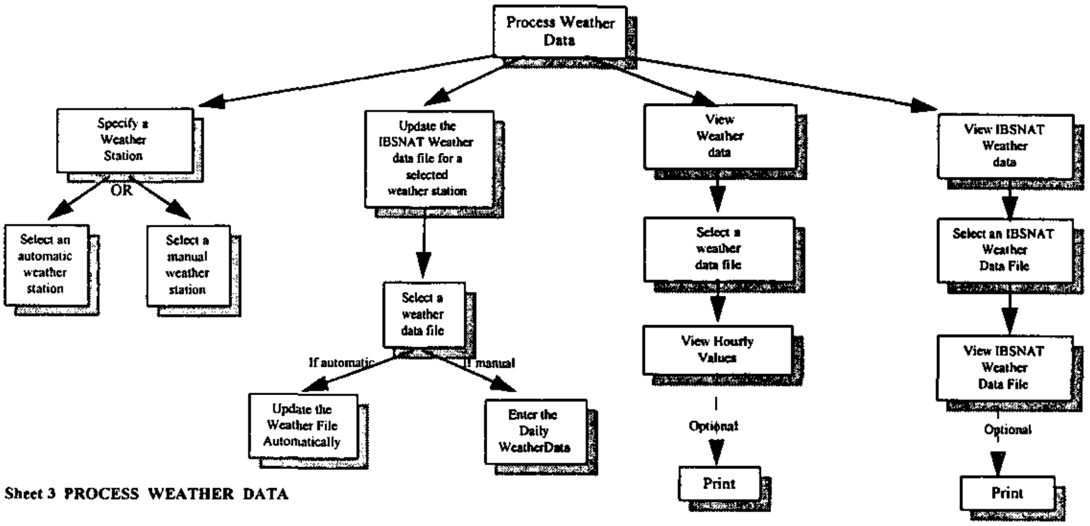
Anycrop, Level 3, permits simulation using the anycrop version. This is a complete CGM utilizing all the theory described in Chapter 7 of this report, for example, the expolinear biomass and leaf growth function, partitioning, etc. It too, is custom designed for specific crops at the time of installation.



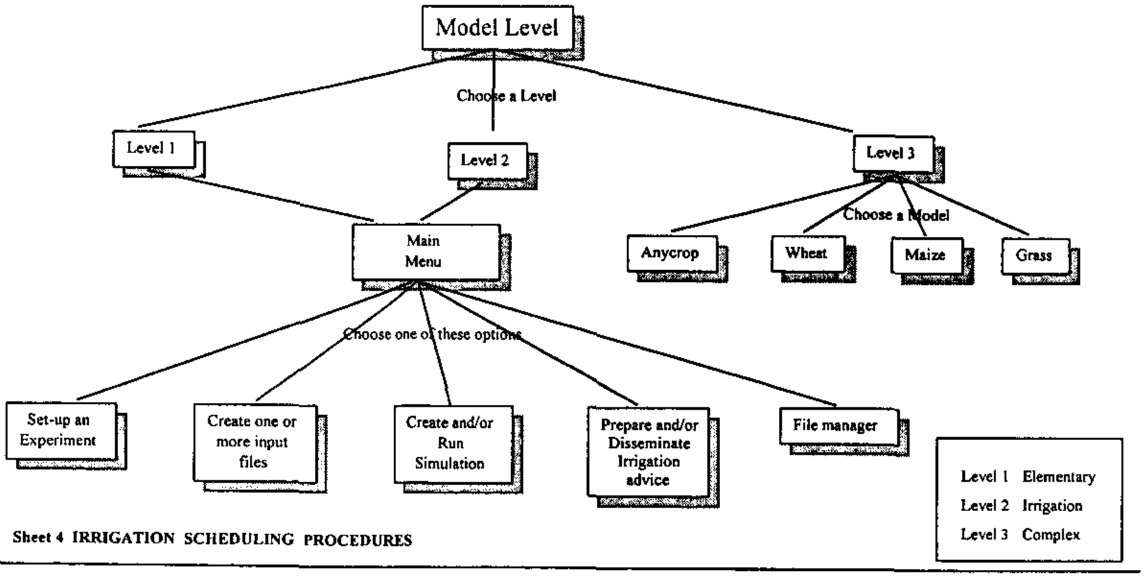
Sheet 1 MAIN DECISION SUPPORT



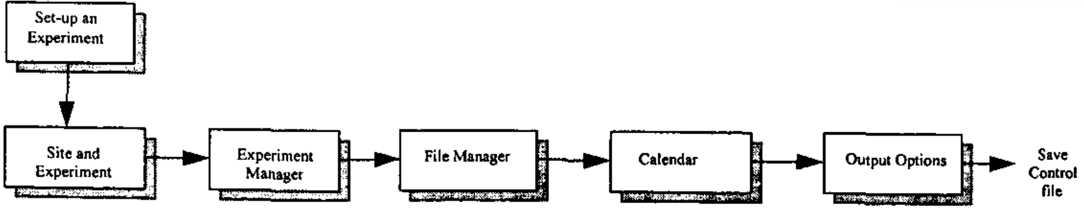
Sheet 2 SEQUENCE OF OPERATIONS FOR SCHEDULING IRRIGATION



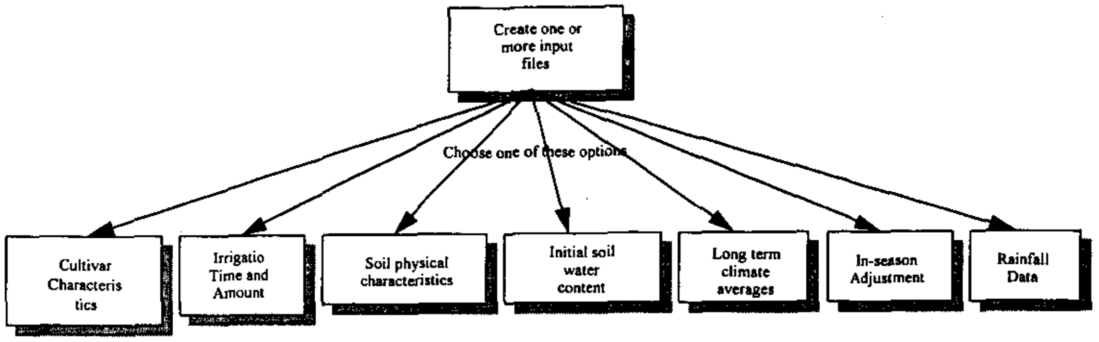
Sheet 3 PROCESS WEATHER DATA



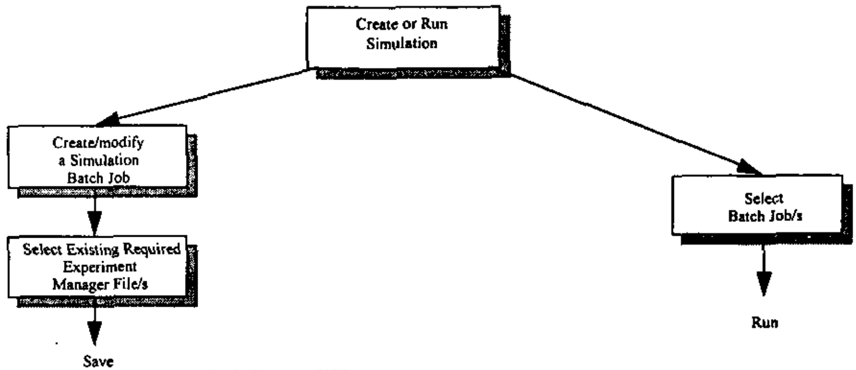
Sheet 4 IRRIGATION SCHEDULING PROCEDURES



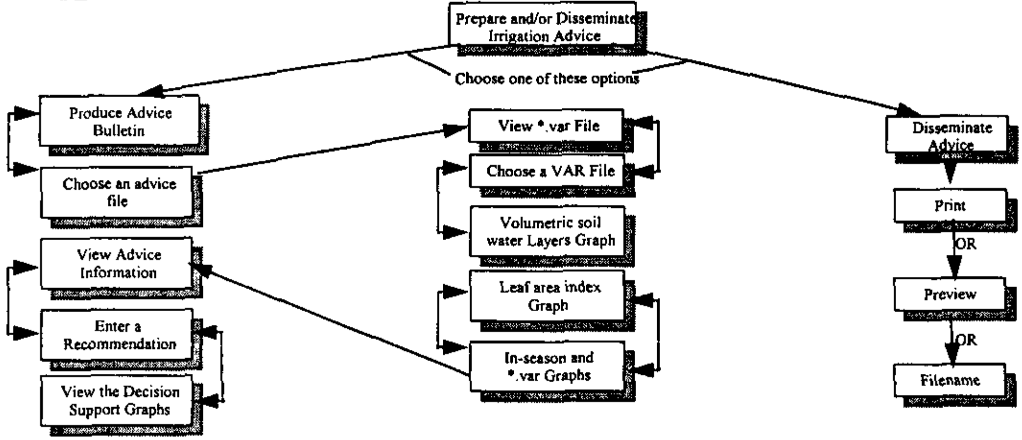
Sheet 5 CREATE AN EXPERIMENT MANAGEMENT (CONTROL) FILE



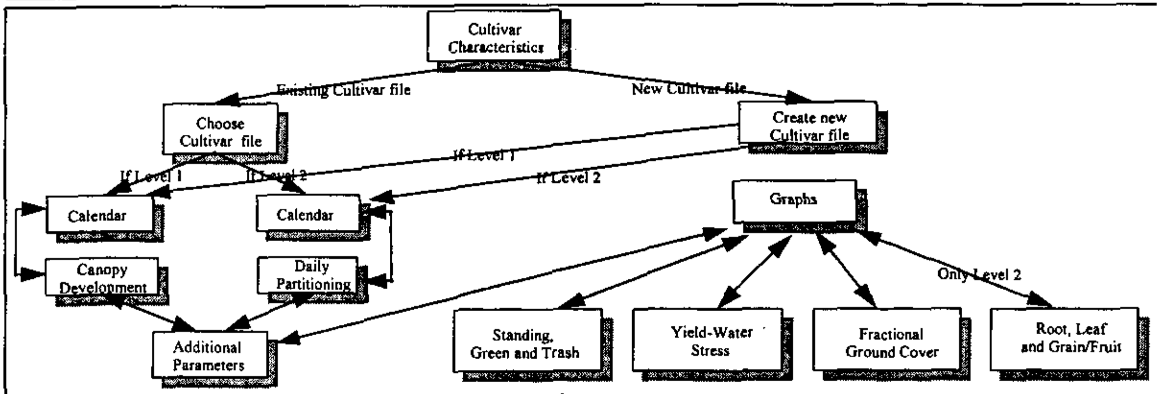
Sheet 6 CREATE INPUT FILES



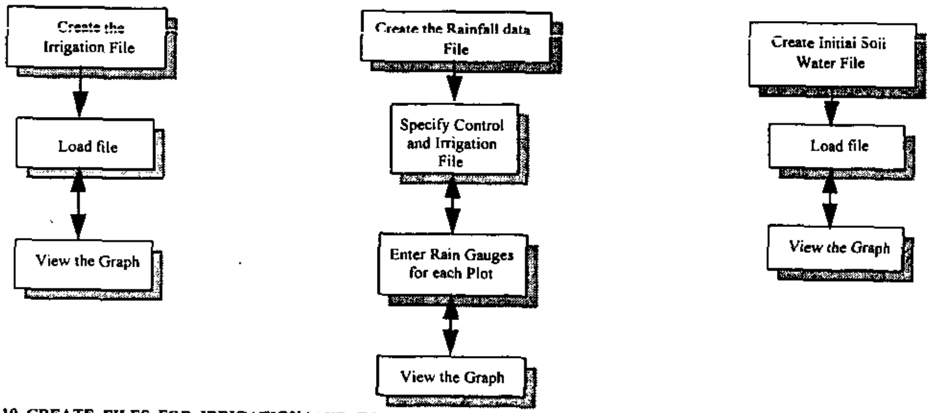
Sheet 7 SIMULATE CROP WATER STATUS AND -USE



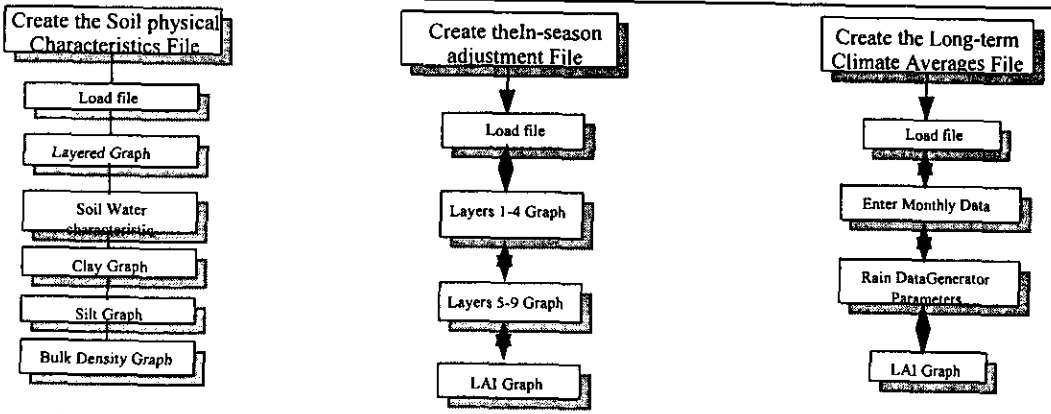
Sheet 8 DECISION DISSEMINATE INFORMATION



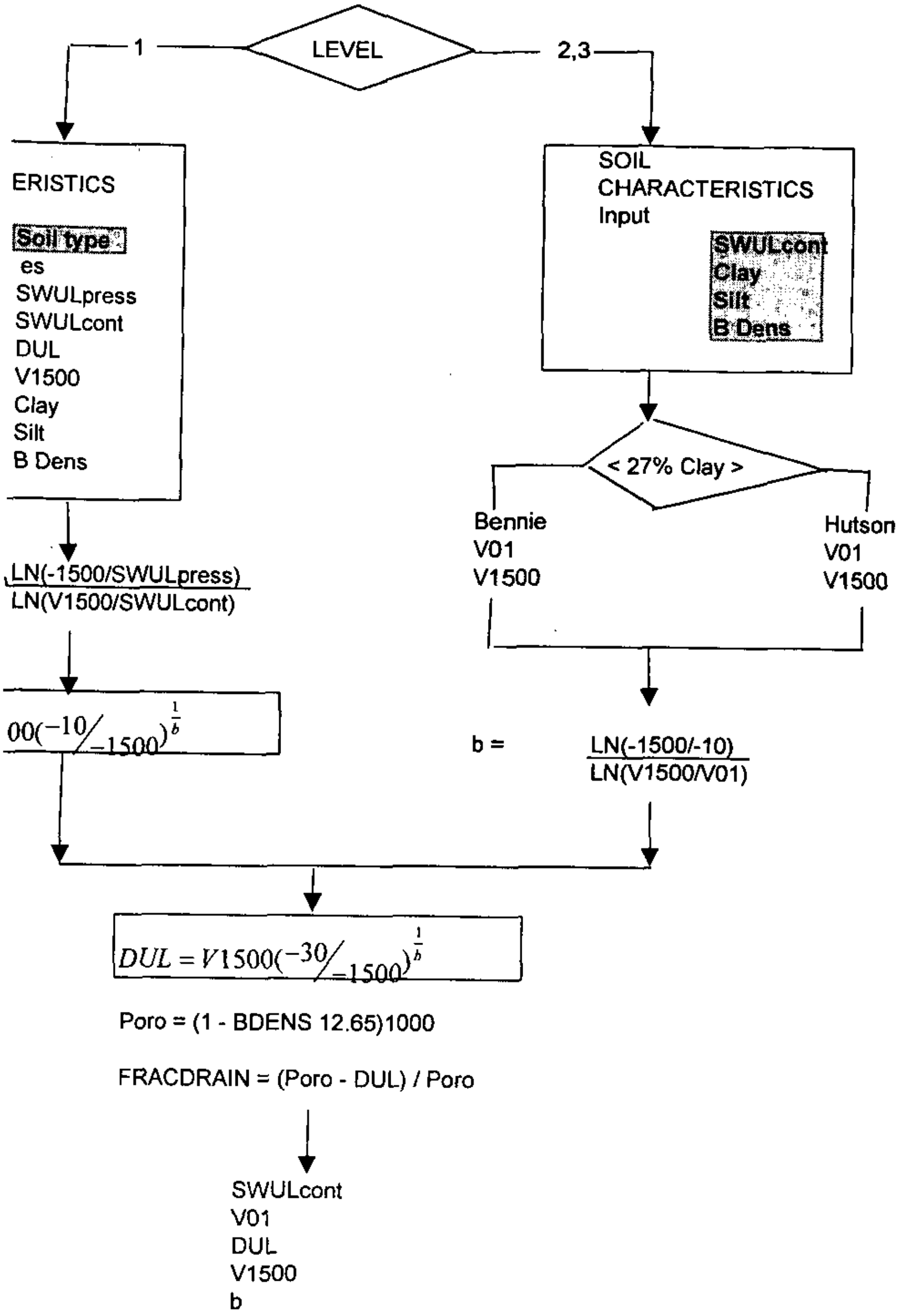
Sheet 9 ESTABLISH CULTIVAR CHARACTERISTICS AND ONTOGENY



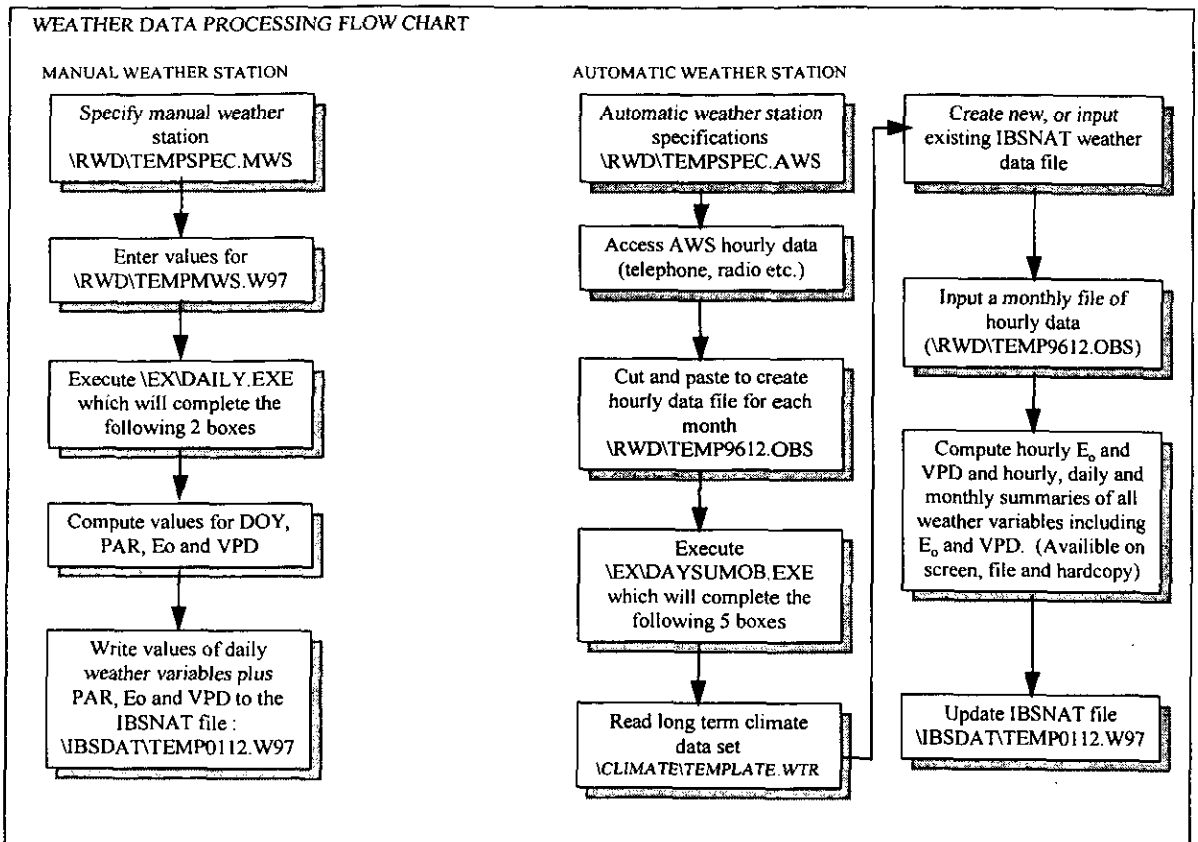
Sheet 10 CREATE FILES FOR IRRIGATION / AND RAINFALL AND SOIL WATER CHARACTERISTIC



Sheet 11 CREATE FILES FOR IN-SEASON ADJUSTMENT, LONG- TERM CLIMATE AND INITIAL SOIL WATER DATA



Sheet 11a Flow diagram for the coputer program SOILWCHR.BAS (Appendix V) for calculating the soil water characteristic



12. FLOWCHARTS ILLUSTRATING THE SEQUENCE OF OPERATIONS UNDERTAKEN WHEN UPDATING IBSNAT FROM MANUAL AND AUTOMATIC WEATHER STATION DATA

Automatic weather station

Hourly data from AWS	use editor to cut and paste to the TEMP9612.OBS file
AWS hourly data	\RWD\TEMP9612.OBS (One file per month)
AWS specifications	\RWD\TEMPSPEC.AWS
Long-term climate data set	\CLIMATE\TEMPLATE.WTR
IBSNAT file	\IBSDAT\TEMP0112.W97 for a given (1997) year

Manual weather station

Long-term climate data set	\CLIMATE\TEMPLATE.WTR
MWS specifications	\RWD\TEMPSPEC.MWS
Raw data file	\RWD\TEMPMWS.W97
IBSNAT file	\IBSDAT\TEMP0112.W97 for a given (1997) year

Information :

When establishing file operators must please note that :

i) a complete set of template files (identification 'TEMP') are provided with Putu

ii) it is not permitted to overwrite any template file, but its name may be changed

iii) weather station names (identification) may be up to four characters in length overwritten on a 'TEMP' file

iv) the file name options therefore are as follows :

\RWD****YYMM.OBS
\RWD****SPEC.AWS
\CLIMATE********.WTR
\IBSDAT****0112.WYY
\RWD****MWS.WYY

13. WEATHER DATA PROCESSING FILES

SOME PRACTICAL HINTS

Growth Stages

Growth stages end on the thermal periods entered in the cultivar file.

Stage 1 -	No Simulation. called the pre-restperiod	In the first year of simulation, the planting date (end of rest period) will occur some time after 1st January. Simulation commences on planting date. The "No-simulation" stage is used only during the first year of simulation and not again. During this period no simulation takes place, but the time progresses from 1 January to plant date.
Stage 2 -	Sow	Growth stage "Sow" terminates the no-simulation stage prior to planting (Stage 1), or the rest period after previous harvest (stage 10) years.
Stage 3 -	Fallow	If desired a "fallow" growth stage may be simulated to commence on the date of sowing and terminate on the day of emergence with an appropriate

fractional interception FI (zero for bare soil) in the cultivar file.

Level of Modelling

The Putu environment (shell) is designed to accommodate different versions of crop growth models such as Putu-maize, -wheat, -grass, -anycrop. The work of this project addressed mainly the simple Elementary and Irrigation models and Water Distribution Maximisation..

Thermal Time

The main difference between the modelling levels is that Elementary requires dates to be entered in the crop cultivar file. Once this is done, Putu automatically computes the critical thermal time at which the crop canopy (cover) matures from one growth stage to the next. This is done the first time a given situation is scheduled.

Thereafter, the Level 2 button on the "Irrigation Scheduling" file may be selected. This menu permits critical thermal periods to be entered in the cultivar file instead of dates. Level 2 then computes and operates on the thermal time (i.e. physiological age) which makes the cultivar parameters and scheduling operation independent of locality. The thermal times entered are read from the Level 1 Calendar.

APPENDIX II

EXAMPLES OF IRRIGATION SCHEDULING OF DIFFERENT CROPS USING PUTU-IDSS

Sample Output from the Putu-IDSS and Irrigation Recommendations for:

Sugarcane - Simunye
Sugarcane - Mlaula
Tomato
Onion
Laggan dairy
Ryegrass

SAMPLE OUTPUT FROM THE PUTU MODEL FOR SUGARCANE PRODUCED UNDER DRAGLINE IRRIGATION IN SIMUNYE, SWAZILAND

```
PUTU9 IRRIGATION SCHEDULING OF SUGAR CANE
                                     Run Date :        04-14-1994          Time :    15:20:12
Land 6L1
        PLANT POPULATION                        CULTIVAR                       PLANTING DATE
            4.76 (m-2)                          SLOW                  10/11/1993

      SOIL DECRIPTION:                 Sibaya
      SOIL MOISTURE:(mm/m)
      MAXIMUM          MINIMUM               INITIAL  EFFECTIVE ROOTING DEPTH
        371              273              350                  0.6 m

1993
DOY      FW      LAI     IR     RAIN     PERC      PPAW      DEF      PSI      HU     kc     AED      Eo     FID
                                                                                       ST      L
                 (%)            (mm)                          (%)          (mm)  (MPA*100)(DD)(%)  (mm*10)
      (d)
Total rainfall in rest period  =  22.8

GROWTH STAGE 2 -                SOW
YRED = 0    TTRANS = 2     TPTRANS = 2    C = 1     BL/C = 0.00    GL/C = 0.00     SL/C = 0.00
DEEPERC = 30                      TSOILVAP = 101    WUSE = 103    TAW = 38

GROWTH STAGE 3          -       ESTABL
YRED = 0    TTRANS = 37    TPTRANS = 37    C = 244    BL/C = 0.19    GL/C = 0.00     SL/C = 0.51

DEEPERC = 48                      PSOILVAP = 143    WUSE = 182    TAW = 72

GROWTH STAGE 4                  DEVELOP
YRED = 0    TTRANS = 16    TPTRANS = 16    C = 345    BL/C = 0.34    GL/C = 0.00     SL/C = 0.36

DEEPERC = 48                      PSOILVAP = 153    WUSE = 207    TAW = 68    HT = 86

GROWTH STAGE 5                  MID
  352      0     423     0      0      48     103      0      -0     -123     616     100     56     56      9
  353      0     457     0      6      48      94      1      -0     -127     635     100     55     55      9
  354      0     488     0      0      48      94      0      -0     -134     653     100     61     61      8
  355      0     514     0      0      48      87      3      -1     -122     670      99     45     45      9
  356      0     539     0      0      48      75      7      -1     -112     687      86     77     89      4
  357      0     563     0      0      48      69     10      -2     -146     706      77     39     51      6
  358      0     580     0      0      48      62     13      -3      -99     720      75     45     60      4
  359      1     596     0      0      48      52     19      -4     -146     735      74     58     80      3
  360      0     610     0      6      48      47     22      -7     -102     750      73     33     45      4
  361      5     623     0      0      48      46     23      -5     -164     765      82     66     85      2
YRED = 1    TTRANS = 57    TPTRANS = 57    C = 656    BL/C = 0.47    GL/C = 0.43    SL/C = -0.07

DEEPERC = 48                      PSOILVAP = 177    WUSE = 288    TAW = 23    HT = 99

GROWTH STAGE 6 -                FLO
  362     21     678     0      0      48      37     29      -9     -180     782      77     56     90      1
  363     32     672    23      0      48      30     33     -15     -186     801      76     45     85      1
  364      2     666     0     70      51      52     21      -6     -153     819     100     79     80      3
  365      0     660     0      0      51     123      0      -0     -147     836     100     80     80      8
YRED = 3    TTRANS = 86    TPTRANS = 90    C = 971    BL/C = 0.36    GL/C = 0.62    SL/C = -0.09
DEEPERC = 63                      PSOILVAP = 200    WUSE = 397    TAW = 48

GROWTH STAGE 7                  GRAIN
YRED = 5    TTRANS = 123   TPTRANS = 137    C = 1540    BL/C = 0.23    GL/C = 0.76    SL/C = -0.06

DEEPERC = 63                      PSOILVAP = 213    WUSE = 533    TAW = 28
```

```
GROWTH STAGE 8 -          RIPE
  81    0   221    0    0   63   44   24    -5  -162  2177  100   49   49    3
  82    0   216    0    0   63   36   30    -7  -201  2192  100   52   53    2
  83    5   210    0    0   63   28   35   -12  -232  2209  100   49   52    1
  84   24   205   23    0   63   21   39   -20  -252  2224  100   42   55    0
  85    0   199    0    0   63   47   26    -7  -169  2242  100   53   53    3
  86    0   194    0    0   63   39   38    -9  -201  2259  100   55   55    2
  87    0   189    0    0   63   37   29   -12  -132  2274  100   12   12    5
  88    0   185    0    0   63   30   33   -13  -192  2285  100   41   41    2
  89    2   182    0    0   63   24   37   -17  -224  2296  100   40   41    1
  90   15   178    0    0   63   18   41   -24  -246  2307  100   35   41   -0
  91   33   175    0    0   63   14   43   -34  -256  2318  100   28   41   -1
  92   49   172    0    0   63   11   45   -47  -261  2326  100   21   41   -1
  93   62   169    0    0   63    8   47   -61  -264  2335  100   15   41   -2
  94   72   166    0    0   63    6   48   -76  -265  2343  100   11   41   -2

SEASONAL TOTALS FOR COMPONENTS OF THE WATER BALANCE (mm) :

LOST FROM ROOT ZONE
DEEP PERCOLATION                         63
RUN OFF                                  70
EVAPORATION FROM SOIL SURFACE           212
EVAPORATION FROM CROP SURVACE           575
GAINED BY ROOT ZONE
RAIN                                    349
IRRIGATION                              395
CAPILLARY RISE FROM WATERTABLE            0

DIFFERENCE BETWEEN INITIAL AND FINAL PROFILE WATER CONTENT 60
```

RECOMMENDATIONS FOR SUGARCANE PRODUCED UNDER DRAGLINE IRRIGATION IN SIMUNYE, SWAZILAND.

Farm XXX
Day of year = 87 Monday 28 March 1994
Period = 22/03/94 - 28/03/94 (DOY 81 - 87)
Total E_o for week = 32.9
Mean daily E_o = 4.7
Rain = 0

FIELD NO.	DOG	PERIOD AED mm	STRESS IND %	DEFICIT mm	IRRIGATION RECOMMENDED	FID	CUMULATIVE IRRIGATION	CUMULAT RAINFALL mm
6L1	138	31.2	0	29	23	5	395	349
6L2	282	30.9	0	34	23	4	721	449
6L3	280	31.2	0	29	23	4	721	449
6L5	279	30.8	0	34	23	4	721	449
6L7	280	30.5	0	31	23	4	721	449
6L8	280	41.8	0	31	23	4	721	449

3 day cycle = 23mm
4 day cycle = 32mm

Irrigation recommendations

Please start a 3 day cycle tomorrow

RESULTS OBTAINED FROM MLAULA SECTION, SIMUNYE, PRODUCING SUGARCANE UNDER IRRIGATION SCHEDULED USING THE PUTU SYSTEM

Field	Variety	Date of 1992 cut	Date of 1993 cut	Deep Percolation mm	Run off mm	Evap. from soil surface mm	Evap. from crop surface mm	Rain mm	Irrig. mm	Cap rise from water table mm	Yield tons/ha	ERS %
501	NCo376	29/4/92	3/5/93	169	91	92	925	390	752	0	98.6	11.80
502	"	29/4/92	2/5/93	179	95	92	954	390	784	0	106.4	12.24
503	"	30/4/92	1/5/93	87	92	90	925	390	752	0	114.4	12.41
504	"	22/6/92	15/6/93	138	110	78	1030	419	878	0	112.3	13.56
505	N14	30/7/92	21/7/93	230	111	62	1000	421	860	0	101.3	14.02
602	NCo376	20/6/92	12/6/93	124	114	70	1018	414	854	0	99.1	13.66
605	"	19/6/92	15/6/93	177	115	69	1027	413	877	0	100.0	13.90
607	"	18/6/92	14/6/93	107	114	69	1013	413	854	0	104.1	13.13
608	"	18/6/92	14/6/93	101	115	69	1027	413	877	0	84.7	12.97
609	"	19/6/92	14/6/93	137	115	65	1022	413	877	0	125.4	12.59
610	N19	30/7/92	10/7/93	6	69	85	769	421	503	0	101.9	13.35
619	NCo376	30/7//92	20/7/93	135	87	72	1004	421	828	0	95.7	13.72

SAMPLE OUTPUT FROM THE PUTU MODEL FOR TOMATOES PRODUCED UNDER DRIP IRRIGATION IN THE MOOKETSI, NORTHERN TRANSVAAL AREA.

```
PUTU9 IRRIGATION SCHEDULING OF TOMATOES
                              Run Date :      04-14-1994          Time :   09:17:39
Land 1L5
       PLANT POPULATION                  CULTIVAR                        PLANTING DATE
         1.2 (m^-2)                   Empire              2/3/1994

     SOIL DESCRIPTION:          Sandy Clay Loam
     SOIL MOISTURE:(mm/m)
     MAXIMUM         MINIMUM            INITIAL EFFECTIVE ROOTING DEPTH
        140             43                105              0.6 m

1994
DOY     FW    LAI    IR    RAIN    PERC    PPAW    DEF    PSI    HU    kc    AED    Eo    FID
                                                                       ST    L
              (%)           (mm)                   (%)        (mm) (MPA*100)(DD)(%) (mm*10)
       (d)
Total rainfall in rest period  =  16.8

GROWTH STAGE 2 -             SOW
YRED = 0    TTRANS = 1    TPTRANS = 1    C = 0    BL/C = 0.00    GL/C = 0.00    SL/C = 0.00
DEEPERC = 0                     TSOILVAP = 72    WUSE = 73    TAW = 24

GROWTH STAGE 3        -      ESTABL
YRED = 0    TTRANS = 7    TPTRANS = 7    C = 33    BL/C = 0.00    GL/C = 0.00    SL/C = 0.69

DEEPERC = 0                     PSOILVAP = 79    WUSE = 88    TAW = 18

GROWTH STAGE 4               DEVELOP
YRED = 0    TTRANS = 56    TPTRANS = 56    C = 394    BL/C = 0.02    GL/C = 0.00    SL/C = 0.68

DEEPERC = 0                     PSOILVAP = 95    WUSE = 159    TAW = 16    HT = 89

GROWTH STAGE 5               MID
   96     1     60    11     0     0     36    41    -11    -142    550     83    37    45     2
   97     0     65     0     0     0     51    33     -8     -88    565     97    31    33     5
   98     0     69    11     0     0     44    37     -9    -111    579     92    35    38     3
   99     1     74     0     0     0     55    31     -7    -134    592    100    54    54     3
  100     4     78     0     0     0     45    36     -9    -158    607     94    53    58     2
  101     0     82     0     1     0     39    39    -11    -114    621     90    30    34     3
  102     0     85    11     1     0     38    40    -13    -137    633     90    15    17     5
  103     0     88     0     0     0     53    32     -9    -108    641    100    38    38     5
  104     0     90     0     0     0     46    36    -10    -118    650     96    36    38     4
  105     0     92     0     0     0     40    39    -11    -130    658     94    35    38     3
  106     1     94     0     0     0     33    43    -14    -145    667     93    34    37     2
  107     5     96     0     0     0     27    46    -17    -162    676     93    33    37     1
  108    13     97     0     0     0     22    49    -22    -175    684     94    30    37     0
  109    27     99     0     0     0     17    51    -29    -184    693     94    26    37    -0

SEASONAL TOTALS FOR COMPONENTS OF THE WATER BALANCE (mm) :

LOST FROM ROOT ZONE
DEEP PERCOLATION                                    0
RUN OFF                                             2
EVAPORATION FROM SOIL SURFACE                     104
EVAPORATION FROM CROP SURFACE                     132
GAINED BY ROOT ZONE
RAIN                                               42
IRRIGATION                                         96
CAPILLARY RISE FROM WATERTABLE                      0

DIFFERENCE BETWEEN INITIAL AND FINAL PROFILE WATER CONTENT 18
```

RECOMMENDATIONS FOR TOMATOES PRODUCED UNDER DRIP IRRIGATION IN THE MOOKETSI NORTHERN TRANSVAAL AREA

Farm XXX
Day of year = 102 Tuesday 12 April 1994
Eo = 1.7
Rain = 1

LAND NO	CROP	DOG	AED mm	IRRIG mm	STRESS %	DEFICIT mm	CUMULATIVE IRRIGATION mm	CUMULAT RAINFALL mm	FID
LAND 1									
1L1	*Tomatoes*	76	*1.6*	*11*	*0*	36	*193*	*90*	7
1L2	Tomatoes	72	1.6	0	0	32	187	90	5
1L3	Tomatoes	70	1.6	0	0	26	185	59	6
1L4	Tomatoes	55	1.6	11	0	39	136	58	5
1L5	Tomatoes	38	1.5	11	0	40	96	42	5
1L6	Tomatoes	29	1.6	0	0	31	58	10	5
LAND 2									
2L1	Tomatoes	79	1.6	11	0	40	210	97	7
2L2	Tomatoes	78	1.6	0	0	36	186	92	5
2L3	Tomatoes	57	1.6	11	0	47	141	58	3
2L4	Tomatoes	48	1.6	11	0	38	96	43	8
2L5	*Tomatoes*	30	*1.6*	*0*	*0*	27	*63*	*10*	6

Irrigation recommendations

Land 1:

1L1	Thursday - 11mm
1L2	*Applying 11mm (Saturday - 11mm)*
1L3	Applying 11mm (Saturday - 11 mm)
1L4	Thursday - 11mm
1L5	Thursday - 11mm
1L6	Applying 1mm (Saturday -11mm)

Land 2:

2L1	Friday - 11mm
2L2	Applying 11mm (Friday - 11mm)
2L3	Thursday - 14mm
2L4	Thursday - 11mm
2L5	Applying 11mm(Sunday - 11mm)

SAMPLE OUTPUT FROM THE PUTU MODEL FOR ONIONS PRODUCED UNDER CENTRE POINT PIVOT IRRIGATION IN MOOKETSI, NORTHERN TRANSVAAL AREA.

```
PUTU9 IRRIGATION SCHEDULING OF ONIONS
                                 Run Date :      04-15-1994          Time :   16:10:58
Land 1L1
        PLANT POPULATION                        CULTIVAR                          PLANTING DATE
             53 (m^-2)                       FAST                      14/2/994

      SOIL DESCRIPTION:             Sandy Loam
      SOIL MOISTURE:(mm/m)
      MAXIMUM          MINIMUM              INITIAL  EFFECTIVE ROOTING DEPTH
          159              54               130             0.3 m

1994
DOY     FW     LAI     IR    RAIN    PERC    PPAW    DEF    PSI    HU    kc    AED    Eo    FID
                                                                          ST    L
                (%)            (mm)                  (%)        (mm) (MPA*100)(DD)(%) (mm*10)
          (d)
Total rainfall in rest period  =  0

GROWTH STAGE 2 -             SOW
YRED = 0    TTRANS = 1     TPTRANS = 1     C = 16     BL/C = 0.00     GL/C = 0.00     SL/C = 0.00
DEEPERC = 0                      TSOILVAP = 8      WUSE = 10     TAW = 27

GROWTH STAGE 3       -       ESTABL
YRED = 0    TTRANS = 9    TPTRANS = 9    C = 54    BL/C = 0.11     GL/C = 0.00     SL/C = 0.38

DEEPERC = 0                      PSOILVAP = 18     WUSE = 29     TAW = 29

GROWTH STAGE 4               DEVELOP
YRED = 0    TTRANS = 15    TPTRANS = 15    C = 134    BL/C = 0.19    GL/C = 0.00    SL/C = 0.43

DEEPERC = 0                      PSOILVAP = 24     WUSE = 49     TAW = 19     HT = 17

GROWTH STAGE 5               MID
YRED = 12    TTRANS = 36    TPTRANS = 51    C = 347    BL/C = 0.42    GL/C = 0.55    SL/C = -0.14

DEEPERC = 0                      PSOILVAP = 29     WUSE = 91     TAW = 14     HT = 66

GROWTH STAGE 6               FLO
YRED = 11    TTRANS = 70    TPTRANS = 90    C = 776    BL/C = 1.50    GL/C = 0.80    SL/C = -1.37

DEEPERC = 0                      PSOILVAP = 34     WUSE = 166     TAW = 25

GROWTH STAGE 7 -             GRAIN
  98      8     376     0      0      0      72     10     -2    -174    722    100    44    48    3
  99     20     373    15      0      0      58     14     -3    -185    735    100    42    52    2
 100     15     370     0      0      0      88      5     -1    -183    748    100    53    62    3
 101      2     368     0      0      0      74      9     -2    -162    759    100    42    43    4
 102      1     365    15      0      0      62     13     -3    -154    770    100    35    36    4
 103      0     364     0      0      0      96      2     -1    -137    781    100    40    40    6
 104      1     361     0      0      0      83      6     -1    -151    794    100    41    41    5
 105      1     359     0      0      0      71     10     -2    -151    803    100    37    38    4
 106      2     357    15      0      0      58     14     -3    -166    811    100    37    37    3
 107      0     356     0      0      0      93      3     -1    -129    820    100    37    37    6
 108      0     354     0      0      0      81      7     -1    -139    828    100    37    37    5
 109      1     352     0      0      0      69     11     -2    -151    837    100    37    37    4
 110      2     350     0      0      0      57     14     -3    -167    846    100    36    37    3
 111      5     349     0      0      0      45     18     -5    -184    854    100    35    37    2

SEASONAL TOTALS FOR COMPONENTS OF THE WATER BALANCE (mm) :

LOST FROM ROOT ZONE
DEEP PERCOLATION                                  0
RUN OFF                                          13
EVAPORATION FROM SOIL SURFACE                    34
```

EVAPORATION FROM CROP SURFACE	203
GAINED BY ROOT ZONE	
RAIN	18
IRRIGATION	230
CAPILLARY RISE FROM WATERTABLE	0

DIFFERENCE BETWEEN INITIAL AND FINAL PROFILE WATER CONTENT 3

RECOMMENDATIONS FOR ONIONS PRODUCED UNDER CENTRAL PIVOT IRRIGATION IN THE MOOKETSI, NORTHERN TRANSVAAL AREA

Farm XXX
Day of year = 104 Thursday 14 April 1994
Eo = 14.1
Rain = 0

LAND NO	CROP	DOG	AED mm	IRRIG mm	STRESS %	PPAW %	DEFICIT mm	CUMULATIVE IRRIGATION mm	CUMULAT RAINFALL mm
LAND 1									
1L1	Onions	60	4.1	0	1	83	6	215	18
1L2	Onions	35	3.8	0	4	50	16	88	55
1L3	Onions	34	3.1	12	17	36	21	121	55
1L4	Onions	35	4.1	0	1	71	10	119	55
1L5	Onions	27	3.9	0	0	72	12	120	8
1L6	Onions	8	3	3	0	84	7	42	0

Irrigation recommendations (starting day of cycle):

Land 1:

1L1	Busy with 15mm (Monday - 10mm)
1L2	Busy with 15mm (Monday - 15mm)
1L3	Saturday - 15mm
1L4	Busy with 10mm (Monday - 15mm)
1L5	Busy with 10mm (Monday - 15mm)
1L6	Applying 3mm/day till emergence

LAGGAN DAIRY

WEEKLY IRRIGATION DATA

Weekly ended Saturday: 28 MARCH 1994

LAND NO.	GRAZING NO.	GRAZING DATE	IRRIGATION DATE	IRRIGATION AMOUNT	RAINFALL DATE	RAINFALL AMOUNT
1			210394	10		
2			220394	10		
3			230394	10		
4			240394	10		
5			250394	10		
6			250394	10		
7			210394	10		
8			220394	10		
9			230394	10		
10			240394	10		
11			250394	10		
12			250394	10		
13			220394	10		
14			230394	10		
15			240394	10		
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						
32	DARGLE	230394				
33	DARGLE	230394				

SAMPLE OUTPUT FROM THE PUTU MODEL FOR RYEGRASS PRODUCED UNDER DRAGLINE IRRIGATION IN NATAL, SOUTH AFRICA

```
PUTU9 IRRIGATION SCHEDULING OF RYEGRASS
                          Run Date :        04-15-1994              Time :    16:19:36
Field 1
      PLANT POPULATION                         CULTIVAR                          PLANTING DATE
         261 (m^-2)                          FAST                   25/2/1994

     SOIL DESCRIPTION:              Hutton
     SOIL MOISTURE:(mm/m)
     MAXIMUM          MINIMUM               INITIAL          EFFECTIVE ROOTING DEPTH
        274              130                257                  0.3 m

1994
DOY      FW      LAI      IR     RAIN     PERC      PPAW      DEF     PSI      HU      kc     AED       Eo      FID
                                                                                   ST    L
               (%)             (mm)                     (%)          (mm)  (MPA*100)(DD)(%)  (mm*10)
    (d)
Total rainfall in rest period  =  0

GROWTH STAGE 2 -               SOW
YRED = 0    TTRANS = 11    TPTRANS = 11    C = 135    BL/C = 0.12    GL/C = 0.00    SL/C = 0.21
DEEPERC = 0                     TSOILVAP = 14     WUSE = 25     TAW = 63
```

```
GROWTH STAGE 3          -          ESTABL
YRED = 0    TTRANS = 15    TPTRANS = 15    C = 230    BL/C = 0.33    GL/C = 0.00    SL/C = 0.15

DEEPERC = 0                         PSOILVAP = 23    WUSE = 49    TAW = 52

GROWTH STAGE 4                     DEVELOP
YRED = 0    TTRANS = 24    TPTRANS = 24    C = 380    BL/C = 0.58    GL/C = 0.00    SL/C = -0.00

DEEPERC = 0                         PSOILVAP = 28    WUSE = 78    TAW = 53    HT = 49

GROWTH STAGE 5                     MID
YRED = 0    TTRANS = 5    TPTRANS = 5    C = 411    BL/C = 0.59    GL/C = 0.00    SL/C = -0.00

DEEPERC = 0                         PSOILVAP = 28    WUSE = 83    TAW = 48    HT = .54

GROWTH STAGE 6                     FLO
YRED = 0    TTRANS = 4    TPTRANS = 4    C = 442    BL/C = 0.62    GL/C = 0.07    SL/C = -0.08

DEEPERC = 0                         PSOILVAP = 29    WUSE = 87    TAW = 44

GROWTH STAGE 7 -                   GRAIN
YRED = 0    TTRANS = 8    TPTRANS = 8    C = 500    BL/C = 0.68    GL/C = 0.18    SL/C = -0.21

DEEPERC = 0                         PSOILVAP = 30    WUSE = 96    TAW = 34

GROWTH STAGE 8 -                   RIPE
    95     0    682    0    0    0    89     3     -1    -111    428    100    44    44     8
    96     0    679    0    2    0    82     4     -1    -106    438    100    39    39     8
    97     0    675    0    0    0    81     4     -1    -143    449    100    26    26    12
    98     0    671    0   12    0    74     6     -1    -100    462    100    34    34     8
    99     0    667    0    0    0    88     3     -1    -116    475    100    46    46     8
   100     0    664    0    0    0    85     4     -1    -124    485    100    20    20    17
   101     0    660    0    0    0    78     5     -1    -105    496    100    37    37     8
   102     0    657    0    0    0    70     7     -1    -115    505    100    38    38     7
   103     0    655    0    0    0    63    10     -2    -123    513    100    38    38     6
   104     0    652    0    0    0    56    14     -3    -133    522     96    36    38     5
   105     1    649    0    0    0    49    18     -4    -144    530     94    35    38     4
   106     3    646    0    0    0    43    21     -5    -156    539     92    34    38     3
   107     7    643    0    0    0    37    24     -7    -168    548     92    32    38     2
   108    14    641    0    0    0    31    27    -10    -179    556     91    29    37     2
SEASONAL TOTALS FOR COMPONENTS OF THE WATER BALANCE (mm) :


LOST FROM ROOT ZONE
DEEP PERCOLATION                                        0
RUN OFF                                                 9
EVAPORATION FROM SOIL SURFACE                          37
EVAPORATION FROM CROP SURVACE                         157
GAINED BY ROOT ZONE
RAIN                                                  164
IRRIGATION                                             15
CAPILLARY RISE FROM WATERTABLE                          0

DIFFERENCE BETWEEN INITIAL AND FINAL PROFILE WATER CONTENT 33
```

RECOMMENDATION FOR RYEGRASS PRODUCED UNDER DRAGLINE IRRIGATION IN NATAL, SOUTH AFRICA.

Farm XXX
Day of year = 101 Monday 11 April 1994
Period = 03/04/94 - 11/04/94 (DOY 95 - 101)
Total Eo for week = 24.6 mm
Mean daily Eo = 3.5 mm
Rain = 14 mm

FIELD NO	DOG	PERIOD AED mm	STRESS IND %	DEFICIT mm	IRRIGATION RECOMMEND mm	FID	CUMULATIVE IRRIGATION mm	CUMULAT RAINFALL mm
1	46	24.6	0	5	10	8	15	164
2	46	24.6	0	5	10	8	15	164
3	47	24.6	0	5	10	8	15	164
4	47	24.6	0	4	10	8	15	164
5	47	24.6	0	4	10	8	15	164
6	48	24.6	0	4	10	8	15	164

APPENDIX III

PROFORMA CONTRACT BETWEEN FARMER AND AGENT

INTRODUCTION

A matter of concern to the author was accountability in the case of crop failure due to poor scheduling advice, or extremely adverse weather conditions. It was therefore deemed advisable to take legal advice and draw up a service agreement (contract). The intention was for cooperators to sign the contract.

In practice the participants were happy to cooperate without a contract and the two main advisers were loathe to use a contract. One of the advisers drew up an agreement outlining the extent and frequency of service provided and the inputs (measured rainfall and irrigation, etc.) required of the manager.

The author is of the opinion that a formal legal document is necessary. A copy of the document follows. It is evident that this contract protects the irrigation adviser perhaps too strongly. As such it might discourage clientele.

vB/lc/1993.04.13/D86

CONSULTATION SERVICE AGREEMENT

The University of the Orange Free State shall render to the Client (described in Part A) the consultation service (described herein below) subject to the terms and conditions contained in Part A and Part B of this agreement.

PART A

1. ***PARTIES***

1.1 ***The University of the Orange Free State***

("the University")

1.2 ***Name of client:***

....

("the client")

1.3 ***Address of client:***

....

2. ***PERIOD OF AGREEMENT***

2.1 ***Commencement date:***

....

2.2 ***Period in months:***

....

3. ***PLACE WHERE AGREEMENT WILL BE EXECUTED***

3.1 ***Name of farm and magisterial district:***

....

....("the farm")

4. ***TECHNICAL VISITS AND SERVICES***

4.1 ***Number of technical visits:***

....

4.2 ***Number of irrigation blocks per annum:***

....

4.3 *Time basis for supply of information:*

....

4.4 *Additional services to be supplied:*

....
....
....
....
....
....
....
....
....

5. ***CONSULTATION FEE AND PAYMENT***

5.1 ***Amount:***

....

5.2 ***Date or dates of payment:***

....

5.3 ***Payable to:***

Irrigation Scheduling Unit,
c/o Department of Agricultural Meteorology,
University of the Orange Free State,
P O Box 339,
BLOEMFONTEIN 9300.

SIGNED at on

AS WITNESS :

1. ....

THE UNIVERSITY OF THE ORANGE FREE STATE

....

NAME AND DESIGNATION OF SIGNATORY

SIGNED at on

AS WITNESS :

1. ....

CLIENT

....

NAME AND DESIGNATION OF SIGNATORY WHO WARRANTS THAT HE HAS BEEN DULY AUTHORISED THERETO

PART B

1 Execution of agreement

The Irrigation Scheduling Unit of the Department of Agricultural Meteorology of the University ("ISU"), will be responsible for the execution of this agreement.

2. Level of Services

2.1 The University shall, unless prevented by technical or other conditions beyond its control or unless it is reasonably unnecessary taking into account the crops and/or growing situation concerned, supply the information contemplated in clause 4 of Part B on an agreed time basis throughout the year during the currency of this agreement.

3. Technical visits

The technical visits contemplated in clause 4 of Part A shall include the following:

3.1 Installation of automatic weather stations and accessories.

3.2 Drawing up a plan of irrigation scheme for reference of scheduling procedures.

3.3 Establishment of input files necessary to run the relevant programmes.

3.4 Technical discussions regarding practical scheduling and any associated problems, including pre-season planning for each crop or planting, as the case may be.

4. *Technical advice*

4.1 Unless otherwise arranged in writing, the following information will be supplied on the time bases stated at, or as near, a predetermined time as possible:

4.1.1 Time base

Amount of irrigation to be applied per block.

Minimum amount of irrigation that must be applied so as to avoid any decrement in yield or quality as a result of water stress.

Cumulative amount of irrigation per block for season.

Cumulative rainfall for growing season.

Stress indicators for each block.

Any other information that the client requires as stated in 4.4 of Part A.

Summary of daily weather data.

4.2 It is recorded that the stress indicators referred to in clause 4.1.1 are of assistance in management planning. The client will be assisted in the development of a management method for the section of the farm in question.

5. *The client's obligations*

5.1 The client shall -

5.1.1 purchase the automatic weather station and associated equipment;

5.1.2 supply ISU with the soil classification and soil textural analysis data concerned, unless arrangements have been made in writing for ISU to supply the same at the client's cost;

5.1.3 supply ISU with the planting dates, plant populations and cultivar types at the start of each season;

5.1.4 supply ISU with accurate daily rainfall and accurate irrigation amounts applied both per block and day of application, which information shall be supplied without any delay;

5.1.5 shall undertake the desired phenological observations and submit these to the ISU weekly or at such other intervals as the ISU may determine, and it is acknowledged that these recordings are necessary to establish coefficients for the particular area and crop;

5.1.6 take soil samples (the times of sampling to be determined by ISU) to determine soil water contents at the various sites and depths in order to provide random checks;

5.1.7 be responsible for the maintenance and repairs of the automatic weather station and associated equipment;

5.1.8 provide a farm or block plan, as the case may be, to scale to facilitate the drawing up of a schedule plan;

5.1.9 check the automatic weather station at regular intervals, but at least once every two weeks, to secure its proper functioning. (ISU will assist in calibration of sensors).

6. *Maintenance and other services*

6.1 The ISU will assist the client where possible with the maintenance and repairs referred to in clause 5.1.7. Should this require additional visits to the farm or the site concerned, the costs thereof will be borne by the client. It is the intention of the ISU to keep these costs to a minimum.

6.2 Should the client fail to perform any of its obligations in terms of this agreement, the ISU shall, subject to any other rights which it (the University) may have, be entitled to carry out such obligation on behalf of the client and the client shall pay to the University on demand all costs and expenses incurred by the University in carrying out the client's neglected obligations.

6.3 Notwithstanding any other provisions of this agreement, the client shall be responsible for all costs and expenses and payment to the University for all services rendered in addition to the services referred to in clauses 2, 3 and 4 of Part B.

7. *Application of data*

7.1 It is recorded that some of the information and data supplied by the client's operations will be used in a research project to be conducted by the Department of Agrometeorology of the

University and the client hereby consents to such use and the publication of the information and data concerned in whatever form.

7.2 It is recorded that the research project contemplated in clause 7.1 will be financially assisted by the Water Research Commission and, as a result of the client's participation with respect to information and data gathered, the services contemplated in this agreement to the client will be subsidised by the aforesaid research project in a proportional amount each year. For the year 1993 the client will be responsible for approximately 40% (FOURTY PERCENT) of the costs, in 1994 approximately 60% (SIXTY PERCENT) and thereafter 100% (ONE HUNDRED PERCENT). Prior to the commencement of each year of this agreement, the ISU will discuss the client's requirements in order to establish the service costs for that year. The subsidy referred to hereinbefore shall be received by the University and the amount set out in clause 5.1 of Part A is the proportioned amount due by the client.

8. *Assignment*

8.1 Neither party shall without the prior written consent of the other party, which consent shall not be unreasonably withheld, be entitled to assign his rights and obligations under this agreement.

9. *Breach of contract*

9.1 Should either party commit a breach of any of the terms of this agreement which goes to the root of the contract and fail to remedy such breach within a reasonable period of time, or a period of time agreed to between both parties, after the receipt of a notice from the other party calling upon the defaulting party so to do, then such other party shall be entitled to cancel this agreement, subject to any other rights which it may have as a result of such breach. Should the University cancel this agreement it shall be entitled to claim payment of all amounts due and owing but unpaid at the date of cancellation without prejudice to its right to claim damages.

10. Indemnity

10.1 The client hereby accepts that the University has taken great care to ensure that the latest and soundest scientific principles and equations have been included in the development and construction of the PUTU system of crop growth models and supplementary software used in the irrigation scheduling service which is the subject-matter of this agreement.

10.2 The client hereby indemnifies the University and any of its employees, agents or servants against -

10.2.1 any claim, whatever the cause thereof, which may be made or instituted against the University or any of its employees, agents or servants for any loss or damage suffered by anyone whatsoever and whatever as a direct or indirect result of any act in connection with the execution of this agreement, any information supplied to the client, the use of, or decisions based directly or indirectly upon results of, information generated by this irrigating scheduling service or any advice given;

10.2.2 any claim, whatever the cause thereof, which may be made or instituted against the University or any of its employees, agents or servants for any loss or damage suffered by anyone whatsoever and whatever as a direct or indirect result of any apparatus, equipment or device used or installed for or in connection with the execution of this agreement;

10.2.3 all charges, costs or disbursements whatever incurred by the University or any of its employees, agents or servants in regard to defending, settling or compromising any claim envisaged in clauses 10.2.1 and 10.2.2, including but not limited to all legal fees on a scale as between an attorney and his own client.

10.3 The client hereby renounces all claims which it may have against the University or any of its employees, agents or servants arising from or out of or in connection with any cause contemplated in clauses 10.2.1 and 10.2.2.

10.4 The indemnification and renunciation referred to in clauses 10.2 and 10.3 shall mutatis mutandis apply in respect of any other person involved in the development or construction of the PUTU system.

10.5 To the extent that the provisions of clauses 10.2, 10.3 and 10.4 refer to persons other than the University it shall be deemed to be stipulations in favour of such third parties and it shall be irrevocable and open for acceptance by such third parties at any time.

11. *Miscellaneous*

11.1 This agreement contains all the terms and conditions of the agreement between the parties concerning the subject-matter hereof and no terms, conditions, warranties or representations whatever apart from those contained in this agreement have been made or agreed to by the parties.

11.2 No variation or consensual termination of this agreement or any part thereof shall be of any force or effect unless in writing and signed by or on behalf of the parties.

APPENDIX IV

BASIC CODE FOR THE PROGRAM USED TO COMPUTE A SOIL WATER CHARACTERISTIC FOR A GIVEN SOIL

```
DECLARE SUB DrawGraph (B1X1!, B1Y1!, B1X2!, B1Y2!, B2X1!, B2Y1!, B2X2!, B2Y2!, B3X1!, B3Y1!, B3X2!, B3Y2!, B4X1!, B4Y1!,
B4X2!, B4Y2!, B!(), AV1500!(), AV10!(), ASWULpress!())
DECLARE SUB GetVideoMode (B1X1!, B1Y1!, B1X2!, B1Y2!, B2X1!, B2Y1!, B2X2!, B2Y2!, B3X1!, B3Y1!, B3X2!, B3Y2!, B4X1!, B4Y1!,
B4X2!, B4Y2!)
REM $INCLUDE: 'SVGABC.BI'
REM $DYNAMIC
'DIM V1500(10), V10(10), V01(10)
'DIM SWULpress(10), SWULcont(10), DUL(10), B(10)
'DIM CLAYFRAC(10), SILTFRAC(10), BULKDENS(10), V1600(10), DZRT(10)
'DIM PSIS1500(10), PORO(10)
DEFINT D, S, V
    '********************************************************************
    '            SOIL WATER CHARACTERISTIC
    '********************************************************************
    ' Programs to compute and createsoil physical characteristics
    ' file(C:\PUTU\********.SOL) for Putu
    CLS
'    GOTO 555
    INPUT " Enter the name of the file to be created (eg. *.SOL)  "; NAMEfile$
    IF UCASE$(NAMEfile$) = "SAND.SOL" OR UCASE$(NAMEfile$) = "LOAMSAND.SOL" OR UCASE$(NAMEfile$) =
"SANDLOAM.SOL" OR UCASE$(NAMEfile$) = "LOAM.SOL" THEN
      FileEx = 1
    END IF
    IF UCASE$(NAMEfile$) = "SNDCLLOM.SOL" OR UCASE$(NAMEfile$) = "SANDCLAY.SOL" OR UCASE$(NAMEfile$) = "CLAY.SOL"
THEN
      FileEx = 1
    END IF
    IF FileEx = 1 THEN
      INPUT " Invalid name. File already exists. Please enter a new name "; NAMEfile$
    END IF

    INPUT " Enter the name of the soil type "; NAMEsoil$
    INPUT " Enter UNI if you have a uniform soil profile "; UNI$
    IF UNI$ = "UNI" THEN
      INPUT "Enter Clay %"; Clay
      INPUT "Enter Silt %"; Silt
      INPUT "Enter Bulkdensity"; Bulkdens
      INPUT "Enter Volumetric water content at -10 kPa"; V10
      INPUT "Enter Volumetric water content at -1500 kPa"; V15
      INPUT "Enter soil water upper limit potential (-5kPa to -10kPa)"; SWULpot
      IF SWULpot > 0 THEN SULpot = -SWULpot
      INPUT "Enter layer thickness mm "; LayerThick
    END IF

    ' SHEET 1  Given soil textural composition find V10, V1500

    PRINT " Given V10, V1500 and SWUL potential find b,V0 and DUL "
    PRINT ""
    PRINT " SHEET 2 : Do you wish to enter values of V10 and V1500 or"
    PRINT "         calculate them from Clay and Silt (1 or 2) ?"
    PRINT "         (1) - Will calculate the values of V10 and V1500 from soil texture "
    PRINT "         (2) - Will permit manual entry of V10 and V1500"
    PRINT " Select-> ? ";
    DO
     Choice$ = UCASE$(INPUT$(1))
     LOOP WHILE Choice$ <> "1" AND Choice$ <> "2"
    PRINT Choice$
```

```
IF VAL(Choice$) = 1 THEN
 PRINT ""
 PRINT " SHEET 1 : Given soil textural composition find V10, V1500"
 PRINT " Insert values for Clay(%), silt(%) and Bulk density(t/m^3)"

LOCATE 19, 1:
FOR K = 19 TO 25
 PRINT "
NEXT K

FOR L = 1 TO 9
   LOCATE L + 13, 2:
   PRINT "CLAYFRAC(" + LTRIM$(STR$(L)) + ") ";
   INPUT ; CLAYFRAC(L)
   CLAYFRAC(L) = Clay
   LOCATE L + 13, 25:
   PRINT "SILTFRAC(" + LTRIM$(STR$(L)) + ") ";
   INPUT ; SILTFRAC(L)
   SILTFRAC(L) = Silt
   LOCATE L + 13, 45:
   PRINT "BULKDENS(" + LTRIM$(STR$(L)) + ") ";
   INPUT ; Bulkdens(L)
   Bulkdens(L) = Bulkdens

   IF CLAYFRAC(L) > 27 THEN
    ' Hutson eq
     V10(L) = (.0558 + .00365 * CLAYFRAC(L) + .00554 * SILTFRAC(L) + .0303 * Bulkdens(L)) * 1000
     V1500(L) = (.0602 + .00322 * CLAYFRAC(L) + .00308 * SILTFRAC(L) - .026 * Bulkdens(L)) * 1000
   ELSE
    ' Bennie  eq
     V10(L) = (.0345 * (CLAYFRAC(L) + SILTFRAC(L)) ^ .611) * 1000
     V1500(L) = (.00385 * (CLAYFRAC(L) + SILTFRAC(L)) + .013) * 1000
   END IF

NEXT L
PRINT ""
PRINT " Enter C to Continue-> ";
DO
 Choice$ = UCASE$(INPUT$(1))
 LOOP WHILE Choice$ <> "c" AND Choice$ <> "C"
 PRINT Choice$
ELSE


PRINT " SHEET 2: Given; V10, V1500 AND PSISo find b, V0 AND DUL"
' SHEET 2  Given V10, V1500 and PSISo find b,V0 and DUL
PRINT " Enter 9 values of V1500 "
  FOR I = 1 TO 9
   IF UNI$ <> "UNI" THEN
    LOCATE I + 12, 1:
    PRINT " V1500(" + LTRIM$(STR$(I)) + ") ";
   INPUT ; V1500(I)
   ELSE
    V1500(I) = V15
   END IF
  NEXT I
LOCATE 12, 30: PRINT "V10 "
  FOR I = 1 TO 9
   IF UNI$ <> "UNI" THEN
    LOCATE I + 12, 30:
    PRINT "V10(" + LTRIM$(STR$(I)) + ") ";
   INPUT ; V10(I)
   ELSE
    V10(I) = V10
   END IF
  NEXT I
END IF

FOR I = 12 TO 25
```

```
 LOCATE I, 1: PRINT "
NEXT I


LOCATE 13, 1
PRINT " SMP at SWUL (-ve values) "
  FOR I = 1 TO 9
   IF UNI$ <> "UNI" THEN
    LOCATE I + 13, 2:
    PRINT "SWUL limit potential(" + LTRIM$(STR$(I)) + ") ";
    INPUT ; SWULpress(I)
    ELSE
     SWULpress(I) = SWULpot
    END IF
  NEXT I


FOR L = 1 TO 9
 PSIS1500(L) = -1500
 B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V10(L) / V1500(L)))
 SWULcont(L) = V1500(L) * (SWULpress(L) / -1500) ^ (1 / B(L))
 DUL(L) = V1500(L) * (-30 / PSIS1500(L)) ^ (1 / B(L))
NEXT L

LOCATE 19, 1
FOR K = 19 TO 25
 PRINT "
NEXT K

LOCATE 4, 1:
PRINT " Select SHEET 3 or 4 or 5-> ";
PRINT " SHEET 3  Given SWUL potential, SWUL content, V1500 find V10 and DUL"
PRINT " SHEET 4  Given V1500, b and SWUL potential find SWUL content V10 and DUL"
PRINT " SHEET 5  Given V1500, DUL(@ -30 kPa) and SWUL potential find SWUL content b and V10"

PRINT " "


DO
 Choice$ = UCASE$(INPUT$(1))
 LOOP WHILE Choice$ <> "3" AND Choice$ <> "4" AND Choice$ <> "5"
 PRINT Choice$

'INPUT "Select SHEET 3 or 4 or 5"; SelectAns

SELECT CASE VAL(Choice$) 'SelectAns

    CASE 3
    ' SHEET 3  Given SWUL potential, SWUL content, V1500 find V10 and DUL"
    ' PRINT "Given SWUL potential, SWUL content, V1500 find V10 and DUL"

    FOR L = 1 TO 9
       B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V10(L) / V1500(L)))
      ' V10(L) = V1500(L) * (-10 / -1500) ^ (1 / B(L))
       DUL(L) = V1500(L) * (-30 / PSIS1500(L)) ^ (1 / B(L))
    NEXT L

   CASE 4

   ' SHEET 4  Given V1500, b and SWUL potential find SWUL content V10 and DUL"
   '  PRINT "Given V1500, b and SWUL potential find SWUL content V10 and DUL"

     FOR L = 1 TO 9
      ' V10(L) = V1500(L) * (-10 / -1500) ^ (1 / B(L))
      V00(L) = V1500(L) * (SWULpress(L) / -1500) ^ (1 / B(L))
      DUL(L) = V1500(L) * (-30 / PSIS1500(L)) ^ (1 / B(L))
     NEXT L


   CASE 5
```

```
  ' SHEET 5  Given V1500, DUL (@ -30 kPa) and SWUL potential find SWUL content b and V10"
  '  PRINT "Given V1500, DUL(@ -30 kPa) and SWUL potential find SWUL content b and V10"

   FOR L = 1 TO 9
     B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V10(L) / V1500(L)))
     ' V10(L) = V1500(L) * (-10 / -1500) ^ (1 / B(L))
     V00(L) = V1500(L) * (SWULpress(L) / -1500) ^ (1 / B(L))
   NEXT L


END SELECT


FOR L = 1 TO 9
  'IF Yes = 2 THEN
    LOCATE L + 3, 45:
    PRINT "BULKDENS(" + LTRIM$(STR$(L)) + ")";
    'INPUT ; BULKDENS(L)
    Bulkdens(L) = 1.45
  'END IF
  PORO(L) = (1 - Bulkdens(L) / 2.65) * 1000
NEXT L

FOR I = 3 TO 25
 LOCATE I, 1: PRINT "
NEXT I

 FOR I = 1 TO 9
 IF UNI$ <> "UNI" THEN
   LOCATE 5, 1: PRINT " Input layer thickness (m)"
   LOCATE I + 6, 1:
   PRINT " DZRT(" + LTRIM$(STR$(I)) + ") ";
   INPUT ; DZRT(I)
  ELSE
  DZRT(I) = LayerThick
  END IF
 NEXT I
 DZRT(1) = 150

LOCATE 4, 1:
PRINT ""
INPUT " Infiltration factor  "; Finfil
INPUT " Percolation factor   "; Fperco
INPUT " Water Table depth    "; WaterTable
INPUT " Maximum effective rooting depth "; ZEFFO



 CLS
 PRINT "Table of soil file"
 PRINT ""
 CN2 = 2
 PRINT "Name of soil file  : " + NAMEfile$
 PRINT "Soil description   : " + NAMEsoil$
 PRINT "Rooting depth    m : " + STR$(ZEFFO)
 PRINT "Layer thickness  m : ";
 PRINT USING "######"; INT(DZRT(1)); INT(DZRT(2)); INT(DZRT(3)); INT(DZRT(4)); INT(DZRT(5)); INT(DZRT(6)); INT(DZRT(7));
INT(DZRT(8)); INT(DZRT(9))
 PRINT "Porosity      mm/m : ";
 PRINT USING "######"; INT(PORO(1)); INT(PORO(2)); INT(PORO(3)); INT(PORO(4)); INT(PORO(5)); INT(PORO(6)); INT(PORO(7));
INT(PORO(8)); INT(PORO(9))
 PRINT "SWULpress     kPa  : ";
 PRINT USING "######"; INT(SWULpress(1)); INT(SWULpress(2)); INT(SWULpress(3)); INT(SWULpress(4)); INT(SWULpress(5));
INT(SWULpress(6)); INT(SWULpress(7)); INT(SWULpress(8)); INT(SWULpress(9))
 PRINT "SWUL          mm/m : ";
 PRINT USING "######"; INT(SWULcont(1)); INT(SWULcont(2)); INT(SWULcont(3)); INT(SWULcont(4)); INT(SWULcont(5));
INT(SWULcont(6)); INT(SWULcont(7)); INT(SWULcont(8)); INT(SWULcont(9))
 PRINT "V10           mm/m : ";
```

```
    PRINT USING "######"; INT(V10(1)); INT(V10(2)); INT(V10(3)); INT(V10(4)); INT(V10(5)); INT(V10(6)); INT(V10(7)); INT(V10(8));
INT(V10(9))
    PRINT "DUL        mm/m : ";
    PRINT USING "######"; INT(DUL(1)); INT(DUL(2)); INT(DUL(3)); INT(DUL(4)); INT(DUL(5)); INT(DUL(6)); INT(DUL(7));
INT(DUL(8)); INT(DUL(9))
    PRINT "V1500      mm/m : ";
    PRINT USING "######"; INT(V1500(1)); INT(V1500(2)); INT(V1500(3)); INT(V1500(4)); INT(V1500(5)); INT(V1500(6)); INT(V1500(7));
INT(V1500(8)); INT(V1500(9))
    PRINT "Bulkdensity Mg/m^3 : ";
    PRINT USING "######"; INT(Bulkdens(1)); INT(Bulkdens(2)); INT(Bulkdens(3)); INT(Bulkdens(4)); INT(Bulkdens(5)); INT(Bulkdens(6));
INT(Bulkdens(7)); INT(Bulkdens(8)); INT(Bulkdens(9))
    PRINT "WaterTable        :" + STR$(WaterTable)
    PRINT "Infiltration factor:" + STR$(Finfil)
    PRINT "Percolation factor :" + STR$(Fperco)

    OPEN NAMEfile$ FOR OUTPUT AS #1
    PRINT #1, NAMEfile$
    PRINT #1, NAMEsoil$
    PRINT #1, CN2
    PRINT #1, ZEFFO
    PRINT #1, USING "##.##"; DZRT(1) / 1000; DZRT(2) / 1000; DZRT(3) / 1000; DZRT(4) / 1000; DZRT(5) / 1000; DZRT(6) / 1000; DZRT(7)
/ 1000; DZRT(8) / 1000; DZRT(9) / 1000
    PRINT #1, USING "####"; PORO(1); PORO(2); PORO(3); PORO(4); PORO(5); PORO(6); PORO(7); PORO(8); PORO(9)
    PRINT #1, USING "####"; SWULpress(1); SWULpress(2); SWULpress(3); SWULpress(4); SWULpress(5); SWULpress(6); SWULpress(7);
SWULpress(8); SWULpress(9)
    PRINT #1, USING "####"; SWULcont(1); SWULcont(2); SWULcont(3); SWULcont(4); SWULcont(5); SWULcont(6); SWULcont(7);
SWULcont(8); SWULcont(9)
    PRINT #1, USING "####"; V10(1); V10(2); V10(3); V10(4); V10(5); V10(6); V10(7); V10(8); V10(9)
    PRINT #1, USING "####"; DUL(1); DUL(2); DUL(3); DUL(4); DUL(5); DUL(6); DUL(7); DUL(8); DUL(9)
    PRINT #1, USING "####"; V1500(1); V1500(2); V1500(3); V1500(4); V1500(5); V1500(6); V1500(7); V1500(8); V1500(9)
    PRINT #1, WaterTable
    PRINT #1, USING "##.##"; Finfil; Fperco
    CLOSE #1


  INPUT K
END

  FOR L = 1 TO 9
'     V1500(L) = 70
'     V10(L) = 150
     SWULpress(L) = -5
     PSIS1500(L) = -1500
     B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V10(L) / V1500(L)))
     SWULcont(L) = V1500(L) * (SWULpress(L) / -1500) ^ (1 / B(L))
     DUL(L) = V1500(L) * (-30 / PSIS1500(L)) ^ (1 / B(L))

     AV10(L) = V10(L)
     AV1500(L) = V1500(L)
     ASWULpress(L) = SWULpress(L)
  NEXT L


'  CALL GetVideoMode(B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2, B4Y2)
'  CALL DrawGraph(B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2, B4Y2, B(),
AV1500(), AV10(), ASWULpress())


   L = 1
   B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V10(L) / V1500(L)))
   FOR press = -1500 TO -5 STEP 5
    VOL = V1500(L) * (press / -1500) ^ (1 / B(L))
    PRINT press, VOL
   NEXT press

   T = 1


  CALL GetVideoMode(B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2, B4Y2)
```

```
'  CALL DrawGraph(StartYr, DOG, B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2,
B4Y2, WM, W1, W2, W3, W4, W5, LAI, LAI1, LAI2, LAI3, LAI4, LAI5, Fv, B(), V1500())

   DUMMY = RESTEXT

'     INPUT k
'     DUMMY = RESTEXT
   DUMMY = RESTEXT

REM $STATIC
DEFSNG D, S, V
SUB DrawGraph (B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2, B4Y2, B(), AV1500(),
AV10(), ASWULpress()) STATIC
DIM W(2000)
DEFINT T, Z

    bText = B1X1
    ' Draw the next layer 1
    L = 1
    B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
    TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
    DOG = 1
    W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1

    FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
     DOG = press
     W(press) = (AV1500(L) * (-press / -1500) ^ (1 / B(L))) * 1
     DRWLINE 1, 1, B1X1 + ((WMOLD - W1) / (TotalW - W1) * ((B1X2 - B1X1) / 2)), B1Y1 - (DOG / 1500 * (B1Y1 - B1Y2)), B1X1 +
((W(DOG) - W1) / (TotalW - W1) * ((B1X2 - B1X1) / 2)), B1Y1 - ((DOG + 1) / 1500 * (B1Y1 - B1Y2))
     WMOLD = W(press)
    NEXT press
    Z = WMOLD
    DRWSTRING 1, 7, 0, STR$(Z), B1X1 - 7, B1Y1 - 15
    DRWSTRING 1, 7, 0, STR$(TotalW), (B1X2 / 2) - 15, B1Y1 - 15

    DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B1X1 + 10, B1Y1 + 5
    DRWSTRING 1, 7, 0, "-1500", B1X1 + 10, B1Y2 - 15

    TITLE$ = "Soil Water characteristic for layers " + STR$(L)
    DRWSTRING 1, 7, 0, TITLE$, bText, 0

    INPUT K
    WMOLD = 0




    ' Draw the next layer 2
    B1Xold = B1X1
    B1X1 = B1Xold + ((B1X2 - B1Xold) / 2)
    Bwidth = B1X2 - B1X1

    L = 2
    B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
    TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
    DOG = 1
    W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1

    FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
     DOG = press
     W(press) = AV1500(L) * (-press / -1500) ^ (1 / B(L))
     DRWLINE 1, 1, B1X1 + ((WMOLD - W1) / (TotalW - W1) * Bwidth), B1Y1 - (DOG / 1500 * (B1Y1 - B1Y2)), B1X1 + ((W(DOG) - W1) /
(TotalW - W1) * Bwidth), B1Y1 - ((DOG + 1) / 1500 * (B1Y1 - B1Y2))
     WMOLD = W(press)
    NEXT press
    DRWSTRING 1, 7, 0, STR$(Z), (B1X2 / 2) + 20, B1Y1 - 15
    DRWSTRING 1, 7, 0, STR$(TotalW), B1X2 - 30, B1Y1 - 15
```

```
DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B1X1 + 10, B1Y1 + 5
DRWSTRING 1, 7, 0, "-1500", B1X1 + 10, B1Y2 - 15
TITLE$ = "Soil Water characteristic for layers " + STR$(L)
DRWSTRING 1, 7, 0, TITLE$, bText, 0

INPUT K
WMOLD = 0

' Draw the next layer 3
L = 3
B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
DOG = 1
W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
 DOG = press
 W(press) = AV1500(L) * (-press / -1500) ^ (1 / B(L))
 DRWLINE 1, 1, B2X1 + ((WMOLD - W1) / (TotalW - W1) * ((B2X2 - B2X1) / 2)), B2Y1 - (DOG / 1500 * (B2Y1 - B2Y2)), B2X1 +
((W(DOG) - W1) / (TotalW - W1) * ((B2X2 - B2X1) / 2)), B2Y1 - ((DOG + 1) / 1500 * (B2Y1 - B2Y2))
 WMOLD = W(press)
NEXT press

DRWSTRING 1, 7, 0, STR$(Z), B2X1 - 5, B2Y1 - 15
DRWSTRING 1, 7, 0, STR$(TotalW), B2X1 + ((B2X2 - B2X1) / 2) - 40, B2Y1 - 15
DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B2X1 + 10, B1Y1 + 5
DRWSTRING 1, 7, 0, "-1500", B2X1 + 10, B1Y2 - 15

TITLE$ = "Soil Water characteristic for layers " + STR$(L)
DRWSTRING 1, 7, 0, TITLE$, bText, 0

INPUT K
WMOLD = 0

' Draw the next layer 4
B2Xold = B2X1
B2X1 = B2Xold + ((B2X2 - B2Xold) / 2)
Bwidth = B2X2 - B2X1

L = 4
B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
DOG = 1
W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
 DOG = press
 W(press) = AV1500(L) * (-press / -1500) ^ (1 / B(L))
 DRWLINE 1, 1, B2X1 + ((WMOLD - W1) / (TotalW - W1) * Bwidth), B2Y1 - (DOG / 1500 * (B2Y1 - B2Y2)), B2X1 + ((W(DOG) - W1) /
(TotalW - W1) * Bwidth), B2Y1 - ((DOG + 1) / 1500 * (B2Y1 - B2Y2))
 WMOLD = W(press)
NEXT press
DRWSTRING 1, 7, 0, STR$(Z), B2X1 - 5, B2Y1 - 15
DRWSTRING 1, 7, 0, STR$(TotalW), B2X2 - 30, B2Y1 - 15
DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B2X1 + 10, B2Y1 + 5
DRWSTRING 1, 7, 0, "-1500", B2X1 + 10, B2Y2 - 15
TITLE$ = "Soil Water characteristic for layers " + STR$(L)
DRWSTRING 1, 7, 0, TITLE$, bText, 0

INPUT K
WMOLD = 0


' Draw the next layer 5
L = 5
B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
DOG = 1
W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
```

```
    FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
     DOG = press
     W(press) = (AV1500(L) * (-press / -1500) ^ (1 / B(L))) * 1
     'DRWLINE 1, 1, B4X1 + (WMOLD / TotalW * ((B4X2 - B4X1) / 2)), B4Y1 - (DOG / 1500 * (B4Y1 - B4Y2)), B4X1 + (W(DOG) / TotalW * ((B4X2 - B4X1) / 2)), B4Y1 - ((DOG + 1) / 1500 * (B4Y1 - B4Y2))
     DRWLINE 1, 1, B4X1 + ((WMOLD - W1) / (TotalW - W1) * ((B4X2 - B4X1) / 2)), B4Y1 - (DOG / 1500 * (B4Y1 - B4Y2)), B4X1 + ((W(DOG) - W1) / (TotalW - W1) * ((B4X2 - B4X1) / 2)), B4Y1 - ((DOG + 1) / 1500 * (B4Y1 - B4Y2))

     WMOLD = W(press)
    NEXT press
    DRWSTRING 1, 7, 0, STR$(Z), B4X1 - 5, B4Y1 - 15
    DRWSTRING 1, 7, 0, STR$(TotalW), (B4X2 / 2) - 15, B4Y1 - 15
    DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B4X1 + 10, B4Y1 + 5
    DRWSTRING 1, 7, 0, "-1500", B4X1 + 10, B4Y2 - 15

    TITLE$ = "Soil Water characteristic for layers " + STR$(L)
    DRWSTRING 1, 7, 0, TITLE$, bText, 0

    INPUT K
    WMOLD = 0

    ' Draw the next layer 6
    B4Xold = B4X1
    B4X1 = B4Xold + ((B4X2 - B4Xold) / 2)
    Bwidth = B4X2 - B4X1

    'B4X1 = B4X1 + ((B4X2 - B4X1) / 2)


    L = 6
    B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
    TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
    DOG = 1
    W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
     DOG = press
     W(press) = AV1500(L) * (-press / -1500) ^ (1 / B(L))
     'DRWLINE 1, 1, B4X1 + (WMOLD / TotalW * (B4X2 - B4X1)), B4Y1 - (DOG / 1500 * (B4Y1 - B4Y2)), B4X1 + (W(DOG) / TotalW * (B4X2 - B4X1)), B4Y1 - ((DOG + 1) / 1500 * (B4Y1 - B4Y2))
     DRWLINE 1, 1, B4X1 + ((WMOLD - W1) / (TotalW - W1) * Bwidth), B4Y1 - (DOG / 1500 * (B4Y1 - B4Y2)), B4X1 + ((W(DOG) - W1) / (TotalW - W1) * Bwidth), B4Y1 - ((DOG + 1) / 1500 * (B4Y1 - B4Y2))

     WMOLD = W(press)
    NEXT press
    DRWSTRING 1, 7, 0, STR$(Z), (B4X2 / 2) + 20, B4Y1 - 15
    DRWSTRING 1, 7, 0, STR$(TotalW), B4X2 - 30, B4Y1 - 15
    DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B4X1 + 10, B4Y1 + 5
    DRWSTRING 1, 7, 0, "-1500", B4X1 + 10, B4Y2 - 15

    TITLE$ = "Soil Water characteristic for layers " + STR$(L)
    DRWSTRING 1, 7, 0, TITLE$, bText, 0

    INPUT K
    WMOLD = 0

    ' Draw the next layer 7
    L = 7
    B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
    TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
    DOG = 1
    W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
    FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
     DOG = press
     W(press) = (AV1500(L) * (-press / -1500) ^ (1 / B(L))) * 1
     'DRWLINE 1, 1, B3X1 + (WMOLD / TotalW * ((B3X2 - B3X1) / 2)), B3Y1 - (DOG / 1500 * (B3Y1 - B3Y2)), B3X1 + (W(DOG) / TotalW * ((B3X2 - B3X1) / 2)), B3Y1 - ((DOG + 1) / 1500 * (B3Y1 - B3Y2))
     DRWLINE 1, 1, B3X1 + ((WMOLD - W1) / (TotalW - W1) * ((B3X2 - B3X1) / 2)), B3Y1 - (DOG / 1500 * (B3Y1 - B3Y2)), B3X1 + ((W(DOG) - W1) / (TotalW - W1) * ((B3X2 - B3X1) / 2)), B3Y1 - ((DOG + 1) / 1500 * (B3Y1 - B3Y2))
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```
       WMOLD = W(press)
      NEXT press
      DRWSTRING 1, 7, 0, STR$(Z), B3X1 - 5, B3Y1 - 15
      DRWSTRING 1, 7, 0, STR$(TotalW), B3X1 + ((B3X2 - B3X1) / 2) - 40, B3Y1 - 15
      DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B3X1 + 10, B3Y1 + 5
      DRWSTRING 1, 7, 0, "-1500", B3X1 + 10, B3Y2 - 15

      TITLE$ = "Soil Water characteristic for layers " + STR$(L)
      DRWSTRING 1, 7, 0, TITLE$, bText, 0
      INPUT K
      WMOLD = 0

      ' Draw the next layer 8
      B3Xold = B3X1
      B3X1 = B3Xold + ((B3X2 - B3Xold) / 2)
      Bwidth = B3X2 - B3X1

     ' B3X1 = B3X1 + ((B3X2 - B3X1) / 2)
      L = 8
      B(L) = LOG(-10 / -1500) / (LOG(AV10(L) / AV1500(L)))
      TotalW = AV1500(L) * ((ASWULpress(L)) / -1500) ^ (1 / B(L))
      DOG = 1
      W1 = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
      WMOLD = (AV1500(L) * (-1500 / -1500) ^ (1 / B(L))) * 1
      FOR press = -1 * ASWULpress(L) TO 1500 STEP 1
       DOG = press
       W(press) = AV1500(L) * (-press / -1500) ^ (1 / B(L))
       DRWLINE 1, 1, B3X1 + ((WMOLD - W1) / (TotalW - W1) * Bwidth), B3Y1 - (DOG / 1500 * (B3Y1 - B3Y2)), B3X1 + ((W(DOG) - W1) /
(TotalW - W1) * Bwidth), B3Y1 - ((DOG + 1) / 1500 * (B3Y1 - B3Y2))
       'DRWLINE 1, 1, B3X1 + (WMOLD / TotalW * (B3X2 - B3X1)), B3Y1 - (DOG / 1500 * (B3Y1 - B3Y2)), B3X1 + (W(DOG) / TotalW *
(B3X2 - B3X1)), B3Y1 - ((DOG + 1) / 1500 * (B3Y1 - B3Y2))
       WMOLD = W(press)
      NEXT press
      DRWSTRING 1, 7, 0, STR$(Z), B3X1 - 5, B3Y1 - 15
      DRWSTRING 1, 7, 0, STR$(TotalW), B3X2 - 30, B3Y1 - 15
      DRWSTRING 1, 7, 0, STR$(ASWULpress(L)), B3X1 + 10, B3Y1 + 5
      DRWSTRING 1, 7, 0, "-1500", B3X1 + 10, B3Y2 - 15

      TITLE$ = "Soil Water characteristic for layers " + STR$(L)
      DRWSTRING 1, 7, 0, TITLE$, bText, 0

      INPUT K
      WMOLD = 0
      DUMMY = RESTEXT
END
END SUB

DEFSNG T, Z
SUB GetVideoMode (B1X1, B1Y1, B1X2, B1Y2, B2X1, B2Y1, B2X2, B2Y2, B3X1, B3Y1, B3X2, B3Y2, B4X1, B4Y1, B4X2, B4Y2)


    STARTVIDEOMODE = VIDEOMODEGET
    VGA = WHICHVGA
    VIDEOMODESET (STARTVIDEOMODE)

    'PALGET ORGPAL, 0, 255
    'PALCOPY ORGPAL, PAL, 0, 255
    'PALCOPY ORGPAL, PAL2, 0, 255
    OK = RES800
'   OK = RES1024
    'OK = RES640L


  '  TITLE$ = "Simulated biomass kg/ha -> "
    ' PALSET PAL, 40, 255

    FILLSCREEN 25
   ' SETVIEW 0, 0, GETMAXX, GETMAXY
   ' DRWSTRING 1, 7, 0, TITLE$, 10, 0
    'DRWSTRING 1, 7, 0, A$, 10, 18
```

```
    'WDTH = (GETMAXX + 1) / 2.25
    WDTH = (GETMAXX + 1) / 2.5
    SPCINGX = ((GETMAXX + 1) - WDTH * 2) / 3
    'HGTH = (GETMAXY + 1 - 35) / 2.25
    HGTH = (GETMAXY + 1 - 35) / 2.5
    SPCINGY = ((GETMAXY + 1 - 35) - HGTH * 2) / 3
    XINC = WDTH * 1.5
    YINC = HGTH * 1.5
    XSUB = WDTH * .25
    YSUB = HGTH * .25


    B1X1 = SPCINGX
    B1X2 = B1X1 + WDTH
    B1Y1 = SPCINGY + 35
    B1Y2 = B1Y1 + HGTH

    B2X2 = GETMAXX - SPCINGX
    B2X1 = B2X2 - WDTH
    B2Y1 = SPCINGY + 35
    B2Y2 = B2Y1 + HGTH

    B3X2 = GETMAXX - SPCINGX
    B3X1 = B3X2 - WDTH
    B3Y2 = GETMAXY - SPCINGY
    B3Y1 = B3Y2 - HGTH

    B4X1 = SPCINGX
    B4X2 = B4X1 + WDTH
    B4Y2 = GETMAXY - SPCINGY
    B4Y1 = B4Y2 - HGTH

    FOR L = 1 TO 2
     DRWBOX 1, 7, B1X1, B1Y1, B1X1 + ((B1X2 - B1X1) / 2) * L, B1Y2
     'B1X1 = B1X1 + ((B1X2 - B1X1) / 2)
     'DRWBOX 1, 7, B1X1, B1Y1, B1X1 + ((B1X2 - B1X1)), B1Y2

     DRWBOX 1, 7, B2X1, B2Y1, B2X1 + ((B2X2 - B2X1) / 2) * L, B2Y2
     DRWBOX 1, 7, B3X1, B3Y1, B3X1 + ((B3X2 - B3X1) / 2) * L, B3Y2
     DRWBOX 1, 7, B4X1, B4Y1, B4X1 + ((B4X2 - B4X1) / 2) * L, B4Y2
    NEXT L


    DRWBOX 1, 7, B1X1, B1Y1, B1X2, B1Y2
    DRWBOX 1, 7, B2X1, B2Y1, B2X2, B2Y2
    DRWBOX 1, 7, B3X1, B3Y1, B3X2, B3Y2
    DRWBOX 1, 7, B4X1, B4Y1, B4X2, B4Y2


    Colr = 1


END SUB
```

OUTCOMES

1. Scientific Articles

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Kennedy, J.A. 1996. Irrigation Scheduling and automatic weather stations. S..A. Institute for Agricultural Engineering Symposium on Irrigation. June. Nelspruit.

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3. Other

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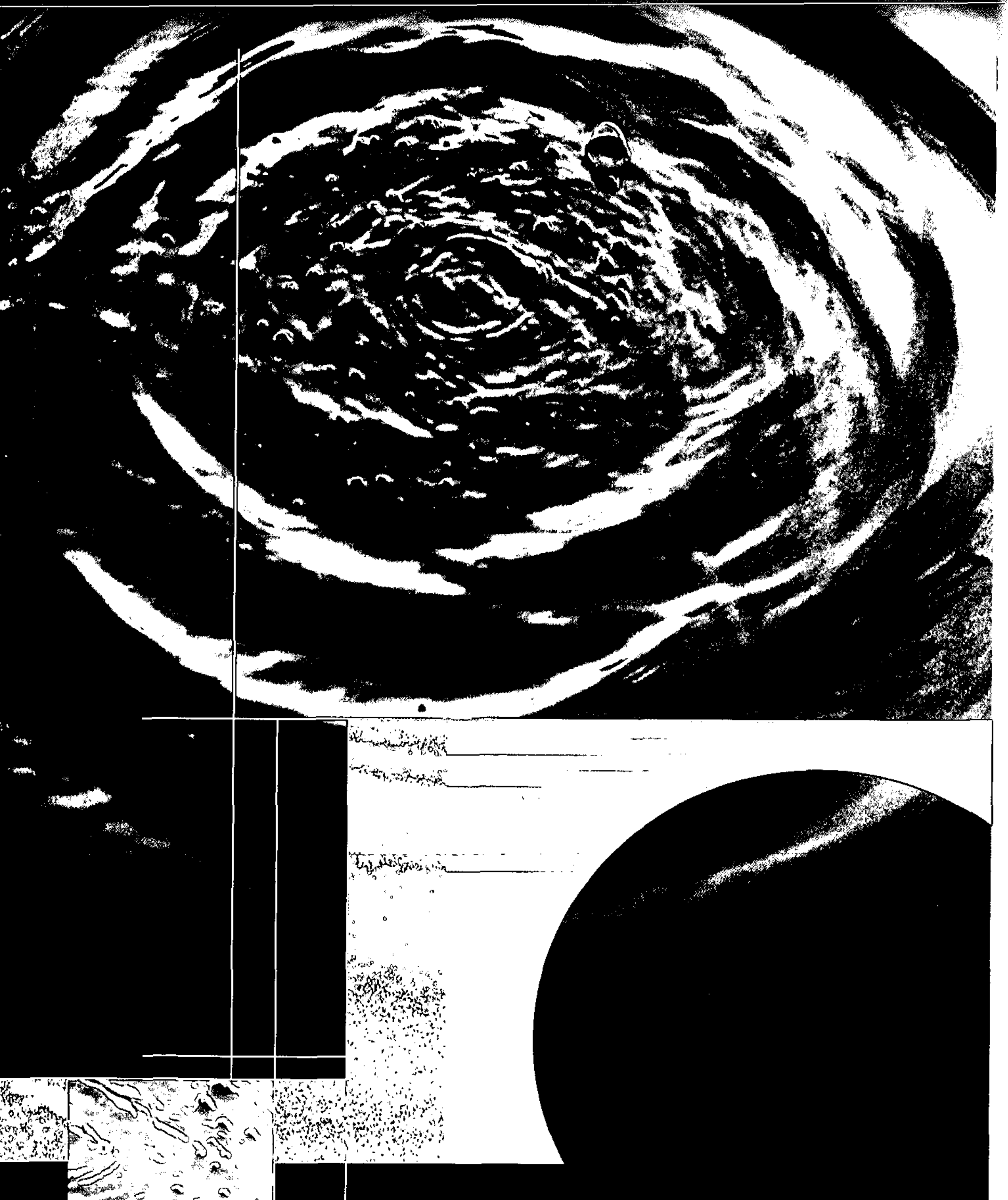

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