

# **RESEARCH ON MAXIMISING IRRIGATION PROJECT EFFICIENCY IN DIFFERENT SOIL-CLIMATE-IRRIGATION SITUATIONS**

By

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**Department of Agrometeorology  
University of the Orange Free State**

**Report to the Water Research Commission on the Project  
"Research on maximising irrigation project efficiency in different soil-climate-irrigation  
situations"**

**Head of Department : Professor J.M. de Jager  
Project Leader : Professor J.M. de Jager**

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**EXECUTIVE SUMMARY**

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**Supplement to WRC Report No.**

**which is the full report to the Water Research Commission  
on the Project**

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## GENERAL

The overall objective of the research here reported was to maximise the efficiency of water use on an irrigation project. It was required to investigate various different climate-soil situations.

Maximisation of overall irrigation project efficiency results from maximisation of irrigation efficiency on the individual farms within the given project. Hence, a bottom up approach was adopted. Much emphasis was placed upon individual farms and indeed single plots of land. In Chapter 11 a mathematical model is presented which permits evaluation of irrigation efficiency in the different components of an irrigation project and the combination thereof to provide an overall efficiency.

A mathematical modelling approach was used throughout. This computerised, numeric, quantitative method ensures non-subjectivity, and furthermore makes possible the application elsewhere of the exact procedures here developed.

Consideration of a variety of climate-soil situations was achieved by conducting investigations in four markedly differing localities, viz.

Winterton	-	medium rainfall and hilly
Taung/Molatedi	-	dry, Highveld
Karkloof	-	humid, high rainfall
Reitz	-	continental, good rainfall

Furthermore, various different types of irrigation system, water supply and conveyance system were employed at each locality providing numerous irrigation scenarios.

The overall objective was divided into three specific objectives. Achievement of these specific objectives will now be described.

## **SITUATION SURVEYS**

A specific objective was to carry out situation surveys on selected projects and, if possible, develop a mathematical model for each project.

Situation surveys were carried out at 24 sites. In most cases no mathematical formulation was possible, information gathered was compiled in guidelines for efficient water use and management on irrigation projects. These guidelines were presented to certain water boards and brought about significant change in their *modus operandi*.

The Little Tugela/Sterkspruit Irrigation Board adopted a new method of decision making based upon the workshops, technology transfer and research results obtained in the area. This improved the effectiveness with which water was apportioned to users. Adoption of Schedwat and the PUTU-system lead to the appointment of a bailiff who now uses these programmes in consultation with this project.

These guidelines were also applied in the Karkloof. This water board had been proclaimed in 1986. Little organization had however taken place subsequently. The guidelines assisted greatly in the formalization of a board for the area and the management of their irrigation water.

## **MODELS DEVELOPMENT AND APPLICATION**

A specific objective was to use and refine computer models for analysing current operations and make recommendations for increasing overall project and on-farm productivity and water use efficiency.

The mere fact that commercial irrigators are employing the PUTU models, albeit on their own, or through the University of the OFS, testifies to the fact that they are both operational and valid.

The validation tests proved that, given suitable yield-water stress response parameters, the models provided accuracies acceptable for decision support purposes. Furthermore, the validity of the additive form of the model for use in linear programming procedures was demonstrated.

Different aspects of crop growth and water balance models were validated at three different sites namely, Roodeplaat, Taung and Molatedi.

The models, when applied in practical situations, highlighted the procedures to be implemented for increasing both overall project water use efficiency and on-farm productivity.

On perennial pastures, an individual farmer realised  $\pm 50\%$  decrease in pumping costs below the previous season when he himself applied the AWS-data and computational procedures. Another dairy farmer in the same district was able to survive on irrigated pastures through the dry 1992 and 1993 seasons. Whereas dairy farmers in the same area were forced to reduce herd size due to lack of adequate irrigated pasture.

In Reitz the validity of using PUTU to irrigate (by drip irrigation) high quality potatoes for the local market, the chipping industry and especially the lucrative export market was proved. Since employing the PUTU procedures the particular farmer claims a 40% saving in pumping costs.

Floods disrupted the early experiments at Taung and Molatedi. Thereafter it was possible to conduct water management trials which could only serve as demonstrations to the local community. One trial, however, did prove the validity of Fw, the water stress factor for identifying stress conditions. A 50% value was found accurately to reflect the onset of stress.

In the Winterton area centre pivot irrigation farmers on average attained approximately 40% increases in yields above those

attained in the surrounding area in which scheduling took place according to normal practice.

#### **MAXIMISATION OF EFFICIENCIES**

A specific objective was application of the models to irrigation project management and the refinement of the models with the aim of maximising overall irrigation efficiency.

Equations for quantifying efficiencies were developed and applied. Water use efficiency was improved in all the cooperator sites. This was mainly due to the effective irrigation scheduling technique made available by the PUTU-system.

Linear programming (LP) procedures for planning strategies for optimizing the area to be cultivated and the amounts of water to be applied in the different crop growth stages were formulated.

With regard to pre-season planning, two Little Tugela farmers utilized the LP developed during the dry 1991/1992 season when water restrictions were operative. Significant financial gain accrued. The Sterkspruit water board have yet to adopt the system.

Routine information regarding irrigation which evidently had good impact upon users was provided to boards, estates and individuals. Advices on water management and distribution, and efficient irrigation scheduling were distributed.

#### **CONTRIBUTION TO THE STATE OF KNOWLEDGE**

Irrigators employing the PUTU-system and allied LP programmes for irrigation scheduling having gained considerable confidence in their own irrigation management capabilities. Several entrepreneurs, both large and small, now employ the system

Some resistance to change, especially on the larger estates, is still evident. This is however diminishing. The fact that the models have been applied in actual situations and produced good results has done much to enhance their credibility. Less electricity and subsequently less water have been consumed to produce increased yields and quality at farm level.

#### EXTERNAL COOPERATION

The industry is eager to adopt the programmes and procedures now available. This is borne out by the willingness of farmers and farm cooperatives to contribute, for own account, seven automatic weather stations towards the project. This involved considerable expense.

Furthermore, other farmers have expressed the desire to become involved in the near future.

#### RECOMMENDATIONS FOR FUTURE RESEARCH

Basic research needs for furthering the approach to irrigation scheduling here promoted, include:

- the soil water table and drainage subroutines of the crop growth models require validation in order to eliminate minor modelling errors,
- the perfecting of radio-telemetry links with automatic weather stations to expedite and simplify data transfer,
- how to manage the large volumes of data and make information accessible to users,
- the establishing of crop growth parameters for both different crops and different cultivars within given species,
- the application of the present computerized techniques of management and water distribution to large and small irrigation projects,
- the establishment of a weather/irrigation service/agency for the farming community, and

- the extension of the techniques here perfected to the special case of irrigation on small holdings.

#### TECHNOLOGY TRANSFER

This project serves as an excellent example of how best to transfer high level technology to the on-farm and industry situations. Using careful diplomacy and purposefulness, the most sophisticated computer technology has been introduced and sustained in numerous practical irrigation scheduling scenarios. This was mainly achieved by:

- collaboration and involvement in water board activities
- routine advisories, on when and how much to irrigate, presented in a form easily digested and applied by managers
- the workshops organised,
- the several oral presentations at local and international congresses and farmers' days, and
- articles in the scientific literature.

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## PART I : INTRODUCTION TO THE STUDY

### CHAPTER 1      RATIONALE

#### 1.1    GENERAL

The decreasing availability of water has made it necessary to attain maximum crop production from all water used for irrigation. Irrigation planning and scheduling is a complex inter-disciplinary exercise. The best way of ensuring overall irrigation project water use efficiency, including on-farm efficiency, is by utilising computerised system analysis.

A previous WRC project (de Jager, van Zyl, Kelbe and Singels, 1987) has shown that it is possible, using automatic weather stations and computerised methods, to plan and schedule irrigation on many plots of land. Weather data and computer (Snyder, Pruitt and Dong, 1985) offer the most useful, convenient and indeed only, means of estimating water use on a large number of individual farms as well as losses from dam, river and canal. It has thus become imperative that they be dedicated to the purposes of controlling and saving water on irrigation schemes.

The work conducted in the study addresses certain research topics identified as high priority studies which were recommended by the Co-ordinating Committee for Irrigation Research (CCIR). These, together with their recommended priorities are:

- Water balance models for scheduling advisory services on a regional basis (B-priority)
- Infiltration and water holding characteristics of soils (A-priority)
- Adaptation of irrigation scheduling techniques to mechanical irrigation systems (B-A priority), and
- Evaluation of management of irrigation water (B-priority).

It is expected that appreciable technology transfer should result

from the investigation. This study describes the computer software which will make possible the analysis and evaluation of scenarios encompassing different climates, crops, soils, irrigation methods and water supply situations.

The primary end-users will be the decision and policy makers in control of irrigation situations. These include water boards, irrigation boards, irrigation consultants, bailiffs and individual farmers, on the one hand, as well as government departments entrusted with funding irrigation enterprises on the other. In 1988 water boards received a government loan (33% subsidised) which had to be redeemed, plus interest, over fifteen years. Application of the computerised systems analyses used in this study will help to ensure long-term economically and financially viable, practically implementable schemes.

Many theories relating to optimum irrigation scheduling, crop water requirements, irrigation strategies for humid versus arid areas and the management of water delivery systems were studied, tested and adapted to Southern African conditions, these included the work of Burman, Cuenca and Weiss (1980); de Jager et al. (1987) and also Benade's (1992) approach to canal simulation and work by Reid (1988).

The advisability of using present strategies needed to be compared to the flexible strategies proposed by De Jager et al., (1987). The maximisation of either water use efficiency, or profits per hectare or per farm (de Jager et al., 1987) required formulation and computerisation (Allen, 1986). The performance of such strategies needed to be tested in various soil-climate situations and the important consequences of water limitations brought into reckoning.

The results of the research were aimed at facilitating the work of farm managers and water bailiffs and simplifying decision making by water boards, government and other agencies.

Computerised management aimed at attaining the most efficient use of water for irrigating numerous plots, containing different crops, from a single central water supply will be an important outcome.

## 1.2 OBJECTIVES OF RESEARCH PROJECT

The overall objective of the research was to maximise the efficiency of water use on an irrigation project.

The specific objectives were to:

- 1.2.1 Carry out situation surveys on selected irrigation projects and, if possible develop a mathematical model of each project.
- 1.2.2 Use and refine the models to analyse current operations and make recommendations for increasing overall project and on-farm productivity and water use efficiency.
- 1.2.3 Apply the models to irrigation project management and refine them with the aim of maximising overall irrigation efficiency. Management includes the control of water releases and distribution, estimation of individual farm water requirements and provision of advice to farmers on irrigation scheduling.

## CHAPTER 2 - LITERATURE SURVEY

### 2.1. INTRODUCTION

"Agriculture is an exploitation of solar energy made possible by an adequate supply of water and nutrients to maintain plant growth" (Monteith, 1985) Crop production depends entirely upon the supply of resources such as water, nutrients and solar radiation. In many areas of the world and especially in Southern Africa, water is the major factor limiting crop production. Water for crop production can come from precipitation, or from irrigation. Where economically viable, irrigation can be used to supplement natural rainfall. In many semi-arid and arid regions, agricultural production is entirely dependent upon irrigation to meet its water needs. Especially in this case, is it necessary to achieve maximum production from the water applied.

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

Approximately 70 per cent of surface water resources is allocated to irrigation in Southern Africa. Of this, up to 30 per cent is lost before reaching the edge of the cropped lands (Bang, 1989). Improving on-farm irrigation efficiencies thus becomes imperative if more water is to be made available for other purposes. This could even lead to groundwater diminution.

The need for responsible, thrifty management of all aspects of water distribution on irrigation projects thus cannot be overemphasize. Water could be saved during conveyance to farms and cropped areas, distribution between farms, physical application to crops, and irrigation scheduling.

The objectives of this chapter are to review literature dealing with:

- a) the estimation of crop water requirements;
- b) soil-crop water use simulation models;
- c) methods of water supply management;
- d) water management on irrigation projects.

## 2.1.1 ESTIMATING IRRIGATION WATER REQUIREMENTS

### 2.1.1.1 Current support technology

Personal computers amongst other things are ideally suited to on-farm irrigation water management. The majority of the calculations involved in estimating irrigation water requirements are repetitive and protracted requiring refined computation.

Dataloggers interfaced to personal computers, are frequently used for accumulating and processing the climatic data needed for estimating irrigation water requirements (see De Jager et al, 1987). In Southern Africa, apart from universities, the Weather Bureau is converting to such automatic weather stations. Section 2.1.6 describes how these weather networks could be utilised for the task at hand.

### 2.1.1.2 Definitions regarding crop evaporation

Precise definitions of the terms and concepts required for estimating crop evaporation are imperative prerequisites for agricultural water management (De Jager and van Zyl, 1989; Burman, Cuenca and Weiss, 1983).

#### Crop Total evaporation (E)

Monteith (1985) suggested that the term crop total evaporation be used to describe the water vapour exchange between natural surfaces and the atmosphere. De Jager and van Zyl (1989) defined total evaporation using:

$$E = E_v + E_s \quad 2.1.1$$

where,

$E$  = total evaporation rate from a natural surface  
(usually expressed in  $\text{mm d}^{-1}$ )  
 $E_v$  = plant evaporation rate ( $\text{mm d}^{-1}$ ), and  
 $E_s$  = soil surface evaporation rate ( $\text{mm d}^{-1}$ ).

#### **Potential total evaporation ( $E_p$ )**

Rosenberg, Blad and Verma (1983) defined potential total evaporation (potential evapotranspiration) 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 total evaporation ( $E_o$ )**

Doorenbos and Pruitt (1977) defined reference total 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 soil water and 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 sustain the energy balance of a given vegetated 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 150mm of soil equals its current value.

##### **2.1.1.3 Estimation of atmospheric evaporative demand (AED) using evaporation coefficients.**

Wright (1982) and De Jager and van Zyl (1989) suggest that evaporation from a vegetated surface must be modeled in terms of both the components of the total evaporation, namely, soil evaporation and plant evaporation. The latter demonstrated that it is incorrect to utilise a single crop coefficient to estimate AED. Two coefficients,  $k_v$  and  $k_s$ , are required.

Thus AED is given by

$$\text{AED} = k_c E_o \quad 2.1.2$$

$k_c$  is the crop total evaporation coefficient. It is the ratio of crop total evaporation to reference evaporation.

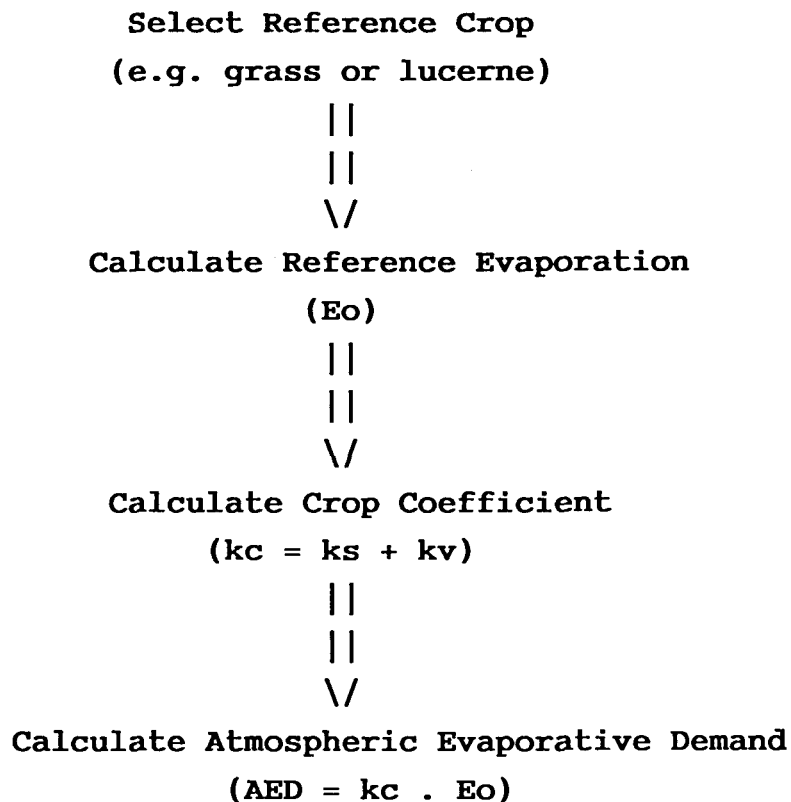
where,  $k_c = k_s + k_v \quad 2.1.3$

with,

$k_s$  = the evaporation coefficient accounting for the influence of soil surface water conditions. It is the ratio of maximum soil evaporation to reference evaporation

$k_v$  = the evaporation coefficient accounting for evaporation from the vegetation. It is the ratio of maximum vegetation evaporation to reference evaporation.

Fig. 2.1.1 illustrates the procedures to be followed when calculating atmospheric evaporative demand.



**Fig. 2.1.1** Flow chart for estimating atmospheric evaporative demand

#### **2.1.1.4 Estimation of Reference Crop Evaporation ( $E_o$ )**

The Penman Equation, PE, was introduced by Penman (1948) for calculating  $E_o$  some 45 years ago. Extensive research has validated the accuracy of this equation (Chang, 1968; de Jager and van Zyl, 1989). Penman (1948) measured water loss from large tanks containing bare soil, grass or water. His original equation was based on the evaporation of water from these tanks. The definition of potential evaporation that arose from these studies implied a maximum value of evaporation. Rosenberg (1974) stated that potential evaporation cannot exceed free water evaporation under the same weather conditions.

Where routine weather data are available, a good estimate of  $E_o$  is obtainable from the Penman equation. Following Burman *et al.* (1983), and Doorenbos and Kassam (1979), the Penman equation may

be written as:

$$E_o = c \{ [s/(s+\gamma)](Rn-G) + [s/(s+\gamma)]f(U)(e_s - e_a) \} \quad 2.1.4$$

where,

- $E_o$  = reference crop evaporation ( $\text{mmd}^{-1}$ )
- $c$  = correction factor which accounts for the effect of day-night and other weather conditions on  $E_o$
- $s$  = slope of vapour pressure temperature curve ( $\text{mbar } ^\circ\text{C}^{-1}$ )
- $\gamma$  = psychometric constant ( $\text{mbar } ^\circ\text{C}^{-1}$ )
- $Rn$  = net radiation ( $\text{mm d}^{-1}$ )
- $G$  = soil heat flux density ( $\text{mm d}^{-1}$ )
- $f(U)$  = wind function ( $\text{mm mbar}^{-1} \text{d}^{-1}$ )
- $e_s$  = saturation vapour pressure of air at reference height (mbar)
- $e_a$  = actual vapour pressure of air at reference height (mbar)

Reference crop evaporation may be measured, or calculated, 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, 1974).

Various methods of calculating vapour pressure, incoming solar radiation, slope of the vapour pressure temperature curve and the psychometric constant for use in this equation exist (Jensen, Burman and Allen, 1990). The methods of calculation adopted acutely affect the final estimate of reference evaporation.

The following method for computing  $F(U)$  is recommended by Burman et al., (1983) for the wind function  $f(U)$  over a lucerne cover, viz:

$$f(U) = 15,36 (0,75 + 0,0115 U_2) \quad 2.1.5$$

where,

- $U_2$  = daily wind run at height 2m ( $\text{km d}^{-1}$ )  
(Wright and Jensen, 1972)

For short grass Doorenbos and Pruitt (1977) recommended the following wind function:

$$f(U) = 0.27(1 + U_2/100) \quad 2.1.6$$

where,

$$U_2 = \text{daily wind run at height 2m (km d}^{-1}\text{)}$$

The recommended formula for calculating vapour pressure deficit is:

$$(e_s - e_a) = 0.5(e_{s\text{max}} + e_{s\text{min}}) - e_s(T_d) \quad 2.1.7$$

where,

$$e_{s\text{max}} = \text{saturation vapour pressure at daily maximum temperature (mbar)}$$

$$e_{s\text{min}} = \text{saturation vapour pressure at daily minimum temperature (mbar)}$$

$$e_s(T_d) = \text{saturation vapour pressure at daily average dew point temperature (mbar)}$$

Saturation vapour pressure is an important term used in all evaporation formula. The Tetens (1930) equation for estimating saturation vapour pressure,  $e_s$ , from air temperature in degrees Celsius ( $T$ ) is most convenient to use as it is easy to differentiate in order to obtain  $S$ , the slope of the saturation vapour pressure curve. It reads:

$$e_s = 6.108 * \text{EXP}[17.27 * T / (T + 237.3)] \quad 2.1.8$$

Priestley-Taylor Equation, PTE, provides an alternative estimate of  $E_o$  should vapour pressure and wind measurements not be available. It is obtained by estimating the aerodynamic term of the PE, thus

$$E_o = \alpha EE$$

$$\text{with, } EE = [s/(s+\gamma)](R_n - G) \quad 2.1.9$$

where,

$$EE = \text{equilibrium evaporation}$$

$$\alpha = \text{empirical coefficient:}$$

$$\text{free water surfaces} = 1.26$$

$$(\text{Priestley and Taylor, 1972})$$

perennial ryegrass = 1,35  
(Mottram, 1975)  
lucerne = 1,42  
(Jury and Tanner, 1975)

De Jager (1992) estimates the radiative term using  
 $R_n - G = 0,65 * R_n$ .

$E_o$  estimates are improved by making the empirical coefficients,  $\alpha$ , a function of temperature. Following Meiring (1989), De Jager (1992) found that the following formula for  $\alpha$  performed well in maize for  $T_{max}$  between 20°C and 40°C:

$$\alpha = 1.26 + 0.02 (T_{max} - 20) \quad 2.1.10$$

where  $\alpha$  is constrained  $1,26 \leq \alpha \leq 1,46$ .

Meyer, Walker and Green (1979) also used maximum daily temperature above a base level satisfactorily simulate crop evaporation from well-watered spring wheat.

Their function was of the form,

$$\alpha = 1.28 + 0.08 (T_{max} - 20) \quad 2.1.11$$

for  $T_{max} > 20^\circ\text{C}$ . For  $T_{max} < 20^\circ\text{C}$  a value of  $\alpha = 1.28$  was used.

**Penman-Monteith Method** - De Jager (1984) suggested that the Penman-Monteith equation provides the best method of determining both potential ( $E_p$ ) and reference ( $E_o$ ) evaporation. Monteith (1985) modified Penman's original theory to account for the effects of vegetation. This modified equation operates best with hourly values of the weather variables.

De Jager and van Zyl (1989) expressed the Penman-Monteith equation, in terms of conductance as follows:

$$\lambda E_o = [s(R_n - G) + \rho C_p (e_s(T) - e) \phi a] / [s + \gamma(1 + \phi a / \phi v)] \quad 2.1.12$$

where,

$\lambda$  = coefficient of specific latent heat of vaporisation  
 $E_o$  = reference crop total evaporation (mm)  
 $\rho$  = density ( $\text{kg m}^{-3}$ )

- $C_p$  = specific heat of air ( $\text{J kg}^{-1} \text{ m}^{-3}$ )  
 $T$  = atmospheric temperature ( $^{\circ}\text{C}$ )  
 $\phi_a$  = atmospheric conductance of gaseous exchange (this is a function of wind speed and crop height) ( $\text{ms}^{-1}$ )  
 $\phi_v$  = conductance of vegetative surface to gaseous water diffusion ( $\text{ms}^{-1}$ )

Conductance is simply the inverse of resistance and Van Zyl and de Jager, 1987 have shown that for reference crop evaporation  $\phi_a$  may be computed from the logarithmic wind profile and  $\phi_v$  for short grass equals  $0,03 \text{ m s}^{-1}$ . Estimates of  $E_o$  may then be applied to determining crop water use with the help of evaporation coefficients (De Jager and van Zyl, 1989; Doorenbos and Kassam, 1979).

#### 2.1.2 CROP WATER USE MODELS

Passioura (1973) cautioned against making models too complex. Model parameters should be few; all should be directly or indirectly measurable, and as far as possible only verified models should be used.

There are several models for estimating soil water deficits using weather inputs (Penman, 1948; Ritchie, Rhoades and Richardson, 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 type 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, Botha and Van Vuuren, (1981) and Singels (1984) developed a wheat growth simulation model, PUTU 6. Given weather input data, this model simulates water balance by extracting daily transpiration losses from the water present in each soil layer. De Jager and Singels (1985) improved upon the accuracy of the simulation of soil water content by including better mathematical equations for hydraulic conductance and an iterative routine. Cultivar differences were included in the latest version, PUTU9-89 (Singels and de Jager, 1991).

Burt, Hayes, O'Rourke, Terzing and Todhunter (1981) recommended that water use modelling always be kept in perspective regarding the level of sophistication and accuracy required. Empirical models are essentially regressions of evaporation on weather variables. Complex mechanistic, dynamic models employ partial differential equations, governing the exchange of energy and mass in the soil-plant-atmosphere system.

Jameison, Wilson and Hanson (1984) used four 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 drought response.

Riestra-Diaz (1985) used a water balance simulation model which provided reasonable estimates of crop evaporation and soil profile water content. Allan (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.

### 2.1.3 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."

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. 2.1.2 illustrates the main factors that should be considered in this process.

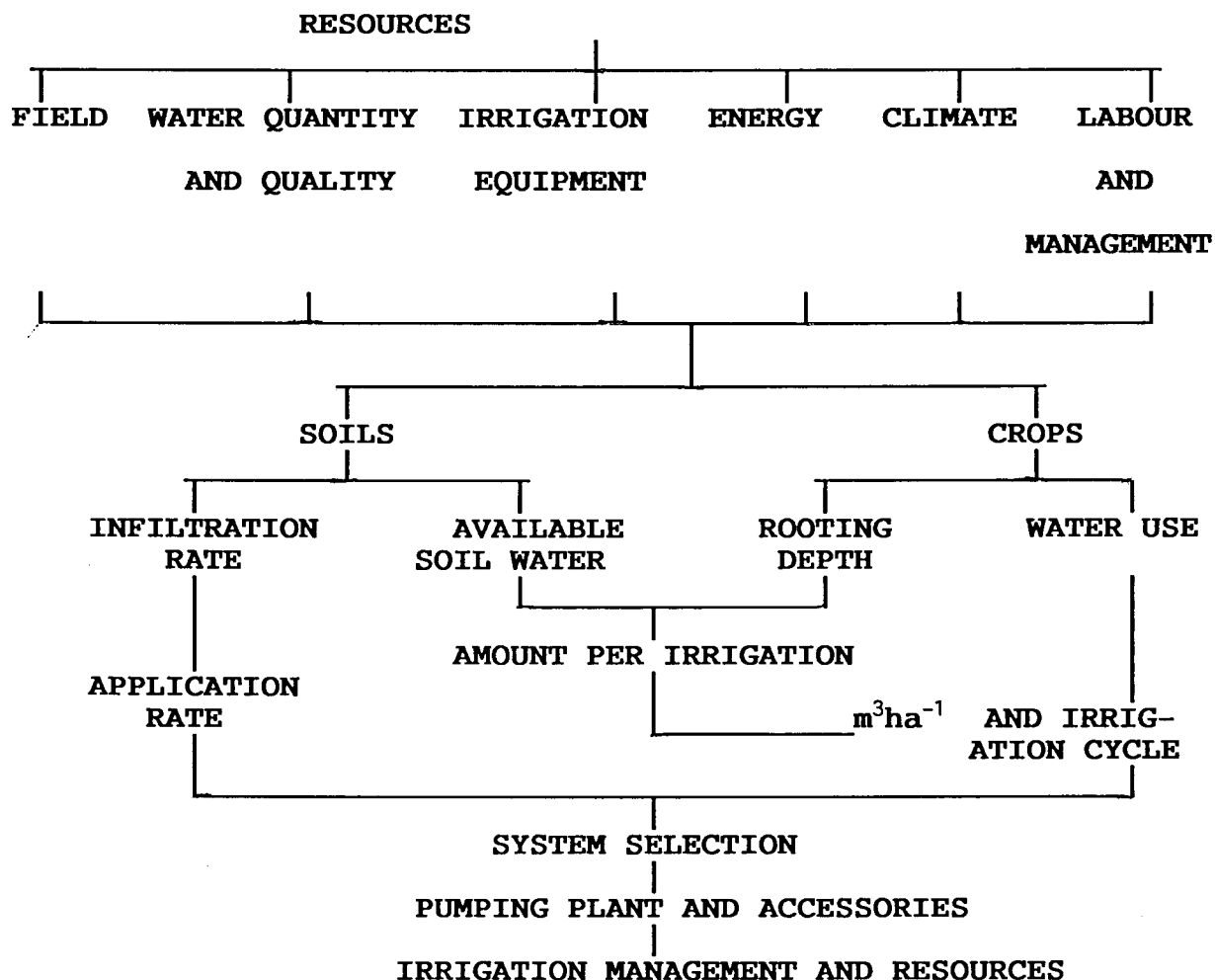


Fig 2.1.2 Flow chart illustrating factors considered in irrigation system selection and management

In 1983, Steinberg, Clapp-Winek and Turner (1983), reviewed USAID irrigation projects and concluded that lack of good management is the principal reason why most irrigation projects fail to attain their potential. Although irrigation normally improves yields, it is not a simple matter to improve financial returns and food deficits. Encouraging farmers to plan carefully, undoubtedly improves management. System maintenance is best done at local level. Existing irrigation boards should be encouraged to promote better irrigation practices with their members. Steinberg *et al.* (1983) found that irrigation project planning is subject to a series of pressures prompting hurried approval. Design problems include poor donor co-ordination and failure to

consider adequately such aspects as farmer's needs, prior country commitment, agronomic realities and social context.

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

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 used in projects is critical in developing countries. 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 under-utilisation of production potential. He prefers 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 (1985) found in his review of small-scale irrigation systems 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 for agriculture. They also stated that 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 as to which remedial action will be the most efficient. Reid et al., (1987) provided successful methods of defining and quantifying conveyance losses, and, proposed remedial methods which they had tested successfully.

Studies (Howarth and Benn, 1986) in the United Kingdom on water management in small-holding irrigation schemes have shown that the supply of water to farmers is both unreliable and unequitable. The causes for this rest both in the main 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 both delivery flexibility and uniformity. However, increasing the delivery flexibility may result in less uniform deliveries, which may also reduce the operational conveyance of the delivery system unless this system is also 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. From purely 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 in evaluating crop production under irrigation is the available and required water supply over time and area. When 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 irrigated area. 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 the total growing season.

Doorenbos and Kassam (1979) proposed that when planning, designing, supplying and distributing water to an irrigation project, in relation to water available and water requirements, the procedure must consider:

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

When water supply is limited, selection of crop and irrigated area should be based on crop yields as affected by the extent to which crop water requirements are met by the available water supply over the growing season. Doorenbos and Kassam (1979) stated that for a full evaluation of the effect of limited water supply on yield and production, consideration must be given to the effect of this limitation during the various crop growth stages. With stress sensitive crops, scheduling of 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.

#### 2.1.4 WATER USE EFFICIENCY

Taylor, Jordan and Sinclair (1983) summarised the understanding of the relationships between crop water use and crop productivity. 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 Musick (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.

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

- a) The work of agricultural scientists is frequently directed at the goal of establishing the levels of water input necessary to achieve maximum yield per unit area. This particular goal is implicit in all efforts intended to ensure that water does not become limiting.
- b) Maximum water use efficiency is said to exist when the crop yield per unit of water input is maximised.
- c) Economists argue that water to be used efficiently should be applied up to the point where the price of the last unit of water applied is just equal to the revenue obtained as a result of 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);

$$Y = f(W)$$

Such relationship is termed a crop-water production function.

The average physical product (APP) or water use efficiency which is the output divided by the input,

$$APP = Y/W$$

and, the marginal physical product (MPP) which is the change in yield or output associated with the addition of one unit water,

$$MPP = \Delta Y / \Delta W$$

2.1.13

Vaux and Pruitt (1983) stated that the yield is maximised when the MPP is equal to zero. They maintained that as long as some positive quantity of water is applied, water use efficiency, or APP, is maximised where MPP is equal to APP. Consequently, maximum water use efficiency (APP) can never coincide with maximum yield, because maximum yield occurs when the MPP is zero and the APP only equals zero at zero production which is a non-seasonal solution.

De Jager et al. (1987) using a crop-water production function maximised profit with respect to water application. After Doll and Ozarem (1984) maximum profit is achieved when:

$$\text{MPP} = P_w / P_y \quad 2.1.14$$

where,

$P_w$  = price per unit variable input,

$P_y$  = price per unit output.

Vaux and Pruitt (1983), while reviewing crop-water production functions, indicated that the relationship between yield and applied water has not been studied sufficiently, but that evidence suggests that this relationship is curvilinear. It is this relationship that is relevant to irrigators, in that applied water and not crop evaporation is what the irrigator has control over. As long as water remains relatively inexpensive, irrigators will have little incentive to economise on water use by permitting water deficits which limit production. A general conclusion is that water would be used more efficiently if it were priced according to its true scarcity value.

Economists claim that the efficient use of water, land and other resources depends upon their value in a given activity relative to their value in achieving other purposes. They maintain that efficient water use requires that the irrigator apply water so long as the additional revenue generated exceeds the additional cost of that water. 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 if irrigators maximise profits, efficient production occurs when  $APP > MPP$ . Vaux and Pruitt (1983) implied that efficient production can never be coincident with maximum water use efficiency and will be consistent with maximum water use only if water does not cost anything. Ayer and Hoyt (1981) suggested that optimum irrigations might be less than required to ensure water non-stressed growing conditions.

Carefully managed water deficits might reduce the use of water for irrigation while minimising the impact of stress on yields. This strategy can only be adopted if precise management is practised. For this to become a reality, complete and comprehensive information on the effects of differing levels of water application and alternative sequences of timing on yield must be available. A computerised crop growth model method of conducting such analyses was described in full by De Jager et al. (1987).

Profitt, Berliner and Oosterhuis (1985) found that high frequency irrigation of spring wheat caused the development of shallow rooting as compared to plants under low frequency irrigation. Low frequency irrigation developed deeper roots highly efficient in extracting water, but total water uptake was insufficient to enable plants to transpire at their potential rate. Higher yields and a better water use efficiency were obtained with high frequency irrigations provided plants did not stress during any stage. This is surprising because high irrigation frequency implies high inefficient evaporation from the soil surface.

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

Meyer, Dunin, Smith Shell and White (1987), in comparing measured and estimated water use by irrigated wheat, found that the upward flux from a water table between 1,2 and 2,1m below the surface

may provide up to 30 per cent of daily evaporation. This upward flux will need to be taken into account if efficient irrigation scheduling is to be undertaken in regions where water tables exist.

Bennie and Botha (1986), in comparing the effects of conventional tillage and controlled traffic during seedbed preparation of a sandy soil which included deep-ripping of the subsoil, found a significant increase in water use efficiency and increase in 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 while maintaining a high soil water depletion level with trickle irrigation increased average lint cotton yields by 685 to 868 kg ha<sup>-1</sup> and irrigation water use efficiency from 22 to 33 kg per 25mm water.

Irrigation boards are currently using simple water allocation methods (Mottram and de Jager, 1990) which, in times of water shortages, can lead to dissatisfaction and sometimes dissent within a community. Such problems may be solved by supplying the necessary real-time data as discussed above and ensuring good decisions by bailiffs. Under conditions of no water restrictions water is pro rated according to registered irrigation area.

#### 2.1.5 WEATHER STATION NETWORKS

Recent advances in electronic datalogging have enabled researchers to compute accurate estimates of real time values of reference crop evaporation from hourly weather data (Snyder et al., 1985). An example is the California Irrigation Management

Information System (CIMIS)(Hawkins and Craddock, 1985). CIMIS provides Californian farmers with daily reference 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, eliminate loss of data due to human error and permit for the calculation of crop evaporation from hourly weather data.

Automatic weather stations do not require commercial power at the site and can operate independently of any telecommunication system. In these cases data are usually stored on magnetic tapes until the station is serviced. These tapes are then down-loaded by tape readers onto computers. If power is available, signals (data and commands) can be transmitted via modems and telecommunications networks enabling access to remote sites.

Solar panels are used to supply power to these units (Evans, 1989; Mottram, de Jager and Melville, 1989). A typical system is one which is configured to monitor wind speed and direction, incoming solar radiation, rainfall amount and intensity, temperature (air and soil) and relative humidity (Burman et al., 1983; Snyder et al., 1985; and, Mottram et al., 1989). The sensors used to monitor these climatic variables are exposed as follows:

- Incoming solar radiation - 2m above grass.
- Air temperature - 1.5m above grass,
- Soil - 150mm below soil surface
- Relative humidity - 1.5m above grass
- Wind speed and direction - 2m above grass)
- Rainfall - 1m above grass (Hawkins and Craddock, 1985)

The weather station maintenance manual for CIMIS calls for site visits every two weeks during the growing season and sensor calibration twice per annum. The maintenance visits consist of cutting the grass, cleaning the sensors and checking their operation. Hawkins and Craddock (1985) noted that this maintenance programme paid dividends in that 43 automatic weather

stations operated with less than 2 per cent down time. Net radiometers proved the most difficult to maintain, the main problem being the plastic domes which deteriorate break down in sunlight. The capacitance type of humidity sensor 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. The CIMIS project specify the middle of a large well-maintained pasture. However, it is felt that the site should be representative but also convenient for maintenance. Once operators become aware of the importance of these requirements and the value of the outputs, more emphasis will be placed on ideal siting as was the case in the early stages of the CIMIS project.

Weather stations are connected via telecommunications network and modems, data in the CIMIS network. Beginning after midnight each day computers automatically call up each weather station in turn and download hourly weather values for the previous day. However, CIMIS experienced delays where telephone lines were down. A similar problem is envisaged in Southern Africa especially with the smaller country exchanges which are not yet automatic. This is, however, not an insurmountable problem.

Dissemination of CIMIS information is by various means, viz.:

- a) direct access 24h a day via computer and modems;
- b) printed monthly summaries which include daily means;
- c) monthly newsletters (CIMIS Update) which also contain tables of current, normal and previous year total evaporation values and rainfall for the different areas;
- d) press, television and radio bulletins;

In South Africa the SA Weather Bureau and Agricultural Research council have erected and maintained weather stations. Many national computer networks are in operation and more are

currently being commissioned. Hopefully, water managers will be allowed to access these data.

#### 2.1.6 IRRIGATION SCHEDULING

The factors influencing decision making regarding when and how much to irrigate, include: water supply, crop type, irrigation system, soil data, weather data and economics. Other factors such as electricity supply, salinity control, crop quality at harvest, and the labour aspects in irrigation farming are also important.

Doorenbos and Kassam (1979) report that the responses of crop yield to limited water supply in each crop growth stage need to be assessed. With restricted water supply, irrigation scheduling should be aimed at minimising water deficits in these stages most sensitive to water stress. 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 is primarily determined by the amount of water available and the amount required to attain an optimum crop yield. When water supply is limited but uncontrolled (e.g. supply from a river) the irrigated area is primarily determined by the available supply during the different growth stages, the effect of stress during these stages and the optimum yield.

There are many methods of determining when and how much to irrigate, but the water budget method has been identified as the technique most likely to encourage improved irrigation scheduling by irrigators (Coord. Comm.Irrig.Res., 1982; De Jager, van Zyl Bristow and van Rooyen, 1982; Hawkins and Craddock, 1985; and, De Jager et al., 1987).

California has a large number of private irrigation scheduling services and some of these had already been using the water budget technique before the CIMIS project (CIMIS, 1985). The pre-CIMIS survey showed that the majority of growers did not

consider hiring such services for a number of reasons. Moderately large farm operators, unable to afford the services of full-time agronomist/irrigation specialists recognising their value, used private agencies. Large operators employed such agronomists, while the smaller farmers either developed their own techniques or did not use the water budget technique. One of the main purposes of the CIMIS project was to provide a method for private scheduling services profitably to add smaller farming operations to their clientele and thereby promote the adoption of the water budget scheduling.

For growers, not inclined to use real-time evaporation information an alternative *modus operandi* has been developed.

It is now possible to use historical means of crop evaporation, or annual pre-programmed schedules in a computer decision support system (de Jager, 1992) when scheduling irrigation.

Generating a water budget schedule can be complex and confusing to untrained personnel. Extension officers and managers require straightforward technologies. This places a user-friendly requirement upon practical systems.

Agriculture offers the computer industry an expanding potential market. Computer owners are likely to make full use of their equipment. One additional benefit is likely to be water budget scheduling. The need for inexpensive user friendly software and crop evaporation information will increase in the future.

A problem inhibiting the spread of irrigation scheduling is the little time available to farmers to devote to real-time data scheduling. Most small to moderate farms are owned and/or operated by a person who must manage all aspects of farming, and cannot devote much time to irrigation scheduling without curtailing other activities. In such cases, farmers require user friendly, rapid decision support systems. Examples of such

systems are the computerized PUTU-system (De Jager, 1992 and CIMIS, 1985). Additional useful information is contained in tables based upon historical means of crop evaporation (Green, 1982). All scheduling procedures should be provided with educational programmes.

## CHAPTER 3 : SITUATION SURVEY

### 3.1 INTRODUCTION

A situation survey was conducted in the Winterton irrigation districts and Karkloof area in order to identify those aspects which control overall irrigation project efficiency as well as on-farm water-use efficiencies. The survey was aimed at assisting irrigation boards in their quest to maximise water usage in terms of profitability. It also lent itself to assessing the conservation potential of the area.

All the project co-operators and certain irrigation board members were consulted in the survey.

The survey questionnaire was divided into three sections:

Section A - General particulars.

This included the farmer/owner's particulars, farm location, area, elevation and rainfall.

Section B - Farmer statistics and attitudes.

This included education, experience, sources of information, enterprises, tillage practices, irrigation system, design and application techniques.

Section C - Physical and financial data.

### 3.2 RESULTS OF THE SURVEY

Initially, in 1988, strong resistance to the postal survey was encountered with little or no success being achieved. The strategy was then changed to include personal visits by the researcher to the individuals concerned. With respect to Sections A and B, much information was obtained, little

information was offered for Section C, notwithstanding the stated confidentiality of the information.

#### SECTION A

Twenty-four returns were received from the Winterton (22) and Karkloof area (2). The farms varied from 200ha to 900ha in total size with irrigated areas varying from 50ha to 280ha per farm. The rainfall varies from 700mm to 1200mm per annum with the main rains occurring in the summer season.

#### SECTION B

Educational standards of irrigators varied from high school through agricultural college to university level. The majority have had in excess of 20 years farming experience and, tend to seek additional advice to assist their farming enterprises, from Cedara Agricultural Research Institute and the local cooperatives.

Little or no use is made of universities for advice in whatever field. It is pertinent to report that the majority were not aware that universities offered such services. Those that were, were also aware that they had to pay for such services. This caused some resistance.

Irrigated agriculture in these areas comprised of the following crops being produced under irrigation:

Maize	-	silage, seed maize and commercial grain (summer)
Wheat	-	(winter)
Soyabeans	-	(summer)
Dry beans	-	(summer)
Dry peas	-	(winter)
Annual and perennial pastures	-	predominantly ryegrass (winter and summer)

Common crop rotations are:

maize, wheat, soyabeans/dry beans  
maize, wheat  
soyabeans, wheat  
maize, dry peas, soyabeans/dry beans

The soil types cultivated were predominantly Hutton and Avalon series with clay contents in excess of 30%. Tillage practices favoured the use of the disc harrow for basic land preparation using tyned and rotovator type implements for seedbed preparation. Certain farmers carry out primary tillage (mouldboard plough, heavy disc) every three to four years either as a result of disease or weed build up.

As illustrated later in this report, farmers are not nearly achieving potential yields e.g. maize grain yields in excess of 10 tonnes.

Irrigation systems in these areas comprise of the following:

Centre pivots	-	low pressure
		medium pressure
		towable and static
Wheel moves		
Big guns		
Conventional	-	portable main lines and laterals
Drag line	-	in-line and portable laterals

In the Winterton area, centre pivot systems are in the majority, although in the last five years their numbers have decreased considerably. The main reason for this decrease was improper selection of suitable soils and management of these systems, resulting in the irrigators incurring debt and loss of system and/or land under irrigation.

With respect to electricity supply, the majority of the systems fall under the "small power user" categories and are on the D Eskom tariff. Eskom personnel from the Central Region Office in

Pietermaritzburg cooperated in both the survey and monitoring of power consumption at the selected pump stations.

The survey was terminated towards the middle of 1991 and the issues pertinent to irrigation extracted. Listed below are the salient findings of this survey.

- a) Management decisions made at irrigation board level are not always acceptable to all irrigators. This is especially the case when water has to be allocated and distributed both within and between boards in the area.
- b) When two or more irrigation boards share the same water resource, disputes concerning the allocation and distribution of water can arise between boards.
- c) There is neither accurate nor consistent monitoring of river flow in any of the rivers involved. It is accepted by the boards that this is essential for allocation and purchase of water, especially during periods when water restrictions are imposed.
- d) Systems are not calibrated on a regular basis, if at all. The irrigators tend to accept what the suppliers tell them, or what appears on their quotations.
- e) The irrigation systems purchased are not always suitable for the soil type, the land slope, soil depth and crop type. There is also a tendency to purchase on price alone.
- f) There is a tendency to over irrigate.
- g) There is a tendency to cut short irrigation well before crops have reached physiological maturity with concomitant reduced yields.
- h) Within the Little Tugela Irrigation Board there are insufficient storage dams which, apart from resulting in a

possible shortfall in water supply, also creates dissension within the community when water has to be shared.

- i) Many basic agronomic practices are not being carried out. With double cropping, seed beds are being hastily prepared, giving rise to poor germination and subsequent poor stands. Initial plant population tends to be low for production under irrigation. Poor weed control is all too often evident.

### 3.3 EVALUATIONS, CONCLUSIONS AND SUBSEQUENT REMEDIAL ACTIONS

The present survey successfully highlighted many practical issues which have a profound influence on achieving optimal water use efficiency upon multi-farm projects. Some of these are:

- a) The Irrigation Project Efficiency, or IPE project has liaised closely with the irrigation boards and provided them with many useful suggestions and guidelines. The project contributed decisions regarding the allocation of irrigation water within the Little Tugela Irrigation Board, and the monitoring of water purchased from the Sterkspruit Irrigation Board.
- b) With the assistance of the Department of Water Affairs, the Little Tugela Irrigation Board was instructed how to monitor flow in their various canals. A recommendation has been made to both boards to obtain suitable equipment for the calibration of pumps and canals.
- c) Accurate river flow can be monitored at the first farm on the Little Tugela only. This measurement is satisfactory for Sub-District 1, which is the area lying above the confluence with the Sterkspruit. In order to assess the input of the Sterkspruit to the Little Tugela, a weir above the confluence on the Sterkspruit needs to be constructed. After recommendations to the two boards, a rectangular weir

has been designed and a suitable position on the Sterkspruit selected. In order to control flow, a buffer weir with a suitable outlet has been constructed further up the Sterkspruit.

- d) For the past four years, the project has successfully scheduled the irrigation on selected cooperators' farms. The Little Tugela board's bailiff is using the project's recommendations on a weekly basis to advise members on when and how much to irrigate. This is operating successfully, but a system scheduling programme needs to be developed in order that an efficient irrigation scheduling service can be provided either by the boards themselves or by outside agencies.
- e) Numerous workshops were held as part of the situation survey. At these workshops, the importance of monitoring irrigation amounts was stressed and recommendations of how simply, but accurately to achieve this, was made. The boards should endeavour to encourage strict monitoring of irrigation applications, e.g. no irrigation measurement submitted - no water allocated! The irrigator is not forced to apply the amounts recommended but must record and submit the actual amounts applied.
- f) The importance of calibrating systems became abundantly evident. This led, with the assistance of the Department of Agricultural Engineering, Silverton, to a selected number of centre pivot systems being calibrated. The results of these calibrations were explained to the boards, as were methods of calibration of all systems.
- g) Technology transfer to the irrigators is extremely important particularly with regard to the correct choice of irrigation system. Improved technology transfer will prevent both over-irrigation and premature termination of irrigation towards the end of season.

- h) The need for pre-season planning and monitoring needs to be emphasised. This should be an on-going exercise conducted over a number of seasons. In this manner the amounts of water required by each farm will become known. From this, together with other feasibility studies, the magnitude of water storage dams may be determined.
- i) Only those irrigators who are prepared to improve their management practices will reap the benefits of irrigation. The irrigation boards, together with other professional organisations, must encourage the improvement of practices.

The following criteria are recommended to assist irrigation boards in their decision making.

- a) Beginning of season - estimate the amount of water that has to be allocated to each registered area in order to maximize profits thereon.
- b) Management of water supply - when the water supply is limited as a result of drought, the crop water requirements are not fully met. Allocation of water must now take the crop sensitivity into account. It is proposed that the PUTU crop sensitivity factor (see Chapter 4 and Chapter 7) be used in conjunction with the estimates of soil water deficit.

## PART II: METHODOLOGY AND RESEARCH SITES

### CHAPTER 4 – METHODOLOGY

#### 4.1 INTRODUCTION

Sources of management water loss may be divided into application, distribution and conveyance losses.

Much can certainly be done to reduce physical leakages during conveyancing of water from source to farm. This, however, is the domain of the engineer and will not be considered here. Of primary importance here will be methods for increasing efficiencies with which water is distributed and applied. The focus of attention is multi- farm situations and particularly overall irrigation project efficiency,  $\epsilon_p$ . Overall project efficiency will be analysed in its various components.

The objectives of Chapter 4 are to:

- (i) Identify aspects of irrigation management which might be manipulated to improve overall irrigation project efficiency;
- (ii) Describe the methodology for accurately determining irrigation requirements for a group of farms.
- (iii) Establish methodology for managing the application, as well as distribution, of irrigation water on individual farms and multi-farm schemes.

#### 4.2 DEFINITIONS

##### 4.2.1 WATER USE AND SUPPLY

Weather is the ultimate determinant of water consumption by crops. Consumption is dictated by atmospheric evaporative

demand. Under water non-stressed (maximum yield) conditions, the total water actually consumed by a plant in a given season is equal to accumulated daily atmospheric evaporative demand as defined in Section 2.1.1.2.

In this study, two cases of management are relevant, these being either water limited and cultivated land area unlimited, or water supply unlimited for the given available irrigable land area. In addition, for both situations, water supply could be either controllable from supply dams, or uncontrollable as when drawn from streams. Certain of the irrigation management procedures here discussed could be applied to both water limited and water unlimited scenarios.

Alexander (1978) has defined numerous concepts significant to this study. Water limited situations usually arise when flow in a river, or the supply from a dam, ceases. With respect to dammed water sources the annual yield,  $AY$ , from a dam was defined as the maximum yield which the dam would be capable of supplying without interruption should the historical flow sequence be repeated in future. This value is obtained from nomograms of annual dam yield. The latter is expressed as a percentage of mean annual run-off,  $MAR$ , and is plotted versus capacity of the dam (also expressed as a percentage of  $MAR$ ). The size of dam providing uninterrupted flow can be obtained from such yield-storage graphs. In most cases dams with a capacity of 160% of  $MAR$  provide an annual yield equal in magnitude to approximately 50% of  $MAR$ . In practice, however, managers frequently, in the case of streams, irrigate areas requiring more water than  $MAR$  or  $AY$  (in the case of dams). This practice results in irrigation scheduling under conditions of limited water supply. When irrigation is provided directly from either a stream or, in the case of a state scheme, a canal, the water supply is uncontrollable (Alexander, 1978). For the latter, minimum stream flow rate,  $SF_{min}$ , will determine the area which could possibly be cultivated to a given crop. Particularly in such cases optimization of water use is imperative.

#### 4.2.2 EFFICIENCIES

Definitions of the concepts important in the investigation of water use and irrigation efficiency follow those given by Shvelik (1987a) with slight modification to make them relevant to this study.

Water use efficiency,  $\epsilon_w$ , is the water evaporated in the crop production process, i.e. plant evaporation  $E_v$ , per unit of water applied over the cropped area,  $V_a$ , viz.

$$\epsilon_w = \frac{E_v}{V_a} \quad 4.2.1$$

Application efficiency is the ratio of the net quantity of irrigation water used to produce the crop to the total quantity applied to the fields. Thus, the application efficiency,  $\epsilon_a$ , is given by the general relationship

$$\epsilon_a = \frac{E - R_e}{V_a} = \frac{V_n}{V_a} \quad 4.2.2$$

where,

- $E$  = crop total evaporation,
- $R_e$  = effective rainfall (rainfall stored in the root zone and used in plant evaporation),
- $V_n$  = net irrigation requirement.

When no water stress occurs;  $E$  is replaced by atmospheric evaporative demand and  $V_n$  is defined as in Eq. 4.2.2.

In practice, some application losses always occur so that  $AED < V_a$  and hence  $V_n < V_a$ . Furthermore, for zero rainfall,  $\epsilon_a$  is a characteristic of the irrigation system itself. Typical data concerning application efficiencies, for zero rainfall, are quoted by Jensen (1980) for different types of systems. They vary between 25% and 95%.

The other relevant efficiencies as defined by ICID (Shvelik, 1987a) are as follows:

Farm canal system efficiency:

$$\epsilon_b = \frac{V_a}{V_f} \quad 4.2.3$$

Farm efficiency:

$$\epsilon_f = \frac{V_n}{V_f} = \epsilon_a \epsilon_b \quad 4.2.4$$

Water conveyance efficiency:

$$\epsilon_c = \frac{V_f}{V_t} \quad 4.2.5$$

Distribution efficiency:

$$\epsilon_d = \frac{V_a}{V_t} = \epsilon_b \epsilon_c \quad 4.2.6$$

Overall project efficiency:

$$\begin{aligned} \epsilon_p &= \frac{V_n}{V_t} \\ &= \epsilon_a \epsilon_b \epsilon_c \\ &= \epsilon_a \epsilon_d \\ &= \epsilon_f \epsilon_c \end{aligned} \quad 4.2.7$$

where,

$V_f$  = water supply to a farm, or to the group of farms,  
and

$V_t$  = total water supply to the irrigation area.

#### 4.2.3 PROJECT/SCHEME

This report will adopt the overseas meaning of the term project. Hence irrigation project is here defined as an irrigation undertaking involving more than one farm.

Thus "project" replaces the conventional "scheme" as used in Southern Africa.

#### 4.2.4 IRRIGATION REQUIREMENT

Net irrigation requirement,  $V_n$ , is defined (see also Eq. 4.2.2) as the difference between crop total evaporation and effective rainfall. Thus,

$$V_n = E - R_e \quad 4.2.8$$

Once again for maximum water non-stressed yields  $E$  may be replaced by AED.

Effective rainfall,  $R_e$ , is the rain water which passes through the plant and produces carbohydrate biomass. It is a function of rainfall amount, soil depth, crop type and cultivation practice.

Most problems experienced, when striving for maximum irrigation efficiency, are caused by the high within and between season variability in  $V_n$ . This feature is adequately illustrated in Fig. 4.2.1. taken from Schvelik (1987a). Using data values subject to such high fluctuation for planning and management decision making, requires careful definition of certain aspects in order to eliminate confusion.

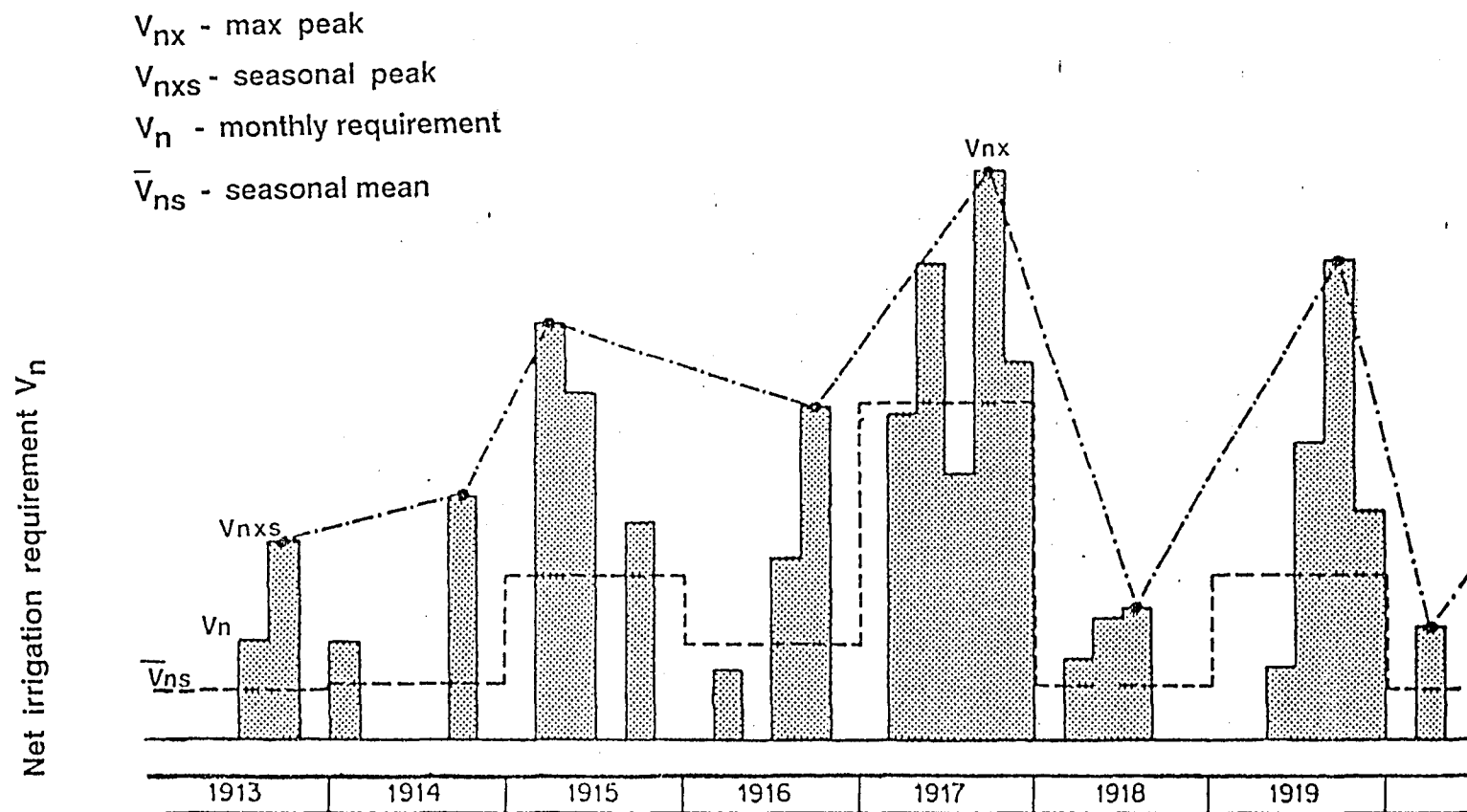


Fig. 4.2.1 Monthly variation in net irrigation requirement for lucerne  
(After Shvelik 1987 b)

It is evident from Figure 4.2.1 that net irrigation requirement varies markedly between and within seasons because of climatic variation. For this reason it is necessary to define:

- the maximum peak net irrigation requirement,  $V_{nx}$ , as the highest historic irrigation requirement,
- the seasonal peak net irrigation requirement,  $V_{nxs}$ , as the peak requirement in a given season,
- the seasonal mean net irrigation requirement,  $V_{ns}$ , as the mean requirement in a given season,
- the mean peak net irrigation requirement,  $V_{nsx}$ , as the average of the peak seasonal requirements,
- the mean net irrigation requirement,  $V_n$  as the average net irrigation requirement over a given period of time, viz., weekly,  $V_{nw}$ ; monthly,  $V_{nm}$ ; and seasonally,  $V_{ns}$ .

The large seasonal fluctuation in all those entities caused by climate is well illustrated in Figure 4.2.1. It is abundantly clear from this that irrigation, (particularly when water supplies are limited) is a highly stochastic phenomenon and any decision must take this into account. These definitions introduce some simple procedures for doing this.

Not only does the variability of the irrigation requirement have a stochastic component, but so does stream flow variability. Thus, the need for calculated risks is unavoidable in irrigation planning and decision making. These risks may be quantified using crop growth models.

**4.3 ASPECTS WHICH CAN BE MANAGED IN ORDER TO IMPROVE EFFICIENCY**  
From the definitions contained in Eq. 4.2.1 to 4.2.8 it is possible to identify critical aspects worthy of consideration

when endeavouring to improve overall project efficiency. These will now briefly be addressed.

#### **Net irrigation requirement (Rainfall efficiency).**

It is evident, from Eq. 4.2.8, that for a given AED and hence presumably also crop yield,  $V_n$  can be decreased by increasing rainfall efficiency  $R_e$ . Increasing  $R_e$  must therefore potentially make a major contribution to increasing the economic efficiency of irrigation water use on an irrigation project. This is best attempted either by paying careful attention to current weather forecasts, or by practising deficit irrigation. The latter dictates that each irrigation must leave sufficient water holding capability in the root zone to ensure that most of any subsequent rainfall will be held in the soil for utilization by plants. The implication is that run-off and deep percolation should be minimized.

Acting upon weather forecasts will diminish the chances of irrigating immediately prior to a rainfall event. This will assist in eliminating run-off and deep percolation.

It is evident that  $R_e$  is not constant for a given situation, but varies each season with rainfall amount and frequency, soil depth and crop type. Because of this, accurate computation of the daily soil water balance becomes imperative for maximising  $R_e$ . Such estimates are computed using a crop growth model.

#### **Overall efficiency**

Once  $V_n$  has been minimised, the next step towards maximization of overall project efficiency (see Eq.4.2.7, viz.  $\epsilon_p = \epsilon_a \epsilon_d$ ) is to maximise individual application and distribution efficiencies.

#### **Water use efficiency**

Water use efficiency (Eq. 4.2.1) is given by  $E_v/V_a$ . Thus, since  $E_v$  is determined by weather and crop, the best manner in which

management could maximise water use efficiency is by minimising  $V_a$ . This can only be achieved by accurate irrigation scheduling.

#### **Application efficiency**

From Eq. 4.2.2 it is apparent that application efficiency is increased by decreasing  $V_a$ , the volume of water applied for a given irrigation requirement. Once again, the way in which to reduce  $V_a$  is to utilize accurate estimates of daily AED and calculations of the daily soil water balance so as to eliminate deep percolation or run-off.

How to determine AED accurately will be discussed in a following section. In addition, a prerequisite for the elimination of drainage is accurate irrigation scheduling, also to be discussed in a following section.

#### **Distribution efficiency**

Distribution efficiencies (see Eq. 4.2.6) are maximised by minimising the amount of water supplied to the irrigation area,  $V_t$ . This generally involves economic optimization of irrigation amounts and the area irrigated for a given quantity of water. Such optimization is ideally carried out using linear programming techniques.

#### **Computation of efficiencies**

The manager may assess his irrigation prowess by attempting to maintain  $V_n$  as low as possible and overall project efficiency,  $\epsilon_p$ , as high as possible. This requires evaluation of Eq. 4.2.7 ( $\epsilon_a \cdot \epsilon_d$ ). Application and distribution efficiencies are calculated using Eqs. 4.2.1, 4.2.2. and 4.2.6 .

Overall project efficiency,  $\epsilon_p$ , is the product of  $\epsilon_a$  and  $\epsilon_d$  (Eq. 4.2.7). As mentioned previously, the former varies between 30% and 100% with 65% a likely value for sprinkler and 92% for drip

systems. Assuming a distribution efficiency to a group of farms of 70% suggests that  $\epsilon_p$  could be of the order of 44% for sprinklers and 64% for drip.

#### 4.4 DETERMINATION OF IRRIGATION REQUIREMENTS

In order to provide optimum  $V_a$  on a farm in a group of farms, it is important to have an accurate estimate of mean and peak irrigation requirements. This will facilitate (a) accurate control of the water supply, and (b) planning of the size of the area to be irrigated and selection of the crop. Peak and mean irrigation requirements have been defined. It is evident that, in order to plan such operation effectively, knowledge regarding past irrigation practices is required. A series of irrigation scenarios needs to be constructed for each crop situation. The best method of obtaining such information is by utilizing a crop growth model in conjunction with an extended climatic time series. From graphs similar to Fig. 4.2.1, estimates of peak ( $V_{nx}$ ), mean peak ( $V_{nxs}$ ), and mean ( $V_n$ ) irrigation requirements may be made.

#### 4.5 ACCURATE DETERMINATION OF AED

There is acute need for the accurate determination of AED as it represents the minimum water requirement for unstressed crop yield. The technique and computational method for determining AED will now be described.

##### Technique

When confronted with a large group of farms, the most convenient and accurate method of estimating AED for a variety of crops and planting dates is to use suitable crop growth models with input data provided by an automatic weather station (AWS).

Recent research has shown that a weather station can provide data for AED computations which are representative of an area of radius up to 50 km around the weather station, depending upon topography. In this way an area, covering a large number of farms, may be served from one central point. This proves to be extremely cost effective and convenient. The installation and maintenance of an AWS for this purpose is described in detail by De Jager, Van Zyl, Kelbe and Singels (1987) and in this report. When several groups of farms which are geographically separated need to be served, it is necessary to transfer data from each of several weather stations to a computational centre. Rapid data transfer is a prerequisite. There are numerous such applications in Southern Africa. The technical details of a suitable telecommunications network providing links to Campbell Scientific weather stations have been described by Mottram, De Jager and Savage (1991).

### Computation

The computation of AED requires an accurate estimate of reference evaporation,  $E_0$ . It has been shown convincingly (Van Zyl and De Jager, 1987; Jensen, Burman and Allen, 1990) that the Penman-Monteith equation is the best available method of achieving this. For the purpose of estimating reference evaporation from AWS data, however, the original Penman-Monteith equation requires several modifications. These modifications, described by Allen, Jensen, Wright and Burman, (1989) have been computerised in the PUTU irrigation model. They include the adjustment of:

- (i) crop canopy resistance to gaseous diffusion according to leaf area index of the reference crop,
- (ii) surface roughness parameters for crop height,
- (iii) windspeed according to height of measuring apparatus, and

- (iv) wind observations to account for whether anemometers were exposed within, or above the equilibrium boundary layer.

Where possible the Penman-Monteith equation should be used in preference to alternative equations. A useful alternative when wind and humidity observations are not available is a modified form of the Priestley-Taylor formula (Meiring, 1989). The necessary algorithms for this are described by De Jager (1992).

The value of  $E_0$  thus obtained is then used to estimate AED and schedule irrigation on the numerous plots of land comprising the irrigation schemes of interest.

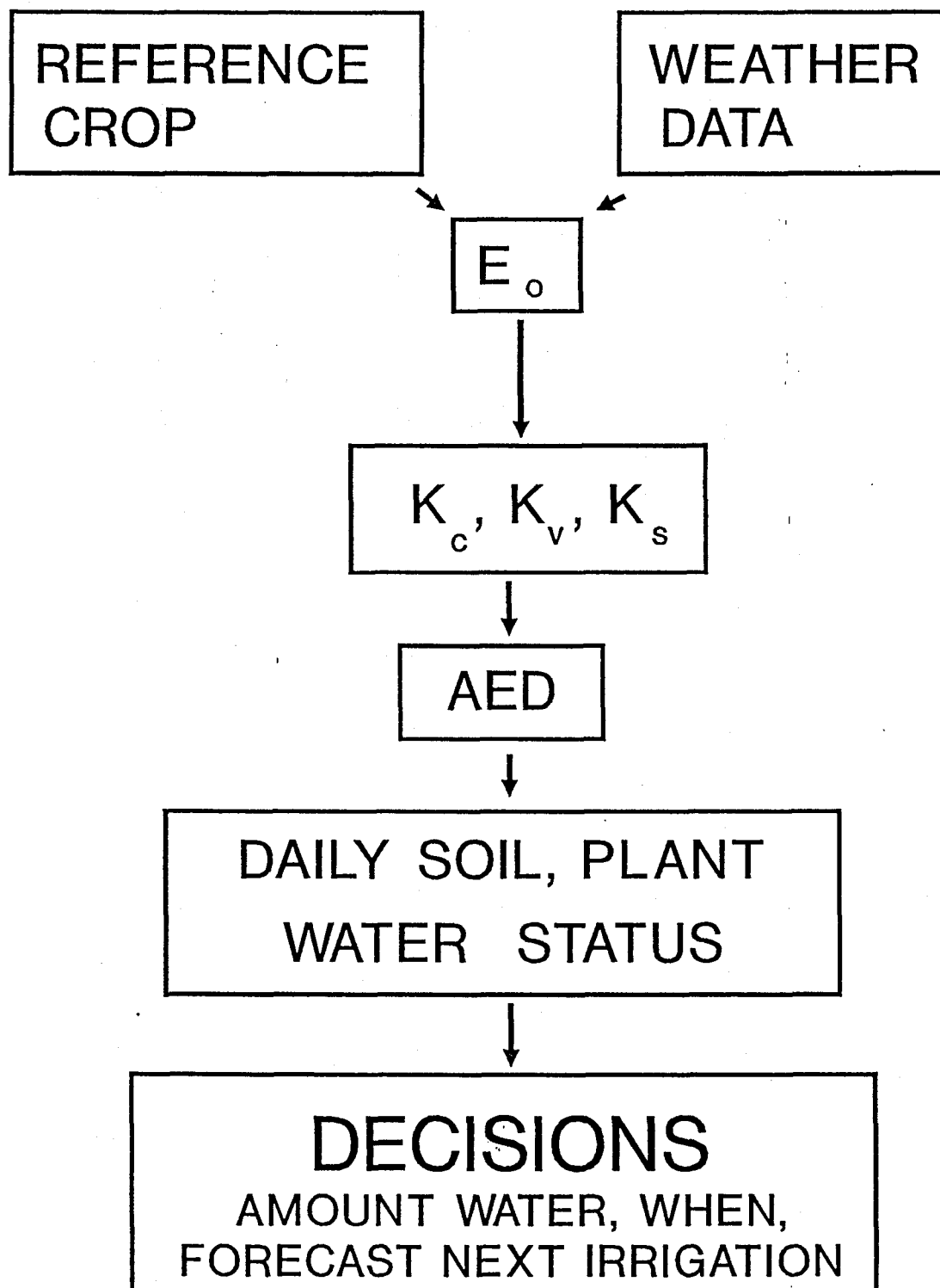


Fig. 4.5.1 Flow chart describing computation of daily soil and plant water status in PUTU which makes possible deciding when how much water should be applied, or how long before the next irrigation. The symbols  $E_o$ ,  $K_c$ ,  $K_v$ ,  $K_s$  and AED are explained in the text.

A description of how AED is obtained from  $E_o$  is given by Mottram and De Jager (1991a). In brief, a computerised decision support system (PUTU) has been developed whereby atmospheric evaporative demand AED and daily crop-water status may be computed from weather data collected by an AWS. The flow chart describing this operation is given in Fig. 4.5.1. Importantly, certain precautions are necessary. These include:

- (a) Selection of a suitable reference crop. The choice here lies between a short grass surface 0,15m or lucerne 0,5m tall, and
- (b) Initialization of the height of all instruments.

Initially AED is computed from reference evaporation,  $E_o$ , multiplied by a crop evaporation coefficient,  $k_c$ . The latter is the sum of a vegetative evaporation coefficient  $k_v$ , defined as the ratio of vegetative to reference evaporation, and a soil evaporation coefficient  $k_s$ , which is the ratio of soil to reference evaporation. Thus, the equation defining actual total evaporation from a cropped surface,  $E$ ,

$$E = k_c E_o, \text{ and} \quad 4.2.9a$$

$$k_c = k_v + k_s \quad 4.2.10$$

Since  $k_v$  is a function of soil water content, leaf area index and  $E_o$ , it can only be obtained by a process of iteration. This technique, which derives daily values of plant water status and plant evaporation ( $E_v$ ), is described in full in De Jager, et al., (1987).  $k_s$  is a function of soil water content of the upper layer of the soil. When atmospheric and soil conditions realise AED, the dependence of  $k_v$  on  $E_o$  disappears and it becomes a function of purely leaf area index. For this case Eq. 4.2.9 is expressed

$$\text{AED} = k_c E_o \quad 4.2.9b$$

Research has shown that both  $k_v$  and  $k_s$  need to be known independently to arrive at a satisfactory value of the overall crop coefficient,  $k_c$ . It is not sufficient to compute a

composite  $k_c$  on the basis of previously measured values of AED and  $E_o$ , as has been a widespread practice. A composite  $k_c$  does not permit adequate simulation of the effect of the drying soil surface on AED. It is therefore necessary to compute  $k_c$  daily using Eq. 4.2.10.

The vegetative evaporation coefficient,  $k_v$ , is computed from leaf area index, which, itself, may either be measured, estimated or computed. The soil evaporation coefficient,  $k_s$ , is computed from the soil water deficit below field capacity in the top 100 mm of the soil.

#### 4.6 DISTRIBUTION STRATEGY

The efficient distribution of water,  $V_t$ , amongst a group of farms is beset with problems. How to attain maximum water use efficiency on a single farm will be considered first. Thereafter, adjustments necessary for the multi-farm situation will be examined. No strategy decisions are possible without crop-water production functions. These are derived using crop growth models and weather data.

##### Use of crop-water production functions

On single plots, the water distribution strategy is decided upon with the assistance of a crop-water production function. An example thereof for wheat is given in Fig. 4.6.1.

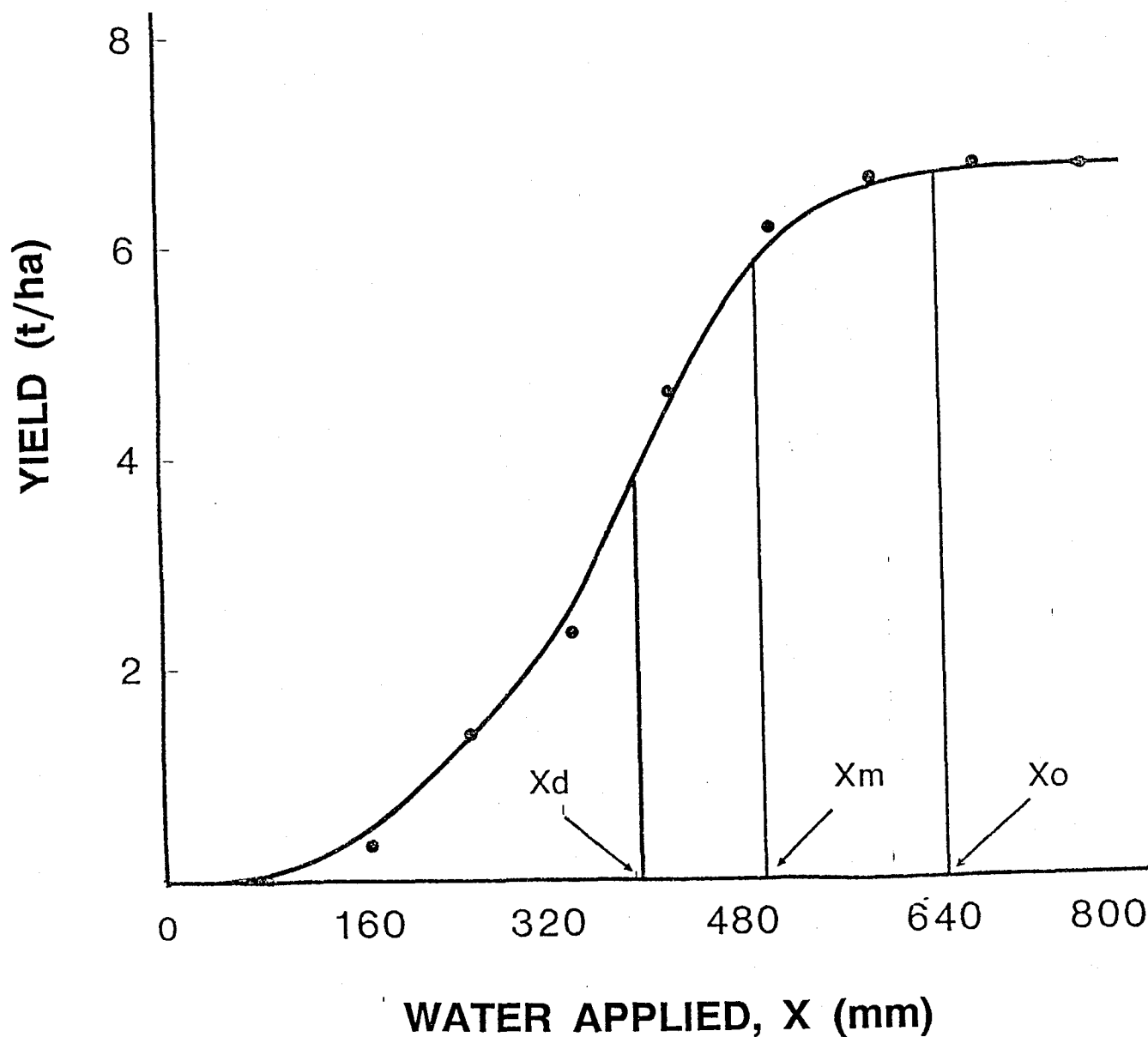


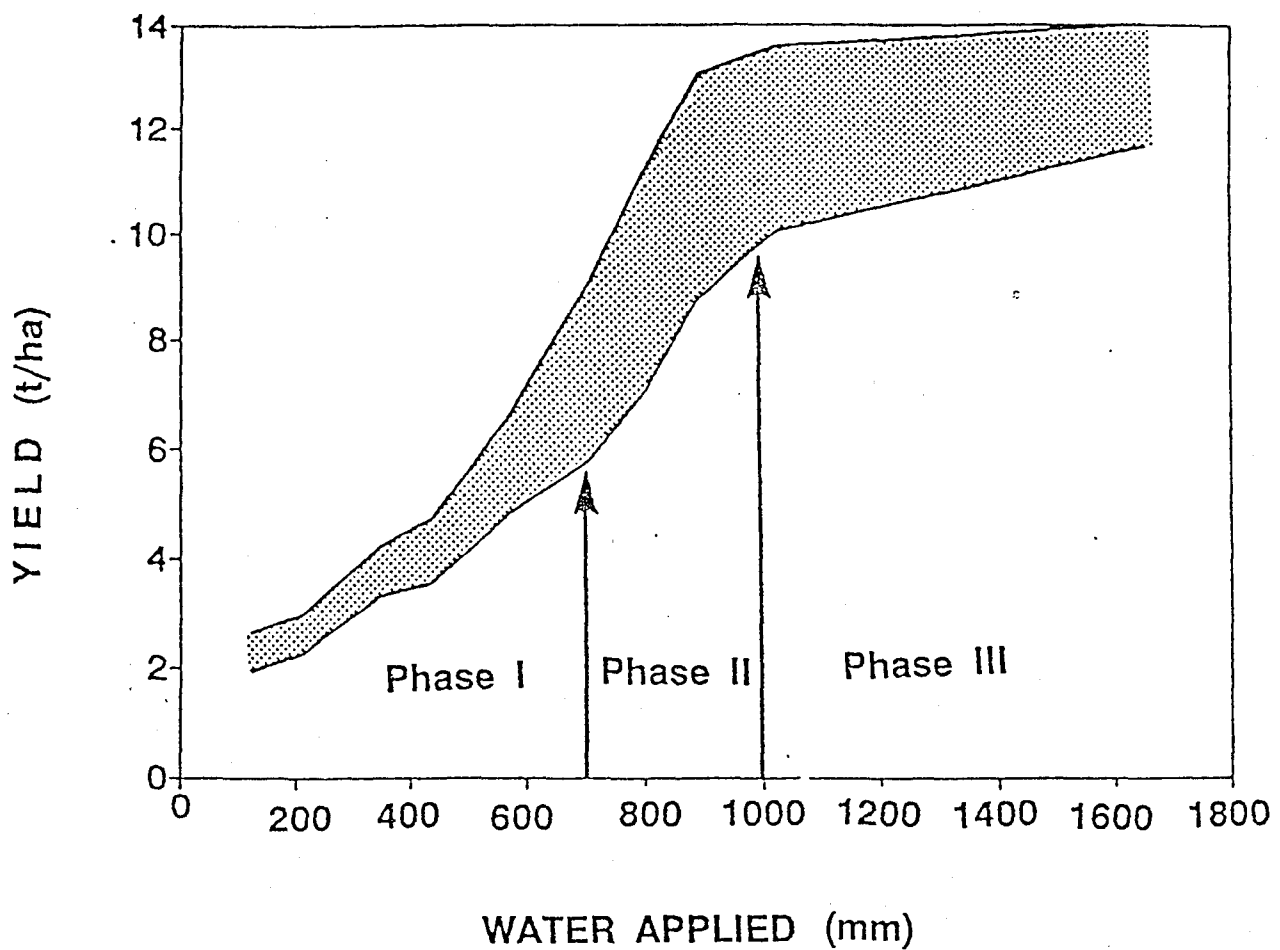
Fig. 4.6.1 The crop-water production curve using several hypothetical irrigation strategies together with weather for the central OFS in the wheat crop growth model PUTU 9. The water application producing the onset of diminishing returns, maximum water use efficiency and the maximum yield are denoted by  $X_d$ ,  $X_m$  and  $X_o$ , respectively.

To ensure economic rationality, the farmer is constrained to operate in the region of diminishing returns (indicated by  $X_d$  and  $X_0$  in Fig. 4.6.1). Maximum water use efficiency is obtained at a water application of  $X_m$ . Similarly, in the multi-farm situation, it must be ensured that all plots receive between  $X_d$  and  $X_0$ . Where a number of plots of land on a number of farms in a group are concerned the equimarginal product principle must be applied (see Doll and Orazem, 1984). This prescribes that the marginal product of additional water must be identical on all plots of land within the project (group of farms). Should this policy be followed, maximum water use efficiency will be attained for the entire project.

The production referred to on the y-axis of the crop-water production function shown in Fig. 4.6.1 is crop yield. Improved decisions would probably result from use of water production functions drawn in terms of gross margin.

#### **Influence of climate**

Seasonal variations in climate drastically affect the shape of crop-water production functions and must be accounted for. Such variability due to climate is illustrated for maize in an arid climate in Fig. 4.6.2, which reflects the mean production function plus or minus one standard deviation. Thus, stochastic effects will necessarily affect the choice of an irrigation strategy.



**Fig. 4.6.2** Variation in crop water production functions for maize due to timing of rainfall and influence of air temperature on phenology and growth processes when a fixed irrigation strategy is applied in an arid climate.

This variability makes it difficult to determine the boundaries of the region of diminishing returns (Phase II in Fig. 4.6.2.). As a first step it is suggested that the curve through the long term mean minus one standard deviation be adopted. This represents a risk averse decision because it means that, on 84% of occasions (seasons) yields will exceed those predicted by such a production function. Phase II for maize is therefore found between the two arrows in Fig. 4.6.2. It is interesting to note that since the standard deviation lines diverge but little from the mean curve, the choice of  $X_d$  and  $X_o$  are relatively insensitive to climatic variation.

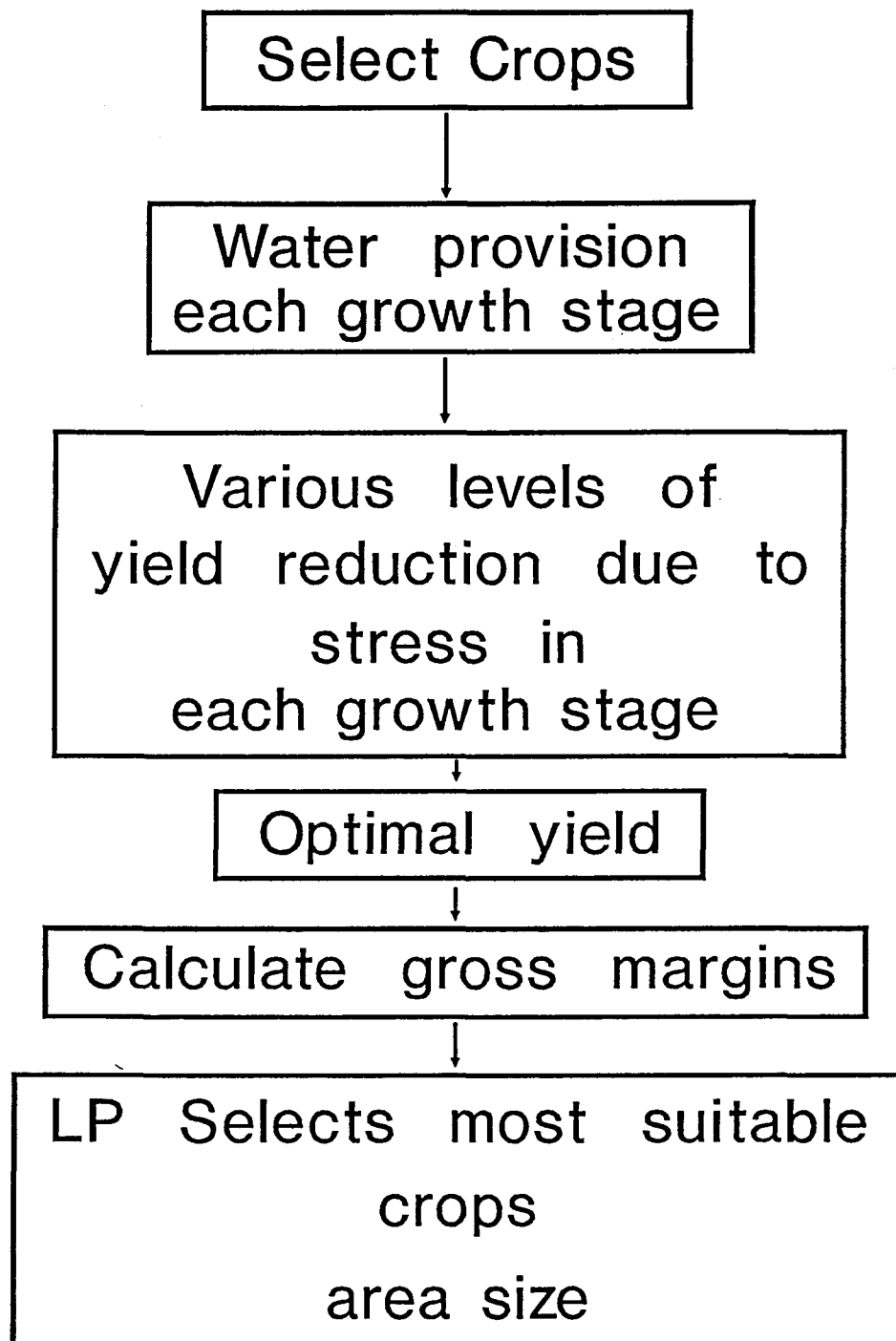
It needs to be stressed that, due to climatic variability, the SE of estimate of yield of crop water production functions can be as high as 27% of the mean yield. Furthermore, we have found (unpublished data) curvilinear crop water production functions fit data better than do straight line functions.

Maximum economic efficiency and maximum water use efficiency seldom correspond.

#### Use of linear programming

As a first approximation, striving for maximum efficiency on each farm in a group with the help of crop-water production functions would lead to a high overall efficiency for the group. The sophisticated approach however, would be to apply the equimarginal product principle recommended by Groenewald (1991). He states that equalizing the degree of yield reduction due to water stress permitted within each crop growth stage will minimize seasonal yield losses. Linear programming procedures can be used for this. The objective of these will be to optimize areas placed under given crops and the amount of water applied. An outline of the procedure for such linear programming is given in Fig. 4.6.3.

# LINEAR PROGRAMME PROCEDURE



**Fig. 4.6.3** Procedure and steps undertaken in linear programme which determines final gross margin, crop rotation and size of area under each crop.

In order to undertake optimization using a linear programme, a suitable objective function in terms of yield, applied irrigation and cropped area needs to be established. An additive form of crop yield equation (see De Jager, 1992) is given by:

$$Y_c = \sum_i Y_{ci} \quad 4.2.11$$

where  $Y_c$  denotes final yield for a given crop  $c$ , and  $i$  represents crop growth stage.

Since it is required to express yield in terms of water applied, Eq. 4.2.11 needs to be transformed to terms of relative yield deficit so that the relationship between this latter concept and relative evaporation deficit of Doorenbos and Kassam (1979) and Stewart et al., (1977) may be invoked. This relationship reads

$$\frac{Y_{oc} - Y_c}{Y_{oc}} = k_{yc} \frac{(AED_c - E_c)}{AED_{oc}} \quad 4.2.12$$

where, subscript  $_o$  denotes maximum value under no water stress and  $k_{yc}$  is called the yield response factor. In this chapter after, Doorenbos and Kassam (1979), the symbol  $k_{yc}$  will be used to denote the yield-water stress response factor. These authors based their work upon Stewart et al., (1977) who used the symbol  $\beta$  for precisely the same factor. When the models are validated in Chapter 9 symbol  $\beta$  will be reverted to so as to conform with the work of Stewart et al., (1977) and Jensen (1968).

When  $\Delta$  is taken to denote decrement below the maximum value,

$$\frac{\Delta Y_c}{Y_{oc}} = k_{yc} \frac{\Delta E_c}{AED_c} \quad 4.2.13$$

Crop yield may then be estimated from

$$Y_c = Y_{oc} \left( 1 - k_{yc} \frac{\Delta E_c}{AED_c} \right) \quad 4.2.14$$

Eq. 4.2.14 can be expressed in terms of reduced applied irrigation by making the simplifying, yet justifiable, assumption

that reduction in  $V_{ac}$ , water applied to the cropped area, is equivalent to the reduction in  $E_c$ . Thus,

$$\Delta E_c = \Delta V_{ac}$$

and, since optimisation involves consideration of irrigation requirement, this may be transformed using Eq. 4.2.2 to read:

$$\Delta E_c = 1/\epsilon_a \Delta V_{nc} \quad 4.2.15$$

Substitution of this relationship into Eq. 4.2.14 and extending it to accommodate individual growth stages, yields.

$$Y_c = \sum_i Y_{oc} (1 - k_{yci} \frac{1/\epsilon_a \Delta V_{nci}}{\Delta AED_{ci}}) \quad 4.2.16$$

Alternatively, the multiplicative law of Jensen (1968) for combining the effects of water stress occurring in different growth stages may be applied yielding

$$Y_c = \prod_i (1 - 1/\epsilon_a \Delta V_{nci} / \Delta AED_{ci})^{\beta_i} \quad 4.2.17$$

where,

$$\beta_i = \text{water stress exponent for the } i^{\text{th}} \text{ growth stage}$$

Since the objective is to optimize profit; Eq. 4.2.16 needs to be transformed so as to enable calculation of gross margin.

First, the maximum gross margin per unit area for the crop when no reduction in yield due to water stress was experienced,  $GM_{oc}$ , may be expressed by

$$GM_{oc} = Y_{oc} * SP_c - DAV_{oc} \quad 4.2.18$$

where  $SP_c$  is the selling price of crop type  $c$  and  $DAV_{oc}$  represents the directly allocatable variable crop production costs without plant water stress.  $DAV_{oc}$  includes production harvest and the variable irrigation costs,  $CW_c * V_{noc}$ . Where  $CW_c$  denotes the cost per unit of irrigation water applied to the given crop. Currently  $CW_c$  is rated at R0,5 mm<sup>-1</sup> of water applied (Meiring, 1989). In the event of less than maximum water requirement ( $\Delta V_{nc}$ ) being applied; the corresponding gross margin is expressed from Eqs.

4.2.16 and 4.2.18 as

$$GM_c = GM_{oc} - \sum_i (Y_{oc} * k_{ci} \frac{1/\epsilon_a \Delta V_{nci}}{AED_{ci}} SP_c - CW_{ci} * \Delta V_{nci}) \quad 4.2.19$$

Apart from the normal variable production costs, it is thus apparent that calculation of  $GM_c$  requires the following input values:

- (a) Water non-stressed final crop yield ( $Y_{oc}$ ).
- (b) Selling price of the crop ( $SP_c$ ).
- (c) Irrigation decrements below maximum in each crop growth stage ( $\Delta V_{nci}$ ).
- (d) Maximum atmospheric demand in each crop growth stage ( $AED_{ci}$ ).

For a variety of different crop types, gross margin can be maximised at given applied irrigation in each growth stage using linear programming. The objective function for this is:

$$MAX = \sum_c \sum_{i=1}^{i=n} GMC_{ci} * A_c \quad 4.2.20$$

where,  $A_c$  is the area planted to crop  $c$  which has  $n$  growth stages. Eq. 4.2.20 is used in conjunction with Eq. 4.2.19.

Integrating yield reductions due to insufficient water applied in growth stage  $i$  (see Eq. 4.2.19), is necessary for the linear programme optimization of area planted, crop type and water applied is to be attempted. How to overcome this is explained in Chapter 7 by Mottram, De Jager, Munton-Jackson and Gordijn, (1991). Examples of the results obtained applying this method to different rotations in Winterton and Rietriver are also given in Chapter 7.

For the purpose of the linear programme;  $GMC_{ci}$  needs to be calculated for each growth stage at each irrigation level. To achieve this, Eq. 4.2.19 must be modified to include

$$\begin{aligned}
\text{GMC}_c &= \sum_i \text{GMC}_{ci} \\
&= \sum_{i=1}^{i=n} [(Y_{oc}/n - Y_{oc} * k_{ci} \cdot 1/\epsilon_a \cdot \Delta V_{nci}/\text{AED}_{ci}) \text{SP}_c - \text{DAV}_{ci}/n] \quad 4.2.21
\end{aligned}$$

where

$$\begin{aligned}
\text{GMC}_{ci} &= \text{Gross margin in growth stage } i \text{ for crop } c \\
n &= \text{Number of crop growth stages, and} \\
\text{DAV}_{ci} &= \text{CW}_c * \Delta V_{nci} \quad 4.2.22
\end{aligned}$$

Necessary information includes either a) knowledge of the water available (say 700 mm ha<sup>-1</sup>) in the pre-season, or b) when the farmer has already planted a given area, how much water will be available for the rest of the season.

It is evident that the method may easily be extended to numerous irrigation plots in a group of farms. As such it constitutes a powerful decision support procedure for managing irrigation.

Use of Eq. 4.2.17 instead of Eq. 4.2.16 for estimating yield decrements in given growth stages complicates the linear programming proceedings. A dynamic linear programming optimisation should however be possible and should be investigated.

#### 4.7 IRRIGATION SCHEDULING FOR MAXIMUM APPLICATION EFFICIENCY

##### The limited water supply situation

As explained, when water supply is limited, two situations are possible, viz. those pertaining when supply is deemed controllable (from water stored in a dam) or, deemed uncontrollable (from a river only). The latter will be discussed here as all the principles relevant to it may be applied to the former as well.

As a first approximation, the area to be cultivated to given crops can be calculated using the following equations.

Where net irrigation requirement is denoted  $V_n$ , the size of irrigated area,  $A$ , may be calculated as follows

Controllable situation:

$$A = \epsilon_a \epsilon_b AY/V_n = 0,5 \text{ MAR}/V_n \quad 4.7.1$$

Uncontrollable situation:

$$A = \epsilon_a \epsilon_b SF_{\min} / V_n \quad 4.7.2$$

where,  $SF_{\min}$  is the minimum expected stream flow rate.

Such calculations are simplistic however, as they do not take into account the vagaries of weather.

Strategy decisions are, however, more appropriately carried out by matching crop water use to minimum water supply rate. The risk of high crop water use at a given site must be determined. De Jager and Singels (1991) offer a good example of a graphical presentation. Here, risk is defined as the probability of non-realisation of a given seasonal peak weekly water requirement. Such information is obtained by computing the highest weekly AED each year using a crop growth model. The longest period possible for which there are data available must be used. The risk averse manager would plan to irrigate fully an area size for which rainless weekly crop water use would not be exceeded in 84% of all seasons (a safe practice).

Further, to facilitate decisions of this nature, the entrepreneur requires an indication of yield losses expected for various reduced stream flow rates. For such conditions peak irrigation equals stream flow rate. Once again, crop growth simulations using weekly weather data may be used to compute expected yield for different minimum stream flow rates. The results may be graphically presented as expected relative yield (as a percen-

tage) versus seasonal peak weekly irrigation supply rate (see De Jager and Singels, 1991). Generally a large variability is expected in yield due to climatic variability. It is much evident from figures reported there.

#### 4.8 WEATHER DATA MEASUREMENT AND RETRIEVAL

##### 4.8.1 INTRODUCTION

Automatic weather stations were used to collect the weather data required by the PUTU system for the various research sites mentioned in Section 5.1. These weather stations monitored hourly values of temperature, relative humidity, incoming solar radiation, rainfall, wind speed and direction. Here follows a description of the measurements and retrieval procedures employed.

Full instructions on how to programme the relevant data loggers is provided with the PUTU-system user manual (De Jager, 1992).

##### 4.8.2 AUTOMATIC WEATHER STATIONS

###### 4.8.2.1 General

Each AWS comprised of a datalogger, tape recorder and the necessary sensors to monitor the weather variables listed in 4.8.1.

Campbell Scientific CR10 dataloggers are used in all but two stations (viz. Taung and Molatedi). CR21 models from Campbell Scientific are used at Taung and Molatedi.

A Campbell Scientific model SC95C short-haul call modem was connected via its interactive port to the RS232 COM1 port of the computer. This SC95C modem is powered by 13,5 VAC and is connected via a shielded twisted pair cable, whose total wire resistance does not exceed 600  $\Omega$  in both directions, to a

Campbell Scientific model SC9A short-haul modem at the weather station. This SC95A modem was connected to the CR10 data logger.

More recently the SC95A and SC95C short-haul modems have been superceded by the RAD haul Model SRM-6A short-haul modem.

The Campbell Scientific PC208 software package (as part of a suite of communication and telecommunication programs) enables the data logger to be computer controlled remotely with respect to programming, real-time data monitoring and data transfer.

Two solar panels, connected in parallel, supply regulated power to the 12 VDC battery during daylight hours. The rectifier circuit is such that these panels do not drain the battery during the night.

An automatic weather station and sensors, as described above, costs approximately R18000 (excluding the cost of the computer). The labour costs incurred in general maintenance of such a station are minimal when compared to those of a SA Weather Bureau First Order weather station monitoring similar variables. The capital costs of a first order weather station are also approximately R18000 (Botha, Cedara, personal communication, 1990). Data obtained using a first order station are daily maximum and minimum values and instantaneous recordings of the variables at specific times viz. 08h00, 13h00 and 18h00. The labour costs of a first order weather station include maintenance costs for the grass surrounds and maintenance of the sensors and recorders, as well as recording certain variables three times per day. There are also significant additional costs associated with the use of wind speed and direction wax chart paper as well as chart paper required by other clock-type recorders. For some stations, Campbell-Stokes sunshine recorder data are used to calculate daily total radiant density from an Angström-type relationship. The cost of this process involves the cost of the recorder, the sunshine cards and the labour costs associated with changing the cards each day and the time-consuming task of

determining the hours of sunshine for each day and then calculating the daily total radiant density. In the case of the automatic weather station, instantaneous solar irradiance is recorded and the daily total radiant density routinely calculated.

The CR10 logger combines a micro-computer, clock, multimeter, calibrator, scanner, timer, frequency counter, and a controller in a compact, sealed, stainless steel package. It is powered by a 9.6 to 16 VDC power supply, in these instances a motor cycle battery electrically charged by a solar panel mounted on the tripod which supports the weather sensors and the weatherproof case housing the logger itself. The standard CR10 utilised, has 12 analog input channels, 8 digital input/output channels, 2 pulse counting channels and 3 switched excitation channels.

The standard CR10 instruction set includes 30 measurement instructions, 43 processing/math instructions and 15 programme control instructions. The CR10 standard memory configuration allows storage of 29900 data points. The RC35 cassette tape recorders employed store 180K data values on one side of a C60 tape. This is equivalent to approximately 6 months' data.

The wind speed sensor utilises a reed switch located on the control axis of the sensor. Two magnets are attached to the hub of the rotating 3 cup assembly, providing two contact closures of the reed switch for each revolution of the cup assembly. The wind direction sensor utilises a 10 kohm plastic potentiometer whose wiper is rotated by a vane assembly. The rotation angle is 358 degrees.

The temperature sensor, an ECO model TP87 comprises a sensing element in series with a resistor to linearise the sensor output. The two components are mounted in a metal tube sealed with polyurethane. The sensing circuit operates as a variable potential divider, the resistance of the sensor varying with temperature. A stable DC reference voltage must be applied. A

programmed reference voltage of 2000 mV DC is supplied by the datalogger. The use of this voltage enables the temperature sensor to be interfaced to the datalogger without the use of further interfacing electronics over the range of  $-20^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ .

A LI-200SA pyranometer sensor from LI-COR, USA, is used to monitor incoming solar radiation. This pyranometer features a silicon photovoltaic detector mounted in a fully cosine-corrected miniature head. This pyranometer does not cover the full range of the solar spectrum, but the error induced is  $\langle +/ - 5\%$  under most conditions of natural sunlight.

Rainfall is monitored using a tipping bucket raingauge which has a resolution of 0,2mm. It is recommended that an insecticide be incorporated within this structure to ensure the funnel leading to the buckets does not become obstructed.

Relative humidity is monitored using a XNAM 10205 humidity sensor. This transducer is generally a composite of organic and inorganic crystals which sense water vapour by the hydromechanical stress of small, but powerful inert cellulose crystallite structures acting on a kovar beam, to which a pair of thermally matched, electrically isolated, silicon strain gauges are bonded in a half Wheatstone bridge configuration. This instrument provides a full range response to relative humidity from 0 to 100%. These XNAM sensors have been found to be subject to drift. It is therefore imperative that regular bi-weekly calibrations checks be carried out. These are easily and rapidly done using sling psychrometers.

Initially, to save costs, wet bulb thermometers were set up to supply the necessary input for the calculation of relative humidity using the wet bulb depression and saturated vapour pressure deficit. These consisted of one of the abovementioned temperature sensors being covered with fine cylindrical gauze bandages, or cotton material, kept moist by cotton streamers connected to water held in suitable glass containers.

These AWS have operated very successfully over the past 5 years with little or no down-time. Lightning problems have occurred where loggers are linked via telephone modems or cable links direct to a desktop computer. This has hopefully been overcome using radiotelemetry which has operated successfully over the last 6 months at one site, having survived numerous electric storms. More work is needed to improve lightning and surge protection.

#### 4.8.2.2 Calibration of sensors

The wind speed sensors are calibrated in a wind tunnel by the supplier/manufacturer prior to their installation. The sensors have a starting threshold of  $0,45\text{ms}^{-1}$  and follow the equation:

$$V = 0,45 + 0,8616f$$

where,

$V$  = wind velocity in  $\text{ms}^{-1}$

$f$  = frequency of the output pulses per second

For a CR10 logger with a 10s scanning interval, this equation becomes,

$$V = 0,0862f(10) + 0,45$$

Thus the multiplier entered in the programme instructions is 0,0862 and the offset 0,45.

The wind direction sensor's potentiometer is protected from high voltage by connecting a 10kohm in series with its own fixed resistance of 10kohms. In order to determine the multiplier and offset of the instrument, carry out the following:

- (a) Connect sensor leads from the logger as follows:
  - analog ground to the potentiometer ground
  - high input channel to the wiper of the potentiometer
  - excitation channel to the fixed resistance of the potentiometer
- (b) Program the CR10 for a multiplier=1 and an offset=0. Enter the \*6 mode and select the wind direction channel. Slowly

rotate the vane until the highest voltage is read on the keyboard. Note the reading, it should be about 1VDC +/- .1VDC.

The multiplier to convert the input voltage to degrees of direction is determined by dividing 360° by the full scale input voltage noted above.

$$\text{e.g. Multiplier} = 360/1,021 = 352,6^{\circ}$$

where,

1,021 is the full scale sensor output

Change the multiplier in the CR10 program instruction to 0,353 and the CR10 will read 0-360° full scale.

The temperature probes are calibrated by the CSIR prior to purchase. On site comparisons with datalogger wet and dry bulb temperatures with a sling psychrometer are made at regular intervals.

The pyranometers were compared with one another under the same conditions to monitor any variation. No significant differences were forthcoming.

The tipping bucket raingauges are checked using pre-determined volumes of water.

The humidity sensor is calibrated by suspending the sensor immediately above saturated salt solutions. Calibration at 12.5% is done over a Lithium chloride saturated salt solution with an excitation voltage of 2000mV. Calibration at 75.5% is done over a saturated sodium chloride solution with an excitation voltage of 2000mV.

#### 4.8.3 DATA RETRIEVAL

##### 4.8.3.1 Introduction

Recent technological developments in electronics have found

application in agricultural systems (Mottram and de Jager, 1990). With respect to estimating irrigation at both research and field levels, electronic data logging has enabled researchers and agricultural consultants to compute accurate and reliable estimates of real time reference values of crop evaporation from hourly weather data accessed by computers from automatic weather stations.

All surface weather networks require that the data collected at a particular site be transmitted to some centre for collation and transformation for user access. These surface weather networks require manpower and this in turn incurs high costs, the possibility of errors during transmission and loss of time.

A near-real time Automated Weather Data Network (AWDN) was developed for support of agriculture in Nebraska (Hubbard, Rosenberg and Nielsen 1983). The automatic weather stations comprised Campbell Scientific (Logan, Utah) CR21 data loggers (now generally replaced by the CR10) and associated sensors and were connected via telephone modems to a centrally located computer. After retrieval, the data were visually checked, sorted for the most recent 24 h period and then merged into the data archive. Thereafter the data were transmitted to a mainframe computer connected to the Agricultural Management Network known as AGNET.

AGNET was established in 1975 and designed to provide information to individuals, firms, and organisations involved in the complex production, marketing and coordinating activities epitomizing modern agriculture (Meyer, Hubbard and Wilhite 1988). Six of the software programs available on AGNET can access weather data directly.

The California Irrigation Management Information System (CIMIS, 1985) is the major irrigation management programme of the California Department of Water Resources (Synder *et al.*, 1985). CIMIS is a computerised weather network that was developed to

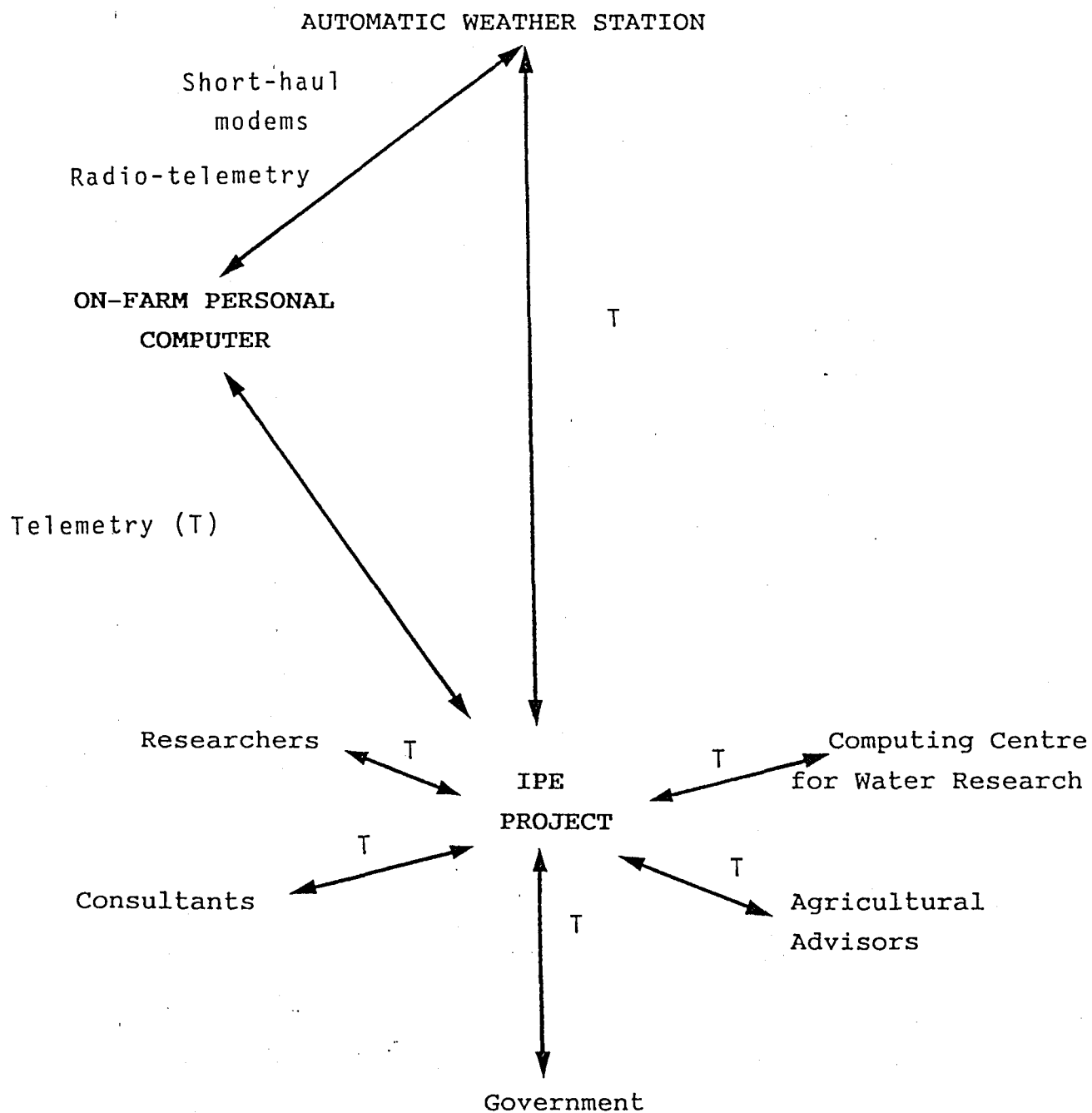
provide crop evaporation information to Californian farmers for irrigation scheduling purposes. In 1985, CIMIS estimated crop evaporation at 43 locations in California using data from automatic weather stations. These automatic weather stations comprise Campbell Scientific data loggers for use with the associated sensors for microclimate measurement. Daily data are transferred to the data acquisition centre in Davis, California where they are quality checked and thereafter used in the estimation of crop evaporation using a modified Penman equation.

Up until the advent of this project, no irrigation scheduling services, using near-real time weather data, were available to Southern African irrigators. In CIMIS (Synder *et al.*, 1985), automatic weather stations are used as they speed up the data collection process and eliminate loss of data due to human error. Doorenbos and Pruitt (1977) suggested that automatic weather stations and computers be used to calculate crop evaporation using hourly weather data.

Many on-farm operational decisions depend upon dynamic and constantly changing factors. One such variable is weather. A weather data network provides the necessary data which can greatly assist farmers by facilitating the scheduling of irrigation, both on-farm and for irrigation project water distribution.

The aim of this section is to present details of a network for collecting, collating and transferring on-farm weather data to a personal computer, in order that it may be used for agricultural management decision making.

An on-farm network and the flow of weather data within a telecommunication network in order to facilitate user access to the data generated by the IPE project (De Jager, Mottram and Melville, 1988) is shown (Fig. 4.8.1).



**Fig. 4.8.1** On-farm weather data network link-up to IPE project indicating the proposed flow of data through the IPE project.

#### 4.8.3.2 Different methods of retrieving data

##### Remote programming of data logger

Use of the program TERM (part of the PC208 software from Campbell Scientific) allows one to remotely program the data logger. One specifies station name followed by /E to edit the parameters used to indicate data logger type, communication adaptor, baud rate as well as the interface device viz. SHORT-HAUL. One specifies T to emulate the terminal and either 7H or 2718H to place the CR10 logger in the remote keyboard state. The CR10 responds by sending a carriage return, line feed and the > prompt. The CR10 logger is now ready to receive the standard keyboard instructions.

Once remote communications are complete, the CR10 logger must be returned to the telecommunication command state by entering \*0.

##### Data logger to tape recorder to computer communication

The logger may be programmed manually or, by computer via the short-haul modems. All the data from its memory may be recorded on an audio-cassette tape at either pre-determined time periods via the logger or manually using the portable key pad. The data on the tape, the latter removed and replaced manually, are downloaded by the computer using the PC201 tape recorder card.

##### Data logger to short-haul modem to PC communication

The modems need to be correctly coupled to each other, the data logger and the mains supply via the 13,5 VAC transformer. In the case of the CR10, instruction 96 has to be executed at the end of the output instructions in the program table. This instruction is used to activate the tape, storage module or serial data (printer) output.

- i) To monitor data loggers at different locations - use the TERM program to select the appropriate data logger and communications port (COM1 or COM2). TERM will prompt for this information whenever a new station name is entered or /P option is entered following an existing station name.

Once the necessary parameters have been entered, a file is saved with the relevant station name plus the extension STN. To monitor recorded values, call the station by pressing the key M. The variables monitored are updated at the rate defined by the CR10 logger's program execution interval of its Table 1. To exit monitoring locations press CTRL\_ and then Q to quit the TERM program.

- ii) To retrieve and store data - the program TELCOM allows PCs to retrieve and store data from a CR10 logger. TELCOM will prompt for the station name.

To edit parameters, the station name must be followed by /e. The edit parameters sub menu requires the data logger type, data collection method (select "since last call or most recent"), append file, data file format (select "comma delineated ASCII"), fix clock time and other options to be specified.

In order to transfer the data in the data logger's final storage, change the "next time to call" to a time a few minutes after current computer time.

To transfer the data from data logger to PC, for example, 9/G is entered. This will cause background transfer of all the finally stored data logger data into the file "9.dat" unless another file name has been specified. Thereafter select 9/C to call the logger and thus append the most recent data to the 9.dat file.

#### Direct cable link between data logger and PC computer.

Using double twisted paired cable similar to that used with the short haul modems above, the data logger can be linked direct to the desk top computer. Set out below are the pin connections for the respective RS232 ports on the logger and the computer.

Datalogger	Computer	
(25 pin)	(25 Pin)	(9Pin)
2	2	3
3	3	2
4	20	4
7	7	5

#### 4.8.3.3 Discussion and summary

Once data have been transferred to the host computer they must be transformed and collated into a usable format for use in the field or for storage in an accessible data base. The pathways involved in this process are illustrated (Fig. 4.8.2).

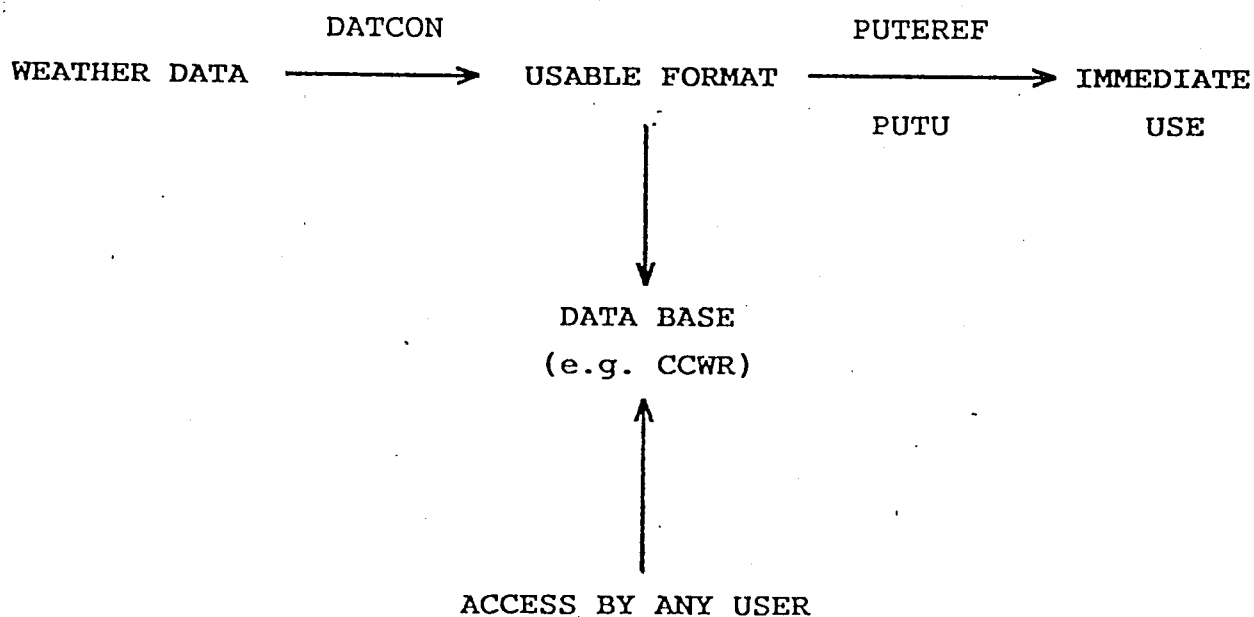


Fig. 4.8.2

Processes involved in data transformation and handling by immediate users and data bases

After retrieval, the data are checked and sorted for the most recent 24 h period and then into a data archive using a wordprocessor package (WordPerfect). Thereafter, the data are converted using the program DATCON. DATCON converts, lists and saves the hourly weather data in the standard format required by the PUTU System, in 1992, for use in the program PUTEREF.

PUTEREF transforms the hourly data to daily data and, calculates daily reference crop evaporation for use in the crop growth simulation model PUTU.

The irrigator can immediately use the reference crop evaporation ratio with the relevant crop factor for scheduling irrigation. Should the PUTU programmes be available, irrigation dates can be forecasted and the sensitivity of the crop to water stress determined from the  $E_0$ -values provided.

These transformed data are also sent *via* modems to the Computing Centre for Water Research, University of Natal, Pietermaritzburg where they become available for registered users.

This network system has been operating successfully for more than 4 years and the weather station has been accessed from various remote computer stations around Southern Africa with no technical problems.

According to the literature, no irrigation scheduling services using near-real time weather data are in operation in Southern Africa at present. As most of the major government irrigation schemes are in the drier areas of the country, water supply is limiting and it is essential that this supply is scheduled effectively.

A network which collects near-real time weather data from an automatic weather station collates and transforms the same, has been established in the IPE project and has been operating successfully. This network included a remote and on-farm PC,

telephone modems with error correction and short-haul modems.

Operational software has been developed and is used together with the commercial software to access the data and transform it for use in locally developed irrigation models and the crop growth simulation model PUTU.

Automatic weather stations which are affordable when compared to current first order manual weather stations. The AWS have proved to be reliable even under extreme conditions and are commercially available. Such weather stations are used in this network which is invaluable for on-farm and between farms water distribution and management.

#### 4.8.3.4 Proposed weather station network

The major goal in operating a weather station network is to ensure that accurate and reliable weather data is collected timeously for use in irrigation scheduling. It is essential that the information be accurate and available near-real time if an irrigator is going to have confidence in it.

The infrastructure of a network which collects near-real time weather data from AWS throughout Southern Africa has been established in this project. The current stations in its network are illustrated in Fig. 4.8.3 and described in Table 4.8.1.

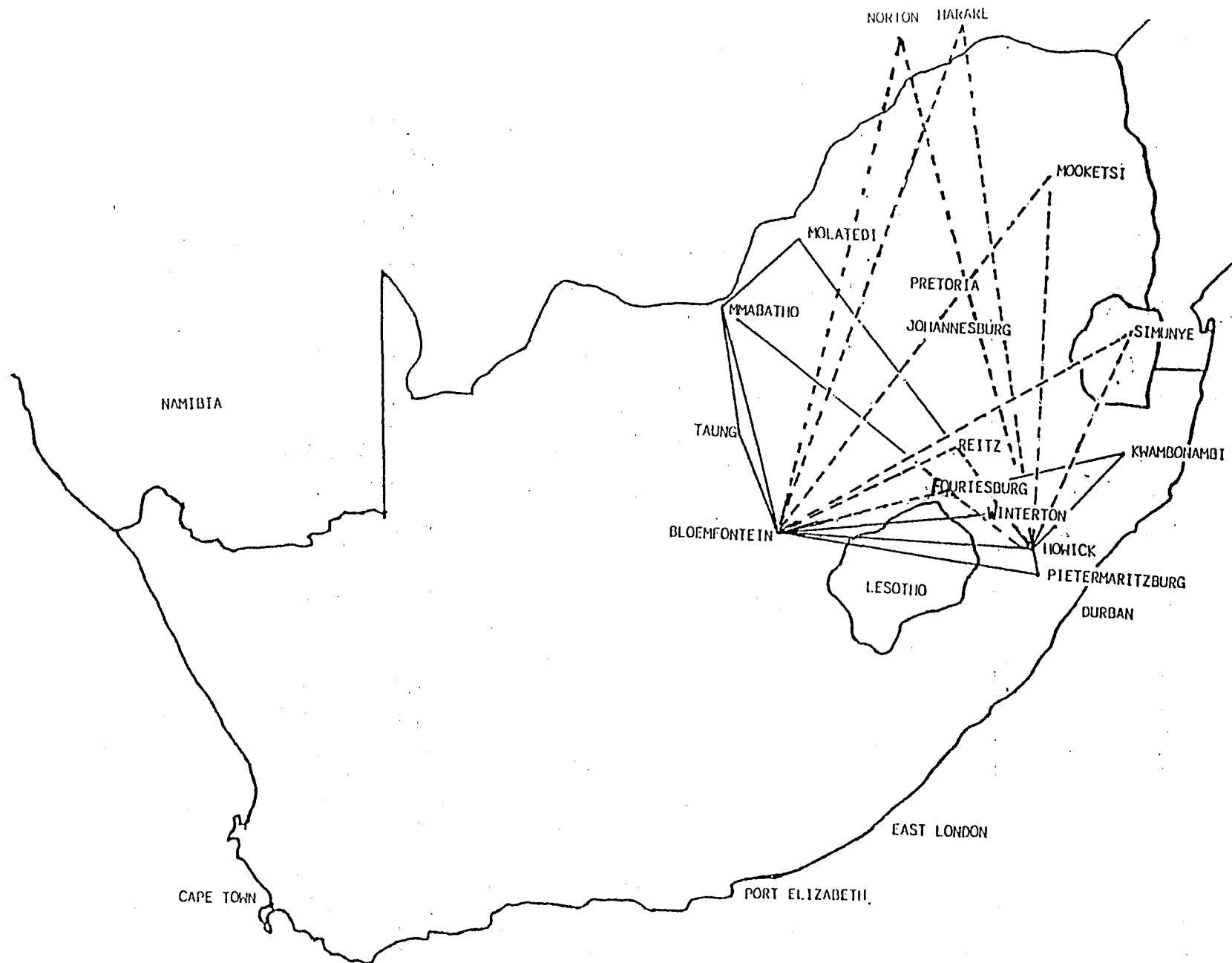


Fig. 4.8.3 Current network for collecting, collating and transferring on-farm weather data in Southern Africa for scheduling irrigation. (Dotted lines indicates those currently being set up)

**Table 4.8.1      Network of automatic weather stations linked to  
the Dept. of Agrometeorology, UOFS, currently in  
operation in Southern Africa**

Station	Location	Network link
8	Reitz, EOFS	Logger via radio telemetry to PC to telephone modem
9	Karkloof, Natal	Logger via direct cable link to PC to telephone modem
10	Winterton, Natal	Logger to telephone modem
11	Winterton, Natal	Logger to telephone modem
12	Winterton, Natal	Logger to telephone modem
20	Taung, Bophutatswana	Logger to cassette tape to tape reader to PC to telephone modem
21	Molatedi, Bophutatswana	Logger to cassette tape to tape reader to PC
23	UOFS	Logger to telephone modem

A number of these stations have been operating successfully in a network for 3 to 4 years. Three of these stations are monitored daily as the irrigators apply water on a daily basis. However, the network has been set up in order that the stations can be accessed at any time.

## **CHAPTER 5 : RESEARCH SITES**

### **5.1 INTRODUCTION**

Experimental areas were selected on the basis of climate, farmer interest, level of management and production potential, and the availability of equipment and personnel.

Here follows a description of participating persons and institutions.

### **5.2 WINTERTON**

The Winterton area in Natal comprises of the Little Tugela and Sterkspruit Irrigation Boards. Fig. 5.2.1 illustrates the areas encompassed by the boards.

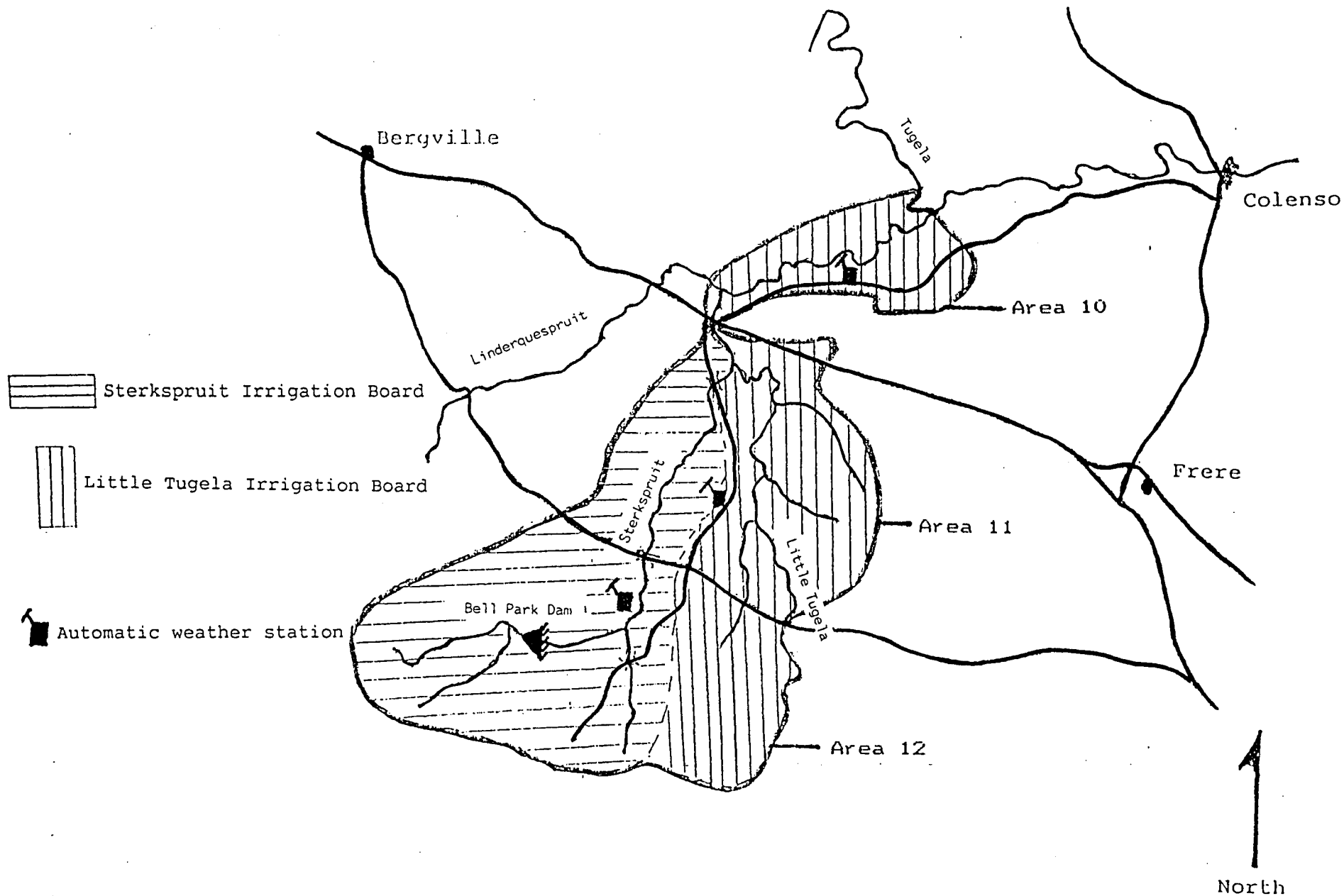


Fig. 5.2.1 Sketch illustrating the area encompassed by the Little Tugela and Sterkspruit irrigation boards

This area was split into three further areas on the basis of rainfall and temperature norms. These areas are:

Area 10 - Gourton Hall area west to the Drakensberg foothills

Area 11 - Gourton Hall area east to the town of Winterton

Area 12 - Winterton, east toward Colenso

Initially in each of these areas two cooperators were chosen to assist with trials. These cooperators were:

Area 10 - D.B.A. Sclanders and A. Muirhead

Area 11 - L. Freese and A. Hall

Area 12 - R. Cobbold and H. Olivier

These cooperators each volunteered an area of their farm to the project with some providing separate irrigation systems for initial trials.

### 5.3 KARKLOOF

This is designated Area 9. An individual farmer, Mr N Hancock, after consultation with the project on irrigation system design, feasibility and scheduling, invested in an automatic weather station, a desktop computer and telecommunications hardware. Annual and perennial pastures are produced under irrigation on +/- 75ha, controlled by the project's computer models.

### 5.4 TAUNG

At Taung, in Bophutatswana, the experimental farm of AGRICOR is used to supply information to the Taung irrigation scheme which

lies north of the Vaalhartz irrigation scheme. Experience in the Taung irrigation scheme has shown that poorly controlled flood irrigation led to salinity build up in many areas. Redevelopment of the Taung scheme involved changes to overhead irrigation, mainly centre-pivot systems. This, together with the inherently good properties of most of the soils occurring in the scheme, has reduced salinity build up.

Since the floods of 1988 the water table has remained high and lateral movement of water pronounced, especially through the experimental plots.

Extensive soil surveys have been conducted of the Taung scheme by outside consultants. Results of these surveys were made available to the project. All irrigation on the farm is from the Taung Irrigation Canal system. Water is however unlimited, thus the project required irrigation treatments could be accommodated. This area is designated Area 20.

#### 5.5 MOLATEDI

Another AGRICOR experimental farm is situated below the Molatedi dam which is on the Groot Marico river some 50km east of Gaberones, Botswana. This farm was established to provide information for future irrigation from the Molatedi dam.

Unfortunately there are no telecommunication links to the farm as TELKOM refuse to cooperate although the farm is alongside the boundary to the RSA. This area is designated Area 21.

#### 5.6 REITZ

An individual farmer, Mr Hennie Saaiman, of Simonsland Boerdery, after consultation with the project, invested in the necessary automatic weather station, desktop computers and telecommunication links. Potatoes are being produced under drip

irrigation for both local and overseas markets.

Simonsland Boerdery is situated some 8km east of Reitz, EOFs, and is designated Area 8. Source of water is limited and controlled by means of a dam.

#### 5.7 SITE SELECTION AND INSTALLATION

AWS have been installed at the following sites. Each site was selected in that it is representative of the area being irrigated. To date, installation and maintenance has been carried out by the project staff. Trouble has been experienced with locally manufactured components and the supplier's service leaves much to be desired. However, this equipment is deemed to be the best available in Southern Africa at present.

- |            |   |   |
|------------|---|---|
| STATION 8  | - | This AWS is situated near Reitz, EOFs, on H. Saaiman's farm, Simonsland, on coordinates 27°48'S and 28°26'E.                  |
| STATION 9  | - | This AWS is situated in the Karkloof, Natal, on N. Hancock's farm, Aldora, on coordinates 29°23'S and 30°14'E.                |
| STATION 10 | - | This AWS is situated in the Winterton area, Natal, on D.B.A. Sclanders' farm, Clydesdale, on coordinates 28°55'S and 29°29'E. |
| STATION 11 | - | This AWS is situated in the Winterton area, Natal, on L. Freese's farm, Dankbaar, on coordinates 28°50'S and 29°32'E.         |
| STATION 12 | - | This AWS is situated in the Winterton   |

area, Natal, on M. O'Brien's farm, Merry Pebbles, on coordinates 28°47'S and 29°37'E.

STATION 20        -        This AWS is situated in the Taung district, Bophutatswana, on the Agricor experiment farm, on coordinates 27°28'S and 24°42'E.

STATION 21        -        This AWS is situated in the Molatedi district, Bophutatswana, on the Agricor experiment farm, on coordinates 28°45'S and 26°37'E.

In addition to the above stations data are kindly made available from two AWS's erected under parallel WRC projects. One is situated at the University of the Orange Free State, Dept. of Agrometeorology, experiment site on coordinates 29°6'S and 26°7'E. The other is situated in the Rietriver area, OFS on the Dept. of Agriculture and Development's experiment farm on coordinates 27°30'S and 24°40'E.

## PART III : RESULTS

### CHAPTER 6 : IRRIGATION BOARD STRATEGIES - PAST, PRESENT AND FUTURE

#### 6.1 INTRODUCTION

Prior to 1980 certain rivers in Southern Africa fell under the jurisdiction of the Department of Water Affairs, with respect to the distribution and allocation of water for irrigation. Since then, this responsibility has developed to involve other organisations such as regional water boards and local irrigation boards in addition to the Minister of Water Affairs and Forestry.

The local irrigation boards were and are formed in order that irrigators in a particular catchment, or demarcated stretch, of river may control the allocation of water therein. The actual allocation and distribution is the responsibility of the farmers, or their elected representatives who constitute these boards. The management decisions regarding water distribution are generally based upon the experience of one or more board members. This perhaps explains the major source of variation between the performance of different projects. Furthermore, the problem of tail enders who fail to receive their fair share of water, is encountered world wide.

#### 6.2 LITTLE TUGELA IRRIGATION BOARD

This district lies to the north and east of the town of Winterton, Natal, astride the Little Tugela river. On its western boundary It is adjacent to the Sterkspruit irrigation district and is one of the main wheat and maize growing areas in Natal.

The district was established primarily for river control in May 1985, and subdivided into 3 sub-districts of which the Winterton irrigation settlement forms one. This settlement exists by

virtue of an Act of Parliament and operates under State regulations regarding water distribution. However since their inclusion in 1985 they are expected to conform, as far as possible, with the rules governing irrigation boards and share in the benefits and burdens of any water works deemed necessary by the irrigation board per se.

#### 6.2.1 EXISTING STRATEGY

Distribution of water within this board is on an apportionment schedule, where irrigators register scheduled areas of land to be irrigated annually for a minimum period of 3 years. The individual irrigator's scheduled area is then calculated as a percentage of the entire area served by the board. This percentage is equivalent to the irrigator's pro rata share of the river flow.

In order, to ensure that such apportionment functions successfully, the following needs to be known:

##### Pump capacity

In many cases the capacities of the irrigators' pumps agree with the manufacturers' specification charts. However, where and when pump impellers have been skimmed, or have become worn, these capacities can be somewhat erroneous, need to be monitored and the pumps recalibrated. In this board, as with the Sterkspruit and the Karkloof boards, the pump capacities are assumed correct, but such assumptions lead to disputes.

##### Scheduled areas

Each pump is treated individually and the irrigator's total scheduled area divided into areas each corresponding to each of these pumps. Problems arise when an irrigator changes his production and subsequently his irrigation strategy, resulting in a change in the area per pump.

### Riverflow

Riverflow is monitored at the boundary of the board's area on a weekly basis and only when the board committee deems it necessary. Where the water is diverted out of the river into earth canals for the other two subdistricts; no monitoring of the flow exists.

The principle of sharing water pro rata per hectare of scheduled land breaks down if a substantial proportion of the scheduled land is not planted. Should this occur, water allocated to the scheduled land not planted will run to waste. Such scheduled water could be shared pro rata per hectare of scheduled land owned. However, sharing water based on scheduled land actually planted does not benefit irrigators who, in their forward planning, voluntarily reduce their planted areas in a given season to accommodate limited water supply.

Table 6.2.1      Water distribution on a pro rata per hectare of scheduled land when not all the scheduled land is planted

	Sub district no.			
	1	2	3	Total
Area of scheduled land partially planted	1282	730	1023	3035
Area of scheduled land not planted	372	462	349	1183
Total area of scheduled land	1654	1192	1372	4218
Percentage share based on total scheduled area	39	28	33	100
Percentage share based on scheduled land partially planted	42	24	34	100

An example of pro rated sharing is given in Table 6.2.1. It can be seen that by calculating the irrigators' percentage share based upon total area scheduled; 28% (i.e.  $1192/4218 * 100$ ) of the total water will not be allocated. This could be avoided by calculating the percentage share based upon the total of scheduled land partially planted, i.e. 3035 ha. This scenario still exists and requires attention.

When water restrictions are imposed, the board meets more regularly to confirm allocations determined by the bailiff. There is no pre-season planning regarding what areas could be planted to which crops with the predicted riverflow/water available for the season.

#### 6.2.2 INTERMEDIATE STRATEGY

During the duration of this project, frequent meetings were held with the Little Tugela board to assist in sharing the water supply. A programme, SCHEDWAT, was developed to assist chairmen of boards to determine for what length of time each pump could be operated per week for a given river flow. Towards the end of the project, this board appointed a full time bailiff to control and monitor water supply within the Little Tugela irrigation district. He further undertook to carry out basic maintenance of the three automatic weather stations in the area.

Throughout the duration of the project, reference crop evaporation for each of the three areas was determined on a daily basis and each week these figures, together with other relevant weather data viz. max. and min. temperature, rainfall, radiation, were displayed in prominent areas (e.g. local co-operative) in order that irrigators could access the same. Many irrigators made use of these figures to either assist in determining future irrigation amounts, or justifying decisions already implemented. Interest tended to wane, especially after satisfactory seasonal rain, until Mr K Hogg, the agronomist employed by the local cooperative firm, offered his assistance and knowledge in

presenting this information in a more "user friendly format". Mr Hogg summarised the planting dates of the various crops and, together with the project, selected relevant crop factors for these crops. A table was produced which included these and the irrigator could extract the irrigation amounts for his individual crop and planting date.

The bailiff has subsequently assumed this task and irrigators contact him directly.

Workshops were held with irrigators. Answers were sought for the following:

- a) Is the IPE project providing a base from which irrigation can be improved in the area?
- b) What are the current problems within the irrigated areas?
- c) Proposals to solve these problems
- d) What guidelines should be provided

The workshops were well attended by irrigators from both the Little Tugela and the Sterkspruit irrigation districts. It was agreed that the IPE project was not only providing a base for improved irrigation control but that without the information provided throughout; 1991 -1992 and 1992 - 1993 would have proved disastrous.

The following problems were identified by the participants at these workshops:

- i) Calibration of irrigation systems
- ii) Measurement of irrigation water applied
- iii) No pre-season planning either within the board areas or on the farm
- iv) True production costs are not forthcoming/available

- v) Pump efficiencies/calibration
- vi) Refinement of the PUTU models - for specific crops and cultivars
- vii) Incorrect irrigation designs
- viii) Lack of technology transfer
- ix) Factors limiting water use efficiency:
  - effect of water imposed stress
  - irrigation systems
  - choice of crop
  - soil type
  - water supply
- x) Electricity:
  - costs
  - supply and downtime at critical periods
- xi) Irrigation scheduling
- xii) Irrigation board problems:
  - pre-season planning
  - distribution and allocation of water
  - losses in canals
  - friction within and between boards
  - resistance to change
  - communication with members

### 6.2.3 PROPOSED STRATEGY

The situation survey (Chapter 3) conducted at the outset of this project highlighted the shortfalls of the systems and methods employed by irrigators and the board in the past. These were all confirmed at the workshops.

The workshops proposed the following solutions:

- i) Irrigation system calibrations - each irrigator could carry this out assisted by the IPE project.
- ii) Measurement of irrigation water applied - coerce irrigators to monitor irrigation applications. The bailiff will collect the irrigator's records on a regular basis. When

no irrigation figures were received; no recommendations would be supplied! The bailiff will monitor riverflow where possible and on a regular time basis.

- iii) Use the linear programming techniques discussed in Chapter 7 to assist in pre-season planning.
- iv) True costs and limiting factors must be supplied by individual irrigators.
- v) The board is to investigate the feasibility of purchasing a suitable instrument for calibrating pumps in situ. The project is available physically to assist, where necessary, as is the Department of Water Affairs.
- vi) Continual refinement of the PUTU models for application to various crops, cultivars and planting dates.
- vii) Use should be made of consultants in their various fields of expertise so as to avoid incorrect, or inefficient irrigation undertakings in the future. These same people can be consulted to improve/rectify present irrigation systems.
- viii) Technology transfer should proceed by means of
  - workshops
  - irrigation courses (at agricultural colleges and universities)
  - farmers' days
  - example/comparisons
  - study groups
  - study tours
- ix) Limiting factors
  - the project together with the irrigator can overcome these, as stated in (vii) above.

x) Electricity

- Farmers associations contact the IPE project in writing with respect to their problems.

xi) Irrigation scheduling

- On individual farms and within the board this will be arranged with the project on a service basis; costs thereof to be borne by irrigators and their boards.

xii) Irrigation board problems

- as above, and
- continued liaison with Department of Water Affairs and relevant consultants
- to overcome resistance to change there must be continuous encouragement from the board and regular but pertinent workshops
- communication by bailiff and the project.

### 6.3 STERKSPRUIT IRRIGATION BOARD

The Sterkspruit irrigation district lies west of Winterton in Natal, astride the Sterkspruit and includes riparian farms down from its headwaters to its junction with the Little Tugela river.

This district was proclaimed on 4 December 1984 and was established primarily to exercise control over the flow of the river and obtain a working knowledge of the irrigation requirements of its riparian owners. An investigation into the water works needed to provide the needs of the district was mounted.

#### 6.3.1 EXISTING STRATEGY

During the latter part of 1985 the Sterkspruit, Little Tugela and Lindeque irrigation boards consulted engineers (Bradford, Conning and Partners, Pietermaritzburg) requesting a water resource survey of the area as a whole. The Sterkspruit board continued

with this survey in depth which eventually led to the construction of a large storage dam. This Bell Park dam is built on the Mtoti river, a tributary of the Sterkspruit, and has a capacity when full of  $\pm 7 \times 10^6 \text{ m}^3$  of usable water. Fig. 6.3.1 illustrates the dam storage capacities at various water levels (Bradford, Conning and Partners, Pietermaritzburg).

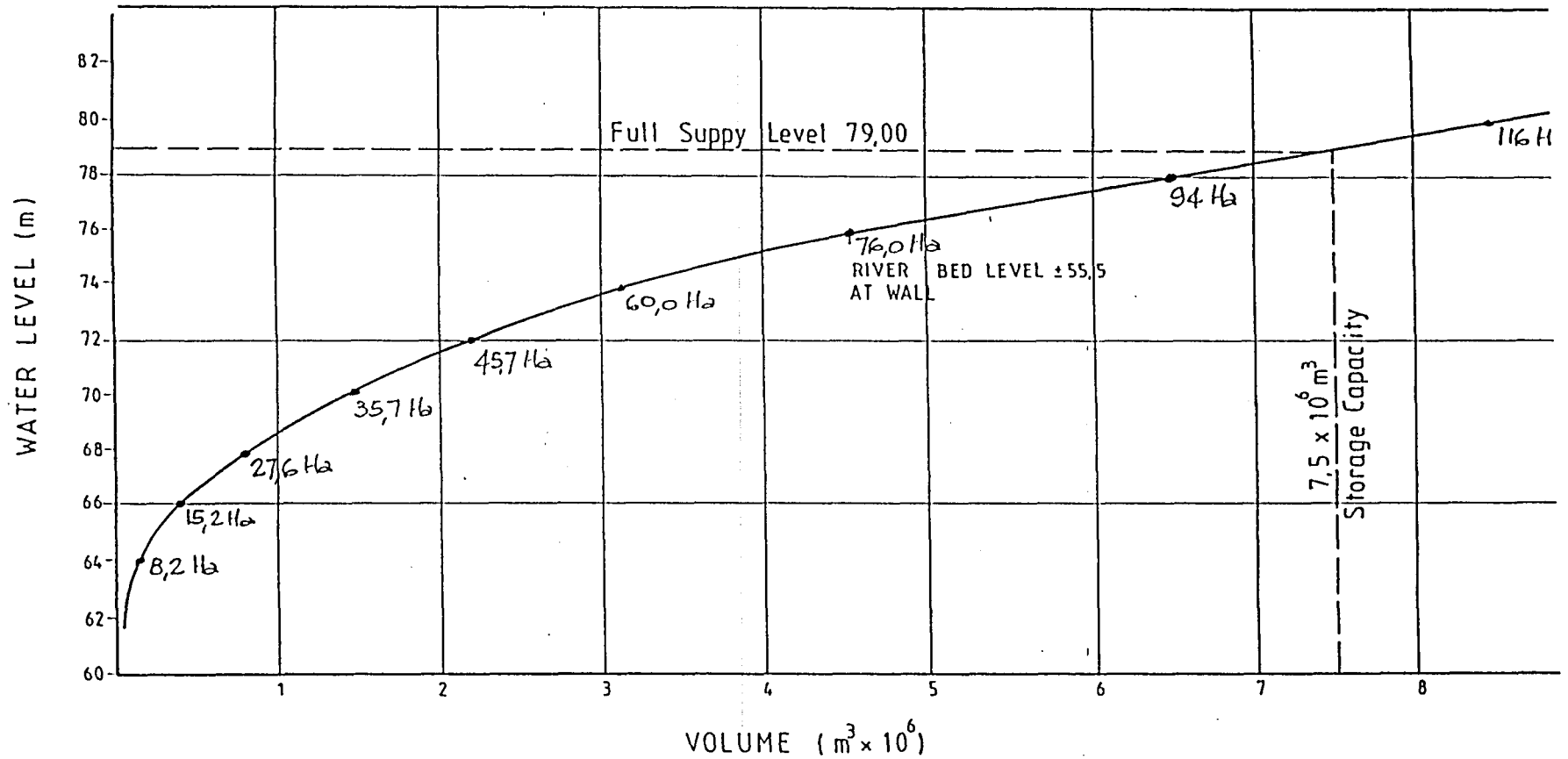


Fig. 6.3.1 Storage capacities of the Bell Park dam at various water levels.

The outflow of this dam is monitored by peg levels in the outlet chute. Fig. 6.3.2 illustrates the flow rates as monitored by the various flow levels in this chute.

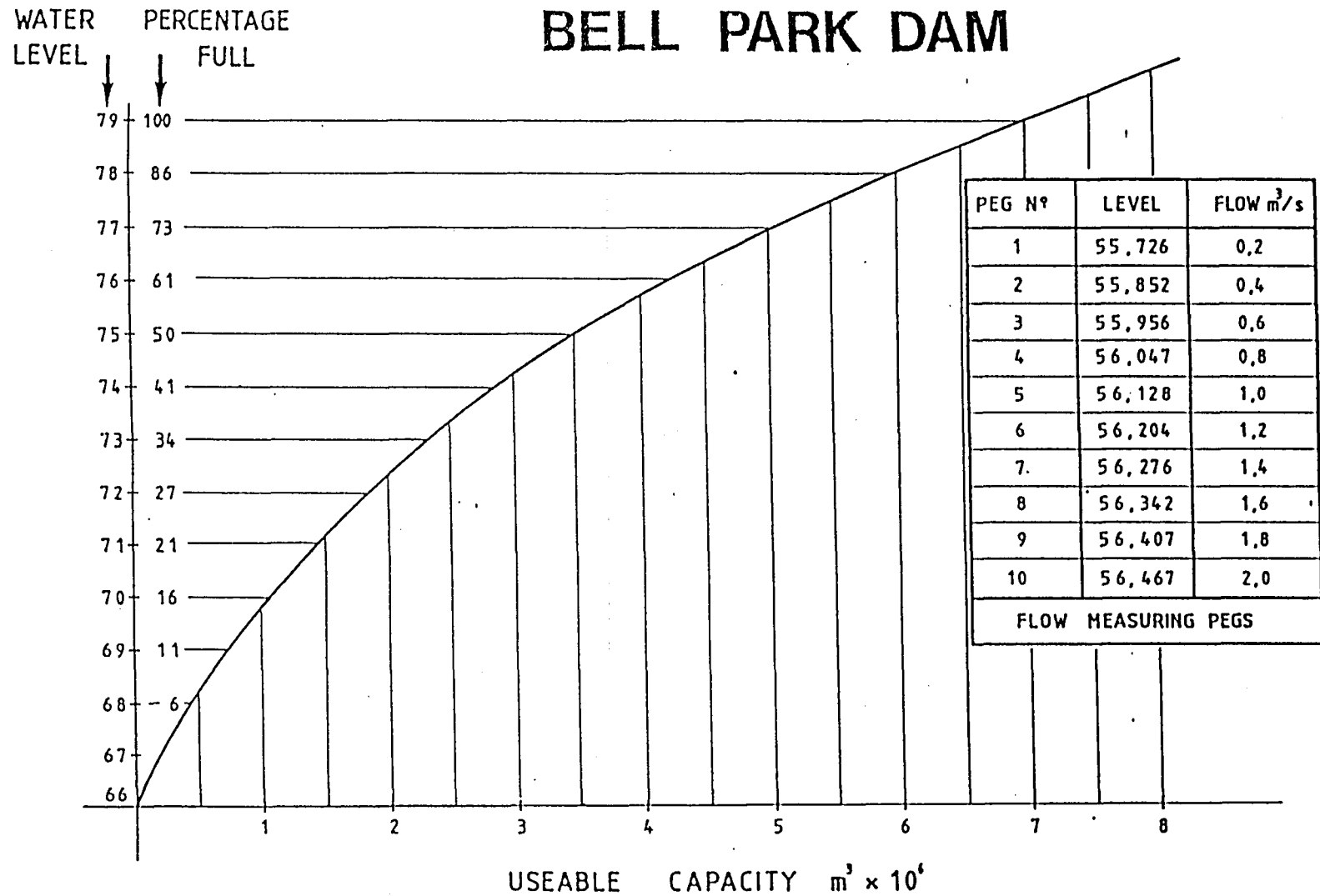


Fig.6.3.2

The usable capacities of the Bell Park dam and the flow rates as monitored by pegs in the outlet chute.

All members of the board contribute to the cost and maintenance of the dam. A bailiff is employed by the board. At the beginning of each season, the bailiff visits each member who in turn fills in a form as to how much of their listed areas they will be utilizing for irrigation. In their pre-season planning, the board allows for 5000 m<sup>3</sup>ha<sup>-1</sup> assuming of course sufficient water in the dam. Once the bailiff has determined the amount of land to be planted; the board, in the event of surplus water being available due to unplanted scheduled land, pools this surplus water. The board then decides whether to sell it either to their own members, or to the Little Tugela board or keep it in reserve. The board members pay in full for their scheduled land and, should surplus water be sold, they are reimbursed pro rata to reduced irrigated area.

By visual monitoring of the mentioned pegs the bailiff ensures that there is sufficient water in the river. This is not a very efficient method of water supply control. There is no advance ordering of water and it is furthermore apparent that the measurement system on the dam's outflow chute is not used effectively.

As stated in the situation survey (Chapter 3) neither measurement of riverflow, nor scheduling of irrigation takes place.

### 6.3.2 INTERMEDIATE STRATEGY

In 1989 the project together with a senior technician from the Dept. of Water Affairs and the chairmen of the Sterkspruit and Little Tugela boards conducted an on site survey of the rivers in these boards' areas. Their aim was to examine the current situation with respect to siting gauging weirs to monitor riverflow - and thence improve water supply. Suitable weir sites were identified as follows:

#### Sterkspruit system

- none above Bell Park dam
- above bridge on district road 277

- below N. Boettiger's weir
- below the weir constructed between S. Hall and K. Mostert's properties above the road bridge. The current weir is incapable of measuring flow and, should it be reconstructed, the inclusion of a sharp crested weir is recommended with the necessary flow measurement devices.

#### Little Tugela system

- existing weir at Estcourt-Gourton road bridge on K. Mostert's property. This weir was upgraded in 1990 by installing a gauging plate, repairing the crests and removing the rocks from the pools above the weir.
- weir at Winterton town. Apart from acting as a diversion weir, this is not suitable for monitoring flow. It was suggested that the board liaise with the Department of Water Affairs proposing the construction of a new weir.
- canal system. Two canals leading to the settlement below Winterton require gauging plates where necessary. It was suggested that the board purchase a current meter.

The members of the Sterkspruit board proposed that buffer weirs be constructed at strategic positions along the river in order to compensate for the wastage of water which occurs; either when ESKOM is down, or extreme north winds prevent irrigation.

In 1992 a buffer weir was constructed where P. Stockil's farms adjoin the river.

No gauging weirs have been constructed and the methods of water supply remain unchanged.

Members of this board also attended the workshops as described in 6.2.2.

### 6.3.3 PROPOSED STRATEGY

The situation survey (Chapter 3) conducted at the outset of this project highlighted the shortfall of the systems and methods employed by irrigators and the board.

In order to improve the water supply and irrigation efficiency of this board, the following was proposed.

- (i) Pre-season planning must be improved with respect to the amount of water allocated. Five years of weather data are available thus water requirements can be more accurately predicted by the methods suggested in Section 4.
- (ii) A gauging weir must be constructed upstream of the confluence with the Sterkspruit. This, together with the employment of the peg monitoring device in Bell Park dam chute and the weir at Boettiger's farm, will enable the bailiff to accurately monitor water supply in the system.
- (iii) Pumps and irrigation systems need to be calibrated.
- (iv) An irrigation scheduling system needs to be adopted by the board and the irrigators. In order to prefect this system, the irrigators must carefully monitor rainfall and irrigation amounts applied.
- (v) Workshops must be arranged by the board to enable the irrigators to implement the recommendations.
- (vi) Closer liaison on a regular basis with the Little Tugela board in order to benefit from the data collection and dissemination which is being carried out by the bailiff and the project.

#### **6.4 KARKLOOF IRRIGATION BOARD**

The Karkloof irrigation district was proclaimed in 1986 as a result of petition and consultation. Up until 1992, no further progress with respect to formalising this district occurred, probably as a result of the plentiful rains and abundant water supply. During 1992 the IPE project was approached for assistance due to the threatened drought and the stricter control measures in the Umgeni river catchment area. The project advised members to formalise a board after studying the future of the Umgeni river catchment area. The board was formalised in October 1992.

##### **6.4.1 EXISTING STRATEGY**

The Karkloof irrigation board falls within the Umgeni river government control area and each irrigator within this area is limited to the amount of public water that he might use for irrigation. The current strategy is that irrigators not exceed these amounts and adhere to the recent amendments to the Water Act.

As a result of the increasing demand from the Durban/Pietermaritzburg metropolitan areas, stringent measures have been imposed upon irrigators.

##### **6.4.2 PROPOSED FORM OF BOARD AND STRATEGY**

The IPE project has advised the Karkloof board to ascertain from its members the potential area that could be irrigated efficiently and economically. Thereafter, with assistance from the Dept. of Water Affairs, a water storage survey of the area should be conducted. The board is awaiting the outcome of a survey initiated by the Dept. of Water Affairs relating to all pump stations, irrigation systems and irrigated areas etc. The board area has been broadly divided for ease of management into three areas viz. Karkloof, nKusane and Umgetu, with representative from each to constitute the board.

IPE project has advised and will offer assistance in future planning and systems operation within the board area. The procedures developed in this project will be used to conduct feasibility studies (see linear programme, Chapter 7) to draw up water schedules with regard to storage and supply, and to schedule irrigation on individual properties.

It is imperative that the board conduct a survey of the area and thereafter draw up a plan in detail for presentation to both the Dept. of Water Affairs and Umgeni Water (a regional control board).

### 7.1 INTRODUCTION

In Southern Africa, a number of simulation models exist to aid in the synthesis of data and information in order to provide the inputs for efficient design, planning and operation of irrigation systems (Lecler, Schulze, Mottram and de Jager, 1992).

As indicated in the situation survey (Chapter 3) little or no scientific pre-season planning with reference to water supply and distribution exists. Strategies for managing irrigation are difficult to plan especially under conditions of limited water supply. Thus a linear programming method was applied to establish guidelines for pre-season planning of crop rotations and planting areas given a known volume of available water for the season. Linear programming matrices, with design and cost estimating procedures to evaluate the economics of deficit irrigation, have been developed.

Pre-season planning involves determination of expected water supply, from water storage and/or seasonal riverflow, and thereafter a selection and costing of environmentally suitable crops. By employing linear programming (LP), production areas and suitable crops may be selected which maximise profits with imposed water restraints (see Chapter 4.3). The inputs required are crop production costs, crop water requirements, water stress induced yield deficit factors, and product prices. The LP output, having economically selected the production areas, allocates the water available for distribution to specific crop growth periods during the season, using the water stress induced yield factors.

Two scenarios are investigated in this report, namely a soyabean-pea/wheat crop rotation in the Rietriver area, and a maize-wheat-soyabean rotation in the Winterton area. The main objective of Chapter 7 is to illustrate the method of optimisation. In many cases the results obtained indicated that in order to maximise

profit with imposed water restrictions, the area planted must be reduced rather than water stress be imposed during the growing season. The LP model may be used to determine which crop in the rotation should have a reduced area and what is the extent of this area.

In practice the situation often arises where no pre-season planning has taken place and the full scheduled area has been planted. Should irrigation water become restricted during the season, the irrigation board must satisfy all its members. In this situation the LP model can be used to determine during which crop growth stage water restrictions can be imposed with minimal yield depression penalties. The output also indicates what returns can be expected from each crop enterprise.

Scenarios for Winterton and Rietrivier were investigated.

## **7.2 METHODOLOGY**

In the Rietrivier area, rainfall was ignored as it is relatively insignificant for crop production and total irrigation is practised with all irrigation water being supplied from storage dams, i.e. water supply could be limited, but is controllable.

In the Winterton area, rainfall plays a significant role in summer and supplementary irrigation is practised. The irrigation water is supplied by,

- (a) dam and river - controlled and limited
- or (b) river alone - uncontrolled and limited

As a first illustrative attempt however, in Winterton too, rainfall was ignored. A matter which will have to be rectified in the future in both areas considered. Table 7.2.1 presents the crop production costs of the various crops. The costs exclude irrigation costs.

**Table 7.2.1 Crop production costs of various crops produced under irrigation**

Crop (Yield)	Production costs (R ha <sup>-1</sup> )
Maize (10tha <sup>-1</sup> )	2010
Wheat (7tha <sup>-1</sup> )	1764
Soyabeans (3tha <sup>-1</sup> )	1236
Dry peas (3tha <sup>-1</sup> )	942

For the purpose of the LP, irrigation costs were allocated in rands per millimetre, to allow for the variable costs when irrigating at different levels. Except for the examples below, where an amount of R1 mm<sup>-1</sup> ha<sup>-1</sup> was used which included irrigation equipment, system repairs, power and pump and motor repairs. It is important to note that one cannot generalise on irrigation costs per mm of water per hectare as each and every scheme is different.

Six crop growth stages were recognised, these being establishment, development, mid-season, flowering, grain formation and ripening.

The total crop water requirements for optimum yield production were taken as,

Maize	1000mm
Wheat	700mm
Soyabeans	900mm
Dry Peas	550mm

The water requirements during each stage are dependent upon climate and the duration of the growth stage. The water required to produce an unstressed yield is equivalent to the atmospheric evaporative demand, AED. For each growth stage,  $i$ , long term climatic norms of reference crop evaporation,  $Eo$ , and crop coefficients,  $kc$ , are required to determine AED from

$$\begin{aligned}
 AED_i &= kc_i Eo_i \\
 AED &= \sum AED_i \\
 &= kc_1 Eo_1 + kc_2 Eo_2 \dots kc_i Eo_i
 \end{aligned}
 \tag{7.2.1}$$

where,

- $AED_i$  = Atmospheric evaporation demand in the  $i$ th crop growth stage (mm)  
 $AED$  = Total atmospheric evaporation demand (mm)  
 $kc_i$  = Average crop evaporation coefficient for the  $i$ th growth stage  
 $Eo_i$  = Average reference crop evaporation for  $i$ th growth stage (mm)

For the purposes of illustrating the LP techniques, the crop water requirements for each stage were estimated and are presented in Table 7.2.2.

**Table 7.2.2** Estimated crop water requirements during the six growth stages of various crops (after Doorenbos and Kassam, 1979)

GROWTH STAGE	MAIZE (mm)	WHEAT (mm)	SOYABEANS (mm)	DRY PEAS (mm)
Establishment	73	58	78	46
Development	73	67	91	63
Mid-season	146	105	130	114
Flowering	244	211	287	167
Grain formation	268	173	196	114
Ripening	196	86	118	46

The model uses reduced irrigation levels in 10 mm steps from 0 (no water limitation) to 50 mm (50 mm less irrigation than is required for a given growth stage). Thus six irrigation levels were applied to each growth stage and the subsequent yield reductions calculated.

The potential yields selected for each crop are:

Maize	11 t ha <sup>-1</sup>
Wheat	7 t ha <sup>-1</sup>
Soyabeans	4 t ha <sup>-1</sup>
Peas	2.5 t ha <sup>-1</sup>

The yield stress factors,  $ky$  (after Doorenbos and Kassam, 1979) used to calculate reduction in yield due to water stress, are shown in Table 7.2.3.

**Table 7.2.3** Stress factors used in calculating yield reduction in each of the six growth stages (after Doorenbos and Kassam, 1979)

STRESS FACTOR	MAIZE	WHEAT	SOYABEANS	PEAS
ky1	0,4	0,2	0,2	0,2
ky2	0,7	0,2	0,2	0,3
ky3	0,5	0,3	0,6	0,9
ky4	2,2	0,65	0,8	0,7
ky5	0,6	0,55	1,0	0,25
ky6	0,4	0,4	0,4	0,2

To calculate the yield reduction taking place in the different growth stages and at the different irrigation levels, the concept of relative yield deficit and relative evaporation deficit as described by Eq.4.2.12 in Chapter 4. As explained earlier, symbol  $ky$  here replaces and is identical to the original  $\beta$  of Stewart, Buenco, Pruitt, Hagan and Tosel (1977). The use of  $ky$  makes for the convenient application of the work of Doorenbos and Kassam (1979).

Eq. 4.2.14 was used to estimate the yield reductions for given evaporation deficit presented in Table 7.2.4.

**Table 7.2.4** Yield reductions for different crop growth stages and irrigation levels for maize (M), wheat (W), soyabeans (S) and dry peas (P)

Water Reduction (mm)	Maize (growth stages 1 to 6) Yield deficits (kg ha <sup>-1</sup> )					
	M1	M2	M3	M4	M5	M6
0	0	0	0	0	0	0
10	603	1055	377	992	246	224
20	1205	2110	753	1984	493	449
30	1808	3164	1130	2975	739	673
40	2411	4219	1507	3967	985	898
50	3014	5274	1884	4959	1231	1122

Water Reduction (mm)	Wheat (growth stages 1 to 6) Yield deficits (kg ha <sup>-1</sup> )					
	W1	W2	W3	W4	W5	W6
0	0	0	0	0	0	0
10	241	209	200	216	223	326
20	483	418	400	431	445	651
30	724	627	600	647	668	977
40	966	836	800	863	890	1302
50	1207	1045	1000	1078	1113	1628

Water Reduction (mm)	Soyabeans (growth stages 1 to 6) Yield deficits (kg ha <sup>-1</sup> )					
	S1	S2	S3	S4	S5	S6
0	0	0	0	0	0	0
10	103	88	185	111	204	136
20	205	176	369	223	408	271
30	308	264	554	334	612	407
40	410	352	738	446	816	542
50	513	440	923	557	1020	678

Water Reduction (mm)	Peas (growth stages 1 to 6) Yield deficits (kg ha <sup>-1</sup> )					
	P1	P2	P3	P4	P5	P6
0	0	0	0	0	0	0
10	109	119	197	105	55	109
20	217	238	395	210	110	217
30	326	357	592	314	164	326
40	435	476	789	419	219	435
50	543	595	987	524	274	543

It deviates from Stewart's original theory, but an additive law of yield limitation is required here to allow use of LP. The Stewart, et al. (1977) original additive law (for which the yield stress parameters  $ky_i$  are available) or the additive law proposed in Eq. 4.2.11 are possible solutions to the problem. In Chapter 9 the various limitation laws are validated for wheat. Both these alternatives were shown to be accurate for the purpose at hand. However, the multiplicative law was shown to be marginally more accurate than the additive Stewart law. In view of all the information available regarding  $ky_i$ , Eq. 4.2.11 was chosen for the calculations here illustrated. Note that the  $ky_i$  as used here are for the multiplicative law. In Chapter 9 it was shown that they can be markedly improved by re-calibration. The results of this chapter must thus at this stage simply serve to demonstrate the proposed method.

The objective of the LP model is to maximise profit at any specified level of water availability. The form of the objective function (Eq.4.2.20), expressed in Rands, is.

$$\text{MAX} = \sum_c \sum_{i=1}^{i=n} \text{GMC}_{ci} * A_c$$

The input variables are the returns for each crop as obtained at the different irrigation levels in each crop growth stage.

The constraints are land area (ha) and water availability (mmha). The unit mmha represents the number of millimetres of water available to the crops over the two seasons multiplied by the number of hectares. For example, 70000mmha represents 1400mm available over two seasons multiplied by 50ha.

### 7.3 RESULTS

#### Example 1

A wheat, maize, soyabean rotation was examined in the Winterton area. The maximum irrigable area was 50ha and the amount of irrigation water available for the two seasons was 70000 mmha, which is insufficient to satisfy the full requirements of any two of these crops.

The solution obtained from the LP procedure indicates that, in order to maximize profits from these enterprises, there should be no reduction in irrigation applied per unit area, but rather a reduction in land area planted.

The rotation which the LP selected as being expected to maximize gross margin in this example was 50ha maize in the summer season and 28.57ha wheat in the winter season.

Unused land was therefore 21.43ha in the winter season. The gross margin (profit) from these two enterprises was R35 171.43.

It should be noted that the selling price of maize used in this model was that offered by Rainbow Chicken Farms (Pty) Ltd. The reason for using this price was that, if the selling price of maize indicated in the COMBUD report for example was used, maize would never be selected in preference to soyabeans.

## Example 2

A wheat, maize, soyabean rotation in the Winterton area was again studied, with the amount of irrigation water available being 70000mmha, as in Example 1. However the area planted was fixed at 50ha. This scenario reflects no pre-season planning.

The optimal rotation resulting from this example is indicated below.

Summer: 50ha soyabeans, irrigated as follows:

1st growth stage	-	50mm reduced (28mm applied)
2nd	"	" - 50mm reduced (41mm applied)
3rd	"	" - full irrigation (130mm applied)
4th	"	" - 50mm reduced (237mm applied)
5th	"	" - full irrigation (196mm applied)
6th	"	" - full irrigation (118mm applied)

Winter: 50ha wheat, irrigated as follows:

1st growth stage	-	full irrigation (58mm applied)
2nd	"	" - 40mm reduced (27mm applied)
3rd	"	" - 50mm reduced (55mm applied)
4th	"	" - full irrigation (211mm applied)
5th	"	" - full irrigation (173mm applied)
6th	"	" - full irrigation (86mm applied)

The gross margin (net loss) of these two enterprises is - R34900.00. This is assuming that input costs are not reduced despite the fact that optimum yield is no longer possible. In order to minimise loss in the case where no pre-season planning has taken place, the farmer could attempt to reduce input costs during the remainder of the growing season.

It can be inferred that, had 50 ha maize been planted in the summer season, an even greater economic loss would have been suffered.

### Example 3

A wheat, pea, soyabean rotation was selected in the Rietrivier area. The maximum irrigable area was 50ha and the amount of irrigation water available was 50000mmha, which is insufficient to satisfy the full requirements of any two of these crops.

As in Example 1, results indicate that, in order to maximise profits, there should be no reduction in irrigation, but rather a reduction in land area planted.

The optimal rotation selected by the LP procedure was 50ha peas in the winter season and 25ha soyabeans in the summer season. Unused land is therefore 25ha in the summer season. The gross margin (net profit) from these two enterprises is R55900.00.

#### Example 4

A wheat, pea, soyabean rotation, the prices and costs in Example 3 were again used, but land area planted was forced at 50ha for both summer and winter crops. The optimal selection is indicated below.

Summer: 50ha soyabeans, irrigated as follows:

1st growth stage	-	50mm reduced (28mm applied)
2nd	"	" - 50mm reduced (41mm applied)
3rd	"	" - 50mm reduced (80mm applied)
4th	"	" - 50mm reduced (237mm applied)
5th	"	" - full irrigation (196mm applied)
6th	"	" - 50mm reduced (68mm applied)

Winter: 50ha peas, irrigated as follows:

1st growth stage	-	40mm reduced (6mm applied)
2nd	"	" - 30mm reduced (33mm applied)
3rd	"	" - full irrigation (114mm applied)
4th	"	" - 50mm reduced (117mm applied)
5th	"	" - 50mm reduced (64mm applied)
6th	"	" - 40mm reduced (6mm applied)

The gross margin (net loss) from these two enterprises is - R102900.00. The marked differences between Examples 3 and 4 are due mainly to the fact that in Example 4 yield reductions resulted from the severe water deficits deemed to have been incurred.

#### Example 5

The actual production costs (as for 1991) obtained from a Winterton farmer, were used in the linear programming model for the purposes of pre-season planning.

As the farmer was uncertain of his water supply prior to the start of the season two scenarios, viz. Examples 5.1 and 5.2,

were created with available water supplies of 70000 mm ha and 50000 mmha respectively.

The following input data were used:

CROP:	MAIZE	WHEAT	SOYABEANS
Yield deficit factor (ky) in each of six growth stages:			

ky1	0.4	0.2	0.2
ky2	0.7	0.2	0.2
ky3	0.5	0.3	0.6
ky4	2.2	0.65	0.8
ky5	0.6	0.55	1.0
ky6	0.4	0.4	0.4

Water required (mm) in each of six growth stages:

Stage 1	59	58	78
Stage 2	59	67	91
Stage 3	117	105	130
Stage 4	195	211	287
Stage 5	214	173	196
Stage 6	156	86	118

Maximum yield (tha <sup>-1</sup> ):	10	7	4
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Selling price (R t <sup>-1</sup> ):	380	576	950
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Production costs (R ha <sup>-1</sup> ):	1452	1542	1275
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Irrigation costs (R mm <sup>-1</sup> ha <sup>-1</sup> ):	0.70	0.70	0.70
--	------	------	------

Example 5.1

Available water:	70000 mmha (1400 mm)
Land area available:	50 ha
Crops Summer:	Maize or Soyabeans
Crops Winter:	Wheat

Optimum: Plant 43.75 ha maize to be fully irrigated  
Plant 50 ha wheat to be fully irrigated

Result: Gross margin from these  
two enterprises = R194 856.30

Example 5.2 Available water: 50000 mmha  
(1000 mm)  
Land area  
available: 50 ha  
Crops Summer: Maize or Soyabeans  
Crops Winter: Wheat

Optimum: Plant 18.75 ha maize to be fully irrigated  
Plant 50 ha wheat to be fully irrigated

Result: Gross margin from these  
two enterprises = R140 681.30

At the start of the season the farmer's water supply was 50 000mm ha. After examining the results of Example 5.2, he chose to produce wheat only and extend the area planted to 100ha(2 X 50ha centre pivot areas). PUTU-irrigation was used to schedule the irrigation which amounted to 412mm for the season and the crop yielded 5.5 tha<sup>-1</sup>.

With a selling price of R576 per tonne a gross margin of R183 040 would have been realised. However the wheat price was increased during the season to R720 per tonne which yielded a gross margin of R212 960.

#### 7.4 DISCUSSION

The examples presented in 7.3 indicate that under conditions of limited water availability, in order to maximize gross margin, in many cases, it would be advisable to reduce the area planted and irrigate the crop to achieve maximum yield, rather than reduce the amount of irrigation water applied.

The value and effectiveness of the LP method has been demonstrated. The results should, at this stage, be considered to be preliminary, mostly because of the simplifying assumptions adopted:

- a) The economic inputs, and particularly the cost of applied irrigation water require revision.
- b) The theory of additive yield reduction could possibly be replaced by a multiplicative theory or the law of the minimum, provided the LP procedures can be adapted.
- c) The correct  $k_y$  for use in the additive limitation law versions of PUTU need to be determined (see Chapter 9).
- d) Rainfall has to be accounted for. This could be done quite easily using long term averages.
- e) Adjustments to irrigation and water use efficiencies are required.

The optimization method applied here is an application of the procedure suggested by de Jager et al. (1987) for maximizing profit on a multi-farm or multi-plot project. This is so, because linear programming applies the equimarginal principle. The method here presented differs however in that the linear programme matrix is constructed using yield deficits estimated from Eq. 4.2.12 instead of being extracted from water production functions created using a crop growth model. The latter should prove more accurate because it takes climatic variation (particularly rainfall) into account. Exactly how to construct crop-water production functions accounting for growth stage sensitivity is uncertain at this stage and requires further research.

An overall conclusion for pre-season planning seems to suggest that maximum yield should be striven for on reduced areas. This is most significant, but must be considered as preliminary at this stage because of the assumptions here made. This conclusion could change as the stated limitations are addressed.

## CHAPTER 8 : IRRIGATION SCHEDULING USING NEAR REAL TIME WEATHER DATA

### 8.1 INTRODUCTION

The need for accurate irrigation scheduling has become critical. Many reference evaporation models have been developed (Blaney and Criddle, 1950; Hamon, 1961; Jensen, Robb and Tranzoy, 1990; Jensen, Wright and Pratt, 1971; Ritchie, 1972; Kanemasu, Rasmussen and Bagley, 1978; Gillooly and Mottram, 1979; Clemence and Schulze, 1982). Some have been tested (du Pisani, 1974; Kanemasu, Stone and Powers, 1976; Mottram, de Jager and Minnaar, 1977; Rosenthal, Kanemasu, Raney and Stone, 1977; Steiner, 1979); but very few have been applied in practice. With the increase in irrigation development, particularly with respect to mechanised systems, where energy costs are high, it has become necessary to increase water-use efficiency. Accurate estimation of  $E_0$  has become imperative. Furthermore, water supplies are not as plentiful as previously. Apart from drought induced restrictions, industry and metropolitan areas are imposing ever increasing demands on existing water resources.

Timeous irrigation does increase yields, but irrigators using present scheduling techniques are not yet achieving the yields practically attainable under irrigation.

As stated in Chapter 3, there existed little or no irrigation scheduling at the commencement of the project in the areas monitored in this report.

The objective of Chapter 8 is to describe the real time irrigation scheduling technique adopted in this research project.

#### 8.1.1 PUTU-system

The first PUTU model, a dynamic seasonal maize crop growth model, was created in 1973. Its initial construction was described by

de Jager (1974) and, De Jager and King (1974). A version of PUTU specifically for wheat, PUTU 6, was developed and all the important functions for this model are described by De Jager, Botha and van Vuuren (1981). PUTU 6 was modified for irrigation scheduling and renamed PUTU 9 and this is described by De Jager et al., (1982). While PUTU 9 utilises most of the functions of PUTU 6, it computes in hourly time steps. De Jager, van Zyl, Kelbe and Singels (1987) reported that, where irrigation scheduling is concerned, daily time steps are adequate and developed a daily iteration irrigation version, PUTU 9.86. Daily values of atmospheric evaporative demand (AED) for each growth stage, and reference crop evaporation ( $E_o$ ) from a short grass surface supplied with adequate water, were computed from hourly weather variables recorded by an automatic weather station.

An attractive feature of the PUTU models is their modular construction. During 1986 (de Jager et al., 1987) the computer programme for PUTU 9.86 was completely re-structured and simplified to make the sequence of operations easy to follow. Since then, the model has been continually updated and validated incorporating the most recent research results. It has been modified to make rapid adaptation to other crops possible and re-named PUTU-Irrigation. The latter has been included in the PUTU-system (De Jager, 1992). This then is capable of providing crop growth simulation models for most crops. Apart from the irrigation version, maize, wheat and grassland models having higher levels of sophistication are also included in the PUTU-system.

#### 8.1.2 PUTU-IRRIGATION

Briefly the input requirements for PUTU-IRRIGATION (AWS version) are:

- (i) Hourly values of temperature, humidity, incoming solar radiation and wind speed to compute reference crop evaporation

- (ii) Estimated fractional radiation interception,  $F_v$ , and crop evaporation coefficient,  $k_c$ , in each crop growth stage
- (iii) Soil data:
  - effective rooting depth of crop
  - depth of each soil layer in profile
  - drained upper limit of soil water content in each layer
  - lower limit of soil water content in each layer
  - soil water content at a potential of -1500kPa in each layer
  - soil particle size distribution in each layer
  - field soil bulk density of each soil layer
  - presence of impermeable layer and depth of occurrence.

The PUTU-IRRIGATION model was used in this study to schedule irrigation.

## 8.2 WINTERTON SCENARIO

Weather data recorded on magnetic tape were collected from the three weather stations (viz. 10, 11 and 12) on a weekly basis. Although telephone modems are now installed at these stations, the direct lines to the stations have yet to be connected.

These data are archived, transformed and the reference crop evaporation ( $E_o$ ) for each site determined. These  $E_o$  values together with daily values of maximum and minimum temperature, rainfall and radiation are sent to the bailiff who in turn supplies them to interested irrigators in the relevant board (see Table 8.2.1)

Since the appointment of the bailiff, the interest shown by irrigators in the PUTU system has grown significantly. The

project has assisted with workshops and is continuing with these in order to explain the system and its benefits.

Certain irrigators record irrigation amounts and PUTU-IRRIGATION is run for individual lands on each farm the recommendations are made as illustrated in Tables 8.2.2 and 8.2.3.

**Table 8.2.1      Weekly output supplied to the Little Tugela Irrigation Board for use by its members.**

DOY	TMAX	TMIN	RAIN	RADD	Eo	SVDD
60	25.30	12.70	0.00	23.62	5.00	11.14
61	26.80	17.60	0.00	21.38	4.78	11.52
62	22.90	16.60	34.20	8.93	1.57	4.20
63	23.00	16.90	6.40	12.80	2.22	5.37
64	27.20	14.70	10.00	23.66	5.00	9.93
65	27.40	12.40	1.00	22.94	4.69	10.83
66	26.40	16.00	0.00	25.80	5.37	12.03

where,

- DOY    =   day of year
- TMAX   =   daily maximum temperature ( $^{\circ}\text{C}$ )
- TMIN   =   daily minimum temperature ( $^{\circ}\text{C}$ )
- RAIN   =   daily rainfall (mm)
- RADD   =   total incoming solar radiation ( $\text{MJ d}^{-1}$ )
- Eo     =   reference crop evaporation (mm)
- SVDD   =   maximum saturation vapour pressure deficit for the day (mbar)

Table 8.2.2 illustrates a PUTU-IRRIGATION model output for the irrigation of potatoes.

**Table 8.2.2 Example of a PUTU-IRRIGATION model output for potatoes.**

LAND = L5B3

PLANT POPULATION  
4 (/m<sup>2</sup>)

CULTIVAR  
POTATO BP1

PLANTING DATE  
28/9/1992

SOIL DESCRIPTION: AVALON

SOIL MOISTURE (mm/m)

MAXIMUM MINIMUM INITIAL EFFECTIVE ROOTING DEPTH  
192 80 171 0.3 m

1992													
DOY	FW	LAI	IRR	RAIN	PERC	PPAW	DEF	PSI	HU	kc	AED	Eo	FID
	(%)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	ST L (MPa*100) (DD)		(%)	(mm*10)		(d)
347	0	163	2	4	23	56	12	-6 -132	766	100	27	27	4
348	1	155	0	4	23	63	10	-3 -166	777	100	39	39	3
349	20	147	2	1	23	60	11	-3 -213	789	100	51	64	2
350	37	137	2	0	23	52	13	-4 -221	802	100	48	76	1
351	44	128	3	0	23	43	15	-7 -225	816	100	43	76	1
352	31	118	6	1	23	40	16	-9 -221	829	100	39	56	1
353	36	108	6	0	23	48	14	-7 -224	844	100	45	70	1
354	20	98	6	0	23	54	12	-5 -219	858	100	48	60	2
355	20	88	5	3	23	58	11	-4 -220	872	100	52	65	2
356	7	78	2	2	23	69	8	-2 -207	886	100	54	58	2

where,

L5B3 = field identification

MAXIMUM = water content at the drained upper limit in the second soil layer (mm m<sup>-1</sup>)

MINIMUM = soil water content at wilting point in the second soil layer (mm m<sup>-1</sup>)

INITIAL = soil water content at time of planting in the second soil layer (mm m<sup>-1</sup>)

EFFECTIVE ROOTING DEPTH = maximum rooting depth within which the majority of the roots will be occur (mm)

DOY = day of year

FW = water stress factor (%)

LAI = leaf area index (%)

IRR = 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 -10kPa water content (mm)  
 PSI = ST plant sensed soil water potential for entire current root zone (MPa x 100)  
       = L leaf water potential for the entire current root zone (MPa x 100)  
 HU = growing degree days (heat units)  
 kc = crop coefficient  
 AED = daily atmospheric evaporative demand (water use) (mm)  
 Eo = daily reference crop evaporation (mm)  
 FID = forecasted period (in days) to the next day on which irrigation will be required to ensure unstressed crop growth

Only a rough estimator for LAI has been included at this stage and the values obtained are not to be taken too seriously. Sophisticated routines are available and can be included on request.

The water stress indicator, FW, is determined by an iteration process for each day, climate and soil condition. It is expressed as the fractional physiological water stress existing in the crop.

The water deficit below the upper limit, DEF, is the amount of water required to replenish the soil profile (rooting zone) to a soil water potential approximating 10 kPa. Should the irrigator not irrigate on the planned day, the water budget computations will continue using the near real time data until such time as irrigation takes place. The FW value must be carefully examined each day during this delay period so as to avoid imposing too great a stress upon the crop. Monitoring FW is vital when deficit irrigation is being practised.

From Table 8.2.2, FW, PPAW and DEF are used to decide when and

how much irrigation is required for the given plot of land (L5 B3).

Examination of DOY = 351, in the example illustrated in Table 8.2.2, yields the following information:

FW = 44% - a fairly high stress indicator  
 PPAW = 43% - the rooting soil profile is approaching a yield depressing depletion level of 43% of the water holding capacity  
 DEF = 15mm - 15mm is required to bring the rooting soil profile back to the upper limit 10 kPa water content

Given the output presented in Table 8.2.2, irrigation advisors can provide suitable information to irrigators facilitating future planning and own decision making.

Table 8.2.3 illustrates the information also supplied to farmers in the irrigation scheduling bulletins.

**Table 8.2.3 - Crop water use, crop and soil water status and irrigation recommendations for potatoes being produced under drip irrigation**

DOY	Eo	AED	DOG	STRESS	DEF	RECOMM. IRRIG.	CUMMUL. IRRIG.	CUM. RAIN
	(mm)	(mm)	(d)	%	(mm)	(mm)	(mm)	(mm)
351	7.6	4.3	80	44	15	6	232	146

where,

DOG = days of growth since germination

In the example of Table 8.2.3, the advisor, having examined FW, PPAW and DEF recommended 6mm of irrigation for DOY 351. The irrigator now knows that at least 6mm of irrigation is required in order to prevent water stress.

Table 8.2.3 represents one irrigation block. Any number of

irrigation blocks can be accounted for in the PUTU system.

### 8.3 KARKLOOF SCENARIO

Weather station no. 9 is situated on N.Hancock's farm in the Karkloof area. This station is directly linked via twisted pair cable to a PC in the farm office.

Data are collected via telecommunications on a weekly basis by the project and processed in a similar manner to that described in Section 8.2.

The farmer and his manager have been instructed on how to collect the data and calculate reference crop evaporation. The project supplied crop coefficients for perennial ryegrass which were used to schedule irrigation. In comparing this method of irrigation control to that previously used where fixed amounts were applied at pre-determined intervals, the farmer reported that a saving of +/- 50% in electricity was realised.

Table 8.3.1 illustrates the advice supplied to a dairy farmer for scheduling irrigation on ryegrass which is strip-grazed at a stocking rate of 200 mature livestock units per hectare per day. The planned irrigation cycle is 5 days and the grazing cycle 28 days.

Whereas other dairy farmers in the area were forced to reduce herd size due to lack of adequate irrigated pasture, the cooperating farmer was able to proceed without such culling action.

Table 8.3.1

Advice supplied to a dairy farmer for scheduling irrigation on ryegrass

LAGGAN DAIRY									
=====									
Day of Year =		227	Sunday 15 August 1993						
Mean Daily E0 =		2.66							
Total Weekly E0 =		18.6							
Rain =		25							
LAND NO.	VARIETY	DOG	TOTAL WEEK AED (mm)	RECOMM IRRIG. (mm)	FORE-CAST IRRIG DATE	STRESS (%)	DEFICIT (mm)	CUMUL-ATIVE IRRIG. (mm)	CUMUL-ATIVE RAIN (mm)
1	Carambra	2	13.5	0	7	0	3	0	0
2	Carambra	1	13.5	0	7	0	4	0	0
3	Carambra	43	17.5	5	5	0	12	80	26
4	Carambra	29	17.9	10	3	0	21	40	26
5	Carambra	28	17.8	10	3	0	22	30	26
6	Carambra	27	18.1	10	3	0	20	35	26
7	Carambra	26	18.3	5	6	0	11	45	26
8	Carambra	25	17.9	0	6	0	8	42	26
9	Carambra	11	16.7	0	9	0	0	30	25
10	Carambra	9	15.7	0	7	0	4	15	25
11	Carambra	7	14.7	5	5	0	14	0	25
12	Carambra	6	16.9	5	5	0	13	0	25
13	Carambra	23	18.3	0	6	0	9	40	26
14	Carambra	21	17.7	0	7	0	5	40	26
15	Carambra	19	17.7	5	5	0	13	30	26
16	Apollo	35	18.0	5	5	0	15	62	26
17	Apollo	33	17.5	10	2	1	24	45	26
18	Apollo	31	17.8	0	6	0	9	60	26
19	Apollo	30	17.7	10	3	0	22	37	26
20	Baspectra	39	17.6	10	2	1	24	57	26
21	Baspectra	38	18.1	5	5	0	14	72	26
22	Baspectra	37	18.2	0	8	0	4	90	26
23	Baspectra	37	17.6	5	6	0	11	70	26
24	New var.	18	17.9	0	6	0	8	30	26
25	New var.	16	17.1	0	8	0	4	30	25
26	New var.	59	17.5	5	5	0	13	115	26
27	New var.	13	16.8	5	5	0	12	15	25
28	Baspectra	49	17.7	10	4	0	17	85	26
29	Baspectra	48	17.5	5	5	0	12	92	26
30	Baspectra	47	17.5	5	5	0	12	85	26
31	Baspectra	46	17.7	10	2	1	24	67	26
32	Carambra	5	13.3	5	5	0	12	0	25
33	Carambra	4	13.2	0	6	0	9	0	0
34	Carambra	3	13.2	0	6	0	8	0	0

Note that the FID (forecast irrigation date) is from Sunday.

With the recent formation of the Karkloof Irrigation Board and subsequent workshops presented by the project, numerous other farmers have expressed interest in scheduling their irrigation using PUTU-irrigation.

#### 8.4 WATER SUPPLY NON-LIMITING

For non-restricted water supply, the benefits accruing from use of the PUTU models are evident in Table 8.4.1 which compares yields obtained on lands scheduled by farmers following their normal practice with those obtained from fields scheduled according to PUTU. As explained, it is imperative to have an accurate estimate of AED for both irrigation scheduling and the estimation of peak and mean net irrigation requirements.

Table 8.4.1 Comparison between yields obtained in the Winterton area from lands on which irrigation was scheduled using PUTU with those obtained on the surrounding area scheduled according to the farmer's normal practice.

SEASON	FARMER	CROP	YIELD	
			PUTU (kg ha <sup>-1</sup> )	Surrounds (kg ha <sup>-1</sup> )
89/90	A.Muirhead	Soyabeans	2950	1800-2300
89/90	J.Muirhead	Soyabeans	2700	1800-2300
89/90	D.Sclanders	Maize	9800	7800
90	J.Muirhead	Wheat	6100	4000-4900
90	L.Freese	Wheat	<u>6500</u>	<u>4000-4900</u>
		MEAN	5610	4160
88/89	D.Sclanders	Soyabean	4394	2700
88/89	A.Muirhead	Wheat	5300	3500
88/89	R.Cobbold	Dry Beans	<u>3154</u>	<u>1250</u>
		MEAN	4283	2483

PUTU contains a simplifying procedure making it possible very easily and quickly to establish a workable crop growth model for any crop. The only expertise required for this is an estimate

of the maximum ratio of plant evaporation to reference evaporation ( $k_{vo} = E_{vo}/E_o$ ) for each crop growth stage. Such ratios can be readily estimated from the literature (Doorenbos and Kassam, 1979; or Hinkle, Gilley and Watts, 1979; or Jensen et al., 1990). For certain crops these ratio's can actually be computed in the programme itself.

Careful scheduling aims at minimizing water applied,  $V_a$ , which for a given net irrigation requirement,  $V_n$ , will increase water application efficiency (Eq. 4.2.1), and hence overall project efficiency (Eq. 4.2.7).

## CHAPTER 9

### CALIBRATION AND VALIDATION OF THE PUTU-IRRIGATION WHEAT GROWTH SIMULATION MODEL

#### 9.1 NOTATION

$E_o$	reference crop evaporation (here short grass) (mm)
$E_s$	evaporation from the soil surface (mm)
$E_v$	evaporation from the vegetation component of the cropped surface (mm)
$F_g$	relative soil evaporation - the fraction of reference crop evaporation rate equivalent to actual soil evaporation
$F_h$	relative vegetation evaporation - the fraction of potential vegetation evaporation possible under the existing atmospheric evaporation demand and soil water conditions
$F_v$	the fractional radiation interception, defined as the fraction of incoming solar radiant flux density intercepted by the vegetative cover, following De Jager (1993)
$k_v$	the vegetation evaporation coefficient quantifying the relationship between actual vegetation evaporation rate and reference crop evaporation rate under the same atmospheric conditions

$k_{vo}$	the potential vegetation evaporation coefficient quantifying the relationship between evaporation rate from the vegetation of a given crop to the reference crop evaporation rate under the same atmospheric conditions
LAI	crop total leaf area per unit of ground surface area
$\hat{RE}$	simulated relative vegetation evaporation ratio
$\hat{RY}$	relative yield (%)
$t$	time elapsed since the last wetting event (d)
$Y$	measured wheat grain yield ( $\text{kg ha}^{-1}$ )
$\hat{Y}$	simulated actual wheat grain yield ( $\text{kg ha}^{-1}$ )
$Y_o$	seasonal potential wheat grain yield ( $\text{kg ha}^{-1}$ )
$\beta_i$	yield water stress response factor in the $i^{\text{th}}$ growth stage

Subscript o denotes the potential or maximum value.

Subscript i denotes the  $i^{\text{th}}$  growth stage in a growing season with a total of G growth stages.

## 9.2 INTRODUCTION

In recent times, plant water stress has been evaluated in terms of the ratio of actual to potential evaporation from vegetation (Jensen, 1968). This ratio will here be termed the vegetation evaporation ratio.

Early, simple growth models of Jensen (1968) related yield reduction due to plant water stress to the ratio of actual to potential vegetation evaporation. Jensen (1968) showed that yield reduction per unit vegetation evaporation ratio (water stress sensitivity) varies with crop growth stage (see also Hanks and Hill, 1980). The yield reductions due to water stress in each of the growth stages need, however, to be combined in order to obtain an estimate of final yield. This has been undertaken in various ways. Multiplicative, additive and exponential laws have been proposed (see Jensen, 1968; Stewart, Danielson, Hanks, Jackson, Hagan, Pruitt, Franklin and Riley, 1977; Doorenbos and Kassam, 1979; De Jager, et al., 1987).

The objective of Chapter 9 will be the assessment of the accuracy of several such evaporation ratio formulae.

Essentially there are five different ways in which vegetation evaporation ratios simulated for different growth stages may be combined to obtain estimates of final yield. These fall into three main categories, viz. multiplicative, additive and exponential. Whereas, Doorenbos and Kassam (1979) suggested use of the Stewart et al., (1977) multiplicative type model, the original exponential type follows the work of Jensen (1968). Two forms of an additive model were produced by Stewart et al., (1977), with a further additive version developed by De Jager et al., (1987).

While multiplicative and exponential types have frequently featured in the literature; the additive types have only lately acquired significance. Their practical value manifests itself in linear programming applications for optimising irrigation efficiency such as those developed in Chapter 4 and Chapter 7. Such procedure holds much promise for optimising both water applications and the area planted under water limited irrigation situations. This special technique can, however, only be utilized (see Chapter 4) if the yield losses due to water stress computed in each growth stage can be summed to provide the overall yield decrement.

The specific objective here was therefore to determine the accuracies of all five the types of model mentioned and ascertain whether an additive combination of individual growth stage yield reduction could provide acceptable accuracy for decision support systems utilizing say linear programming techniques.

### 9.3 METHOD

#### 9.3.1 Cultivation Practices

Field measured data from Roodeplaat were used to calibrate and validate the models. Data for 1986 and 1988, as reported in unpublished reports (Laarman and Berliner, 1988; Nel and Dijkhuis, 1990) of the Soil and Irrigation Research Institute, were made available by kind permission of Dr. Sue Walker and the

Director of the Institute for Soil, Climate and Water Research, Pretoria. This considerable contribution is herewith recognised.

A field experiment with a split-plot design was conducted at Roodeplaat (latitude 25°35' S, longitude 28°21' E) during 1986. Spring wheat (*Triticum aestivum*, L., cv. Zaragosa) grown on a Hutton form Shorrocks series (Rhodic Paleustalf) soil, was sown on 16 June 1986 (i.e. calendar day, DOY=167). Plant density was 180 plants m<sup>-2</sup> in a row width of 0.25 m. The essential soil characteristics of the Rhodic Paleustalf are as follows: effective rooting depth 1,8 m; drained upper limit (DUL) 200 mm m<sup>-1</sup>; lower limit of soil water extraction (LL) 100 mm m<sup>-1</sup>; clay content 26-38 %; silt 16% and bulk density 1.47-1.64 g cm<sup>-3</sup>.

During 1988, the spring wheat cultivar SST 66 was planted on 8 June 1988 (DOY 160) at a rate of 64 kg ha<sup>-1</sup> in 0.25 m rows on a Hutton form Shorrocks series (Rhodic Paleustalf) soil. Emergence took place from 16 to 20 June (8-12 days after planting) resulting in a density of 140 plants m<sup>-2</sup>. The essential soil characteristics of the Hutton form Shorrocks series are: maximum effective rooting depth 1,8 m ; DUL 200 mm m<sup>-1</sup>; LL 100 mm m<sup>-1</sup>; clay 12-21 %; silt 10% and bulk density 1.47-1.64 g cm<sup>-3</sup>.

The researchers applied 39 different irrigation strategies over the two seasons. This produced 39 different sets of growing

conditions and 39 corresponding yields which could be used for calibration and validation of the models.

#### 9.3.2 Climate data

The daily maximum temperature, minimum temperature, rainfall and sunshine duration for the experimental periods during both 1986 and 1988 seasons were supplied by the Institute for Soil, Climate and Water Research. All weather, soil and plant data were manipulated by means of standard procedures found in the PUTU-System (De Jager, 1992).

#### 9.3.3 Model calibration

The study commenced with calibration of the three yield models described below. This was done using trial and error to determine the appropriate yield-stress  $\beta$ -parameters. The procedure followed, entailed minimizing differences between measured and simulated yields for the arbitrarily selected first 10 plots in the Roodeplaat data list for 1988. All calibration commenced with the cultivar specific  $\beta$ -parameters for wheat suggested by Doorenbos and Kassam (1979). These were then adjusted by trial and error to produce the new  $\beta$ -parameters for the De Jager additive model (denoted Model I) given in Column 4 of Table 9.1. Similarly,  $\beta$ -values for the Stewart additive (Model IV) and exponential (Model V) models were obtained. These are given in Columns 5 and 6 respectively of Table 9.1. The  $\beta$ -

values for the multiplicative model (Model II) and full season model (Model III), were taken directly from Doorenbos and Kassam (1979). The other crop specific model input required, viz.  $F_v$ , the fractional interception; was based upon knowledge of the growth characteristics of wheat at Roodeplaat.

#### 9.4 MODEL DESCRIPTION

##### 9.4.1 The yield models

The PUTU-Irrigation model (De Jager, 1992) offers a choice between all the abovementioned versions of the evaporation ratio model. They make possible the rapid estimation of final seasonal yield. Each utilizes the same iterative vegetation evaporation and multi-layered soil water balance model common in all PUTU models. The iterative routine is described in detail in De Jager et al., 1987. As such, PUTU-Irrigation offered a most convenient basis for the experiment.

Five sub-models (Model I to IV) for computing final yields from vegetation evaporation ratios simulated during each of the crop growth stages were tested. They may be expressed as follows:

The relative vegetation evaporation and relative yield are defined:

$$\hat{RE}_i = \hat{E}_{vi} / \hat{E}_{voi} \quad (9.1)$$

$$\hat{RY} = \hat{Y}/Y_0 * 100 \quad (9.2)$$

Using these definitions then the different models may be expressed mathematically as follows:

(I) Additive

$$\hat{RY} = 100 \left[ 1 - \sum_{i=1}^{i=G} \beta_i (1 - RE_i) \right] \quad \begin{matrix} \text{(De Jager et} \\ \text{al., 1987)} \end{matrix} \quad (9.3)$$

(II) Multiplicative

$$\hat{RY} = 100 \prod_{i=1}^{i=G} [1 - \beta_i (1 - RE_i)] \quad \begin{matrix} \text{(Stewart et} \\ \text{al., 1977)} \end{matrix} \quad (9.4)$$

(III) Full season

$$\hat{RY} = 100 \left[ 1 - \beta \left( 1 - \frac{\sum_{i=1}^{i=G} E_{vi}}{\sum_{i=1}^{i=G} E_{voi}} \right) \right] \quad \begin{matrix} \text{(Stewart et} \\ \text{al., 1977)} \end{matrix} \quad (9.5)$$

Here,  $\beta$  refers to a single  $\beta$ -value for the entire growing season.

(IV) Additive

$$\hat{RY} = 100 \left\{ 1 - \left[ \sum_{i=1}^{i=G} \beta_i (E_{voi} - E_{vi}) \right] / \sum E_{voi} \right\} \quad \begin{matrix} \text{(Stewart et} \\ \text{al., 1977)} \end{matrix} \quad (9.6)$$

(V) Exponential

$$\hat{RY} = 100 \sum_{i=1}^{i=G} \pi \hat{RE}_i^{\beta_i} \quad (\text{Jensen, 1968}) \quad (9.7)$$

The values of the model parameters used in the validation of the different models are given for each growth stage in Table 1.

#### 9.4.2 Vegetation evaporation model

Evaporation from the vegetative component of the cropped surface was computed in PUTU-Irrigation using the evaporation coefficient theory developed by De Jager and Van Zyl (1989). Basically this may be considered either for growing conditions with no water stress, or for conditions exhibiting water stress.

**No water stress:** Here non-water stressed, or potential, vegetation evaporation,  $E_{VO}$ , is assumed to be:

- (i) directly proportional to the fraction of incoming solar radiant-flux density intercepted by the crop,  $F_v$ , and also
- (ii) bears a strict relationship to  $E_o$ , the reference evaporation. Said relationship is quantified by  $k_{VO}$ , the potential vegetation evaporation coefficient.

These assumptions may be defined mathematically by

$$E_{VO} = F_V k_{VO} E_O \quad (9.8)$$

where,  $k_{VO}$  is defined as the ratio of potential vegetation evaporation rate to the reference crop evaporation rate under identical atmospheric conditions. It is an empirical coefficient reflecting the interaction between climate and crop morphology and crop physiology for a given crop growth stage.

Radiation fractional interception may be obtained in one of three ways, viz.

- simulation using  $F_V = 1 - e^{-0.7LAI}$  (9.9)
- measuring the sun fleck area per unit ground surface
- setting  $F_V$  equal to the visually estimated vertical projection of vegetation cover per unit of ground surface area.

The third of these approximation methods is employed in PUTU-Irrigation. It represents an approach similar to the methods of estimating the crop evaporative coefficient adopted by Abbaspour, Hall, and Moon (1992) and Smith (1989) for example. Abbaspour et al., (1992) used this method in a modeling exercise and the Smith (1989) work is aimed at practical irrigation scheduling. In South Africa, irrigation managers follow the third of the mentioned techniques with success (see Chapter 10).

**Water stress conditons:** Under water stress conditions, the interaction between atmospheric evaporative demand, crop physiological capabilities and soil water limitation inhibits the conductance of water through the vegetation. The relative vegetation evaporation rate,  $F_h$ , quantifies this process. It quantifies the influence of the hydraulic conductance of the soil-plant-atmosphere system and is sometimes calculated as the relative hydraulic conductance, i.e. the ratio of crop hydraulic conductance under the existing soil-plant-atmospheric conditions (which could be water stressed) to the hydraulic conductance under no-water stress.  $F_h$  is defined by

$$E_v = F_h E_{v0} \quad (9.10)$$

Thus, by substituting for  $E_v$  from Eq. 9.8,

$$E_v = F_h F_v k_{v0} E_o \quad (9.11)$$

which yields the vegetation evaporation coefficient

$$k_v = F_h F_v k_{v0} \quad (9.12)$$

for use in

$$E_v = k_v E_o \quad (9.13)$$

In all models in the PUTU-System the evaluation of  $F_h$  reduces to the solution of a non-linear equation. This is undertaken by an iterative technique described in De Jager et al. (1987).

Cause for much concern in practical irrigation scheduling, is the climatic dependence of evaporation coefficients as demonstrated for example by Van Zyl and De Jager (1992). It is evident that

here, by definition, the influence of climate upon the vegetation evaporation coefficient manifests itself entirely in  $k_{VO}$ .

It is also evident that the water non-stressed (potential) vegetation evaporation,  $E_{VO}$ , is a special case of Eq. 9.11 for which  $F_h = 1$  (see Eq. 9.8).

#### 9.4.3 Soil evaporation model

By similar arguments De Jager and Van Zyl (1989) defined soil evaporation coefficients, viz:

$$E_S = k_S E_O \quad (9.14)$$

$$\text{or,} \quad E_S = F_g k_{SO} E_O \quad (9.15)$$

$F_g$  effectively describes the limitations placed on soil evaporation due to the gradual drying out of the soil surface. The soil evaporation coefficient relates potential soil evaporation to reference crop evaporation. Thus,

$$E_{SO} = k_{SO} E_O \quad (9.16)$$

$$\text{Hence,} \quad k_S = F_g k_{SO} \quad (9.17)$$

$$\text{with,} \quad F_g = e^{-0.4t} \quad (9.18)$$

Here also the climate dependence of the soil evaporation coefficient is accounted for in the potential soil evaporation,  $k_{SO}$ .

#### 9.4.4 Model validation

After calibration; simulated yields obtained with all five models were compared with grain yields measured during 1988 as well as 1986. Data sets other than the ten used for calibration purposes were used. The slope through the origin, coefficient of determination, index of agreement, mean absolute difference, root mean square error and 80% accuracy frequency were calculated and are presented in Table 9.2. Graphs obtained during validation of, what were deemed to be two of the best performers, the additive (Model I) and multiplicative (Model II) models, are given in Figs. 9.1(a) and 9.1(b).

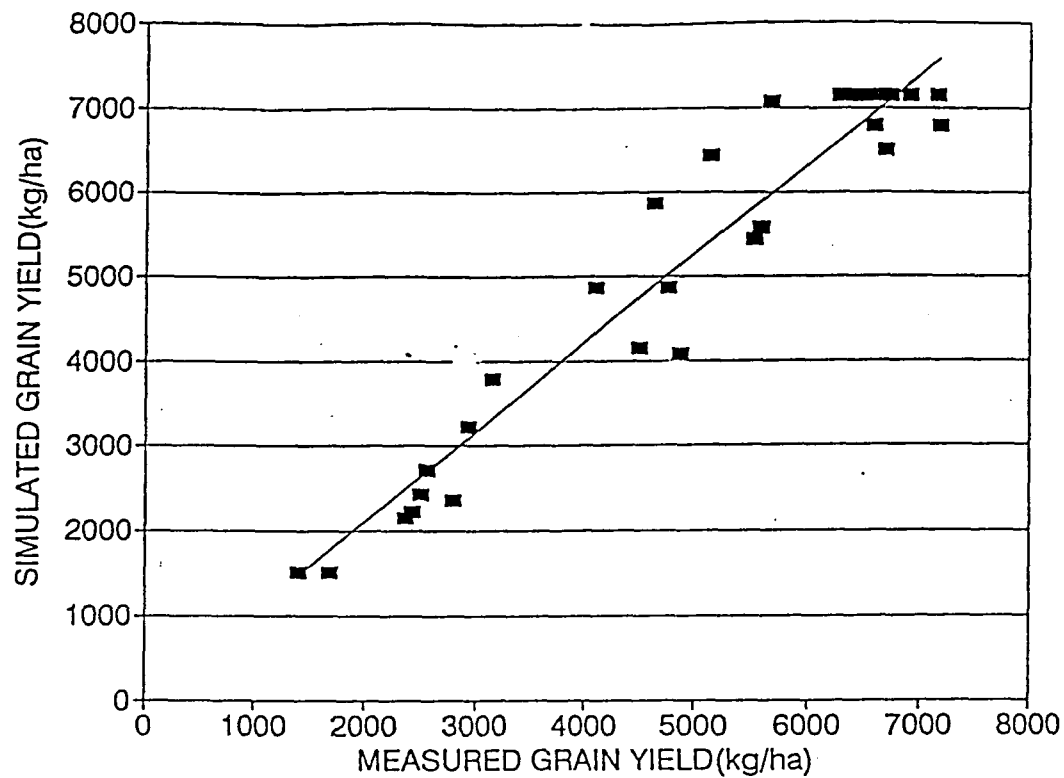


Fig. 9.1.a Comparison of the measured wheat grain yield produced at the Rooedeplaat experiment station in 1986 and 1988 to that simulated using the additive version (Model I) for the validation of PUTU-Irrigation.

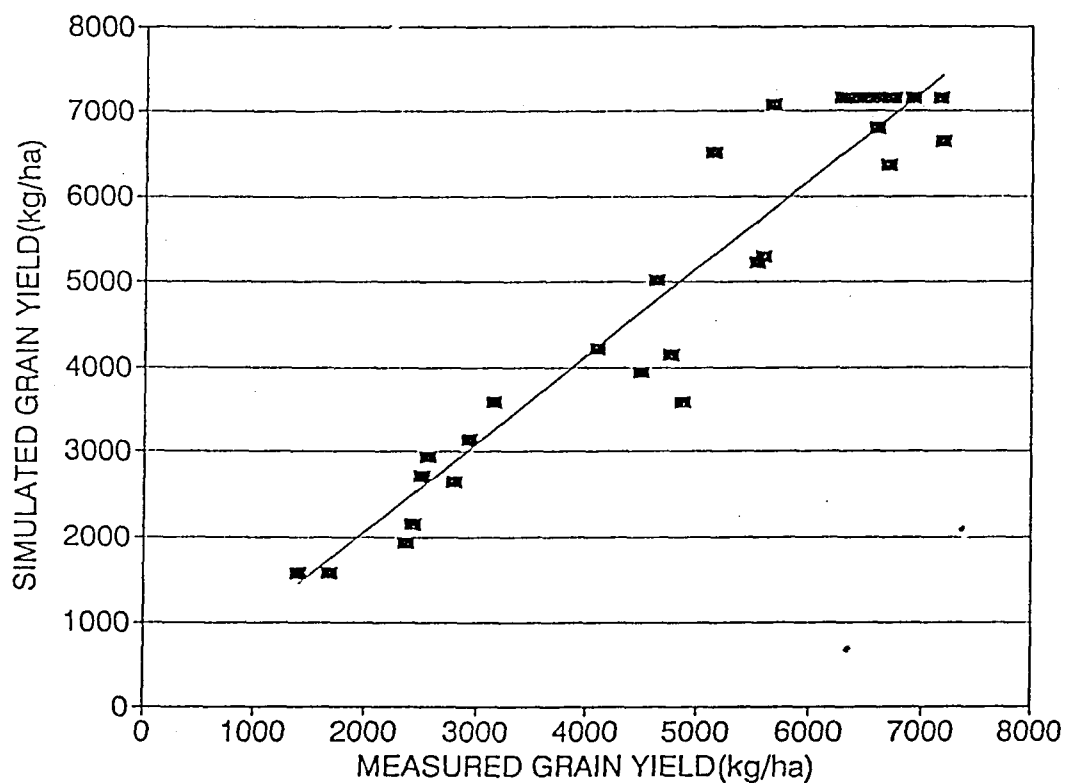


Fig. 9.1.b Comparison of the measured wheat grain yield produced at the Rooedeplaat experiment station in 1986 and 1988 to that simulated using the multiplicative version (Model II) for the validation of PUTU-Irrigation.

#### 9.4.5 Reference crop evaporation

Reference crop evaporation,  $E_0$ , was computed using automatic weather station data and the form of the Penman-Monteith equation as applied in the PUTU-System (see De Jager, 1992).

#### 9.4.6 Statistical analyses

Five different validation characteristics were used to assess each model's accuracy when simulated wheat grain yields were compared to corresponding measured values. The statistical parameters determined were denoted:

S	slope through the origin
$r^2$	coefficient of determination
D	index of agreement of Willmot (1982)
RMSE	root of the mean square error
MAE	mean absolute error expressed as a percentage of the mean of the measured values
D80	the 80% accuracy frequency

These are defined:

$$r^2 = \frac{\sum_{n=1}^{n=N} (\hat{Y}_n - \bar{Y}) (\bar{Y} - Y_n)^2}{\sum_{n=1}^{n=N} (\hat{Y}_n - \bar{Y})^2 (\bar{Y} - Y_n)^2} \quad (9.19)$$

$$D = 1 - \frac{\sum_{n=1}^{n=N} (\hat{Y}_n - Y_n)^2}{\sum_{i=1}^{n=N} (|\hat{Y}_n - \bar{Y}| + |Y_n - \bar{Y}|)^2}, \quad 0 \leq D \leq 1 \quad (9.20)$$

$$RMSE = [N - 1 \sum_{n=1}^{n=N} (\hat{Y}_n - Y_n)^2]^{0.5} \quad (9.21)$$

$$MAE = 100 \frac{\sum_{n=1}^{n=N} |\hat{Y}_n - Y_n|}{N \bar{Y}} \quad (9.22)$$

The D80 statistic was computed as the percentage of simulated values agreeing within 20% of the measured values.

where, the following notation applies

$n$  denotes the  $n^{\text{th}}$  year of a series totaling  $N$  seasons

$\hat{Y}_n$  simulated grain yield ( $\text{kg ha}^{-1}$ )

$Y_n$  measured grain yield ( $\text{kg ha}^{-1}$ )

$\bar{Y}$  arithmetic mean of the measured yields ( $\text{kg ha}^{-1}$ )

$\bar{\hat{Y}}$  arithmetic mean of the simulated yields ( $\text{kg ha}^{-1}$ )

Acceptable criteria for model reliability, for example, for agricultural decision support purposes, were deemed to be as follows:

$$0.9 < S < 1.1$$

$$r^2 > 0.8$$

$$D > 0.7$$

$$\text{RMSE} < 700 \text{ kg ha}^{-1}$$

$$\text{MAE} < 20\%$$

$$\text{D80} > 80\%$$

## 9.5 RESULTS AND DISCUSSION

### 9.5.1 Calibration

The calibrated versions of models I, IV and V all provided acceptable reliability to permit further validation thereof. Statistical parameters resulting from the model calibrations are given in Table 9.1.

The statistical tests showed that, marked improvements in  $r^2$ , index of agreement (D) and the accuracy frequency (D80), were attained with the re-calibrated version of the additive model (Model I). The original  $\beta$ -values (De Jager et al., 1987) tended to lead to underestimation of grain yield under high water stress conditions.

**Table 9.1.** Day of the growing season, DOG; vegetation cover factor, Fv, and the cultivar specific yield water stress response parameters,  $\beta_i$ , for wheat as used in the five models denoted I through V.

Growth stage	DOG	Fv	$\beta$ -values used in different models				
			I	II	III	IV	V
Rest	0	0.00	0.00	1.00	0.99	0.88	0.00
Sow	1	0.00	0.00	0.00	1.70	0.00	0.00
Establishment	2	0.25	0.10	0.20	1.70	0.70	0.10
Development	49	0.63	0.10	0.20	1.70	0.70	0.10
Mid season	70	0.92	0.30	0.30	1.70	1.05	0.30
Flowering	100	1.00	0.40	0.65	1.70	2.25	0.60
Grain fill	110	0.83	0.35	0.55	1.70	2.00	0.45
Ripening	138	0.54	0.00	0.00	1.70	0.00	0.00
Rest	139	0.17	0.00	0.00	1.70	0.00	0.00

1. The value  $\beta=1.70$  was used in Model III, the Full Season transpiration ratio model.
2. Potential wheat grain yield for Roodeplaat was subjectively set at  $7150 \text{ kg ha}^{-1}$

#### 9.5.2 Model validation

Results of the model validations are given in Table 9.2. The multiplicative Model II ( $S=1.03$ ,  $MAE=10\%$  and  $D80=90\%$ ) or Stewart

additive Model IV ( $S=1.05$ ,  $MAE=9\%$  and  $D80=86\%$ ) proved to be the most accurate vegetation evaporation ratio models of those tested. These are followed in descending order of accuracy by the De Jager additive Model I ( $S=0.97$ ,  $MAE=12\%$  and  $D80=83\%$ ), the exponential Model V ( $S=1.02$ ,  $MAE=11\%$  and  $D80=76\%$ ), with the least accurate being Model III, which utilized an entire season evaporation ratio, ( $S=1.05$ ,  $MAE=11\%$  and  $D80=72\%$ ). When tested against the required validation criteria; Models I, II, IV and V proved satisfactory for decision support purposes. Only the full season Model III with a  $D80$  of  $72\%$  yielded marginally unacceptable test results.

**Table 9.2.** Model validation. The coefficient of determination ( $R^2$ ), index of agreement ( $D$ ), mean absolute difference ( $MAE$ ), root mean square error ( $RMSE$ ), 80% accuracy frequency ( $D80$ ) and number of comparisons ( $N$ ) obtained from the tests carried out on the five different versions of the evaporation ratio-yield model.

Statistical parameter	Value obtained for each model				
	I	II	III	IV	V
S	0.97	1.03	1.07	1.05	1.02
$R^2$	0.90	0.91	0.91	0.93	0.92
D	0.97	0.98	0.97	0.98	0.97
MAE (%)	12	10	11	9	11
RMSE	675	599	676	595	615
D80 (%)	83	90	72	86	76
N	29	29	29	29	29

When the suitably calibrated  $\beta$ -parameters (see Table 9.1) were used, an accurate ( $S=0.97$ ,  $MAE=12\%$ ,  $D80=83\%$ ) decision support tool resulted for the De Jager additive Model I. Furthermore, the Stewart additive Model IV also performed most satisfactorily ( $S=1.07$ ,  $MAE=9\%$  and  $D80=86\%$ ). It is thus possible to report that either of these models reflect adequate accuracy permitting of their application in, for example, the linear programming procedures of Chapter 7.

Noteworthy is that this approach requires local knowledge for setting the duration of the individual growth stages and magnitudes of Fv factors. Such approach has been applied in numerous studies, notably Abbaspour, et al., (1992), Smith (1990) and Doorenbos and Kassam (1979). It needs to be stressed here that model reliability is highly sensitive to both duration of growth phase and the magnitude and shape of the green leaf fractional interception factors, Fv. Great care needs to be exercised to ensure selection of realistic values.

On the other hand, however, the yield response parameters determined in this study may be taken to reflect fundamental climate-plant responses. As such they are not site specific.

### Validation on several crops in other areas

The multiplicative Model II was used to compare yields of several crops, measured at the Taung and Molatedi experiment stations with yields simulated by PUTU-Irrigation. The crops involved were wheat, peas, cotton and groundnuts planted from 1988 through 1991 and identical modelling procedures to those described above were used. The measured and simulated results are shown in Table 9.3

**Table 9.3** Simulated yields obtained with the multiplicative version (Model II), of PUTU-Irrigation and measured yields of various crops grown under scheduled irrigation at Taung and Molatedi.

Station	Crop	Year	Yield	
			Measured (kg/ha)	Simulated (kg/ha)
Taung	Peas	1988	2615	2868
		1989	2040	2086
		1990	3668	3368
		1991	3134	3157
	Wheat	1988	4189	3413
		1989	4325	3698
		1990	5861	4934
		1991	6334	5996
Molatedi	Cotton	1988/1989	2580	2999
	Groundnuts	1988/1989	3936	4000
	Peas	1989	3601	3294
	Wheat	1989	4130	3613

When the 12 sets of data were lumped for regression and correlation, the following statistics resulted:

$$R^2 = 0,82$$

$$S = 1,02$$

This impressive agreement suggests that PUTU-Irrigation can be applied in differing sets of climate-soil conditions.

#### Soil water balance validation

It is further, worthy of mention that during the course of the Roodeplaat experiments total soil water contents down to five different levels (viz. 0,52m, 0,67m, 0,97m, 1,27m and 1,90m) were recorded at approximately two to three day intervals. The measured soil water content for each of these depths were compared to those estimated by the PUTU-Irrigation model. For modelling purposes the soil profile was assumed to be at field capacity at the beginning of the season. It is not known whether this was indeed the case with the Roodeplaat experiment. Nevertheless, good agreement between measured and simulated soil water content was evident (see Figs. 9.2 through 9.6). This provides added evidence supporting the reliability of the model. Particularly worthy of note is Fig. 9.4 which shows good agreement between simulated and measured soil water content in the zone down to 0,97 m. This represents probably the entire root zone for wheat.

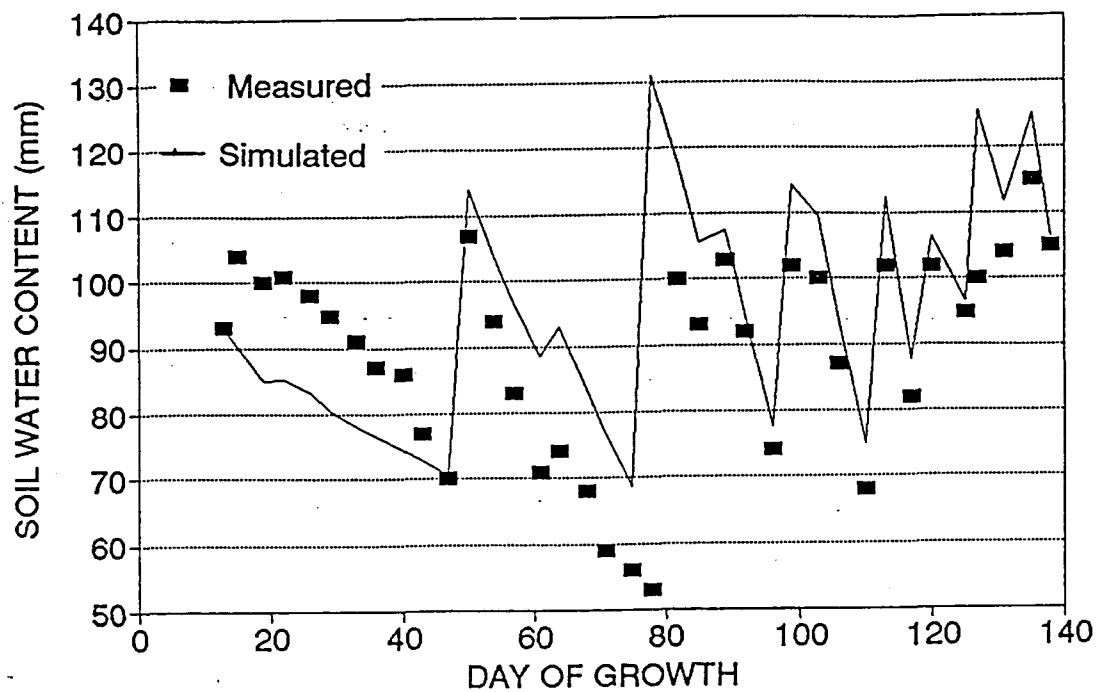


Fig. 9.2 Comparison of soil water content of the 0.52m soil layer of a Shorrock serie soil on the Rooideplaar experiment farm, to that simulated by PUTU-Irrigation.

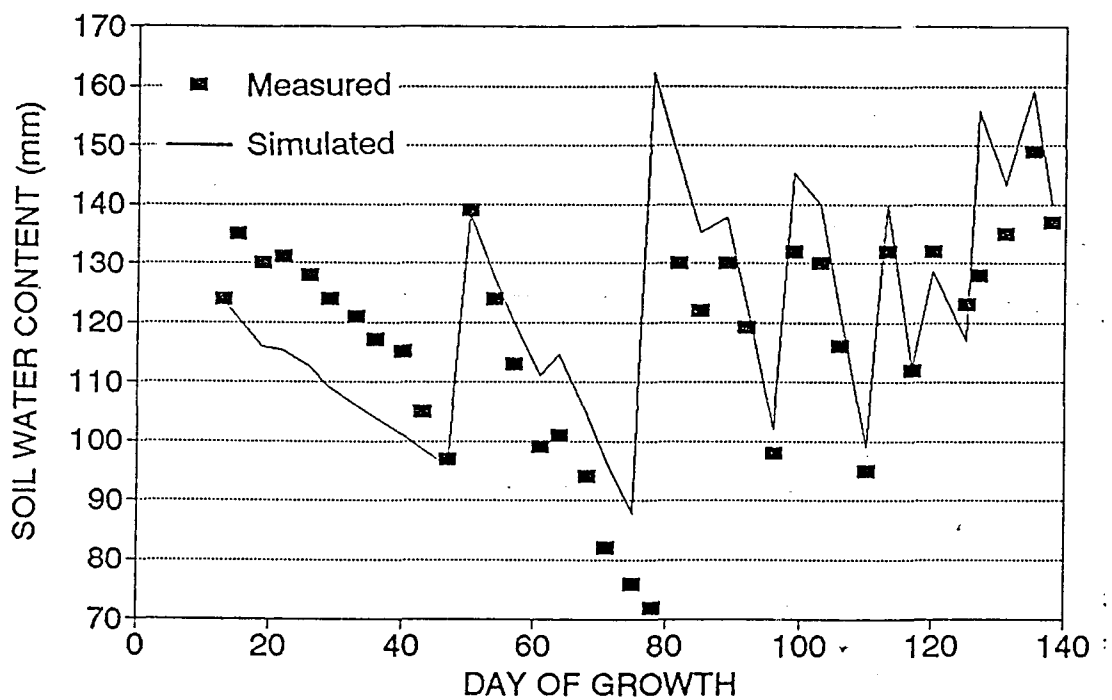


Fig. 9.3 Comparison of soil water content of the 0.67m soil layer of a Shorrock serie soil on the Rooideplaar experiment farm, to that simulated by PUTU-Irrigation.

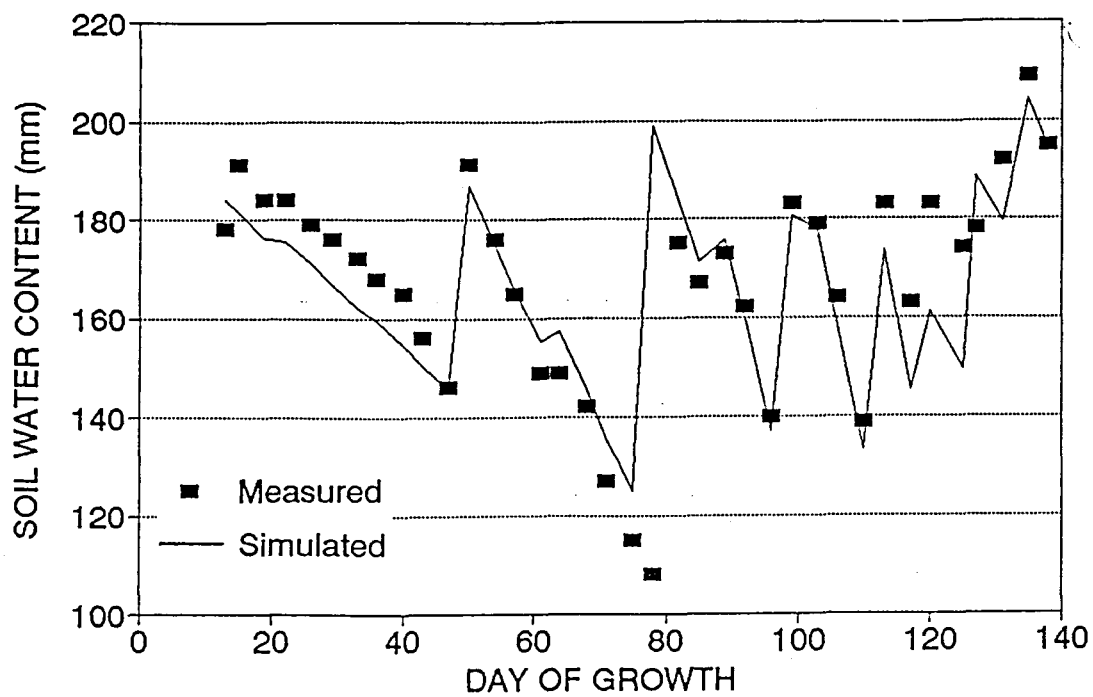


Fig. 9.4 Comparison of soil water content of the 0.97m soil layer of a Shorrocks series soil on the Roodeplaat experiment farm, to that simulated by PUTU-Irrigation.

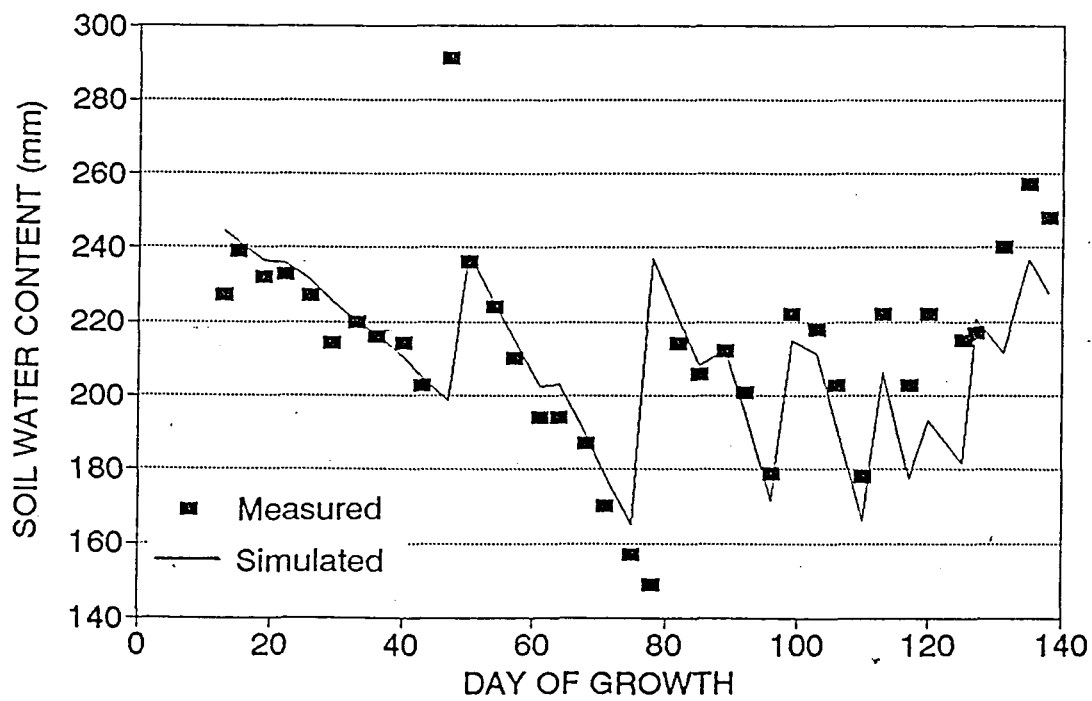


Fig. 9.5 Comparison of soil water content of the 1.27m soil layer of a Shorrocks series soil on the Roodeplaat experiment farm, to that simulated by PUTU-Irrigation.

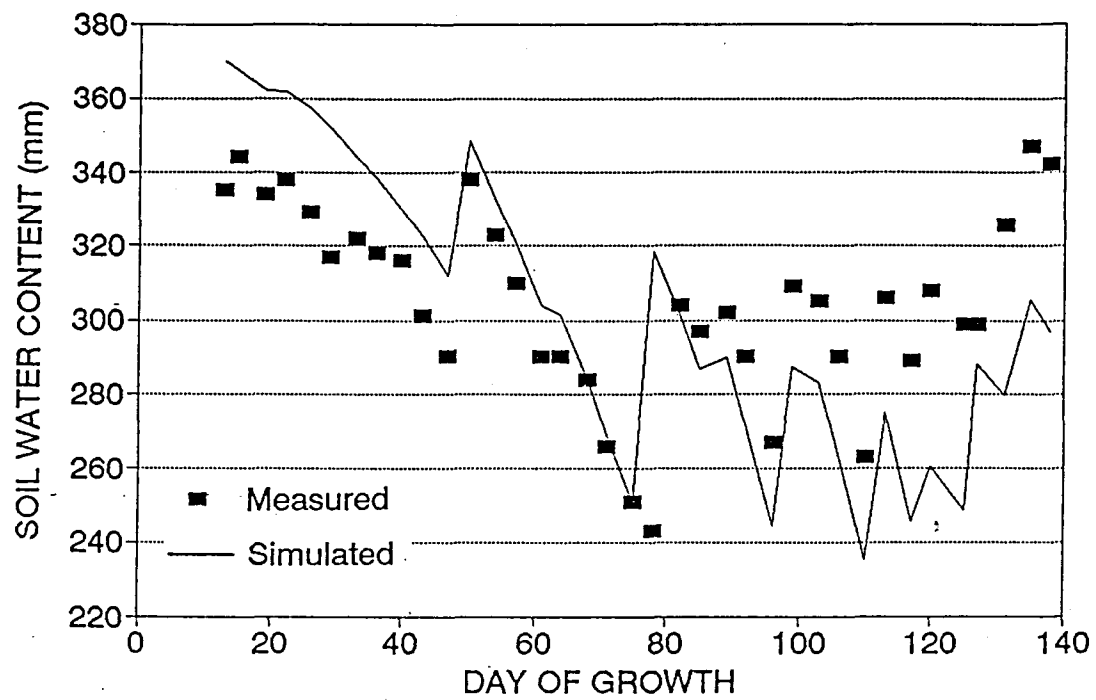


Fig. 9.6 Comparison of soil water content of the 1.9m soil layer of a Shorrocks series soil on the Rooideplaar experiment farm, to that simulated by PUTU-Irrigation.

## 9.6 CONCLUSIONS

The validation tests proved that given suitable yield-water stress response parameters, all five types of model tested provide accuracies acceptable for decision support purposes. The multiplicative type model on this evidence proved to be the most accurate. Importantly, the validity of at least two forms of additive model (viz. Model I and Model IV) for use in linear programming procedures was also proved.

## 9.7 ACKNOWLEDGEMENTS

The author wishes to record his sincere appreciation to Dr. Sue Walker and ISCW for making the meticulous field data available. Mr. Bertus Kruger carried out the many and complicated computations in a most professional manner.

## CHAPTER 10 : PROCEDURES AND INTERMEDIATE RESULTS

### 10.1 INTRODUCTION

In a previous WRC report (de Jager et al, 1987) the computer software was developed whereby automatic weather station data could be utilized for the irrigation of wheat on numerous plots. The usefulness and reliability of the PUTU9 growth model was demonstrated in the Western Orange Free State. It was decided to apply this system to reaching the objectives of the present project. Initially, the programmes as listed in de Jager et al, (1987) were used. In the later part of the project, the user friendly PUTU decision support system (de Jager, 1992) developed on request and with funding of the WRC and Dept. Agricultural Development were utilized. Of particular relevance to this study is the PUTU-Irrigation model which represents a refinement of PUTIRRI.

The programmes briefly described below were initially used in the project separately and then incorporated in the final model PUTU-IRRIGATION.

- DATCON        -        used to convert, list and save hourly data from an automatic weather station in a standard format for use in PUTEREF
  
- PARAMM       -        creates a parameter file with mean monthly values of maximum and minimum temperature, solar radiation, wind speed, rainfall, pan evaporation and relative humidity for a particular site. It is used when missing data is encountered when running PUTEREF.

- PUTEREF - transforms hourly data converted by DATCON to daily data and calculates reference crop evaporation using the Penman-Monteith approach from hourly weather data. After all computations are complete, it creates a weather file for use in the main PUTU programme.
- IRINITIO - creates a carry over file containing all the initial conditions, viz. plant and soil water characteristics, for use in the other models.
- PUTIRRI - this model based upon the standard soil water budget model included in all the PUTU models, was developed in previous WRC projects (see also Chapter 2). It determines the atmospheric evaporative demand of the crop using specific crop evaporation coefficients which can either be inputted into the programme, or themselves developed in the model. The programme determines the soil water balance for nine soil layers and in doing so provides information regarding the soil water deficit in the effective rooting zone and a stress indicator. The latter two factors are used in forecasting irrigation dates.
- SCHEDWAT - programme developed for the Winterton irrigation boards to calculate the volumes of water allocated to the irrigators and scheduled pumping hours. This is to assist the bailiff and the board when water restrictions are employed. Inputs for the programme are riverflow, pump capacity and scheduled area.

## 10.2 ON FARM EXPERIMENTS

The winter season of 1988 was used to locate experimental and irrigation equipment on the cooperators sites, supplement if necessary and thereafter test the same. Other equipment such as the neutron probe, access tubes etc., were ordered and tested upon arrival. Various winter crops were planted and preliminary trials run. Emphasis was placed on the sites selected, equipment available, and attitude of the cooperator, so that assessments could be made before embarking upon detailed trials. Crops such as wheat, dry peas and potatoes were planted by the cooperators in the experimental plots in the same manner as in their lands.

### 10.2.1 Sclanders

In 1988 wheat was planted under a solid set sprinkler system adjacent to a commercial centre pivot block. A basic fertility trial was laid out on this block. Irrigation was applied using the irrigation scheduling programme IRRISCHED (Mottram and Clemence, 1984) as the only weather variables available were pan evaporation and daily rainfall.

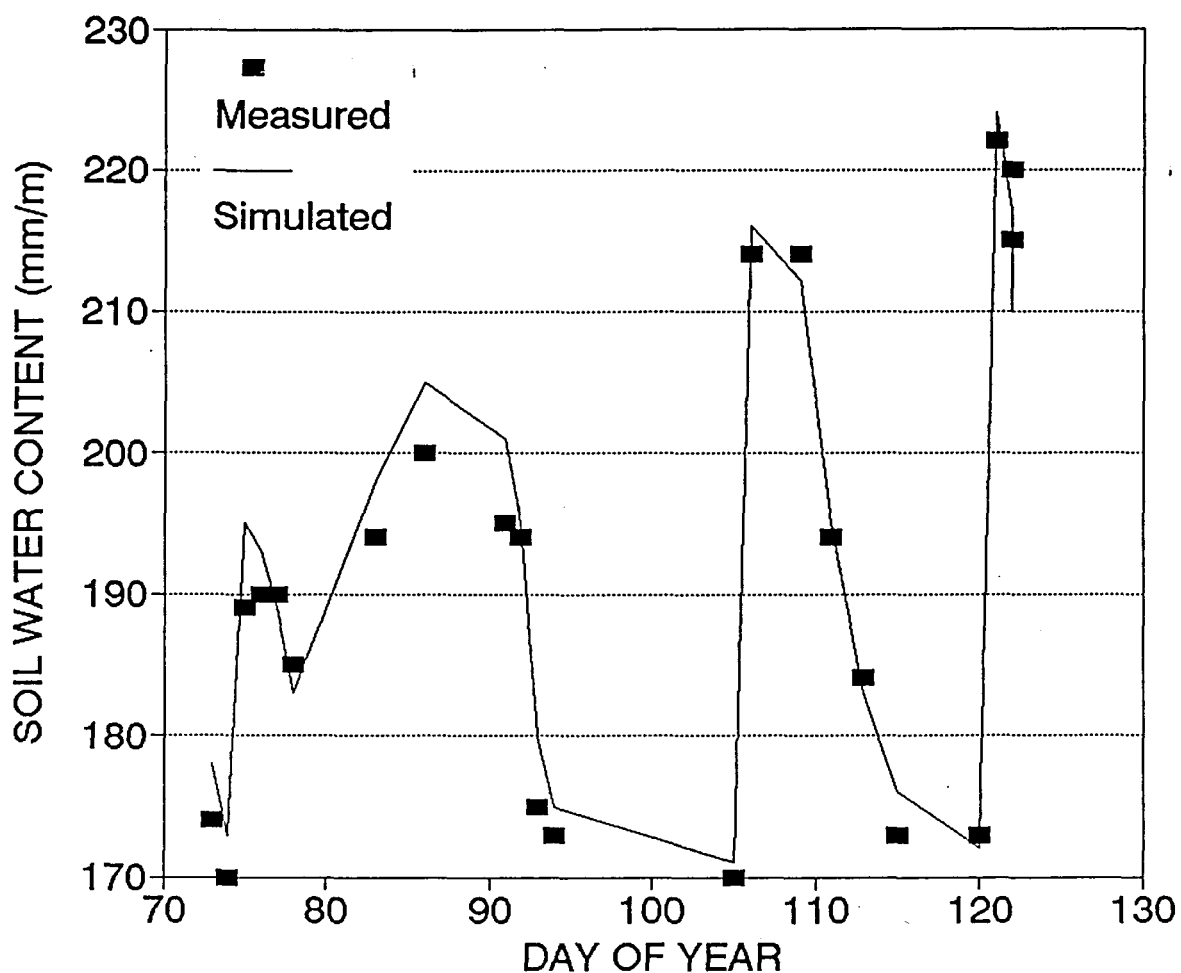
Irrigation applied amounted to 248mm with 12mm of rainfall being received on the experiment block. There was serious lodging due to high winds which affected harvesting and subsequent yields. This resulted in the analysis of results not being carried out as they would have been meaningless.

However the plots which received the same fertilizer as the commercial block alongside all yielded higher than the latter. The mean yield on the commercial block was 4200 kg ha<sup>-1</sup> while the mean yield for the 3 similar plots was 5755 kg ha<sup>-1</sup>. No irrigation amounts were recorded on the commercial block.

In 1988/1989 soyabeans, variety 577G were planted in a fertility trial.

All the yields obtained in the trial were above the average yield for the area viz.  $\pm 2500 \text{ kg ha}^{-1}$  indicating the benefit of scheduling the irrigation. Although there was a 33% variation between the highest yield of  $4394 \text{ kg ha}^{-1}$  and the lowest of  $3300 \text{ kg ha}^{-1}$ , an analysis of variance did not identify between plot any significant differences. The mean soyabean yield obtained by Sclanders' on his irrigated land was  $2700 \text{ kg ha}^{-1}$ , which illustrates the benefit of the irrigation scheduling during the season.

During the course of the season, gravimetric soil samples were taken at three different levels viz. 150, 300 and 450 mm, to compare the measured soil water content of the effective rooting depth estimated by subtraction using the PUTIRRI model. At the start of the season the soil profile was irrigated till assumed full. Fig. 10.2.1 illustrates this comparison.



**Fig. 10.2.1** Comparison of gravimetric soil water content of the effective rooting depth of a Hutton series soil on Sclander's farm, to that estimated in the soil water budget created using PUTIRRI

During the 1988/89 season the upper limits of soil water content were both calculated and determined for three different soils which occur on the cooperators' farms. The upper limit of soil water content ( $UL_{det}$ ) was determined by saturating an area of the particular soil (approximately 2,00 m x 2,00 m), covering this area with plastic sheeting to avoid soil surface evaporation and, after 48h, sampling gravimetrically at 150 mm intervals.

The upper limit of soil water content ( $UL_{calc}$ ) was calculated using the equation developed by Mottram, Hutson and Goodman (1981) which uses particle size distribution viz.

$$UL_{calc} = 21.11 + 0.44C + 0.29Si + 1.06OM - 11.91BD$$

where,

- C = clay content (%)
- Si = silt content (%)
- OM = organic matter content (%)
- BD = soil bulk density ( $g\ cm^{-3}$ )

**Table 10.2.1** Calculated and field determined upper limits of soil water content of different soil types

Soil form	Depth (mm)	$UL_{calc}$ ( $mm^{-1}$ )	$UL_{det}$ ( $mm^{-1}$ )
Hutton	150	154	161
Avalon	150	89	95
Avalon	150	128	136
Clovelly	150	142	133

As concluded by Mottram et al (1981) the results presented in Table 10.2.1 indicate that the estimation of water retention values from soil textured properties and organic matter content is valid especially when considering the time and cost factors in laboratory and field determinations of these values.

During the winter of 1989 peas were planted in a fertility trial but were severely damaged by herbicide and the trial was abandoned.

During the summer of 1989/90 maize was planted under a centre pivot irrigation system. Test plots were carefully monitored and the irrigation scheduled using the PUTU system model PUTU-IRRIGATION. The four test plots yielded 9900, 8950, 10100 and 10250 kg $\text{ha}^{-1}$ . The mean maize yield for the remaining areas where PUTU-Irrigation was not used was 7800 kg $\text{ha}^{-1}$ . The test plots received 64mm of irrigation and 530mm rainfall.

During the 1990/91 summer and 1991 winter season, maize, soyabeans, dry beans and wheat were grown under scheduled irrigation using PUTIRRI. The results of these water management trials are presented in Table 10.2.2.

Table 10.2.2      Yields of crops grown under scheduled irrigation on Sclanders' farm, Clydesdale, Winterton, during 1990/91

Season	Crop	Yield (kg $\text{ha}^{-1}$ )	Irrig. (mm)	Rain (mm)
90/91	Maize	9200	54	761
90/91	Soyabeans	2500	32	568
90/91	Dry Beans	1800	32	568
91	Wheat	4000	186	326

Note:      Wheat crop had a severe incidence of "Takeall" disease.

#### 10.2.2 Freese

On L Freese's farm, dry beans were planted in a basic fertility trial, similar to that on Sclanders' farm, during the 1988/89 season. Three weeks after germination, this trial was destroyed by hail. The trial was replanted but due to (a) poor germination

resulting in another replant and (b) late date of this replant, the trial was abandoned.

During 1990 a lupin variety and time of planting trial which included irrigation water management using PUTIRRI was carried out. Lupins were being examined as a protein supplement in the feed industry. Table 10.2.3. presents the results of this trial.

**Table 10.2.3 Results of an irrigated lupin variety and time of planting trial conducted on an Avalon soil on L.Freese's farm, Dankbaar, Winterton**

Planting date	Variety	Plant population	Yield (kg ha <sup>-1</sup> )	Irrig (mm)	Rain (mm)
10/5/90	Kiev	123200	1409	154	173
22/5/90	Kiev	158900	1755	142	
6/6/90	Kiev	130000	1387	130	
10/5/90	Esta	90000	160	154	173
22/5/90	Esta	77700	1756	142	
6/6/90	Esta	84400	942	130	
10/5/90	Lucrop	217500	486	154	173
22/5/90	Lucrop	165500	1158	142	
6/6/90	Lucrop	261100	1445	130	

During summer of 1990/91 and winter of 1991, maize, soyabeans and wheat were grown under scheduled irrigation using PUTIRRI. The results of these water management trials are presented in Table 10.2.4.

**Table 10.2.4** Yields of crops grown under scheduled irrigation on L Freese's farm, Dankbaar, Winterton, during 1990/91

Season	Crop	Yield (kg ha <sup>-1</sup> )	Irrig. (mm)	Rain (mm)
90/91	Maize	9750	62	651
90/91	Soyabeans	3800	40	502
91	Wheat	5250	224	265

#### 10.2.3 Hall

A water management trial (irrigation scheduling using PUTEREF) was commenced on A Hall's farm, but due to lack of variables monitored by the cooperator no significant or reliable results were forthcoming.

#### 10.2.4 Cobbold

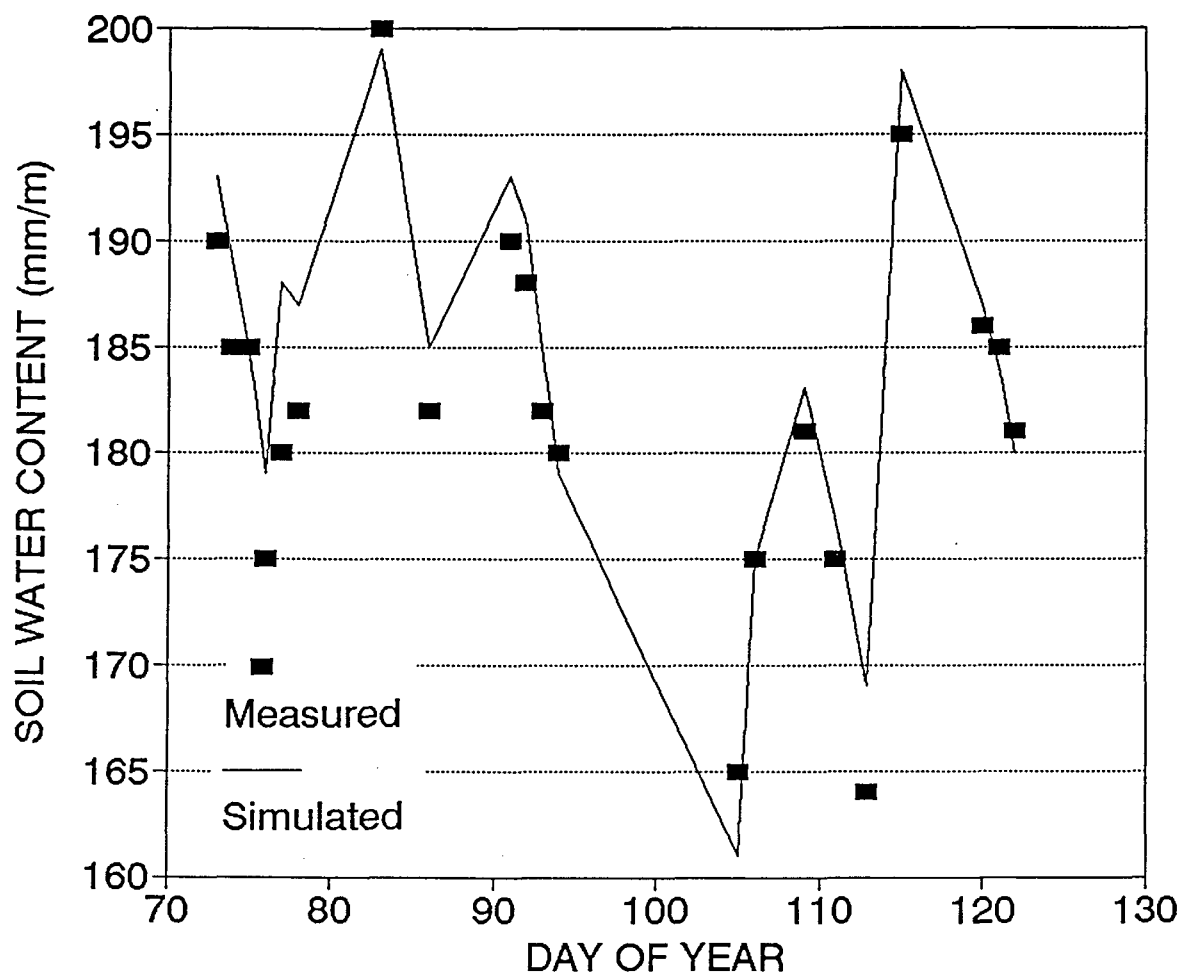
Dry beans were planted in a basic fertility trial on R Cobbold's farm during the 1988/89 season.

Irrigation applied amounted to 118 mm with 296mm of rainfall being received on the experimental block.

All the yields obtained in the trial were above the average yield for the area viz.  $\pm 1800$  kg ha<sup>-1</sup> indicating the benefit of scheduling the irrigation. Although there was a 67% variation between the highest yield of 3154 kg ha<sup>-1</sup> and the lowest yield of 1852 kg ha<sup>-1</sup> the analysis of variance employed did not show any significance within treatments.

The mean yield obtained by the cooperator on the remainder of his irrigated land was 1250 kg ha<sup>-1</sup>. The lowest yield in the trial was significantly higher than this, illustrating the benefit of scheduling the irrigation.

During the course of the season, gravimetric soil samples were taken at three different levels viz. 150, 300 and 450 mm to compare the measured and modelled soil water content of the effective rooting depth. Figure 10.2.2 illustrates this comparison.



**Fig. 10.2.2** Comparison of gravimetric soil water content of the effective rooting depth of a Hutton series soil on Cobbold's farm, to that estimated in the soil water budget created using PUTIRRI

#### 10.2.5 Muirhead

During the 1989 winter season wheat was planted under two 50 ha centre pivots on A Muirhead's farm. Irrigation was scheduled using the reference crop evaporation calculated using PUTEREF. The mean yield harvested from these two 50ha areas was 5300 kg ha<sup>-1</sup>. The yields recorded on surrounding farms varied from 3500 to 4200 kg ha<sup>-1</sup>. No irrigation amounts were obtained from surrounding farms as these irrigators did not monitor their irrigation. It was evident that, apart from not employing strict irrigation scheduling, the majority of these irrigators either stopped, or drastically reduced their irrigation once the crop started to change colour. Irrigation scheduling on A. Muirhead's pivot area continued through till physiological maturity. Irrigation applied amounted to 115mm with 306,3mm rainfall being received on the centre pivot areas.

During the summer of 1990/91 and winter of 1991, maize, soyabeans and wheat were grown under scheduled irrigation using PUTIRRI on both J and A Muirhead's farms. The results of these water management trials are presented in Table 10.2.5.

Table 10.2.5      Yields of crops grown under scheduled irrigation on Messrs J and A Muirhead's farms, Winterton, during 1990/91

Season	Crop	Yield (kg ha <sup>-1</sup> )	Irrigation (mm)	Rain (mm)
90/91	Maize (J Muirhead)	9000	62	655
90/91	Maize (A Muirhead)	9100	64	651
90/91	Soyabeans (A Muirhead)	3200	40	502
91	Wheat (J Muirhead)	4500	194	260

#### 10.2.6 Olivier

A water management trial was conducted on perennial ryegrass grown under irrigation on H. Olivier's farm. This trial progressed well for the first part of the season and the results of the first two harvests are presented in Table 10.2.6. The cooperator experienced pump problems throughout the remainder of the season so accurate scheduling could not be maintained.

**Table 10.2.6 Dry matter yields of irrigated perennial ryegrass harvested on H. Olivier's farm, using PUTEREF to schedule the irrigation**

Harvest	Irrigation applied (mm)	Dry matter yield (kg ha <sup>-1</sup> )
First	84	965
Second	96	1260

Mean dry matter yields harvested outside the scheduled area were 513 and 962 kg ha<sup>-1</sup> respectively, indicating the benefit of scheduling.

Note: No further trials were conducted on this farm due to inconsistent monitoring by the cooperator.

#### 10.2.7 Hancock

A water management trial was conducted on perennial ryegrass during the 1989 winter season on N. Hancock's farm in the Karkloof. From mid season the river flow became critically low and pumping time had to be reduced to one hour for each standtime of the dragline irrigation system. The normal standtime is four hours. Using the reference crop evaporation (E<sub>o</sub>) from PUTEREF, irrigation was

applied initially on a five day irrigation cycle and then on a reduced two day cycle so as to avoid crop water stress. Although yields were reduced, the crop was maintained in a productive state throughout the remainder of the season as indicated in Table 10.2.7.

**Table 10.2.7    Dry matter yields of perennial ryegrass grown under scheduled irrigation using PUTEREF on N. Hancock's farm in the Karkloof**

Harvest	Irrig. applied (mm)	Rain (mm)	Dry matter yield (kg ha <sup>-1</sup> )
First (March)			885
Second			1320
Third			980
Fourth			820
Fifth (July)	86	2.0	160
Sixth	132	9.4	215
Seventh	118	19.4	695
Eighth	119	79.4	855
Ninth	91	188.4	915
Tenth (December)	141	144.2	880

Sample harvests were taken approximately every four weeks and oven dried. Approximately 90% of the roots of Italian ryegrass occur in the top 150 mm of soil (Mottram, 1976). As water supply became limiting the standtime was reduced as was the cycle so as to satisfy the shallow root system. Capillary water movement could not be relied upon to satisfy plant needs from soil layers below 150 mm . Low yields are normally experienced during July and

August as a result of low radiation and temperatures. The fifth and sixth harvests covered this period in the 1989 season and Table 10.2.4 indicates the low rainfall and yields. Atmospheric evaporative demand was unusually high during this period.

#### 10.2.8 Rietriver

For interest, it is here reported that weather data from the automatic weather station at Rietriver has also been used in the PUTU-system for scheduling irrigations on experimental plots. These experiments are being conducted by Prof. A.P. Pretorius, Dept. of Agronomy, UOFS. Detailed results are available in the relevant interim WRC reports. Suffice it to say that the water use efficiencies obtained using the PUTU-system's software was bettered by only one treatment in the 1989 experiments. This particular treatment too was considered impractical because it was well outside the region of diminishing returns.

#### 10.2.9 Saaiman

Since December 1991, potatoes have been produced under irrigation on H. Saaiman's farm, Simonsium, Reitz. These potatoes are table potatoes produced primarily for the high quality market (Woolworths), the ordinary market and the chipping industry. Recently imported potato varieties have been produced for the overseas market (Marks & Spencers, U.K.).

These potatoes are planted throughout most of the year and are both irrigated and fertigated each day of their growing period.

The initial plant populations were 45000 plants per hectare planted in double rows with the dripper line lying between these rows. A water management trial was conducted on several irrigation blocks and the results are presented in Table 10.2.8.

Table 10.2.8 Potato yields obtained under scheduled drip irrigation and fertigation on H Saaiman's farm, Simonsium, Reitz, EOfS, using the PUTIRRI model in the 1991/92 season

Land No.	Plant popul- ation ( $\times 10^3$ )ha <sup>-1</sup>	Planting Date (DOY)	Days after Emergence to harvest	Harvest Date (DOY)	Yield (kg ha <sup>-1</sup> )	Recovery % for Woolworths (%)	Irrig- ation (mm)	Rain (mm)
L1 B1-4	45	300	87	22	63104	14.2	317.6	290.2
B5-7	45	279	80	364	54382	51.2	264.5	202.5
B8-9	45	265	60	333	41283	66.4	278.6	173.8
L2 B5-6	45	330	70	57	58000	40.0	368.9	217.4

The low recovery rates were due to swollen lenticels occurring on the potato skins, and this is usually as a result of too wet soil conditions. Blocks 1-4 of Land 1 are situated at the bottom of the slope and, due to their slightly higher clay content and position, did not drain well. Furthermore, when the irrigation was switched off, the water tended to drain out onto these blocks.

As the high quality/income market does not want potatoes much in excess of 200g, the plant populations were doubled to 90000 plants per hectare.

Due to the fact that the crop was irrigated daily, the continuously wet soil surface resulted in high water use rates; i.e. a crop coefficient (kc) of 1 or more caused potential crop evaporation rates.

H. Saaiman reported that his electricity account for his irrigation pump had reduced by some 40% since employing the scheduling technique incorporating PUTIRRI. Consequently there must have been a similar percentage saving in water applied. The yields obtained were reportedly higher although the aim is toward quality and not quantity.

It was these results that confirmed H. Saaiman's attitude toward irrigation scheduling and, apart from his entire irrigation

enterprise now being scheduled using the PUTU system, he has and is recommending the system to other irrigators, who in turn have subsequently requested the services using the PUTU system.

### 10.3 ON RESEARCH STATION EXPERIMENTS

#### 10.3.1 Taung

The experimental farm established at Taung to supply the Taung Irrigation Scheme with information was used to conduct basic trials to validate the PUTU system models.

Experience in the Taung scheme has shown that in the past poorly controlled flood irrigation led to salinity build up in many areas. Redevelopment of the scheme involved changes to overhead irrigation, mainly centre pivot systems. This together with the inherent good properties of most of the soils in the scheme has reduced overall salinity build up.

After the floods of 1988 the water table in the area remained high and lateral movement of water was pronounced, especially through the experimental farm.

During the summer of 1989/90 basic fertility and management trials were initiated but due to drastic damage and underground water problems, these were abandoned. Extensive drainage works were installed thereafter.

During the winter seasons from 1988 to 1991 water management trials were conducted on dry peas and wheat, the results of which appear in Table 10.3.1.

**Table 10.3.1 Yields of crops grown under scheduled irrigation on the Taung Research Station, Bophutatswana.**

Season	Crop	Yield (kg ha <sup>-1</sup> )	Irrig. (mm)	Rain (mm)
88	Dry peas	5230	215	238
88	Wheat	4189	175	278
89	Dry peas	4079	354	26
89	Wheat	4325	432	32
90	Dry peas	3668	442	13
90	Wheat	5941	579	13
91	Dry peas	3134	434	67
91	Wheat	6330	709	86

Overall at Taung there appeared to be too much irrigation applied. Analysing the amounts applied during each season showed that there were instances when too much water was applied per irrigation. Although some of the yields obtained were not low, they could have been higher. Upon examining PUTIRRI's daily output there were instances where stress was indicated. Being unable to supply water at those times came about as a result of there being insufficient water in the main supply canal.

#### 10.3.2 Molatedi

The experiment farm established at Molatedi to study the feasibility of irrigated agriculture in the surrounding areas was used to conduct basic trials to validate the PUTU system models.

Table 10.3.2 summarises the water management trials that were carried out on the Molatedi Research Station. Irrigation was scheduled using PUTIRRI.

**Table 10.3.1** Yields of crops grown under scheduled irrigation on the Molatedi Research Station, Bophutatswana.

Season	Crop	Yield (kg ha <sup>-1</sup> )	Irrig. (mm)	Rain (mm)
88	Dry peas	5230	215	238
88	Wheat	4189	175	278
88/89	Cotton	4079	354	26
88/89	Groundnuts	4325	432	32
89	Wheat	3668	442	13
89	Peas	5941	579	13

As was the situation at Taung there appeared to be over irrigation at certain times and due to faulty irrigation equipment, under- or no irrigation at other times.

A plant water stress trial using wheat was conducted at the Molatedi experiment farm during 1991. Four stress treatments replicated four times constituted the trial. The stress treatments, the onset of which was identified when the PUTIRRI stress factor,  $F_w$ , attained 50% were:

Control	-	Normal irrigation throughout
Preflowering	-	Once a 50% stress level was attained (approx. 70 days after planting) no irrigation was applied for 10 days. Thereafter the soil profile was re-filled and normal scheduling continued.
Flowering	-	Stress for ten days approximately 85 days after planting.
Grain fill	-	Stress for 10 days approximately 100 days after planting.

The grain yields obtained were:

Control	-	3400 kg ha <sup>-1</sup>
Preflowering	-	2353 kg ha <sup>-1</sup>
Flowering	-	1498 kg ha <sup>-1</sup>
Grain fill	-	1574 kg ha <sup>-1</sup>

Although the yields were relatively low the sensitive growth stages were identified and significant yield differences resulted due to the imposed stresses. The flowering and grain fill stages being the most sensitive.

This indicates the usefulness of the stress factor,  $F_w$ , in identifying and quantifying stress.

## 11.1 OBJECTIVE

The objective of Chapter 11 was to develop equations whereby the water use efficiency may be calculated in the different branches of an irrigation project. Combine these to provide a measure of overall project efficiency and apply the theory to an irrigation project consisting of two farms in the Little Tugela/Sterkspruit system.

## 11.2 RELEVANT DEFINITIONS

The same symbols and concepts as defined in Chapter 4 will be used in this chapter. Briefly they are as follows:

AED	-	Atmospheric evaporative demand
E	-	Crop total evaporation
Ev	-	Plant evaporation
Es	-	Soil surface evaporation
R	-	Total rainfall
Re	-	Effective rainfall
	-	Rainfall used to produce vegetation
Vn	-	Net irrigation requirement
Va	-	Water applied by irrigation to the cropped surface
Vf	-	Water supplied to a farm or a group of farms
Vt	-	Total water supplied to the irrigation project

From Chapter 4,  $\epsilon_r$ ,  $\epsilon_w$ ,  $\epsilon_a$ ,  $\epsilon_b$ ,  $\epsilon_f$ ,  $\epsilon_c$ ,  $\epsilon_d$ , and  $\epsilon_p$  are the efficiencies in the different branches of an irrigation project, viz.

rainfall use ( $\epsilon_r$ ), water use ( $\epsilon_w$ ), application ( $\epsilon_a$ ), farm ditch ( $\epsilon_b$ ), farm ( $\epsilon_f$ ), water conveyance ( $\epsilon_c$ ), distribution ( $\epsilon_d$ ) and project/plot ( $\epsilon_p$ ) respectively.

By definition irrigation project could pertain to either a number of fields (plots) on a single farm, or a group of farms. Let there be  $n$  irrigated plots in the irrigation plot. Consider the  $j$ th plot. Then following definitions formulated by the International Commission on Irrigation and Drainage, ICID:

$\epsilon_{rj}$	=	$R_{ej}/R_j$ ,	for rainfall use efficiency	11.1
$V_{nj}$	=	$E_j - R_{ej}$ ,	or for the special no water stress case	
$V_{nj}$	=	$AED_j - R_{ej}$ ,	for the net irrigation requirement	11.2
$\epsilon_{wj}$	=	$E_{vj}/V_{aj}$ ,	for irrigated water use efficiency	11.3
$\epsilon_{aj}$	=	$V_{nj}/V_{aj}$ ,	for application efficiency	11.4
$\epsilon_{bj}$	=	$V_{aj}/V_{fj}$ ,	for farm ditch efficiency	11.5
$\epsilon_{cj}$	=	$V_{fj}/V_{tj}$ ,	for water conveyance efficiency	11.6
$\epsilon_{dj}$	=	$V_{aj}/V_{tj} = \epsilon_b \epsilon_c$ ,	for distribution efficiency	11.7
$\epsilon_{fj}$	=	$V_{nj}/V_{fj} = \epsilon_a \epsilon_b$ ,	for farm efficiency	11.8
$\epsilon_{pj}$	=	$V_{nj}/V_{tj} = \epsilon_{aj} \epsilon_{bj} \epsilon_{cj} = \epsilon_{aj} \epsilon_{dj} = \epsilon_{fj} \epsilon_{cj}$ ,	for overall plot portion efficiency as derived from the ICID formulation	11.9

The appearance of  $j$  in the symbol signifies the portion of total water flow for the  $j^{\text{th}}$  plot.

All water amounts should be expressed in mm accumulated over a given uniform time period.

As here defined application efficiency,  $\epsilon_a$ , accounts for water losses due to both the irrigation systems employed, and the inefficient timing and injudicious application of irrigation.

Evaluation of the efficiencies obtained on an entire irrigation project are often required in practice. Computation of this is simply carried out by summing the water amounts applied (the  $R$  and  $V$ ) over all the relevant plots ( $j$ ).

By way of explanation, in normal terminology the project quota is  $V_f$  and  $V_t$  equals the project water quota plus any additional

water lost while conveying it to the farm boundary from the water source.

An interesting deviation from the ICID formulation (Eq. 11.9) of individual irrigated plot portion overall efficiency,  $\epsilon_{pj}$ , may be calculated from

$$\epsilon_{pj} = E_{vj}/V_{tj}, \quad 11.10$$

However, should it be necessary to account for the efficiencies in the individual subsections of the irrigation pathway, it is possible to express  $\epsilon_{pj}$  as

$$\epsilon_{pj} = \epsilon_{wj} \cdot \epsilon_{aj} \cdot \epsilon_{bj} \cdot \epsilon_{cj} \quad 11.11$$

Eq. 11.11 represents a variation upon the ICID formulation in that it introduces  $\epsilon_{wj}$ , the water use efficiency prevailing in the vegetation (crop) production process. The advantage of such expression is that it reflects the efficiency with which rainfall is utilized by the entrepreneur. Generally it should result in overall project efficiencies exceeding unity because the benefit of rainfall is accounted for. The standard ICID formulation (Eq. 11.9) corresponding to Eq. 11.11 is derived by making  $\epsilon_{wj} = 1$ , an assumption inferring zero rainfall and 100% utilisation of applied water, i.e.  $V_{aj} = V_{nj}$ .

Thus, incorporation of this modification in Eq. 11.11, yields the normal ICID expression (Eq. 11.9) for plot efficiency, viz.

$$\epsilon_{pj} = \epsilon_{aj} \epsilon_{bj} \epsilon_{cj}$$

Using the definition expressed in Eq. 11.10 and summing the plot portion efficiency, the overall irrigation project efficiency,  $\epsilon_p$ , may be calculated from

$$\epsilon_p = \frac{\sum_j^n E_{vj}}{\sum_j^n V_{tj}}, \quad 11.12$$

$$\text{or, using the ICID formula, } \epsilon_p = \frac{\sum_j^n V_{nj}}{\sum_j^n V_{tj}} \quad 11.13$$

Similarly, the individual efficiencies for the different branches in the entire project may be calculated. For example, for a project, the application efficiency  $\epsilon_{ap}$ , will be given by

$$\epsilon_{ap} = \frac{\sum_j^n V_{nj}}{\sum_j^n V_{aj}} \quad 11.14$$

### 11.3 APPLICATION

A farmer/manager would be interested in mainly on-farm efficiencies  $\epsilon_f$ , expressed by Eq. 11.8, i.e.,

$$\epsilon_f = \epsilon_a \cdot \epsilon_b$$

or, scientists would probably be interested in

$$\epsilon_f = \epsilon_w \cdot \epsilon_a \cdot \epsilon_b \quad 11.15$$

Both equations provide assessments of the farmer's performance in regard to the management of water on his own farm. Water managers, policy makers, and bailiffs on the other hand are concerned with overall project efficiency  $\epsilon_p$ , expressed as either,

$$\epsilon_p = \epsilon_w \cdot \epsilon_a \cdot \epsilon_b \cdot \epsilon_c,$$

or, ignoring rainfall

$$\epsilon_p = \epsilon_a \cdot \epsilon_b \cdot \epsilon_c$$

Eq. 11.9 and 11.11 provide information as to where water is being wasted in the scheme. For example,  $\epsilon_r$  provides information on how efficiently the rain has been used;  $\epsilon_a$  the efficiency of the irrigation systems and the scheduling;  $\epsilon_b$  the water tightness of the farm canals, pipes, pumps and ditches, and  $\epsilon_c$  the efficiency with which water is conveyed from the water source to the farm itself.

$R_e$  or  $R$  is important for determining net-irrigation requirement and  $\epsilon_w$  when necessary.  $R_e$  is defined

$$R_e = R - E_s - \text{Drainage} - \text{Runoff} \quad 11.16$$

#### 11.4 WORKED EXAMPLE

To illustrate the method the above equations were applied to a project consisting of two farms in the Little Tugela/Sterkspruit system. The conventional ICID equation was used.

Consider two situations namely A and B.

The objective of the exercise was to find the information required by

- a) a farmer who wishes to ascertain where he is losing water, or being inefficient,
- b) an irrigation project manager who requires information on the efficiency prevailing in the project consisting of the two situations.

The first step was to establish the data matrix required for the calculations.

Table 11.1 Data matrix for computing irrigation efficiencies.

SITUATION	j	R	Re	Ev	Es	AED	Vn	Va	Vf	Vt
A	1	211	177	381	109	490	213	412	515	644
B	2	100	100	273	79	352	252	274	315	347

In this table the values for  $R_j$ ,  $Re_j$ ,  $Ev_j$ ,  $Es_j$ , and  $AED_j$  were extracted from printouts from PUTU-IRRIGATION.

*In situ* measurements were made of  $V_{aj}$  and  $V_{fj}$  and  $V_{tj}$  was estimated.

It is interesting to note that for Farm B water is drawn directly from a free-flowing stream. Hence the water loss from  $V_t$  to  $V_f$  (32mm) is due to pump inefficiency. In situation A, water supplied by river from a large storage dam, the river continuously

flows (i.e. a wet bed) delivering a prescribed base flow and is vegetation covered. A 10% loss due to evaporation occurs from the water and vegetation, on its passage from the dam to Farm A. A further loss of 15% occurs as a result of it not being possible precisely to synchronise pump activation with the arrival of the parcel of water specifically ordered and destined for the farm. Thus losses occur at the time of activation and de-activation of the pump. These could vary according to the skill of the manager.

The flows constituting  $V_t$  are reckoned above the base flow of the river as prescribed by the water law.

Once the data matrix has been established the Quattro spreadsheet IREF computes all the required efficiencies and displays them as illustrated in Table 11.2.

**Table 11.2**      Irrigation efficiency computed using the ICID conventional forms of Eq. 11.1 to 11.9 and the input values listed in Table 11.1

SITUATION	EFFICIENCIES							
	$E_w$	$E_r$	$E_a$	$E_b$	$E_c$	$E_d$	$E_f$	$E_p$
A	92	84	52	80	80	64	41	33
B	100	100	92	87	91	79	80	73

Equations 11.3, 11.1, 11.4, 11.5, 11.6, 11.7, 11.8 and 11.9 were used to calculate these efficiencies. The overall project efficiency was computed from Eq. 11.9.

#### 11.5      DISCUSSION

From the results listed in Table 11.2 it is possible to provide the information required for objective a) and b) above.

- a) Greatest inefficiency on Farm A occurs during the application and scheduling phase ( $\epsilon_a$ ) and the conveyancing phase ( $\epsilon_f$ ).
- b) The overall irrigation efficiency for the project consisting of Farm A and Farm B is low at 47%. The cause being mainly the poor efficiency on Farm A in the phases indicated under a) above.

This procedure illustrates the value of evaluating the efficiencies in each branch of an irrigation project. The spreadsheet IREF could accommodate numerous plots of land on many farms in an irrigation project.

No generalisation as to the magnitude of component and overall efficiencies may be had from this brief illustrative analysis. The values do give an indication of the values to be expected in practice.

## CHAPTER 12 : SUMMARY

### 12.1 GENERAL

The overall objective of the research here reported was to maximise the efficiency of water use on an irrigation project. It was required to investigate various different climate-soil situations.

Maximisation of overall irrigation project efficiency results from maximisation of irrigation efficiency on the individual farms within the given project. Hence, a bottom up approach was adopted. Much emphasis was placed upon individual farms and indeed single plots of land. In Chapter 11 a mathematical model is presented which permits evaluation of irrigation efficiency in the different components of an irrigation project and the combination thereof to provide an overall efficiency.

A mathematical modelling approach was used throughout. This computerised, numeric, quantitative method ensures non-subjectivity, and furthermore makes possible the application elsewhere of the exact procedures here developed.

Consideration of a variety of climate-soil situations was achieved by conducting investigations in four markedly differing localities, viz.

Winterton	-	medium rainfall and hilly
Taung/Molatedi	-	dry, Highveld
Karkloof	-	humid, high rainfall
Reitz	-	continental, good rainfall

Furthermore, various different types of irrigation system, water supply and conveyance system were employed at each locality providing numerous irrigation scenarios.

The overall objective was divided into three specific objectives. Achievement of these specific objectives will now be described.

## 12.2 SITUATION SURVEYS

A specific objective was to carry out situation surveys on selected projects and, if possible, develop a mathematical model for each project.

Situation surveys were carried out at 24 sites. In most cases no mathematical formulation was possible, information gathered was compiled in guidelines for efficient water use and management on irrigation projects. These guidelines were presented to certain water boards and brought about significant change in their *modus operandi*.

The Little Tugela/Sterkspruit Irrigation Board adopted a new method of decision making based upon the workshops, technology transfer and research results obtained in the area. This improved the effectiveness with which water was apportioned to users. Adoption of Schedwat and the PUTU-system lead to the appointment of a bailiff who now uses these programmes in consultation with this project.

These guidelines were also applied in the Karkloof. This water board had been proclaimed in 1986. Little organization had however taken place subsequently. The guidelines assisted greatly in the formalization of a board for the area and the management of their irrigation water.

## 12.3 MODELS DEVELOPMENT AND APPLICATION

A specific objective was to use and refine computer models for analysing current operations and make recommendations for increasing overall project and on-farm productivity and water use efficiency.

The mere fact that commercial irrigators are employing the PUTU models, albeit on their own, or through the University of the OFS, testifies to the fact that they are both operational and valid.

The validation tests proved that, given suitable yield-water stress response parameters, the models provided accuracies acceptable for decision support purposes. Furthermore, the validity of the additive form of the model for use in linear programming procedures was demonstrated.

Different aspects of crop growth and water balance models were validated at three different sites namely, Roodeplaat, Taung and Molatedi.

The models, when applied in practical situations, highlighted the procedures to be implemented for increasing both overall project water use efficiency and on-farm productivity.

On perennial pastures, an individual farmer realised  $\pm 50\%$  decrease in pumping costs below the previous season when he himself applied the AWS-data and computational procedures. Another dairy farmer in the same district was able to survive on irrigated pastures through the dry 1992 and 1993 seasons. Whereas dairy farmers in the same area were forced to reduce herd size due to lack of adequate irrigated pasture.

In Reitz the validity of using PUTU to irrigate (by drip irrigation) high quality potatoes for the local market, the chipping industry and especially the lucrative export market was proved. Since employing the PUTU procedures the particular farmer claims a 40% saving in pumping costs.

Floods disrupted the early experiments at Taung and Molatedi. Thereafter it was possible to conduct water management trials which could only serve as demonstrations to the local community. One trial, however, did prove the validity of Fw, the water stress factor for identifying stress conditions. A 50% value was found accurately to reflect the onset of stress.

In the Winterton area centre pivot irrigation farmers on average attained approximately 40% increases in yields above those

attained in the surrounding area in which scheduling took place according to normal practice.

#### 12.4 MAXIMISATION OF EFFICIENCIES

A specific objective was application of the models to irrigation project management and the refinement of the models with the aim of maximising overall irrigation efficiency.

Equations for quantifying efficiencies were developed and applied. Water use efficiency was improved in all the cooperator sites. This was mainly due to the effective irrigation scheduling technique made available by the PUTU-system.

Linear programming (LP) procedures for planning strategies for optimizing the area to be cultivated and the amounts of water to be applied in the different crop growth stages were formulated.

With regard to pre-season planning, two Little Tugela farmers utilized the LP developed during the dry 1991/1992 season when water restrictions were operative. Significant financial gain accrued. The Sterkspruit water board have yet to adopt the system.

Routine information regarding irrigation which evidently had good impact upon users was provided to boards, estates and individuals. Advices on water management and distribution, and efficient irrigation scheduling were distributed.

#### 12.5 CONTRIBUTION TO THE STATE OF KNOWLEDGE

Irrigators employing the PUTU-system and allied LP programmes for irrigation scheduling having gained considerable confidence in their own irrigation management capabilities. Several entrepreneurs, both large and small, now employ the system

Some resistance to change, especially on the larger estates, is still evident. This is however diminishing. The fact that the models have been applied in actual situations and produced good results has done much to enhance their credibility. Less electricity and subsequently less water have been consumed to produce increased yields and quality at farm level.

#### 12.6 EXTERNAL COOPERATION

The industry is eager to adopt the programmes and procedures now available. This is borne out by the willingness of farmers and farm cooperatives to contribute, for own account, seven automatic weather stations towards the project. This involved considerable expense.

Furthermore, other farmers have expressed the desire to become involved in the near future.

#### 12.7 RECOMMENDATIONS FOR FUTURE RESEARCH

Basic research needs for furthering the approach to irrigation scheduling here promoted, include:

- the soil water table and drainage subroutines of the crop growth models require validation in order to eliminate minor modelling errors,
- the perfecting of radio-telemetry links with automatic weather stations to expedite and simplify data transfer,
- how to manage the large volumes of data and make information accessible to users,
- the establishing of crop growth parameters for both different crops and different cultivars within given species,
- the application of the present computerized techniques of management and water distribution to large and small irrigation projects,

- the establishment of a weather/irrigation service/agency for the farming community, and
- the extension of the techniques here perfected to the special case of irrigation on small holdings.

#### 12.8 TECHNOLOGY TRANSFER

This project serves as an excellent example of how best to transfer high level technology to the on-farm and industry situations. Using careful diplomacy and purposefulness, the most sophisticated computer technology has been introduced and sustained in numerous practical irrigation scheduling scenarios. This was mainly achieved by:

- collaboration and involvement in water board activities
- routine advisories, on when and how much to irrigate, presented in a form easily digested and applied by managers
- the workshops organised,
- the several oral presentations at local and international congresses and farmers' days, and
- articles in the scientific literature.

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Dr. G.C. Green	-	Water Research Commission
Mr. D.J. du Rand	-	Department of Agriculture
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