

**SHORT TERM PLANNING AND OPERATION  
OF IRRIGATION SYSTEMS**



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**TO MY PARENTS AND TEACHERS**

## ABSTRACT

In recent times, with regards to rural water supplies in Victoria and most other parts of Australia, emphasis is placed more on efficient use of existing water resources than on new resource developments. This is especially true for irrigation systems. This emphasis is mainly due to limited funds available for construction works, lack of suitable hydrologic sites, and the spirited and justifiable lobbying of environmental groups against construction of new projects. Hence to meet the increased water demands, efficient operation of existing irrigation systems is required.

A considerable amount of research and development work in terms of developing effective simulation models has been done on long and medium term planning and operation of irrigation systems, but very little research has been done on the short term (up to 14 days) aspects. Ad hoc methods, mainly based on experience and simple analytical tools, have been used in the past on short term planning and operation of irrigation systems, in particular on irrigation scheduling. These ad hoc methods were considered to be satisfactory at the time of their introduction. However, the advances in irrigation science and technology have provided the break-through required to accurately quantify the effects of plant, soil and climate on the processes of on-farm irrigation scheduling. In addition, with high computational power of personal computers, irrigation scheduling based on an accounting of soil water budget components has become popular in recent times around the world. This research project focuses on such irrigation scheduling techniques, with the aim of improving the efficiency of water use, thus leading to conservation of water resources. Furthermore, the accurate prediction of crop water use for irrigation scheduling will reduce over-irrigation, which in turn will minimise waterlogging, soil salinisation and algal bloom hazards - the three rapidly growing environmental problems of irrigation, responsible for land and water degradation.

The research project was centred around developing an irrigation scheduling computer software package (IRPSAEV) for use in dairy farms in the Goulburn-Murray Irrigation Area in Victoria (Australia). The model employed simple algorithms for simulating the soil-plant-atmosphere system, and uses water balance

approach. The major drivers (or inputs) of the irrigation-scheduling model were the crop evapotranspiration and the expected rainfall during the irrigation interval.

A common procedure for estimating crop water use or crop evapotranspiration ( $ET_c$ ) is first to determine the daily reference crop evapotranspiration, and then multiply it by the relevant crop coefficient ( $K_c$ ). Daily reference evapotranspiration ( $ET_o$ ) can be determined by direct measurements (e.g. lysimetry) or estimated by empirical methods using climatic data. For use with computer-based irrigation scheduling programs, the  $ET_o$  estimation methods are preferred. A critical review of the previous studies indicated that to date no study was undertaken to evaluate  $ET_o$  methods under Australian conditions, specifically for use with the irrigation scheduling models. Hence, ten  $ET_o$  estimation methods ranging from simple temperature-based to data extensive combination methods were selected to study their suitability in estimating daily  $ET_o$  under Australian conditions. For this purpose, three study sites in Australia were used. The analysis revealed that no single daily  $ET_o$  estimation method using meteorological data was satisfactory for all sites. It was also observed that all  $ET_o$  estimation methods required local calibration against measured lysimeter  $ET_o$  data for better performance. Based on these conclusions, a user-friendly menu driven computer software (REF\_ET) was developed to estimate daily  $ET_o$  using ten  $ET_o$  methods.

Since the crop water use is significantly influenced by rainfall, a reliable estimate of the expected rainfall in any irrigation period of the crop-growing season is of fundamental importance for short-term irrigation planning and operation. However, the short-term rainfall data series experience problems in fitting conventional statistical distributions because of the presence of zeros and outliers in these data series. After reviewing literature, two methods namely the total probability theorem (TPT) and leaky-law (LL) method were selected to model the short-term rainfall data series. Three rainfall sites in Victoria were selected for this study. The analysis of short-term rainfall data series at the three sites revealed that although TPT and LL were satisfactory methods to model rainfall series with zeros, none of these two methods was individually able to fit all short-term rainfall data series at the three sites. Therefore, the joint use of TPT and LL methods was recommended, in which each rainfall data series was successfully fitted by at least one of these two methods. Based

on the concept of joint use of TPT and LL methods, a user-friendly menu driven computer software (RAIN\_PRE) was developed to predict the expected rainfall during the next irrigation season.

The developed irrigation scheduling model (IRPSAEV) was loosely linked with REF\_ET and RAIN\_PRE software through their output files. IRPSAEV was tested using soil moisture data of a pasture farm in Tongala in the Goulburn-Murray Irrigation Area. The qualitative and quantitative procedures adopted for model evaluation showed that there was a good agreement between the predicted and measured soil moisture values, and hence the IRPSAEV package can be safely employed for irrigation scheduling at a farm level to make significant water savings in addition to other environmental related benefits.

The IRPSAEV computer software is user-friendly, and can be operated under three operational modes namely PLANning, SCHEduling and EVALuation modes. In addition, there is an option for calibrating the model to suite local conditions. The PLANning mode computes the expected (or future) irrigation schedules as well as estimates of total irrigation water demand over the entire season before the actual irrigation season starts, to serve as a pre-season planning tool. The pre-season planning will help the farmer to decide how much area to bring under cultivation for specific crops to maximize the net farm profits. The SCHEduling mode provides the schedule (i.e. time and amount) for the next irrigation during any time of the irrigation season. This information can be used by the farmer for real-time operation of an irrigation system. Hence, this mode serves as a real-time operational tool.

The EVALuation mode evaluates the performance of the irrigation schedules adopted by the farmer during the past irrigation season by comparing against the IRPSAEV-predicted irrigation schedules. This mode of operation is included in the package to encourage the farmers to use computer-based irrigation scheduling to achieve water savings in future seasons. Hence, this mode serves as an evaluation tool. The package has flexibility for its use under a wide range of soil, crop and climatic conditions. In order to use the package under different soil and environmental conditions, the IRPSAEV computer software needs to be calibrated against appropriate measured soil moisture data under local conditions. This can be done using the CALibration mode of the package.

## **STATEMENT**

This thesis contains no material, which has been previously submitted for any other degree or diploma in any University, and to the best of the author's knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference has been made in the text.



**Aftab H Azhar**

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## LIST OF PUBLICATIONS

This thesis is the result of more than four years of research work at the School of the Built Environment, Victoria University of Technology. During this period, following research publications related to this project were published.

Azhar, A.H. and B.J.C. Perera (1994). Modelling of Series of Zero and Non-Zero Rainfalls Using Statistical Distributions. (Proc. Conf. on Engineering in Agriculture, Christchurch, New Zealand, August 1994).

Azhar, A.H. and B.J.C. Perera (1996). Comparison of Evapotranspiration Methods for Use in Irrigation Planning and Scheduling. (Proc. Irrigation Australia, 96 - Australian Solutions: Adelaide, SA. May 1996).

Azhar, A.H. and B.J.C. Perera (1999), Irrigation Water Demand Model for Use in Irrigation Planning and Scheduling. (Proc. Civil and Environmental Engineering Conference: New Frontiers and Challenges, Bangkok, Thailand, November 1999).

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# CHAPTER 1

## INTRODUCTION

### 1.1 BACKGROUND

Australia has around two million hectares of irrigated agriculture, which produce most of Australia's dairy products, cotton, rice, fruit, vegetables and wine, generating about \$6 billion in gross national product and accounting for about 70% of Australia's water use (Austin, 1998). The Murray-Darling Basin (MDB) in south-eastern Australia occupies one-seventh of the total country's land mass and encompasses four federal states (Figure 1.1). Irrigated agriculture accounts for over 95% of water used within the Basin (MDBMC, 1995), and approximately half of this is used for dairying (Turrall, 1993). The MDB's irrigated dairy production is almost exclusively pasture based, typically consisting of a mixture of white clover and perennial ryegrass. Surface irrigation, primarily border-check, is the predominant method used for the irrigation of pastures in the area (Smith, 1993; Mulcahy and Schroen, 1993; and VIDA, 1994).

The largest concentration of irrigated dairy production in the MDB is in northern Victoria and southern New South Wales (NSW). These areas account for over a quarter of the national milk production (Armstrong et al., 1998). Recent survey results indicate that the dairy industry in these areas is expanding and hence the demand for water is likely to increase (Douglass and Poulton, 1998). However, the additional irrigation water supplies are unavailable to meet the increased demands associated with this agricultural expansion.

Currently water diversions from river catchments in the MDB have been capped at 1993-94 development levels by the Murray-Darling Basin Commission (MDBC, 1996). The limits on the availability of irrigation water in the MDB mean that further expansion of irrigated dairying in northern Victoria and southern NSW is dependent on better management of existing irrigation water allocations. Water savings can be made through the adoption of more efficient irrigation practices.

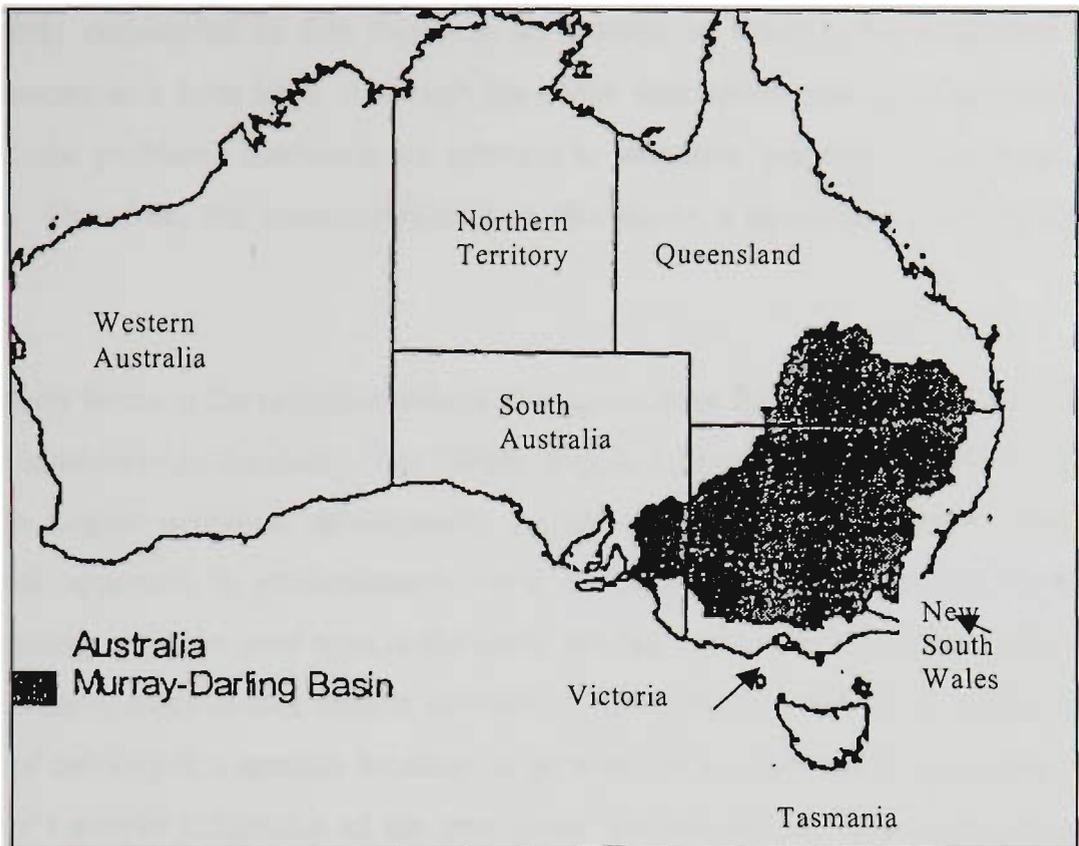


Figure 1.1 Location of the Murray-Darling Basin within Australia

The management of water on border-irrigated pastures is largely by trial and error, so that border irrigation is characterized by excessive run-off and variable water use efficiencies. Hence, the adverse impacts of irrigated agriculture such as salinity, sodicity, waterlogging, acidity and algal blooms are well documented and are in part a consequence of the poor irrigation management (Austin and Prendergast, 1997). A study conducted by Nexhip et al. (1997) reported that on average 20% of the irrigation water applied at dairy farms was lost as irrigation runoff. In a recent study, Austin et al. (2000) quantified the runoff and reported a range of 13% to 34% with an average of 22%. Wood et al. (1998) showed that irrigators tended to apply too much water too early and frequently during the irrigation season. Many management techniques have been identified to reduce the runoff, and the most effective of these was identified through improved irrigation management at farm/border level (Austin et al., 1995; and Austin, 1998). These techniques include border design improvements, use of alternative irrigation application technologies and adoption of irrigation scheduling practices. The short-term planning and operation of irrigation

systems essentially addresses the issue of irrigation scheduling and this issue is primarily considered in this thesis in an attempt to achieve the improved water efficiencies at a farm level. Although the above description was concentrated on the MDB, the problems discussed are relevant to irrigation systems in any part of the world. Therefore, the issue considered in this thesis is applicable to any irrigation system.

The dairy farms in the Goulburn-Murray Irrigation Area (GMIA) in northeast Victoria were considered in the study. The GMIA (Figure 1.2) is part of the MDB and is one of the largest irrigation development projects of Australia. A simple fixed time interval approach is predominantly used in the GMIA for irrigation scheduling. Depending upon the crop type at the farm, the farmers place their water orders with the authority three to four days in advance by specifying the volume of water and the time of delivery at a specific location. In general, these water orders are based on the farmer's simple judgement of the crop water use and his/her other activities at the farm. In most cases, it follows a fixed time interval such as 7-days, 10-days or 14 days etc.

## **1.2 IRRIGATION SCHEDULING**

Irrigation scheduling is the decision making process used by irrigators to decide when to irrigate and how much water to apply. The question of when to irrigate is approached in several ways. However, these methods can be broadly classified under the following headings (Phene et al., 1990):

- (i) plant indicators,
- (ii) soil indicators, and
- (iii) water balance approach.

The plant indicator methods include appearance and growth (Haise and Hagen, 1967), leaf temperature, leaf water potential and stomatal resistance. However, these methods are either too crude and subjective, or call for the use of specialised instrumentation (Singh et al., 1994). The major drawback of these methods is that the decision to irrigate is made after the plant has suffered some amount of moisture



stress, which may sometimes irreversibly damage the plant and affect the crop yield. Besides, these methods do not lend themselves easily to automation.

The soil-based measurements as indicators of the irrigation requirements of plants include appearance and feel, gravimetry, soil matric potential using tensiometers, electrical resistance using gypsum blocks, pulse propagation using Aquaflex, heat pulse using microlink, capacitance using enviroscan and neutron probes etc. Like the plant indicator methods, these techniques provide a posterior measure of irrigation needs when the plant might have been already adversely affected by water stress. These methods also involve disturbing the soil in the vicinity of the plant, thereby affecting the measurement being made.

The water-balance method solves for the irrigation requirement (IR) of the water balance equation, which deals with all processes such as rainfall, crop evapotranspiration, capillary rise, deep percolation, surface runoff etc. The crop evapotranspiration (ET) is one of the major drivers of the water balance equation. The crop ET is usually obtained by multiplying the reference crop evapotranspiration ( $ET_0$ ) with the crop coefficient;  $ET_0$  is calculated using climatic data (Clark et al., 1992). Computer aided scheduling programs using water balance approach offer the advantage of predicting IR a few days ahead, if weather forecasts are available. Forecasting can also be achieved without weather forecast information just using the past weather history. In addition, the water balance models provide an effective but cheap way to introduce irrigators to the concepts of scheduling when climatic data are available.

With the advent of new technologies for real-time monitoring of soil and plant water status, the plant and soil indicator methods have been revisited recently (Phene et al., 1990; and Singh et al., 1994,1995) for irrigation scheduling, especially at research farms. However, due to the requirement of sophisticated instrumentation involving high capital investment, these new technologies become impractical for most commercial farms. Another disadvantage associated with these methods is that the installation of monitoring equipment requires digging up the soil. By digging up the soil not only is the soil structure altered, but the root growth pattern is also altered, probably with greater root depths than elsewhere in the field. This will give a biased

account of both rooting depth and mass, and subsequently an unrepresentative view of moisture conditions in other parts of the field (Wood and Malano, 1996).

In view of the above stated aspects, the irrigation scheduling based on the water balance approach shows high promise to improve water use at an on-farm level. In addition, the water balance method can also be used for estimation of irrigation water requirements of a crop before the start of irrigation season, if the historical  $ET_0$  data are available. This pre-season planning can help the farmer to decide how much area to bring under cultivation for a specific crop for maximising the farm income.

The adoption of improved irrigation scheduling can lead to significant on-farm water savings. Camp et al. (1988) compared three scheduling techniques for corn and soybean crops in USA and reported that the computer based scheduling method had the advantage of predicting irrigation requirements up to 5 days in advance. Irrigation scheduling resulted in water savings of 29% on a mixed farming property in Kansas, USA (Buchleiter et al., 1996) and saving of between 10 and 47% on a sugar cane farm in the Burdekin district of Queensland, Australia (Shannon et al., 1996).

A field trial was conducted during the 1998-99 irrigation season at Tatura (Victoria, Australia) that compared the potential production and environmental benefits from improved irrigation scheduling techniques. The study compared three improved scheduling practices with the traditional every 7-day irrigation practice. The improved practices included the use of tensiometers to schedule irrigation events, the Target 10 recommended practice (i.e. of using 'Class A' pan evaporation minus rainfall (E-R) equal to 50mm to trigger an irrigation), and counting the number of days since the previous irrigation. The study revealed that these three techniques resulted in 23, 17 and 21 irrigations respectively as compared to the 28 irrigations based on the 7-day practice over the entire season (Bush et al., 2000).

The advances in irrigation science and technology have provided the break-through required to accurately quantify the effects of plant, soil and climate on the processes of on-farm irrigation scheduling. In addition, with high computational power of personal computers, irrigation scheduling based on an accounting of soil water budget components has become popular in recent times around the world.

During the last two decades, several computer programs (e.g. Poulton, 1982; Siddig, 1982; Curwen and Massie, 1985; Camp et al., 1988; Murty et al., 1992; Clark et al., 1992; Stapper et al., SIRAG 1993; Buchleiter, 1995; Hess, 1996; and Thivianathan et al., 1998) with varying degree of sophistication have been evolved in the literature. However, these computer based scheduling programs are not yet widely practiced by the farmers. In USA, even though some of the scheduling programs were offered free of charge, the acceptance of these programs among farmers has been reported to be very slow. The limited use of these irrigation scheduling programs among farmers could be attributed to one (or more) of the following reasons (Pleban and Israeli, 1989):

- i) The computer programs were not user-friendly, but were research-oriented tools for use by professionals only.
- ii) The programs considered the scheduling problem from the point of view of the crop and academic research, and not particularly from the viewpoint of the farmers.
- iii) Some computer programs employed complex algorithms for water movement through the root zone, and required the measurement of a large number of soil, plant, and climatic parameters, which are not routinely available in most irrigation systems.

Adoum (1993) reported that computer models which require radical changes to the existing practices of users will not be widely used or accepted. The model must work with the farmer rather than the farmer to work around the results produced by the model. In Australia, in particular in Northern Victoria, a farmer survey report (Maskey, 1995) revealed that an interest had been shown by farmers for use of improved scheduling techniques at farm level, provided that the techniques are simple and compatible with their needs.

Farmers are generally busy in making different management decisions during the irrigation season. Consequently, any aid for improving irrigation decisions should minimise the efforts required to obtain input data and should provide output that is easy to understand and use. If farmers perceive the required data are difficult to obtain

or that a considerable time is required to obtain and process the required data, they are unlikely to use the irrigation scheduling computer programs on an ongoing basis (Buchleiter, 1995).

An efficient irrigation scheduling computer program must at a minimum provide information on the timing of the next irrigation and the amount of water to apply so as to serve as a real-time operational tool. In addition, the program should also be able to predict the expected irrigation schedules as well as the estimates of total expected irrigation water requirements for the entire season (before the actual season starts), to render itself as a planning tool.

Another desirable feature of irrigation scheduling program is that it should manage the concepts and complex mathematics behind the curtain, so that the user can benefit from this technology directly without any mathematical knowledge (Austin, 2000). If a model is to find acceptance for real-time control of irrigation, it must be simple, accurate, robust and inexpensive.

In the spirit of above stated desirable features, the development of a simple model for efficient scheduling and forecasting of irrigation water requirements at an on-farm level was intended in this study. The model employed simple algorithms for simulating the soil-plant-atmosphere system. An effort was made to develop the model with minimum and readily available inputs (e.g. general soil physical properties such as saturation level, field capacity, wilting point etc. and other crop related parameters such as crop coefficients, root zone depth, etc.), so that the model could be calibrated without the need for extensive field measurements, for use in actual field situations.

Irrigation scheduling requires the estimation of crop evapotranspiration and expected rainfall during the irrigation interval. These aspects are briefly discussed in Sections 1.3 and 1.4 respectively.

### 1.3 CROP EVAPOTRANSPIRATION

As stated above, the irrigation scheduling programs require an accurate estimate of water use by the crop. A common procedure for estimating crop water use is to first determine the daily reference crop evapotranspiration ( $ET_o$ ), and then multiply it by a specific crop coefficient ( $K_c$ ), as given by Doorenbos and Pruitt (1977) and Wright (1981,1982). This gives the potential (or maximum) crop evapotranspiration ( $ET_c$ ), which can be adjusted using the moisture content of the soil to calculate the actual evapotranspiration ( $ET_a$ ).  $ET_o$  can be determined by direct measurements (e.g. lysimetry) or estimated by empirical methods. Direct measurements generally produce more accurate values than the empirical methods, but are often expensive, laborious and involve complex instrumentation. For this reason, limited data are available from direct measurements. Therefore, for use with computer based irrigation scheduling programs, there is a need to model the  $ET_o$ .

There are numerous empirical methods available for estimating  $ET_o$  using meteorological data. However, the choice of the method for estimating  $ET_o$  is essentially based on the location, the climate, the intended estimation period, and the input data availability for the site in question. In addition, these methods need to be evaluated and calibrated under local conditions before using them in irrigation scheduling studies (Jensen et al., 1990). There are no evaluation and calibration studies reported for these  $ET_o$  estimation methods for use in the GMIA.

### 1.4 SHORT-TERM RAINFALL PREDICTION

Since the crop water use is significantly influenced by rainfall, a reliable estimate of the expected rainfall in any irrigation period of the crop-growing season is of fundamental importance. Rainfall is not only a random event, but has a variable and highly unpredictable effect on irrigation needs, depending on the intensity and quantity of rain. Efficient utilization of rainfall during the rainy season will help in saving water in the storage reservoir that could be used in the dry season.

In most irrigation systems especially in Victoria (Australia), the irrigation interval (or cycle) ranges between 7-14 days depending on the number of irrigations per season.

For predicting the expected rainfall at 7-14 day time scale without embarking on meteorological forecasts, the most common approach has been to fit an appropriate statistical distribution to the rainfall data series. The rainfall is then predicted with a certain probability of exceedance (Yevjevich, 1972; and Buishand, 1978). These rainfall series typically are highly positively skewed and contain a considerable number of zero values. Therefore, these series are unique in their statistical properties, and require special distributions for modelling. Very few studies have been conducted to model these rainfall series around the globe. Unfortunately, there is no such study conducted for modelling these short-term rainfall series, which can be used for irrigation scheduling purposes in the GMIA.

## **1.5 AIMS OF THE PROJECT**

The main aim of this research project was to develop methods and tools to make efficient use of available water at an on-farm level, which is important in short-term planning and operation of irrigation systems. As stated in Section 1.1, irrigation scheduling was considered as the primary focus of the study. These methodologies and tools will assist the farmers to use water efficiently at their farms. Dairy pasture farms were considered in the study because of their popularity in the GMIA. To achieve the main aim of the study, the following specific tasks were undertaken.

- (i) Understand the basic processes of irrigation scheduling at an on-farm level.
- (ii) Review various  $ET_0$  estimation methods currently available, which use climatic data for daily  $ET_0$  estimates.
- (iii) Identify the most suitable  $ET_0$  estimation methods, evaluate them under Victorian (Australia) conditions, and then develop a computer software for daily  $ET_0$  estimates for use in the irrigation scheduling model.
- (iv) Review and evaluate short-term (7-14 days) rainfall prediction methods, and then develop a short-term rainfall prediction computer software for use in the irrigation scheduling model.
- (v) Review and if necessary, develop algorithms to build a simple irrigation scheduling mathematical model to aid farm managers in the management of on-farm irrigation.

- (vi) Develop an integrated irrigation scheduling computer software by linking the above stated  $ET_0$  and rainfall prediction software with the irrigation scheduling mathematical model algorithms developed in (v) to facilitate efficient water use at an on-farm level (i.e. to serve as a short-term operational tool).
- (vii) Incorporate an option in the above integrated computer software for estimation of irrigation schedules for the entire season before the actual season starts to serve as a pre-season planning tool, to plan for the area of cultivation for a particular crop to bring maximum returns.
- (viii) Incorporate an option in the above integrated computer software for evaluation of existing irrigation scheduling practice so as to demonstrate its capability to serve as an evaluation tool at farm level, and then to demonstrate the use of the package to improve water savings by implementing irrigation scheduling using this software.

## **1.6 BRIEF METHODOLOGY**

The methodology used in this thesis closely follows the tasks outlined in Section 1.5. First, a literature review was conducted on irrigation scheduling techniques, crop evapotranspiration and analysis of short duration rainfalls, with the aim of investigating the state-of-the-technology in these areas and further refining these methods to develop an improved irrigation scheduling model.

Several  $ET_0$  estimation methods were identified for further analysis in this thesis. These methods were evaluated for their suitability under Victorian (Australia) conditions using three study sites. Techniques were developed to estimate certain variables of these methods, which were not measured, from other climate data. Criteria were introduced to rank the  $ET_0$  estimation methods in estimating  $ET_0$ . As a result of the evaluation, a generalised computer software package, REF\_ET, was developed to estimate daily  $ET_0$  from climatic data for use in irrigation planning and scheduling.

In general, the short duration rainfall series consist of zero and non-zero values. Therefore, the methods that account for both zero and non-zero values were

investigated in predicting short duration rainfall. In particular, two methods namely total probability theorem and leaky law were evaluated for their feasibility and accuracy, using three study sites in the GMIA. Based on this analysis, a generalised computer software, RAIN\_PRE, was developed to predict the 5-30 days rainfall for certain levels of probability of exceedance, for use in irrigation planning and scheduling.

Algorithms were developed to formulate an irrigation scheduling model, which uses the water balance approach. Components of the water balance model were studied in detail especially in relation to estimation. In particular, the crop evapotranspiration was considered, since it is the major driver of crop water use. Attention was given to develop algorithms, which can be used with readily available data, yet accurate enough to represent the processes of irrigation scheduling. Commonly used irrigation timing criteria were considered. A case study (i.e. a study site in the GMIA which had appropriate data for testing) was conducted to demonstrate the applicability of these algorithms in irrigation scheduling.

Finally, an integrated software for irrigation planning and scheduling (IRPSAEV) was developed by linking the formulated algorithms of the above irrigation scheduling model with REF\_ET and RAIN\_PRE software. The major features that were considered in developing this software were that it should be robust, computationally fast and user-friendly, and should be able to be used by farmers with easily available data. In developing the package, several modes were considered namely planning, (real-time) scheduling, evaluation and calibration. The planning mode (which is also referred to as pre-season planning in this thesis) computes the expected irrigation water requirements and irrigation frequency for the entire irrigation season, before the season starts; this mode can be used to compute the area that can be cultivated based on the amount of water available to the farmer. Real-time scheduling deals with the next irrigation, and addresses the issues of when to irrigate and how much to irrigate. The evaluation mode evaluates the irrigation schedules of the last irrigation season and compares these against the model-predicted irrigation schedules, in an attempt to encourage the farmers to use computer models for irrigation scheduling. Like any other model, this computer software was developed to calibrate it under different climatic and crop conditions.

## 1.7 SIGNIFICANCE OF THE PROJECT

In recent times, with regards to rural water supplies in Victoria and most other parts of Australia, emphasis is placed more on efficient use of existing water resources than on new resource developments. This is especially true for the case of irrigation systems. This emphasis is mainly due to limited funds available for construction works, lack of suitable hydrological sites, and spirited and justifiable lobbying of environmental groups against construction of new development projects. Hence to meet the ever-increasing water demands, efficient operation of these existing irrigation systems is required.

A considerable amount of research and development work in terms of developing effective simulation models has been done on long and medium term planning and operation of irrigation systems, but very little research has been done on the short-term (upto about 14 days) aspects. Ad hoc methods, mainly based on experience and simple analytical tools, have been used in the past on short-term planning and operation of irrigation systems. These methods were considered to be satisfactory at the time of their introduction. However, because of improved understanding of the irrigation science of soil-water-atmospheric continuum and the increased computing power of computers at affordable costs, new technologies can be developed to achieve water use efficiencies and improved irrigation management practices. These new technologies include design improvements in border-irrigated dairy farms to reduce loss of water and nutrients, use of alternative irrigation application technologies, introduction of farm drainage systems and adoption of improved irrigation scheduling practices. Irrigation scheduling was considered in this thesis in an attempt for farmers to determine the correct timing to irrigate the crops and to determine the correct amount of irrigation water at the time of irrigation. Irrigation scheduling controls or eliminates the crop water stress caused by inadequate water supply and excessive periods of anaerobic conditions caused by water logging due to over-irrigation (Austin, 1998; and Wood et al., 1998).

As found in many studies (e.g. Camp et al, 1988; Buchleiter, 1995; Shannon et al., 1996; Wood et al., 1998; Robertson et al., 2000; and Wood and Martin, 2000),

significant water savings can be achieved through adoption of improved irrigation scheduling techniques. These improved water savings reduce the cost of irrigation water for the farmers and can be used for further expansion of dairy farm areas, if necessary. With the recent cap of water allocation levels in the Murray-Darling Basin (MDBC, 1996), these water savings are important and are the only way of expanding the areas of irrigated pasture, if required. Alternatively, the water savings can be used for other purposes such as urban water use, environmental flows required for river and stream health, and production of crops with high economic returns. The efficiency of water use basically leads to conservation of water resources.

Furthermore, the accurate prediction of irrigation water requirement will reduce over-irrigation, which in turn will minimise waterlogging and soil salinity hazards in the irrigated lands. It will also facilitate to control algal breaks in the streams receiving drainage water. As Austin (1998) pointed out, the improved irrigation scheduling provides added benefits of limiting nutrient leaching, nutrient runoff and local salinity problems by reducing runoff and deep percolation. Another possible benefit from effective irrigation scheduling is that it may also encourage deeper crop root growth by not constantly replenishing water levels close to the surface, allowing plants to use more of the available water further down the soil profile.

## **1.8 OUTLINE OF THE THESIS**

In Chapter 2, a critical review of existing irrigation scheduling models is presented, and the characteristics of these models that restrict their use as effective irrigation management tools by farmers are identified. As stated earlier,  $ET_0$  is also an important component of any irrigation scheduling model. There are numerous empirical methods available for estimating  $ET_0$  using climatic data. A review of the existing  $ET_0$  estimation methods is presented in Chapter 2. A review of rainfall prediction methods for use with effective water management programs via irrigation scheduling at an on-farm level is also discussed in Chapter 2. Based on the review of various rainfall prediction methods, the techniques having potential to predict short-term (7-14 days) rainfall under Victorian (Australia) conditions were identified for investigation and use in irrigation scheduling for effective short-term planning and operation of irrigation systems.

Chapter 3 presents the mathematical details of ten  $ET_0$  methods selected for this study. The evaluation and calibration of these methods under Victorian (Australia) conditions for use in irrigation scheduling is also presented. Furthermore, the development of a computer software (REF\_ET) for computing daily  $ET_0$  estimates using the above ten methods is described in the chapter.

Chapter 4 describes the mathematical details of the short-term rainfall prediction methods. Analysis of short-term rainfall data series at three study sites in Victoria (Australia) is also presented in this chapter. Finally, a computer software that was developed for short-term rainfall predictions (RAIN\_PRE) is described in this chapter.

Chapter 5 presents the development of algorithms for use in an irrigation scheduling model, which uses simple water balance approach. The mathematical details of various components of the irrigation scheduling model are discussed in this chapter. Using the field measured soil moisture data from the literature, the performance of the developed irrigation scheduling model was tested, and the details of this evaluation are described in the chapter.

The details of the integrated irrigation scheduling computer software package (developed as part of this thesis) by linking REF\_ET (Chapter 3) and RAIN\_PRE (Chapter 4) software with the algorithms of the irrigation scheduling model (Chapter 5) are discussed separately in Appendix C. The description of various inputs of the integrated computer software is also outlined in this Appendix. A case study is also presented to illustrate the applicability of this package as an effective irrigation management tool at a farm level. In order to use under distinct climatic and environmental conditions, the integrated software needs calibration. The calibration technique and limitations of the integrated computer software are also described.

Finally, the conclusions drawn from the study are presented in Chapter 6, followed by the recommendations for future research work arising from the research in this thesis.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 INTRODUCTION

Increasing concern of the limited water supplies has forced the farmers to adopt effective on-farm water management techniques to use available water more efficiently at farm level. Sound irrigation scheduling which deals with frequency and dosage of irrigation water applications has been demonstrated as one of these potential effective on-farm management techniques (Watts et al., 1984; Vanvleck et al., 1986).

To implement irrigation scheduling, it is necessary to obtain an accurate estimate of water use by the crop. A common procedure for estimating crop water use or crop evapotranspiration ( $ET_c$ ) is first to determine the daily reference crop evapotranspiration, and then multiply it by a specific crop coefficient ( $K_c$ ), as given by Doorenbos and Pruitt (1977) and Wright (1981,1982). Daily reference evapotranspiration ( $ET_o$ ) can be determined by direct measurements (e.g. lysimetry) or estimated by empirical methods. Direct measurements generally produce more accurate values than the empirical methods, but direct measurement of  $ET_o$  is often expensive, laborious and involves complex instrumentation. For this reason, limited data are available from direct measurements. Therefore, for use with computer based irrigation scheduling programs, there is a need to model the  $ET_o$ .

There are numerous empirical methods available for estimating  $ET_o$  using meteorological data. However, the choice of the method for estimating  $ET_o$  is essentially based on the location, the climate, the intended estimation period, and the input data availability for the site in question (Jensen et al., 1990).

Apart from the water use by the crop, rainfall also plays an important role in irrigation scheduling. Efficient utilisation of rainfall during the rainy season will help in saving water in the storage reservoir that can be used in the dry season. In this chapter, the literature review on the aforementioned three major components namely irrigation scheduling, evapotranspiration and rainfall is presented.

## **2.2 IRRIGATION SCHEDULING**

Irrigation scheduling which deals with the time and dosage of irrigation water application accounts for interactions between many variables related to crop, soil, climate and agricultural practices. Soil moisture simulation models are effective tools in integrating these interactions. They can be classified into two categories: empirical models and physically based numerical models. The empirical models usually use the concept of field capacity, wilting point and other soil moisture definitions in modelling the soil moisture profile. Examples of such models are Curwen and Massie (1985), Singh et al. (1994) and Singh et al. (1995). The numerical models solve the Richard (1931) partial differential equation for unsaturated flow in soils and include those of Feddes et al. (1978); Belmans et al. (1983); Hayhoe and De Jong (1988); Wesseling and van de Broek, 1988; Murty et al. (1991,1992); De Faria et al., 1994; and Mahdian and Gallichand, 1996. However, the latter approach is data extensive, and the required data are not readily available in most irrigation systems. Since a major objective of this thesis is to develop an irrigation scheduling computer software with minimum and readily available input data, the latter approach of soil moisture simulation models was not further considered (in this thesis). In contrast to the latter approach, the empirical soil moisture simulation models coupled with daily water balance models have become effective tools for irrigation scheduling (Buchleiter, 1995; Hess, 1996). Therefore, literature on these models is reviewed below.

Literature on irrigation scheduling is voluminous as mentioned in ASAE (1985) and ICID (1995), with various methods utilised or proposed for use in different climate regions with different levels of technological input. Irrigation scheduling models typically calculate the soil moisture depletion due to crop water use, soil moisture

storage, soil moisture movement and evapotranspiration to determine irrigation scheduling and application quantity (Akhand, 1992). Scheduling programs have utilised handbooks and calculators. However, only the literature on the computer based irrigation scheduling programs is discussed here, as they are the ones related to this thesis.

Baier and Robertson (1966) and Jensen et al. (1970) presented a practical approach to schedule irrigations by using climatic, crop and soil data without a need for direct measurement of soil moisture status or plant stress. Kincaid and Heerman (1974) described the procedure known as the USDA-ARS irrigation scheduling method for use with a programmable calculator. They used the water balance principle to schedule irrigation to each field. These procedures were basically developed to suit only under the USA environment.

Saxton et al. (1974) presented a semi-empirical Soil-Plant-Air-Water (SPAW) model for scheduling irrigations of agricultural crops using soil, crop and climatic data. This model computes the soil water balance on a daily basis. The reliability of the SPAW model was tested in Ontario (Canada) against measured data of soybean crop. It was reported that this model was quite reliable for irrigation schedules (Hayhoe and De Jong, 1988). Field et al. (1988) modified the SPAW model and tested for maize crop under USA conditions. They reported that the modified SPAW model showed good agreement with field-measured moisture content data. However, some components of this model (e.g. surface evaporation, transpiration, infiltration etc.) require certain input data related to the soil and crop that are not routinely available in many irrigation systems.

Henry (1978) developed a computer model for estimating the water requirements of any given crop based on water balance approach. The ET component of this model employs the recommendations of the FAO (Doorenbos and Pruitt, 1977). Poplawski and Stewart (1984) tested the accuracy of this model under Queensland (Australia) conditions. They reported that the model's performance was good. However, the major problem with the application of this model is that it was developed as a research tool rather than an irrigation scheduling program for use by the farmers.

Watts et al. (1984) presented a computer model based on water balance approach for both short-term scheduling of irrigation and long-term prediction of water requirements of agricultural crops. This model requires few input data items. The accuracy of this model has not been tested against field-measured data. The technical detail of this model is not well documented. In addition, no formal software of this model is available for use by the farmers. However, the authors reported that the model had produced reasonable results under the existing farmer-practice of irrigation application for cotton crop in Queensland.

Stegman and Coe (1984) developed an irrigation scheduling computer program using the water balance method for use in personal computers. The source code of this program was written to accommodate the locally calibrated regression coefficients for polynomial relationships fitted to crop coefficient curves. Hence, the use of this program was limited only to the locally tested sites.

Watts and Hancock (1984) developed a computer program for irrigation water requirement of agricultural crops in Queensland (Australia). This program used the physically based combination formula (details of which are given in Section 2.3.4) for actual crop water use estimates. This program was used to estimate the pumping rate for a cotton farm to meet the irrigation requirement. Although, this program was claimed to be reliable for scheduling, no testing of this model was done against the field-measured data. In addition, some input data items required by this program (e.g. surface resistance, aerodynamic resistance etc.) are not easily available for most agricultural crops. Furthermore, no user-friendly document was reported to be available for this program for use by the farmers.

Camp et al. (1985) developed a simple computer based water balance (CBWB) model for irrigation scheduling of agricultural crops. The evapotranspiration (ET) component of this model used the modified Jensen-Haise (1963) method. Later on, Camp et al. (1988) tested the accuracy of this model against field-measured data for various crops grown under USA conditions. They reported that the performance of the model was good.

However, the major problem with the application of this model was the rigidity of ET component to be estimated with only Jensen-Haise method. In addition, the program was developed as a research tool rather than an irrigation scheduling program for use by the farmers, and hence no formal user manual for CBWB model was available.

The CERES (Crop Environment REsearch Synthesis) models for various agricultural crops (e.g. maize, wheat, rice, soybeans etc.) were developed to evaluate current and alternative cropping practices to increase net income of small farm holders. These models were technically supported by the International Benchmark Sites Network Agrotechnology Transfer (IBSNAT) program since 1982 (Allison et al., 1993). The CERES models are based on a simplified soil water balance described by Ritchie (1985). Although these models can be successfully employed to improve the overall small farm management, the use of these models to serve as an irrigation scheduling tool is limited because of the extensive input data requirements.

A computer model called RART (Right Time and Right Amount) was developed by Poulton (1982) in early eighties for scheduling horticultural crops in Victoria (Australia). This model was based on the water budgeting approach using little input data such as US Class-A pan evaporation, rainfall and irrigation data. Initially, this program was developed for an irrigation service extended to the farmers of the Northern Victoria. Later on, many improvements were made to this original program, and the latest version of this program (Dale and Thompson, 1992) allows a degree of customising to suit one's own farm. In spite of many good features such as user-friendliness, the program has not yet been fully developed to address all farmer needs. Furthermore, the program is not well suited to surface irrigation systems, rather is best suited to the sprinkler or spray irrigated crops (Dale and Thompson, 1992).

An irrigation scheduling program was introduced by the New South Wales Department of Agriculture (Australia) for scheduling summer and winter crops. This program was basically developed to extend an irrigation scheduling service namely WATER WATCH (Hedditch, 1985), to the farmers in the Murrumbidgee Irrigation Area (MIA) and

Coleambally Irrigation Area (CIA) of New South Wales (NSW). Since this program was produced to extend an irrigation service to the farmers, it was devised as a research tool used by irrigation professionals. As a result, no user-friendly version of this program was available to the farmers for use at individual farm for scheduling purposes.

Buchleiter et al. (1988) developed an irrigation scheduling computer model called SCHED, based on soil water budget approach to improve water management at an on-farm level. The original version of SCHED relied on the concepts developed by Heerman et al. (1976) for scheduling of crops irrigated with centre pivots. Later on, it was revised to minimise the data requirements and to use data and parameters that farmers were likely to know or could readily obtain (Buchleiter, 1995). SCHED was evaluated by Kaisi et al. (1997) against field-measured moisture data for spring wheat crop under South Western Colorado (USA) conditions. They reported that wheat water use was under-estimated by SCHED, because of the polynomial functions used for crop coefficients in SCHED. Hence, they recommended the use of locally developed crop coefficients with this program to achieve the improved water use efficiency. Based on this, they emphasised that local environment be considered in any adaptation or transfer of water management programs to achieve the objectives of such programs in improving water use efficiency. Although the performance of SCHED has been reported good under USA conditions with the use of local parameters, the application of this model is limited only to those crops which are irrigated with centre pivots irrigation method (ICID, 1995).

A model for the management and forecasting of irrigation water requirements at an on-farm level was developed by Tracy and Marino (1989). The model included mechanisms for simulating root and soil-moisture movement, root growth, and crop yield. The model testing against field-measured data of cotton crop demonstrated the usefulness of the model as an effective irrigation scheduling tool for agricultural crops. Since the model used complex algorithms to model the plan-root system, it is data extensive and most of the input data are not available in many irrigation systems. Therefore, the use of this model is limited for research-oriented studies.

The interactive computer program (SCHEDPEN) developed by Scherer et al. (1990) calculates ET by the Penman method (as described later in Section 2.3.4) using “growing degree days” based crop coefficients, which makes the program applicable to different climatic conditions. The program has been tested successfully at two locations in Arizona, USA for cotton crop. The use of SCHEDPEN is limited to those sites for which complete climatic data for Penman ET method is available.

A computer package called SIRAG-FIELD, was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in collaboration with the NSW Department of Agriculture, Australia for irrigation scheduling of annual field crops (Stapper, 1991). Another program, SIRAG-ORCHARD, was developed to schedule orchards crops and vineyards. SIRAG-FIELD is based on the water balance approach, and can be used to schedule irrigations for many paddocks and different crops, on more than one farm and across a range of districts. This package was developed to suite both flood and spray irrigation over a range of soil and crop conditions. The package was basically developed and tested in the Murrumbidgee and Coleambally irrigation areas of the NSW for wheat, triticale, maize and soybean crops. However, the package can also be used by adjusting the relevant input data items for sites outside the above areas and for other crops. The performance of SIRAG-FIELD and SIRAG-ORCHARD packages has been reported good in terms of scheduling of irrigation for agricultural crops. Although the packages can be run under menu-driven options, the use of these packages by an ordinary farmer is not easy, since they are not sufficiently user-friendly.

Erlanger et al. (1992) presented a generalised computer Program for Regional Irrigation DEMand (PRIDE) based on estimated irrigation water requirement for main crop types using seasonally varying crop factor and climatic variables. This model was developed and tested under Northern Victoria (Australia) conditions. Since this model was primarily developed for estimation of regional water demands, the use of this model as an irrigation scheduling tool for a farmer is not possible.

Danuso et al. (1993) devised a computer model (BIdriCo 2) for irrigation scheduling and planning purposes. This model is based on the water balance approach and can also assess the relative crop yield reduction due to water stress. In addition, the model has the built-in capability for automatic calibration under local field conditions. However, this model is relatively complex and requires input data that are not easily available in most irrigation systems.

Singh et al. (1994) developed an irrigation scheduling model called AIS IRRIG based on the water balance approach for agricultural crops. For this model, the crop evapotranspiration was calculated using a customised software package, EDA. This model was developed as a part of a fully automated system called Surface Energy and Water Balance System (SEWBS) which was devised for scanning, monitoring and storing of climatic and soil data required for deciding the time and amount of an irrigation. The first version of AIS IRRIG program was not user-friendly. Hence, Singh et al. (1995) improved the AIS IRRIG in terms of user-friendliness and then used this improved version with another automatic system namely Automatic Irrigation Scheduling System of the University of Montreal (AISSUM), in Canada. Since AIS IRRIG was written as a part of sophisticated automatic irrigation scheduling system (such as SEWBS and AISSUM), due to high investment costs involved the use of this model at an ordinary farm is not economically feasible.

The irrigation scheduling program RELREG presented by Teixeira et al. (1995) is one of the most desirable irrigation scheduling computer programs based on the water balance approach. This model was an improved version of ISAREG (Teixeira and Pereira, 1992) simulation model. The model inputs regarding the crop, soil and the meteorological variables are simple and easily obtainable. This model has the capability to forecast the irrigation needs five days in advance. In addition, the model has the flexibility to accept the feedback from the field observations to update the calculations. However, the model has not yet been utilised by farmers, but only by engineers and students working in experimental fields in Portugal.

The RENANA model developed by Giannerini (1995), is a computer model for irrigation scheduling employed for large irrigation systems. The basic nucleus upon which this model was developed consists of water balance calculations on a daily basis. This model was developed to respond to the need for an irrigation advisory service in Italy. Therefore, this model has no use for a farmer to serve as an irrigation scheduling tool on the individual farm.

An irrigation scheduling computer package for use on farms was presented by Hess (1996). This package was developed from an original computer program by Siddig (1982). The package comprises of four models; a reference crop evapotranspiration model, an actual evapotranspiration model, a soil water balance model and an irrigation forecast model. This package was shown to produce reliable irrigation schedules for potatoes, sugarbeet and vegetables in UK.

Broner et al. (1998) developed a general crop management program to provide irrigation and fertility management advice to assist farmers in maintaining or increasing crop yields. The program, being a crop Decision Support System (DSS), can be used by a farmer without understanding the complex physical processes of the model. This computer program was basically developed and tested in USA, and no testing under any other place was reported. In addition, this program serves more as a pre-season planning or post-season evaluation tool rather than an irrigation scheduling tool for a farmer for use during the irrigation season.

Theiveyanathan et al. (1998) presented a water balance based irrigation scheduling model called WATSKED for Eucalypt plantations. This model was developed and tested against field-measured water use data of Eucalypt plantations in New South Wales (Australia), and was reported to be quite satisfactory. However, the use of this model for other agricultural crops is not possible.

## 2.3 EVAPOTRANSPIRATION

As stated earlier, the effective use of water supplies for irrigation requires correct estimates of crop evapotranspiration ( $ET_c$ ). Since reference crop evapotranspiration ( $ET_o$ ) is the basic component of  $ET_c$ , the accuracy in  $ET_o$  estimation is of paramount importance. There are numerous empirical methods available for estimating  $ET_o$  using meteorological data.

It is important to note that two crops namely 'Grass' and 'Alfalfa' are commonly used as the reference crops in irrigation scheduling and planning studies. In this study, grass was adopted as the reference crop because of its growth over a wider range of climatic conditions throughout the world than alfalfa crop. The grass related reference evapotranspiration ( $ET_o$ ) is defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos and Pruitt, 1977).

One of the objectives of this thesis is to investigate the suitability of various  $ET_o$  estimation methods and to calibrate these methods under conditions in Victoria for use in short-term irrigation planning and operational studies. Therefore, in this section, a critical review of various  $ET_o$  estimation methods is presented together with their limitations.

During the past half century, due to continuing need of  $ET_o$  data for use in hydrologic studies, a large number of methods for calculation of  $ET_o$  from climatic data have been developed. These methods ranged from simple empirical relationships to highly data extensive complex methods which are based on physical processes. They have been tested for varying geographical and climatic conditions around the globe. A report prepared by the Technical Committee on Irrigation Water Requirements, American Society of Civil Engineers – ASCE (Jensen, 1974) describes sixteen  $ET_o$  estimating methods. Since then, numerous other new methods have appeared in the literature as given in Burman et al. (1983), Stewart (1983) and Jensen et al. (1990).

Based on the requirements of input climatic data used in the calculations, these methods are categorised into four general categories as follows:

- I. Temperature methods
- II. Temperature-radiation methods
- III. Evaporation methods
- IV. Combination methods

These methods are reviewed below.

### **2.3.1 Temperature Methods**

The temperature methods are basically developed for estimating  $ET_o$  in situations where data are limited, and only maximum and minimum air temperature data are available. Over the last five or six decades, many investigators have attempted to relate evapotranspiration to the air temperature, and have developed various empirical relationships. A brief summary of these investigations is given in Jensen et al. (1990). However, with time, due to the advent of modern technology and advances in knowledge, most of these methods were phased out and only a few remain popular among researchers and irrigation practitioners, which are reviewed in this section.

Thornthwaite (1948) developed a relationship between mean monthly air temperature and ET estimates. The relationship was primarily developed for climatic conditions in East Central USA. These climatic conditions in general do not exist in arid and semi-arid areas. Hence, the use of this relationship in the arid and semi-arid areas can lead to misleading results and was strongly discouraged (Thornthwaite and Mather, 1955).

The United States Department of Agriculture - USDA Blaney-Criddle (1950) method based on temperature and day length (i.e. sunshine hours) data has been extensively used throughout the world. This method was developed to give an estimate of actual evapotranspiration rather than the  $ET_o$  estimates on a seasonal basis. An empirical factor

“f” was introduced in this method to account for different crops. Doorenbos and Pruitt (1977) modified the USDA Blaney-Criddle formula, to give the reference evapotranspiration estimates. This modified method is now known as the FAO-24 version of the Blaney-Criddle method (FAO stands for Food and Agriculture Organisation of the United Nations). However, this method requires some additional meteorological information such as humidity and daytime wind estimates to compute  $ET_o$ . These additional meteorological information are daily average values of historical records of respective months. Doorenbos and Pruitt (1977) suggested that this method should be used with caution in coastal areas and in mid-latitude climates where a wide variability in sunshine hours exists. They also recommended that this method should only be used when temperature data are the only measured weather data available.

Allen and Pruitt (1986) further improved the above method by including an adjustment factor to account for the effect of altitude on  $ET_o$  estimates. Although the FAO-24 Blaney-Criddle method was the highest ranked temperature method for humid regions in the analysis of Jensen et al. (1990), the FAO (Smith, 1992) did not recommend the Blaney-Criddle method for general applications in view of difficulties in estimating humidity, sunshine, and wind parameters. However, FAO states that the method will maintain its use for irrigation planning purposes where appropriate local factors can be found. Elliott et al. (1992) used the FAO-24 version of the Blaney-Criddle formula with locally derived crop factors for irrigation planning on a monthly basis in the USA, and have reported reasonable results.

Baier and Robertson (1965) developed an  $ET_o$  estimation method for use under humid climatic conditions of Canada. This method was one of the first to express solar radiation effects on evapotranspiration as a function of upper atmospheric extraterrestrial radiation ( $R_a$ ) and daily maximum and minimum temperatures (Barnett et al., 1998). Since radiation was not a direct input parameter in this method, but only an estimated variable for the location in question, this method is still categorised as a temperature method. The performance of this method has been reported good under humid climatic conditions of Canada. The problem with this method is that it includes multiple-regression type

equations having regression coefficients which are suitable only for those climatic conditions for which this method was originally developed. Therefore, the use of this method under other climatic conditions is restricted.

Hargreaves (1975) developed an  $ET_0$  estimation method, which was later improved by Hargreaves and Samani (1985). This improved method is now known as the Hargreaves (HAR) method. This method uses temperature and solar radiation data, and produces more satisfactory results than other ordinary temperature methods (Hargreaves, 1990). Like the Baier-Robertson method, radiation is not a direct input parameter in this method, but only an estimated variable for the location in question, and therefore, this method is also categorised as a temperature method. The principal feature of this method over the other temperature related methods is the inclusion of *temperature range* (defined as the difference between the maximum,  $T_{max}$  and minimum,  $T_{min}$  temperatures), a term which accounts for the humidity and cloudiness effects of the local environment. This is very important in terms of  $ET_0$  estimates due to the fact that when humidity levels are high, the differences between  $T_{max}$  and  $T_{min}$  are relatively low and also evapotranspiration rates become relatively low. When cloud cover occurs, maximum temperatures are less due to decreased solar radiation, and minimum temperatures are usually higher due to increased long-wave emittance and reflection by night-time cloud cover (ASCE, 1996).

Many researchers (e.g. Hargreaves and Samani, 1985; Hargreaves et al., 1989; Jensen et al., 1990; Hargreaves, 1990 and 1991; and ASCE, 1996) have favoured the use of calibrated HAR method for  $ET_0$  estimates where temperature data are the only measured data available. Allen (1992) reported that the HAR method requiring only measurements of maximum and minimum temperatures, is quite satisfactory for  $ET_0$  estimates over five-day or longer periods for a wide range of latitudes and climates. He recommended that this simple and easily-used method should be tested for three to seven-day periods in various climates before using it in irrigation planning and operational studies. Amatya et al. (1995) reported that the HAR method, although originally developed to estimate total  $ET_0$  for a 10-day period, have also been widely used to estimate  $ET_0$  on a daily basis.

Since the HAR method is based on a single weather factor (i.e. temperature), the empiricism involved in this method is inevitably high. Therefore, Meek and Phene (1991) attempted to mitigate this problem by introducing an empirical wind term to account for the advection effects of local conditions. They reported that after the introduction of empirical wind term, the HAR method was significantly improved. In this thesis, the HAR method with empirical wind term is referred to as the improved Hargreaves (IHA) method.

Elliott et al. (1992) commented that despite the availability of more sophisticated physically based approaches, the temperature methods still remain popular for  $ET_0$  estimates due to their minimal data requirements. Having recognised the importance of the temperature methods, the FAO (Smith, 1992) has recommended further investigations and refinements for the temperature methods, and the development of alternative temperature methods using the extraterrestrial radiation and temperature data which can be used under a wide range of climatic conditions.

### **2.3.2 Temperature-Radiation Methods**

The temperature-radiation methods (also termed as *radiation methods*) are generally based on the energy balance variables. These methods require measurements of temperature and solar radiation data as the main input for  $ET_0$  estimates.

Several researchers introduced  $ET_0$  estimation methods based on measured solar radiation and temperature data only. Turc (1961) presented the first simplified form of the radiation equation for estimating daily  $ET_0$  values under Western Europe climatic conditions. The development of this equation involved the evapotranspiration data from several locations in Europe. Jensen et al. (1990) reported that Turc's radiation-based method compared very favourably with the combination methods (Section 2.3.4) for humid locations.

Jensen and Haise (1963) developed an expression for alfalfa-related reference crop evapotranspiration estimates using evapotranspiration data of 35 years from Western USA. This method requires the determination of regression based site specific calibration constants and is only useful for the sites under which calibration is done. This method also has alternative procedures for estimating grass ET but these have not been widely used (Burman et al., 1983).

Priestley and Taylors (1972) developed an equation for potential evapotranspiration estimates. This method is actually a truncated form of the Penman combination equation (Section 2.3.4) in which the aerodynamic component is not present, and instead only the radiation term with the multiplication of an empirical coefficient ( $\alpha$ ) was included. They also established the values of  $\alpha$  which ranged from 1.1 to 1.3 from the comparison with lysimetric data. This method was basically developed for potential *ET* estimates for humid regions which are characterised with no or low advective conditions, and has been reported to produce good results under these conditions (Jury and Tanner, 1975; Clothier et al. 1982; Jamieson, 1982; and Thivianathan et al., 1991). However, this method has also been reported to be widely used for  $ET_0$  estimates on a daily basis under semi-arid conditions (Jensen et al., 1990; Amatya et al., 1995; and Hatfield and Allen, 1996).

Jury and Tanner (1975) revealed that advection greatly affects the empirical coefficient  $\alpha$  values, and therefore,  $\alpha$  should be calibrated under local conditions. To account for the advection effects, they also derived a modification factor based on vapour pressure deficit parameter for use with the  $\alpha$  values. Steiner et al. (1991) reported that the Priestley-Taylors method with  $\alpha$  values modified by the modification factor of Jury and Tanner (1975) produced good evapotranspiration estimates in semi-arid climates.

Linacre (1977) presented an approximation to the Penman combination formula (Section 2.3.4), for estimation of evapotranspiration in various climates using temperature and net radiation data. This method was actually an adaptation of the McIlroy (1966) equation (Section 2.3.4) which was further simplified to use the measured temperature and

estimated radiation data as inputs for evapotranspiration estimates. This method no longer appears in the recent literature.

Doorenbos and Pruitt (1977) presented the FAO-24 radiation method for  $ET_o$  estimates using solar radiation. This method has been recommended as an alternative to the Penman combination method when measured wind and humidity data are not available. This method has been reported to give satisfactory results by Jensen et al. (1990). It is important to mention that the FAO-24 radiation method requires an empirical adjustment factor. For computer-based  $ET_o$  estimates, Frevert et al. (1983) presented a polynomial equation to compute this adjustment factor. However, the requirement of day-time wind speed measurements instead of 24-hr average values for this polynomial equation makes the FAO-24 radiation method less attractive among other less input data requiring computer oriented  $ET_o$  methods. In addition, the FAO (Smith, 1992) has also emphasised the need to further improve this method.

Chiew et al. (1995) comparing the FAO-24 reference evapotranspiration methods, recommended that the FAO-24 radiation method can be used as a surrogate for the Penman-Monteith method (Section 2.3.4) where wind speed data are not available. It is important to note that in their analysis, the Penman-Monteith method was adopted as the base method which was used for comparison of other  $ET_o$  methods. However, the Penman-Monteith method has been reported to produce lower estimates (Meyer et al., 1995).

Ritchie (1985) introduced a method to estimate  $ET_o$  based on the radiant energy concept of the Priestley-Taylor's (1972) method. Like any other empirical radiation-based method, the Ritchie (1985) method also requires an advection correction factor. A modification of this method for grass related reference evapotranspiration estimates was presented in Meyer et al. (1995). They derived an advection correction factor for use in this method to account for local advection effects and reported that the modified Ritchie method produced quite favourable  $ET_o$  estimates in Griffith (Australia). In situations where limited climatic data are available, this simple method can be very useful.

### 2.3.3 Pan Evaporation Methods

The evaporation pans are an integral part of most agricultural weather stations. The pan evaporation integrates many of the climatic factors that govern the process of evapotranspiration; these include wind, incident solar radiation, humidity, soil heat flux, and air temperature (Burman et al., 1980). Since the evaporation pans provide a measurement of the integrated effect of several climatic factors, the method assumes that the pans behave in the same way as a crop with zero resistance. Hence, the amount of water lost per day from a pan is considered to be a measure of evapotranspiration from an agricultural crop.

The initial use of evaporation pans to estimate the evaporation was probably introduced during early nineteen fifties. Since then, various pans were designed. They include; Aslyng Denmark, Australian Standards, CGI-20 and GGI 3000 Russian, Simmons UK, U.S. BPI and Class-A pans, Colorado, Israel and Netherlands sunken pans. Each pan varied in diameter, colour, construction material, depth and installation with respect to the ground level. For detailed features of these pans, the reader is referred to Bonython (1950), McIlroy and Angus (1964), Hounam (1966 and 1973), Doorenbos and Pruitt (1977) and Van Vleck et al. (1986).

Among the different types of evaporation pans mentioned above, the US Class-A pan has been the most common pan in use around the world. This pan is 121 cm in diameter and 25.5 cm deep. It is usually made up of galvanised steel or Monel metal, and is placed on a wooden platform and levelled. The bottom of the pan is usually about 15 cm above the ground level. The water level is maintained within a range of from 5 to 7.5 cm below the rim. Changes in water level are measured by a vernier hook gauge placed in a stilling well.

As stated earlier, the evaporation pans experience similar integrated effect of climatic factors as the plants, and therefore the investigations have also been focused on the

predictions of ET from agricultural crops using pan measurements. Data from evaporation pans have been correlated with measured and/or estimated evapotranspiration rates for many years. A significant correlation has been found in many situations between pan evaporation and evapotranspiration rates as determined by other evapotranspiration methods (AWRC, 1970; Campbell and Phene, 1976; Dilley and Shepherd, 1972; and Mukammal and Neuman, 1977). Doorenbos and Pruitt (1977) quoted fifteen references where the pan measurements had been widely used in irrigation scheduling schemes in eight different countries.

Measurements of US Class-A pan evaporation are widely available and many researchers in the field of agriculture have used them for grass related reference evapotranspiration estimates. Christiansen and Hargreaves (1969) developed an equation for estimating  $ET_0$  from US Class-A pan evaporation data and several other weather parameters as related to the pan environment. However, this method is data extensive and less accurate as compared with other pan  $ET_0$  estimation methods (Jensen et al., 1990).

Doorenbos and Pruitt (1977) presented an alternative simple method for using US Class-A pan data to estimate the grass reference evapotranspiration. This method is known as the FAO-24 pan method. In this method, the US Class-A pan measurements are multiplied by a pan coefficient ( $K_p$ ) to give daily  $ET_0$  estimates.  $K_p$  is dependent on the pan type and a number of other factors such as pan exposure, wind velocity, relative humidity, and the distance of surrounding grass-fetch to the windward side. Many additional factors can also affect the pan coefficients. McIlroy (1966), Hounam (1973), and Jensen (1974) discuss the additional factors that influence pan evaporation and hence the pan coefficient.

Doorenbos and Pruitt (1977) presented the background of the development of the FAO-24 pan evaporation method, which was first published in Jensen (1974) and subsequently by Doorenbos and Pruitt (1975,1977), Burman et al. (1980), Jensen et al. (1990) and Shuttleworth (1992). This method is based on the data from several studies (e.g. Ramdas, 1957; Pruitt, 1960,1966; and Stanhill, 1962) considering the effect of pan type, local

environment and general weather conditions on pan coefficients. A table of pan coefficients relating US Class-A pan data to  $ET_o$  values is given in Doorenbos and Pruitt (1977). The same reference also presents a table of conversion factors along with a narrative discussion relating various types of pans to the Colorado Sunken Pan (and subsequently to the US Class-A pan). For those who use digital computer programs for  $ET_o$  estimates from the FAO-24 pan method, the polynomial equation developed by Frevert et al. (1983) for FAO-24 pan coefficients is given in Jensen et al. (1990).

It is important to note that the use of FAO-24 pan method for estimating  $ET_o$  is controversial. This is mainly due to three different reasons as given below:

- The process of evaporation from pans is influenced by the integrated effect of several environmental factors which results in a wide range of  $K_p$  values. This wide range of  $K_p$  could lead to the conclusion that the use of pan evaporation data in estimating  $ET_o$  should not be recommended (Jensen et al., 1990).
- The method assumes that the pan behaves in the same way as a crop with zero resistance. However pans, unlike crops, are small in area and experience advection differently. Hence, they do not reflect heat storage and transfer characteristics of a crop properly (Jensen, 1974).
- An extreme care is required for the operation of a pan as compared to any other climatic instrument (Watts and Hancock, 1984).

Therefore, considering these aspects, some researchers (e.g. Watts and Hancock, 1984; Thivianathan et al., 1991; and Amatya et al., 1996) disfavour the use of this method.

Watts and Hancock (1984) discussed the sources of potential errors inherent with the use of Class-A pan data and concluded that all evaporation pan data should be regarded as untrustworthy, quoting the studies of Thom et al. (1981) and Weeks (1983). Thivianathan et al. (1991) conducted a comparative study for wheat  $ET_c$  estimates using five different estimation methods and reported that the pan evaporation data were poorly correlated

with measured lysimeter wheat  $ET_c$  values adding weight to the growing concern about the utility of the pan evaporation method.

Amatya et al. (1996), discussing various  $ET_o$  estimation methods, reported that the pan evaporation method was considered reliable for a wide range of locations and conditions. However, they reported that reliable application of this method requires consistent maintenance and calibration of the pans, which are normally done strictly in research activities, but is often difficult and overlooked at normal weather stations. This leads to the conclusion that the routine use of pan evaporation data for estimating  $ET_o$  is questionable.

While some researchers disfavoured the use of the FAO-24 pan method as discussed above, there are many other investigators (e.g. Parmele and McGuinness, 1974; Doorenbos and Pruitt, 1977; Howell, 1983; and O'Leary et. el., 1985) who actively favour the use of this method. Those who support the use of this method, are of the opinion that the wide range of  $K_p$  is not a problem for many climates, since most areas only occasionally experience dry, strong-wind conditions that dictate major deviations in the evaporation rates (and hence the  $K_p$  values). Therefore, where a pan environment is well maintained, the evaporation pans may be as reliable for estimating  $ET_o$  as any other good  $ET_o$  methods.

Parmele and McGuinness (1974) used the pan evaporation data in their study under humid climate and reported good results from this method. Doorenbos and Pruitt (1977) reported that notwithstanding some of the deficiencies associated with the pan method, the use of pans to predict crop water requirements for periods of 10-days or longer is still warranted with possible errors of about 15% depending upon the location of pans. Howell (1983) favoured the use of this method due to the availability of long evaporation records at most sites and the ease of use with minimum input climatic data. He reported quite satisfactory results from the pan evaporation method. O'Leary et el., (1985) used the pan measurements data for  $ET_o$  estimates and found good results.

Jensen et al. (1990), advocating the use of this method, stated that where a standard pan environment is carefully maintained, and where strong dry-wind conditions occur only occasionally, the US Class-A pans may be as reliable for estimating  $ET_0$  as any other  $ET_0$  estimation method. A similar statement was reported by Meyer et al. (1995) as a result of their study conducted under semi-arid conditions in Griffith (Australia). They however reported that there could be a little bias towards over-estimation at high evaporation rates under semi-arid conditions.

The expert consultation on the revision of FAO-24 methodologies (Smith, 1992) recognised the practical value of the pan evaporation method, and recommended the use of this method for irrigation scheduling purposes and for comparative  $ET_0$  estimates. However, it does emphasise that the use of this method for estimating reference evapotranspiration should be recommended only if instrumentation and the site are properly calibrated and maintained.

Baki (1993) reported that the US Class-A pan data have been used to estimate potential evapotranspiration in many studies (e.g. Boughton, 1984; Yau, 1985; and Boyd et al., 1986), and all of them had reported quite good results. Chiew et al. (1995) compared the FAO-24  $ET_0$  methods over a wide range of climatic conditions in Australia. In their analysis, the Penman-Monteith method was adopted as the standard calibration basis, and it was reported that the pan measurements correlated very well with the Penman-Monteith estimated  $ET_0$  values.

Thom et al. (1981) performed a comprehensive analysis of the energy exchange and aerodynamic processes for the proper use of the US Class-A pans. Based on their analysis, they developed a “reasonably physically-based” approach using US Class-A pan measurements which avoids the obvious high degree of empiricism involved in the FAO-24 pan method. Although this is a valuable method, it is complex and also requires data from piche-type atmometers for  $ET_0$  estimates. Therefore, this method was not popular among the investigators.

With regards to  $ET_0$  estimates using the FAO-24 pan method, some researchers (e.g. Dilley and Shepherd, 1972; Chiew et al., 1995; and Meyer et al., 1995) developed a regression based site-specific calibration coefficient instead of pan coefficient to use with the US Class-A pan evaporation data. This calibration coefficient, unlike FAO-24 pan method  $K_p$ , does not require the measurements of relative humidity and wind speed data. In this thesis, this method is termed as the *Simplified US Class-A Pan Evaporation* (SEV) method. Meyer et al. (1995) tested the SEV method and reported that this method produced quite favourable results in Griffith (Australia). However, they reported that for evaporation values greater than about 10 mm/day, the Class-A pan had given  $ET_0$  estimates which were over-estimated by up to about 30%.

### 2.3.4 Combination Methods

The process of evapotranspiration from natural surfaces is essentially governed by two factors: a source of energy to provide the latent heat of vaporisation to change water from liquid to vapour phase; and a vapour transport mechanism (through turbulent transfer) to continuously move water vapours away from the surface and maintain a vapour pressure gradient between the evaporating surface and the surrounding air.

Up to about 1950s, the evapotranspiration has been investigated only considering either of these two above mentioned factors. Penman (1948) was the first to combine both factors of the energy supply and the turbulent transfer, and to develop a method what is now commonly known as the combination method. The input data requirements for this combination method were temperature, radiation, humidity and wind speed. The original Penman (1948) equation included an empirical wind function and was basically intended for the estimation of evapotranspiration from a free water surface. However, modifications and improvements were made to this equation by several researchers including Penman himself (e.g. Penman and Shofield, 1951; Penman, 1952,1961,1963; Businger, 1956; and Tanner and Pelton, 1960) to estimate ET from any surface. After an extensive study, Penman (1963) suggested a new calibration procedure for the empirical wind function of his original Penman (1948) equation for computation of

evapotranspiration from short, green, well-watered grass reference crop. It is this equation which is now commonly known as the *Penman combination method*. This equation has a strong theoretical basis to represent the process of evapotranspiration and has been widely used by researchers in the profession of irrigation.

Since the introduction of the Penman combination method, many investigators (e.g. Wright and Jensen, 1972; Doorenbos and Pruitt, 1977; and Wright, 1982) revised this combination equation in terms of alternative wind function calibration factors for use under a wide range of climatic conditions around the globe. Hence, several versions of the Penman combination method can be found in the literature. However, all of these versions of the Penman combination method are essentially the same except for the variation of the wind function and the method of computing the vapour-saturation deficit. The wind function varies with location and climatic conditions, and a different empirical relationship must be established for each situation (Chiew and McMahon, 1991). For more detailed discussions of various versions of the Penman combination method, the reader is referred to Jensen et al. (1990) and Paul (1991).

Until the publication of FAO (Smith, 1992), the Doorenbos and Pruitt (1977) version of the Penman combination method (hereafter referred to as the FAO-24 Penman) has been advocated by many researchers (e.g. Batchelor, 1984; Hussain et al., 1990; Michalopoulos and Papaioannou, 1991; and Mohan, 1991) to be one of the most reliable  $ET_0$  methods. This method incorporates a correction factor “c” which is based on the wind-speed and relative humidity climatic parameters to suit the local conditions. However, it has been reported that there is a tendency to over-estimate  $ET_0$  using the FAO-24 Penman method over a wide range of locations (Pruitt and Swann, 1986; Allen et al., 1989; and Hargreaves, 1989). A major study conducted by Jensen et al. (1990) showed that various versions of the Penman combination method (with the exception of the FAO-24 Penman) were the most reliable methods among all other  $ET_0$  estimation methods. This study also revealed that when the correction factor (c) of the FAO-24 Penman method was adopted as equal to 1, its performance was improved. It appears that by adopting c as 1 and local

calibration against lysimeter measurements, the over-estimation problem of FAO-24 Penman method can be solved.

A revision of the FAO-24 methodologies (Smith, 1992), although recommended the Penman-Monteith equation (described later in this section) as the ideal approach, recognised the continuing need of FAO-24 methodologies including the FAO-24 Penman method for  $ET_0$  estimates around the world. However, to improve the general presentation of the Penman combination formula, the FAO (Smith, 1992) suggested some minor modifications to the existing form of the FAO-24 Penman method. In addition, for reliable  $ET_0$  estimates, the need for local calibration was also recommended by the FAO. In this thesis, the FAO-24 Penman method with the modifications as suggested by Smith (1992) is termed as the *modified Penman (M\_P) method*.

The above stated FAO (Smith, 1992) calibration sentiment was adopted by Meyer (1994) and Meyer et al. (1995), when they conducted the wind function calibration study of the M\_P method against the lysimeter data from Griffith. The locally derived parameters used in the calibration of the M\_P method resulting from their study are of paramount importance in terms of their utility in irrigation scheduling studies in Australia. The calibrated M\_P equation had produced comparable results to lysimeter data for Griffith. In this thesis, the M\_P method using locally calibrated wind function of Meyer et al. (1995) is referred to as the *modified Penman\_Meyer (M\_Y) method*. The M\_Y method uses the wind function parameters developed for Griffith.

Recognising the historical value of the Penman combination method and the great number of users, Mohan and Arumugam (1996) also favoured the use of M\_P method. However, they state that the M\_P method should also be compared with the Penman-Monteith method, for its reliability. Barnett et al. (1998) reported that the use of locally calibrated parameters in M\_P method can produce quite reliable results.

Chiew and McMahon (1991) reported that Watts and Hancock (1984) after reviewing the work of other researchers, presented a generalised wind function for use with the M\_P

method. Chiew and McMahon (1991) used this wind function with the Penman method for estimates of potential evapotranspiration of grass for use in rainfall-runoff modelling applications, and reported quite satisfactory results. In a recent study, Hussein (1999) also tested this wind function for  $ET_0$  estimates against field-measured grass evapotranspiration data in Sudan for irrigation scheduling purposes, and revealed that the performance of this wind function was very good. In this thesis, the M\_P method using Watts and Hancock (1984) wind function is referred to as the modified Penman\_Watts&Hancock (W\_H) method.

Slatyer and McIlroy (1961) developed a form of the combination equation for use in Australia, which requires the measurement of wet bulb depression and the resistance of the air layer above the crop in addition to the data items required by other combination methods. This method is commonly known as the McIlroy (1961) method. In this method, the resistance of the air layer above the crop is a wind function equivalent term which needs to be calibrated under site specific conditions (McIlroy and Angus, 1964). This equation was locally calibrated against the lysimeter data at Aspendale (Australia) by Dilley and Shepherd (1972) for  $ET_0$  estimates and was found to give quite satisfactory results.

Bouchet (1963) proposed a combination relationship for estimating potential evapotranspiration. Subsequent development by Morton (1983) produced such a model that was capable of estimating potential as well actual evapotranspiration for use in rainfall-runoff modeling. This model is known as Morton's complementary relationship and requires only simple daily climatic data such as dry bulb and wet bulb temperatures, sunshine hours, latitude, altitude etc. Chiew and Jayasuriya (1990) investigated the ability of Morton's complementary model against the Penman estimates and lysimeter data in Australia, and reported that during moderate evapotranspiration rate days its performance was good. However, at low and high ET rates this model over-estimated and under-estimated respectively. Chiew and McMahon (1991) suggested that during moderate climatic conditions, estimates from this model can be successfully used in

rainfall-runoff modeling applications. However, this model has not been tested in terms of reference crop evapotranspiration ( $ET_o$ ) estimates.

Rijtema (1965) presented a combination method which was initially calibrated for use with a homogeneous grass cover, but was later modified and improved (Rijtema and Ryhiner, 1966; and Rijtema, 1968) for  $ET_c$  estimates of other agricultural crops. Although the performance of this method for  $ET_c$  estimates of various agricultural crops was reported to be good, the method has not been extensively tested in terms of reference crop evapotranspiration ( $ET_o$ ) estimates.

Brown and Rosenberg (1973) developed a combination method which requires an iterative solution and is only applicable to surfaces with full canopy cover. This model has been claimed to give quite satisfactory results by the authors. However, the model seems to be unnecessarily cumbersome because of its iterative solution, and hence has not been widely accepted by other researchers.

The original Penman (1948) equation did not include the surface resistance function for water vapour transfer. Monteith (1965) introduced a surface resistance parameter in the Penman (1948) equation, and also replaced the empirical linear wind function term with what is known as the aerodynamic resistance parameter. The aerodynamic resistance parameter incorporated by Monteith was actually the adaptation of the wind function which was derived by Businger (1956). This version of the Penman equation, which includes the aerodynamic and surface resistance terms is commonly referred to as the Penman-Monteith (1965) equation, and to date is recognised as the best physically based equation for  $ET_o$  estimates (Allen et al., 1994a,1994b; and ASCE, 1996).

It is worthwhile to note that the Penman-Monteith (1965) method was basically developed for use with homogeneous canopies. Hence, Monteith (1965) illustrated its use for various homogeneous crop covers. Therefore, as quoted in Vanderkimpfen (1991), the Penman-Montieth method soon after its development was applied to a wide range of crops including alfalfa and grass by several investigators (e.g. Van Bavel 1967; Szeicz et

al., 1969; Nkemdirin, 1976; Russel, 1980; McNaughton and Jarvis, 1984; and Van Zyl and Jager, 1987) and had produced satisfactory results. By now, the use of the Penman-Monteith equation has become widespread and numerous applications of this method can be found in the literature. However, keeping in view of the scope of the present study, in this thesis the review of the Penman-Monteith method will mainly be centred around its role as a reference evapotranspiration estimation method.

Due to the promising use of the Penman-Monteith (1965) method in irrigation and agricultural water management sector, Allen (1986) and Allen et al. (1989) reviewed the Penman-Monteith method and observed some of the ambiguities of this method in estimating reference evapotranspiration estimates. In order to remove the ambiguity in the Penman-Monteith (1965) method and to achieve a meaningful comparison of  $ET_0$  estimates from various combination methods around the globe, Allen et al. (1989) urged the need for standardisation of certain parameters in the Penman-Monteith method and presented a consistent set of algorithms for the computation of these parameters. Based on this standardisation, they also suggested a new hypothetical definition of grass-based reference evapotranspiration. This hypothetical grass-based reference  $ET_0$  as related to the Penman-Monteith method was defined as “the rate of evapotranspiration from a hypothetical crop with an assumed crop height of 12 cm and a fixed canopy resistance of 70 s/m and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water”. This definition closely resembles with that of the Doorenbos and Pruitt (1977) grass related reference evapotranspiration definition.

In a comparative study of various  $ET_0$  methods, Jensen et al. (1990) concluded that different versions of the Penman combination method were superior to all other  $ET_0$  estimation methods. Among them, the Penman-Monteith version with standardised parameters (hereafter referred to as the P\_M method) as suggested by Allen et al. (1989) was the top-ranked method for  $ET_0$  estimates on a daily basis. In their analysis, lysimeter data from three sites in the USA representing a wide range of climatic conditions were used as the standard for comparison of different methods. Ranking was performed on the

basis of the standard error of the estimation method versus the lysimeter  $ET_0$  measurements.

Unanimous agreement was also reached among the expert consultation on revision of FAO reference ET methodologies, to recommend the P\_M method as the best performing equation in the absence of measured  $ET_0$  data (Smith, 1992). However, the committee suggested further studies to be carried out using the measured evapotranspiration data from lysimeters to validate this method under a wide range of climatic conditions. Many researchers (e.g. De Souza and Yoder, 1994; Mohan, 1991; Amatya et al., 1995; Chiew et al., 1995; and Mohan and Arumugam, 1996) have adopted the P\_M method in their studies as the standard for evaluation of other empirical evapotranspiration methods. Allen et al. (1994a), advocating the use of P\_M method for standardisation purposes, recommended that the standardised P\_M reference estimates should be globally used and should not require any local calibration. They also suggested that new crop coefficients compatible with this standardised method should be developed in future studies.

Meyer et al. (1995) compared the P\_M method with the locally calibrated modified Penman (M\_Y) method for  $ET_0$  estimates in Griffith. They reported that the P\_M reference evapotranspiration estimates were on average 30% less than the  $ET_0$  values of the M\_Y method, which had produced comparable results to lysimeter data. This causes some concern to the common belief that the P\_M method could be used in the absence of measured data for calibration of other empirical methods as proposed by some investigators (eg. Allen et al. 1994a; ASCE, 1996). It is important to note that in the study of Jensen et al. (1990), the P\_M method had also under-estimated  $ET_0$  for Aspendale (Australia).

## **2.4 RAINFALL**

As stated earlier in Section 2.1, for short-term (i.e. 7-14 day) planning and operation of irrigation systems, an accurate estimate of irrigation water requirement is of major concern. Since the irrigation water requirement is significantly influenced by rainfall, a

reliable estimate of the expected rainfall in any irrigation period of the crop-growing season is of fundamental importance. Efficient utilization of rainfall during the rainy season will help in saving water in the storage reservoir that could be used in the dry season.

Rainfall modelling has been the subject of study by various researchers for a long time from various disciplines including climatology, meteorology and hydrology. Rainfall is the end result of a complex combination of dynamic, thermodynamic and cloud microphysical processes. Because of the complexity and the randomness of the above physical processes, stochastic approaches have been used in rainfall modelling for both space and time (Khaliq, 1995).

In recent years, a large effort has been devoted to seeking a mathematical description of the temporal variability of rainfall for use in various applications (Khaliq, 1995). Hence, mathematical descriptions have been sought at various time scales ranging from monthly to as small as ten-minute intervals. The small time intervals (such as minutes and hours) are important for urban storm-sewer designs, whereas the short term duration time scales (e.g. days and weeks) are important for agricultural purposes. The large time scales (such as seasonal or annual) are employed for design of large storage reservoirs. As the interest of the study of this thesis lies in 7-14 day rainfall predictions for use in irrigation scheduling, this section reviews the rainfall prediction studies which are mainly concerned with 7-14 day rainfall time scales, in particular for use under Australian conditions. The low flows have similar characteristics (such as zero values, high skewness etc.) to those of short-term rainfall series. Therefore, the results of low flow studies could provide some information to select the appropriate distributions for short-term rainfall predictions. The studies related to both low flow and short-term rainfall distributions are reviewed in Section 2.4.1 and 2.4.2 respectively.

In most irrigation systems, the irrigation interval (or cycle) ranges between 7-14 days depending on the number of irrigations per season. For predicting the expected rainfall at 7-14 day time scale, the most common approach has been to fit an appropriate statistical

distribution to the rainfall data series. The rainfall is then predicted with a certain probability of exceedance (Yevjevich, 1972; and Buishand, 1978). The probability distributions generally used to model rainfall and other hydrological data series include normal, lognormal, exponential, exponential mixture, gamma, Weibull and log Pearson type-III. A description of these and other distributions can be found in Hann (1977), Kite (1977) and McMahon and Arenaz (1982).

#### **2.4.1 Low Flow Distributions**

Several comparative studies (e.g. Matalas, 1963; Eratakulan, 1970; and Adamson, 1984) in Australia as well as elsewhere have been undertaken to determine the suitability of various probability distributions for prediction of low flows. A close examination of the results of aforementioned low flow analysis studies indicated that the lognormal, gamma, Weibull and log-Pearson type-III distributions held the most promise. Nathan (1990) employed the above four distributions to analyse the 7- and 15-day low flows of Australian streams. This study reported that among these four distributions, only the log-Pearson type-III and Weibull distributions were suitable for these low flows. The concluding remarks by Nathan (1990) further revealed that even these two distributions were not able to fit all the data series completely because of the presence of zeros in some of these series.

In the same study, Nathan adopted the Total Probability Theorem, TPT (Haan, 1977) and reported that this method was quite satisfactory to fit the low flow data series having zero values. The TPT approach is based on a joint/conditional probability function where the probability of zero flow (or rainfall) is jointly combined with the function that when flow (or rainfall) does occur the flow (or rainfall) exceeds some specified value. In this method, zeros are analysed separately and the non-zero values are checked against the possibility of fitting an appropriate distribution, and then both are combined together through a joint/conditional probability function (Haan, 1977).

Adamowski (1996) analysed the low flow series having zeros using log-Pearson type-III distribution, Weibull distribution, and a nonparametric (NP) method. He reported that the nonparametric method gave more accurate results than the two parametric distribution methods. In the same study, Adamowski also adopted the TPT method in which the probability of zero and non zero flows were estimated separately. In this analyses, the probability of zero flows was estimated using the Adamowski (1981) probability plotting formulas, whereas for nonzero flows a NP distribution was adopted. The detail of the density function of NP distribution is given in Adamowski (1985), Adamowski and Feluch (1990) and Adamowski (1996).

#### **2.4.2 Short-Term Rainfall Distribution**

Attempts to define the best probability distribution for rainfall data series by Benson (1968) revealed that there is no clearly superior distribution of universal acceptability. This is primarily due to the varying nature of rainfall series observed in different parts of the world.

A study of rainfall records at many locations in Thailand indicated that short term rainfall series were positively skewed and could consist of a considerable number of non-rainy periods giving zero values in the data series (Phien et al. 1978). A similar pattern is observed in Victoria, Australia (as will be shown later in Sections 4.6.1 and 4.6.2). For rainfall data series with positive skewness, the log-normal and gamma distributions should yield the best fit among available distributions (Phien et al., 1980). However, these distributions are not appropriate when the sequences under consideration (such as 7-14 day rainfall series) have many zero values (Phien et al., 1980; and Nathan, 1990).

Buishand (1977) proposed a mixed distribution known as Leaky Law (LL) to analyse data series having zero values with a finite probability of occurrence. The LL involved a point mass assigned at the origin to the probability of zero rainfall, and a continuous distribution for the positive values. This distribution was satisfactorily used by Phien et al. (1978) for monthly rainfall data in Northern Thailand. A similar approach was

adopted by Burman et al. (1982) to analyse the frequent occurrence of zero irrigation requirement.

Since a single superior probability distribution could not be found for all rainfall series, Donnelly (1992) developed a computer software to analyse the rainfall for user-specified prediction period. This package was basically designed for timely harvesting of grain crops to avoid the yield losses associated with the post-season rainfalls. This software produces the percentile level of exceedance corresponding to a user-specified rainfall amount. Since the main interest of irrigation scheduling is to predict the rainfall amount at a given exceedance probability level, this software is of limited use for planning the short term operation of irrigation systems.

## **2.5 SUMMARY AND CONCLUSIONS**

### **2.5.1 Irrigation Scheduling**

The literature reviewed for irrigation scheduling models showed that currently there is no reliable irrigation scheduling computer model available for use under Victorian (Australia) conditions. Therefore, there is a growing need to develop a simple computer package for short-term irrigation planning and scheduling of agricultural crops.

### **2.5.2 Evapotranspiration**

As stated in Section 2.3, crop evapotranspiration ( $ET_c$ ) is an important component of the irrigation water requirement estimates. Since reference crop evapotranspiration ( $ET_o$ ) is the basic component of  $ET_c$ , the accuracy in  $ET_o$  estimation is of paramount importance. A review of the literature cited in Section 2.3 indicates that a large number of methods for estimation of  $ET_o$  from weather data have been developed, and tested for varying geographic and climatic conditions around the world. These methods vary from simple empirical relationships to complex methods based on physical processes such as the Penman (1948), McIlroy (1961) and the Penman\_Monteith (1965) combination methods.

Although the literature in general provides ample evidence about the superiority of the combination methods when required input data are available, these inputs are difficult to obtain for many applications. Also, some recent studies (eg. Meyer, 1994; Meyer et al., 1995) have revealed that no single method is universally satisfactory for all climatic regions for estimating  $ET_0$  using meteorological data, without some local calibration. A need therefore, exists for  $ET_0$  estimates to be locally calibrated with properly measured water use data.

Recognising the limitations of the availability of reliable climatic data, the consultation group of the FAO (Smith, 1992) also emphasised that several  $ET_0$  methods should be investigated based on the type of climatic data available for the site under question and the method which yields best results to be used for the site.

Keeping in view of the above considerations, nine different methods (*four combination: modified Penman\_Meyer, modified Penman\_Watts&Hancock, McIlroy and the Standardised Penman-Monteith; one evaporation: FAO-24 pan; two Temperature-radiation based: Ritchie and FAO-24 radiation; and two temperature based: Hargreaves, and Improved Hargreaves*) were selected for investigation in this thesis. These selected methods range from simple temperature-based to complex data extensive combination methods. These methods are selected since they have been widely used for  $ET_0$  estimates in the irrigation profession. The mathematical details along with the computational procedures of the parameters of these methods are presented in Section 3.2. In addition to the above mentioned nine methods, the SEV method (Section 2.3.3) which uses the US Class-A pan evaporation for  $ET_0$  estimates without requiring any other measured climatic data will also be tested in this study.

### **2.5.3 Rainfall Prediction**

The review of literature cited in Section 2.4 reveals that not much effort has been focused on the short-term (i.e. 7-14 day) rainfall predictions under Australian conditions (i.e.

short-term rainfall series with high variability, high skewness and zero values). Therefore, there is a need to investigate this aspect and to develop a general computer software to predict short-term rainfall at a given probability level, which could be used in short term planning and operation of irrigation systems.

The review also showed that modelling of rainfall of short (such as 7-14 day) time scales is not as straightforward as of the monthly time scales. The short-term rainfall data series consist of many zero values. These zero values pose problems when fitting a distribution to these data series. In addition, the studies by Benson (1968), Kite (1977), Nathan (1990) and Khaliq (1995) also revealed that there was no clearly a single superior distribution which could suit all applications of short term rainfall and/or low flow data series. Hence, in this thesis an alternative approach is proposed. According to this approach, two methods (i.e. the Total Probability Theorem and Leaky Law) which account for zero values explicitly will be considered in fitting short-term rainfall data series, and the best method that fits the series will be used to predict rainfall at a given level of probability of exceedance. The best method will be selected using some objective goodness-of-fit tests such as the Kolmogorov-Smirnov test (Yevjevich, 1972). The details are given in Chapter 4.

# CHAPTER 3

## EVAPOTRANSPIRATION

### 3.1 INTRODUCTION

In planning the short-term (i.e. 7-14 day) operation of irrigation systems, an estimate of irrigation water requirement is of major concern. Since the irrigation water requirement is mainly dictated by crop water use, a reliable estimate of the crop water use in any irrigation period of the crop-growing season is of fundamental importance. Accurate estimates of crop water use during the irrigation season will facilitate the use of available water efficiently, which in turn would help in saving water in the storage reservoir that could be used in the dry season.

The most common procedure employed for estimating daily crop water use has been first to calculate reference evapotranspiration ( $ET_o$ ) based on measured climatic data, and then multiply it by a crop coefficient ( $K_c$ ) which is a function of the particular crop and its stage of growth as given by Doorenbos and Pruitt (1977) and Wright (1981,1982). This procedure gives the potential (maximum) crop water use ( $ET_p$ ). Finally, the actual crop water use (or actual crop evapotranspiration,  $ET_a$ ) is determined based on the availability of soil moisture at that time. Modelling evapotranspiration is also important in crop growth simulation, water quality and other hydrologic modelling applications.

The daily  $ET_o$  can be determined by direct measurements (e.g. lysimeter) or estimated by empirical methods. Direct measurements generally produce more accurate values than the empirical methods. However, direct measurement of  $ET_o$  is often expensive, laborious and involves complex instrumentation. For this reason, limited data are available from direct measurements. Therefore, the empirical  $ET_o$  estimation methods are very popular for daily  $ET_o$  estimates. The results from these  $ET_o$  estimation methods can also be successfully used in computer based irrigation scheduling programs, such as the study described in Chapter 5 and Appendix C of this thesis.

During the past half-century, a large number of methods for calculation of  $ET_o$  from climatic data have been developed. These methods ranged from simple empirical relationships to highly data extensive complex methods that were based on physical processes. They have been tested for varying geographical and climatic conditions around the globe. A report prepared by the Technical Committee on Irrigation Water Requirements, American Society of Civil Engineers – ASCE (Jensen, 1974) described sixteen  $ET_o$  estimation methods. Since then, numerous other new methods have appeared in the literature as given in Burman et al. (1983), Stewart (1983) and Jensen et al. (1990). However, the choice of the method for estimating  $ET_o$  is essentially based on the location, the climate, the intended estimation period, and the input data availability for the site in question (Jensen et al., 1990). Therefore, there is a need to select an appropriate  $ET_o$  method for a particular site by comparing various  $ET_o$  estimation methods. This is considered in this chapter. As stated in Section 2.3, the “grass” reference crop was adopted in the  $ET_o$  estimation comparison study described in this chapter.

As summarised in Section 2.5.2, no single  $ET_o$  method is universally satisfactory for all climatic regions for estimating  $ET_o$  using meteorological data, without local calibration. Even after local calibration, still there is a possibility that these methods cannot be used for certain days at a particular site because of lack of meteorological data on these days. Therefore, there is also a need to estimate  $ET_o$  using available meteorological data based on one or more  $ET_o$  methods. This can be achieved by developing a computer software, which computes  $ET_o$  for a particular day using available meteorological data and the  $ET_o$  method selected from an  $ET_o$  method ranking schedule. This aspect is also considered in this chapter.

The first part of this chapter describes the theoretical details of the ten  $ET_o$  estimation methods selected for this study (Section 2.5.2) including the estimation of parameters associated with these methods. This is followed by a discussion of the performance and calibration of these ten  $ET_o$  methods at three selected sites (Section 3.3) namely Aspendale and Tatura in Victoria, and Griffith in New South Wales (NSW, Australia). A reference crop evapotranspiration estimation computer software (REF\_ET) developed as part of this study based on the aforementioned ten  $ET_o$

estimation methods is presented at the end of this chapter. The operational details of REF\_ET are given in Appendix A.

### 3.2 ET<sub>o</sub> METHODS SELECTED FOR THE STUDY

As stated earlier (Section 2.5.2), ten ET<sub>o</sub> estimation methods ranging from simple temperature-based to data-extensive were selected for this study. They are as follows:

- (i) Hargreaves method (HAR)
- (ii) Improved Hargreaves method (IHA)
- (iii) Ritchie method (RIT)
- (iv) FAO-24 Radiation method (RAD)
- (v) FAO-24 Pan method (PEV)
- (vi) Simplified US Class-A Pan Evaporation method (SEV)
- (vii) Modified Penman-Meyer method (M\_Y)
- (viii) Modified Penman-Watts&Hancock method (W\_H)
- (ix) McIlroy Method (McI)
- (x) Penman-Monteith method (P\_M)

These methods are ordered according to their general input climatic data requirements with less data extensive methods listed first. These methods are selected since they have been widely used for ET<sub>o</sub> estimation within the irrigation profession. As stated earlier (Section 2.5.2), methods (i) and (ii) are *temperature based*; methods (iii) and (iv) are *temperature-radiation based*; methods (v) and (vi) are *pan evaporation based*; and methods (vii) – (x) are *combination based*. The main input climatic data items required for each of these ten methods are given in Table 3.1.

With regards to the input parameters for the ET<sub>o</sub> methods, it is worth mentioning that some of the ET<sub>o</sub> estimation methods require the computation of certain input parameters such as latent heat of vaporisation, saturation vapour pressure, psychrometric constant, from other measured weather data. The Smithsonian Meteorological Tables as given by List (1963,1984) and many other text books in hydrology present the values of these parameters in tabular form. However, the digital computer oriented ET<sub>o</sub> methods require the mathematical algorithms for computing

these climatic parameters. The FAO expert committee (Smith, 1992) reviewed the algorithms currently available to determine the above climatic parameters. Based on the relative accuracy and simplicity of several algorithms, a standard uniform procedure was proposed by the FAO committee to determine each of these input parameters throughout the world. To avoid any ambiguity in the calculation procedures, the values for several parameters were also fixed based on their general and global validity by this committee. In line with these revised international recommendations and to achieve uniformity in the calculation procedures, various parameters in the  $ET_0$  estimation methods selected for this study will also be computed using the procedures as recommended by the FAO (Smith, 1992) expert committee, unless some locally calibrated parameters are available.

Table: 3.1 Input Climatic Data Requirements for Various  $ET_0$  Methods

Methods	T	Tdew	RH <sub>m</sub>	U	R <sub>so</sub>	R <sub>s</sub>	R <sub>n</sub>	Epan	G
HAR	*				(*)				
IHA	*	(*)			(*)				
RIT	*					*			
RAD	*								
PEV			(*)	*				*	
SEV								*	
M_Y	*	(*)		*			(*)		(*)
W_H	*	(*)		*			(*)		(*)
McI	*	(*)		*			(*)		(*)
P_M	*	(*)		*			(*)		(*)

\* measured data; (\*) if measured data available, otherwise to be estimated using alternative measured data

T = daily temperature

RH<sub>m</sub> = Mean Relative Humidity

R<sub>so</sub> = Clear-day (maximum) Solar Radiation

R<sub>n</sub> = Net Radiation

G = Soil Heat Flux Density

T<sub>dew</sub> = Dew point temperature

U = Wind Speed

R<sub>s</sub> = Solar Radiation

Epan = US Class-A Pan Evaporation

The estimation procedures of various parameters are presented in the relevant section wherever they appear first, and then a reference is made to them in the subsequent sections if they re-appear. Although most of the parameter estimation procedures described in these sections are brief, the comprehensive full details of these parameters and their algorithms can be found in the relevant references. A brief description of each of the aforementioned  $ET_o$  methods selected for this study is given in Sections 3.2.1 to 3.2.10.

### 3.2.1 Hargreaves Method (HAR)

The Hargreaves method selected for this study is the revised version of the original Hargreaves (1975) equation for estimating the grass-related reference evapotranspiration (Hargreaves and Samani, 1985). According to this method:

$$ET_o = 2.3 \times 10^{-3} R_a \sqrt{TR} (T_m + 17.8) \quad (3.1)$$

$$TR = (T_{\max} - T_{\min}) \quad (3.2)$$

$$T_m = \frac{(T_{\max} + T_{\min})}{2} \quad (3.3)$$

where  $ET_o$  = reference crop evapotranspiration (mm/day)

$R_a$  = extraterrestrial radiation in equivalent evaporation (mm/day)

TR = temperature range ( $^{\circ}C$ )

$T_m$  = mean daily air temperature ( $^{\circ}C$ )

$T_{\max}$  = maximum daily temperature ( $^{\circ}C$ )

$T_{\min}$  = minimum daily temperature ( $^{\circ}C$ )

In Eq. 3.1,  $R_a$  refers to the amount of solar radiation received above the atmosphere, and is dependent on latitude and the time of the year.  $R_a$  can be estimated using the generalised equations of Duffie and Beckman (1980), as given in Jensen et al. (1990). Keeping in view of the empirical aspect of the HAR method, if locally measured data of clear-day (maximum) global radiation ( $R_{so}$ ), which is also dependent on the latitude and the time of the year, are available, they can be used instead of  $R_a$  for improved results from Eq. 3.1 (Angus, 1995; personal communication). For Australian conditions, locally derived clear-day (maximum) global radiation ( $R_{so}$ ) equations were presented in Angus (1980). Therefore, in order to make use of the locally derived  $R_{so}$  equations for improved  $ET_o$  estimates,  $R_{so}$  was adopted for use in Eq. 3.1 in this study instead of extraterrestrial radiation.

As clear day radiation ( $R_{so}$ ) is not a directly measured input parameter in the HAR method, the only measured variable required for a given time period and location is the air temperature. Therefore, this method is categorised as a temperature based method (ASCE, 1996). Estimation procedure for  $R_{so}$  climatic parameter to be used in Eq. 3.1 is given below.

#### *Estimation of daily clear day (maximum) radiation ( $R_{so}$ )*

If long-term daily measured incoming solar radiation ( $R_s$ ) data are available, then values of  $R_{so}$  can be obtained by fitting an envelope curve to the maximum measured daily  $R_s$  values.  $R_s$  can be measured using Pyranometer at the site under consideration. Meyer (1994) developed a polynomial equation for an envelope curve fitted to the maximum measured daily  $R_s$  values at Griffith (Australia) as:

$$R_{so} = 22.357 + 11.0947 \cos D - 2.3594 \sin D \quad (3.4)$$

$$D = \left( \frac{J}{365.25} \right) 2\pi \quad (3.5)$$

where  $J$  = Julian day

Meyer (1994) reported that if long-term daily measured  $R_s$  data are not available, then the values of  $R_{so}$  can also be estimated using the generalised computer software of

Stapper et al. (1986) which can be applied to any location in Australia. The input data required for this software are latitude and Julian day. However, as will be shown later (in Section 3.6.1), this software overestimated the  $R_{so}$  values for Griffith. Meyer et al. (1995) emphasised the use of fitted envelope curve based on the locally measured  $R_s$  data for reliable estimates. Therefore, it was decided to develop the envelope curves for  $R_{so}$  for the study sites used in this thesis. The fitting of envelope curves is described below.

Angus (1980) developed the  $R_{so}$  envelope curves using historical daily measured  $R_s$  data for 18 stations in Australia. In latitude, these stations ranged from Darwin (12 °S) to Hobart (43 °S), and hence covered both coastal and inland stations over a wide range of latitudes in the southern hemisphere. Based on the analysis of these envelope curves, he revealed that envelope curves were symmetrical about 22<sup>nd</sup> June, with minimum and maximum  $R_{so}$  values at 22<sup>nd</sup> June and 22<sup>nd</sup> December respectively. Therefore, he presented a set of polynomial equations which can be used to compute the  $R_{so}$  values for 22<sup>nd</sup> day of each calendar month as a function of latitude for Australian conditions. According to Angus (1980):

$$\text{for } 22^{\text{nd}} \text{ Dec: } R_{so} = A \left( 6.2468 + 0.2148L - 3.5 \times 10^{-3} L^2 \right) \quad (3.6)$$

$$22^{\text{nd}} \text{ Jan/Nov: } R_{so} = A \left( 6.8819 + 0.1680L - 2.9 \times 10^{-3} L^2 \right) \quad (3.7)$$

$$22^{\text{nd}} \text{ Feb/Oct: } R_{so} = A \left( 7.5896 + 0.0974L - 2.4 \times 10^{-3} L^2 \right) \quad (3.8)$$

$$22^{\text{nd}} \text{ Mar/Sep: } R_{so} = A \left( 8.1286 + 1.83 \times 10^{-2} L - 1.9 \times 10^{-3} L^2 \right) \quad (3.9)$$

$$22^{\text{nd}} \text{ Apr/Aug: } R_{so} = A \left( 8.0311 - 5.64 \times 10^{-2} L - 1.1 \times 10^{-3} L^2 \right) \quad (3.10)$$

$$22^{\text{nd}} \text{ May/July: } R_{so} = A \left( 7.5275 - 8.80 \times 10^{-2} L - 7.0 \times 10^{-4} L^2 \right) \quad (3.11)$$

$$22^{\text{nd}} \text{ June: } R_{so} = A \left( 7.09 - 8.99 \times 10^{-2} L - 7.0 \times 10^{-4} L^2 \right) \quad (3.12)$$

where  $L$  = southern latitude (degrees)

$A$  = unit conversion factor, which is equal to 3.6

As can be seen, in the absence of long-term daily measured  $R_s$  data, the use of Eqs. 3.6-3.12 can provide at least 12 data points to construct the  $R_{so}$  envelope curve for the site under consideration. Since the equations of Angus (1980) give  $R_{so}$  only for 22<sup>nd</sup>

day of each calendar month, for a particular site if these data values are plotted on Y-axis against the corresponding Angus\_day (i.e. 22<sup>nd</sup> Dec as 1, 22<sup>nd</sup> Jan as 31 and 22<sup>nd</sup> Feb as 62 etc. and finally 22<sup>nd</sup> Dec of the following year as 366) can provide an  $R_{so}$  envelope curve for that site. This envelope curve can then be used to obtain  $R_{so}$  values for any day of the year at that site. However, for computer based calculations this envelope curve needs to be fitted with a mathematical equation. Since the equations of Angus (1980) were derived using measured radiation data only at 18 sites over a wide range of latitudes in Australia, in this thesis, these equations will be tested for their suitability to provide daily  $R_{so}$  estimates for calculation of  $ET_o$ . For this purpose, the locally derived Meyer (1994) envelope curve for Griffith will be used as the basis. It is important to note that the Griffith site was not included in the study of Angus (1980). Hence, an accuracy check at the Griffith site would give confidence about the use of Angus (1980) equations

It is important to mention that the aforementioned  $R_{so}$  envelope curve fitting technique requires a separate equation to be developed for each location. However, it is laborious to develop a curve for each site if a large number of sites are to be dealt with. Meyer et al. (1995) reported that if an  $R_{so}$  envelope curve is developed for a certain site, it can be safely used for other sites which are within  $\pm 2^\circ$  latitudes provided these sites are topographically and climatically similar.

In order to overcome the aforementioned limitation associated with the envelope curve fitting and for more generalised use of the equations of Angus (1980), an alternative procedure which can be adopted is to interpolate the remaining data points among the 12 known  $R_{so}$  data points. For this purpose, some mathematical interpolation technique can be quite useful. As will be shown later (Section 3.6.1), the plot of 12  $R_{so}$  data points (obtained from Angus, 1980 equations) followed a curvilinear pattern, for which the cubic spline interpolation method can be successfully used. The cubic spline technique would facilitate to interpolate the intermediate values between the 12 data points. The detail of cubic spline technique can be found in any standard numerical analysis text book such as Wold (1974). The cubic spline interpolation for Angus (1980) data points for the study sites is discussed in Section 3.6.1.

### 3.2.2 Improved Hargreaves Method (IHA)

Meek and Phene (1991) found that the Hargreaves (1985) method underestimates  $ET_o$  and hence introduced an empirical wind term to account for 'advection' that does not require wind-speed measurements. This method is termed as the improved Hargreaves method in this thesis. In order to improve the performance of the HAR method, the empirical wind term was added to estimates of Eq. 3.1 as:

$$ET_o = \left[ \left\{ 2.3 \times 10^{-3} R_a \sqrt{TR} (T_m + 17.8) \right\} + c \left\{ 6.9 \left( \frac{\gamma}{\Delta + \gamma} \right) (e_z^* - e_d) \right\} \right] \quad (3.13)$$

where  $c$  = empirical constant

$\gamma$  = psychrometric constant ( $\text{kPa}^\circ\text{C}^{-1}$ )

$\Delta$  = slope of the saturation vapour pressure-temperature curve ( $\text{kPa}^\circ\text{C}^{-1}$ )

$e_z^*$  = saturation vapour pressure (kPa) at mean daily air temperature at reference height  $z$ , usually taken as 2m

$e_d$  = saturation vapour pressure (kPa) at the dew point temperature

and all other terms are as defined earlier.

The empirical constant  $c$  in above equation can be estimated as an integer multiplier using a trial and error procedure to suite local conditions by matching  $ET_o$  estimates with measured  $ET_o$  (Meek and Phien, 1991). Estimation procedures for various climatic parameters used in Eq. 3.13 are given below.

#### *Estimation of $\Delta$*

The slope of the saturation vapour pressure-temperature curve ( $\Delta$ ) in  $\text{kPa}^\circ\text{C}^{-1}$  can be estimated at mean daily air temperature ( $^\circ\text{C}$ ) using the Bosen (1960) equation as quoted in Jensen et al. (1990) as:

$$\Delta = 0.20 (7.38 \times 10^{-3} T_m + 0.8072)^7 - 1.16 \times 10^{-4} \quad (3.14)$$

### *Estimation of $\gamma$*

The psychrometric constant ( $\gamma$ ) in  $\text{kPa}^\circ\text{C}^{-1}$  can be estimated by using the Brunt (1952) relationship as:

$$\gamma = \frac{C_p P}{0.622 \lambda} \quad (3.15)$$

- where  $C_p$  = specific heat of moist air at constant pressure and is equal to  $1.013 \times 10^{-3} \text{ (MJkg}^{-1} \text{ }^\circ\text{C}^{-1}\text{)}$   
 $P$  = atmospheric pressure (kPa)  
 $\lambda$  = latent heat of vaporisation ( $\text{MJkg}^{-1}$ )

The atmospheric pressure ( $P$ ) in kPa can be estimated using the ideal gas law as suggested by Burman et al. (1987):

$$P = P_o \left[ \frac{T_o - \alpha E_{lv}}{T_o} \right]^a \quad (3.16)$$

- where  $P_o$  = atmospheric pressure at mean sea level and is equal to 101.3 kPa (List, 1963,1984)  
 $T_o$  = absolute temperature at mean sea level and is equal to 288.0 °K (List, 1963,1984)  
 $\alpha$  = constant lapse rate of moist air and is equal to 0.01  $\text{Km}^{-1}$  (Jensen et al., 1990)  
 $E_{lv}$  = elevation of the study site above sea level (m)  
 $a$  = the exponent of gas equation and is equal to 5.257

The latent heat of vaporisation ( $\lambda$ ) parameter for use in Eq. 3.15 can be estimated at mean daily temperature using an equation developed by Harrison (1963) as:

$$\lambda = 2.501 - 2.36 \times 10^{-3} T_m \quad (3.17)$$

### *Estimation of $e_z^*$*

As stated earlier, the  $e_z^*$  parameter in Eq. 3.13 is calculated at mean daily air temperature. Saturation vapour pressure at different temperatures can be estimated using the methods developed by Tetens (1930) or Murray (1967). However, both these methods are complicated, which require excessive computer time. Lowe (1976) presented a simplified polynomial equation to use with digital computers for saturation vapour pressure estimates. In this study, the Lowe (1976) polynomial equation is adopted since it uses less computer time. According to this method:

$$e^* = \{a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 + a_6 T^6\} \quad (3.18)$$

$$a_0 = 6.107799961 \times 10^{-1}$$

$$a_1 = 4.436518521 \times 10^{-2}$$

$$a_2 = 1.428945805 \times 10^{-3}$$

$$a_3 = 2.650648471 \times 10^{-5}$$

$$a_4 = 3.031240396 \times 10^{-7}$$

$$a_5 = 2.034080948 \times 10^{-9}$$

$$a_6 = 6.136820929 \times 10^{-12}$$

where  $e^*$  = saturation vapour pressure at temperature T (kPa)

T = temperature (°C)

### *Estimation of $e_d$*

The  $e_d$  parameter for use in Eq. 3.13 can be calculated using the aforementioned Lowe (1976) procedure at given dew point temperature.

### **3.2.3 Ritchie Method (RIT)**

The Ritchie (1985) method, as quoted in Meyer et al. (1995) is principally based on the radiant energy concept of the Priestley-Taylor's (1972) equation. This method

produces an estimate called daily potential evaporation ( $E_o$ ), which represents an equivalent  $ET_o$ . The  $E_o$  term is given by Eqs. 3.19 and 3.20 as:

$$E_{eq} = R_s (0.00488 - 0.00437 \alpha) (T_{adjm} + 29) \quad (3.19)$$

$$E_o = 1.1 E_{eq} \quad (3.20)$$

where  $E_{eq}$  = equilibrium evapotranspiration (mm/day)

$\alpha$  = albedo, the short-wave reflectance coefficient which is equal to 0.23

$T_{adjm}$  = adjusted mean daily temperature defined as  $(0.6 T_{max} + 0.4 T_{min})$

$E_o$  = daily potential evaporation, representing an equivalent  $ET_o$  value (mm/day)

Like any other empirical radiation-based method, the Ritchie (1985) method also requires an advection correction factor. Hence, Meyer et al. (1995) derived an advection correction factor for use in this method to account for local advection effects. They reported that with the introduction of the advection correction factor, the RIT method produced quite favourable  $ET_o$  estimates in Griffith (Australia). After the aforementioned Meyer et al. (1995) advection correction factor, the RIT method can be expressed as:

(i) For winter/spring season:

$$E_o = 1.1 E_{eq} \quad \text{for} \quad T_{max} < 24^\circ C \quad (3.21a)$$

$$E_o = [0.05 (T_{max} - 24) + 1.1] E_{eq} \quad \text{for} \quad T_{max} \geq 24^\circ C \quad (3.21b)$$

(ii) For summer/autumn season:

$$E_o = 1.1 E_{eq} \quad \text{for} \quad T_{max} < 35^\circ C \quad (3.22a)$$

$$E_o = [0.05 (T_{max} - 35) + 1.1] E_{eq} \quad \text{for} \quad T_{max} \geq 35^\circ C \quad (3.22b)$$

In this thesis, the RIT method was adopted with the advection correction factor of Meyer et al. (1995).

### 3.2.4 FAO-24 Radiation Method (RAD)

Doorenbos and Pruitt (1977) also presented a radiation method to estimate  $ET_o$  using solar radiation as follows:

$$ET_o = \left[ a + b \left( \frac{\Delta R_s}{\Delta + \gamma} \right) \right] \quad (3.23)$$

where  $R_s$  = solar radiation ( $\text{mm d}^{-1}$ )

$a$  = empirical constant equal to  $-0.3$  ( $\text{mm d}^{-1}$ )

$b$  = an adjustment factor that varies with mean relative humidity and daytime wind speed and can be estimated as per Eq. 3.23.

and other symbols are as defined earlier.

#### *Estimation of b*

Frevert et al. (1983) developed a polynomial equation for estimating  $b$  for use in computer calculations as:

$$b = \left[ 1.066 - 1.3 \times 10^{-3} RH_m + 4.5 \times 10^{-2} U_d - 2.0 \times 10^{-4} U_d (RH_m) - 31.5 \times 10^{-6} \{RH_m\}^2 - 1.1 \times 10^{-3} (U_d)^2 \right] \quad (3.24)$$

where  $RH_m$  = mean relative humidity (%)

$U_d$  = mean daytime wind speed measured at 2m height ( $\text{m s}^{-1}$ )

Limits on the above equation are:

$$10 \leq RH_m \leq 100\%$$

$$0 \leq U_d \leq 10 \text{ m/s}$$

For estimation of the adjustment factor  $b$  outside the above limits, the climatic variables  $RH_m$  and  $U_d$  should be set to the respective limit.

### 3.2.5 FAO-24 Pan Method (PEV)

Doorenbos and Pruitt (1977) provided a simple proportional relationship to estimate  $ET_o$  from US class-A pan evaporation as follows:

$$ET_o = K_p E_{pan} \quad (3.25)$$

where  $K_p$  = pan coefficient which depends on the relative humidity, wind speed and the pan environment in relation to its surrounding area

$E_{pan}$  = US Class-A pan evaporation (mm/day)

$K_p$  values can be obtained either from FAO-24 Table-18 (Doorenbos and Pruitt, 1977) or estimated from the polynomial equations derived by Allen and Pruitt (1989) as given by Jensen et al. (1990). Depending upon the surrounding area of the evaporation pan, Allen and Pruitt (1989) presented two types of polynomial equations, one for the dry fetch and the other for the green fetch. In this study, these polynomial equations were adopted. These equations are described as below.

#### *Estimation of $K_p$ for green fetch*

$$K_p = \left[ 0.108 - 3.31 \times 10^{-4} U + 4.22 \times 10^{-2} \ln(F) + 0.1434 \ln(RH_m) - 6.31 \times 10^{-4} \{ \ln(F) \}^2 \ln(RH_m) \right] \quad (3.26)$$

where  $U$  = wind speed measured at 2m height (km/day)

$F$  = fetch length surrounding the Class-A pan (m)

$RH_m$  = mean relative humidity (%)

Limits on the above equation are:

$$84 \leq U \leq 700 \text{ km/day}$$

$$1 \leq F \leq 1000 \text{ m}$$

$$30 \leq RH_m \leq 84\%$$

For estimation of pan coefficients outside the above limits, the climatic variables U, F and  $RH_m$  should be set to the respective lower or upper limits.

### *Estimation of $K_p$ for dry fetch*

$$\begin{aligned}
 K_p = & \left[ 0.61 + 3.41 \times 10^{-3} RH_m - 1.87 \times 10^{-6} U RH_m - 1.11 \times 10^{-7} U F \right. \\
 & + 3.78 \times 10^{-5} U \ln(F) - 3.32 \times 10^{-5} U \ln(U) - 1.06 \times 10^{-2} \ln(U) \ln(F) \\
 & \left. + 6.3 \times 10^{-4} \{\ln(F)\}^2 \ln(U) \right] \quad (3.27)
 \end{aligned}$$

Limits on the above equation are the same as given for Eq. 3.26. For estimation of pan coefficients outside these limits, the climatic variables U, F and  $RH_m$  should be set to the respective lower or upper limits.

### **3.2.6 Simplified US Class-A Pan Evaporation Method (SEV)**

The US Class-A pan evaporation can be used to estimate  $ET_o$  without requiring any other measured climatic data. According to this method:

$$ET_o = K_s E_{pan} \quad (3.28)$$

where  $K_s$  = coefficient for SEV method  
and all other terms are as defined earlier.

$K_s$  can be obtained through the linear regression of daily US Class-A pan data against the measured  $ET_o$  for the site under consideration. Meyer et al. (1995) reported that the SEV method produced quite favourable results in Griffith (Australia). However,

they reported that for evaporation values greater than about 10 mm/day, this method had given  $ET_o$  estimates which were up to 30% greater.

### 3.2.7 Modified Penman-Meyer Method (M\_Y)

As stated in Section 2.3.4, this is a combination type formula which has evolved after the modification of the FAO-Penman method using the wind function developed by Meyer (1994) and is expressed as:

$$ET_o = \frac{1}{\lambda} \left[ \left( \frac{\Delta}{\Delta + \gamma} \right) (R_n - G) + \left( \frac{\gamma}{\Delta + \gamma} \right) f(u) (e_z^* - e_d) \right] \quad (3.29)$$

where  $ET_o$  = the grass reference evapotranspiration ( $\text{mm d}^{-1}$ )

$R_n$  = net radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )

$G$  = soil heat flux density ( $\text{MJ m}^{-2} \text{d}^{-1}$ )

$f(u)$  = wind function of the form  $f(u) = a + b u$ , ( $\text{MJ m}^{-2} \text{kPa}^{-1} \text{d}^{-1}$ )

$a, b$  = locally calibrated empirical constants

$u$  = wind speed measured at 2m height (m/s)

$e_z^*$  = saturation vapour pressure at mean daily air temperature at reference height  $z$ , usually taken as 2m (kPa)

and all other terms are as defined earlier (Section 3.2.2).

The parameters  $\lambda$ ,  $\Delta$ ,  $\gamma$ ,  $e_z^*$  and  $e_d$  of Eq. 3.29 can be calculated as per methods described in Section 3.2.2. The estimation procedures for remaining climatic parameters are described below.

#### *Estimation of $R_n$*

Generally  $R_n$  is a measured input data item on a daily basis. The instrument used for  $R_n$  measurements is known as the Radiometer. In case if measured  $R_n$  is not available, it can be calculated from the radiation balance equation given by Doorenbos and Pruitt (1977) as:

$$R_n = R_{ns} - R_{nl} \quad (3.30)$$

where  $R_n$  = net radiation ( $\text{MJ m}^{-2} \text{ d}^{-1}$ )

$R_{ns}$  = net incoming short-wave radiation ( $\text{MJ m}^{-2} \text{ d}^{-1}$ )

$R_{nl}$  = net outgoing long-wave radiation ( $\text{MJ m}^{-2} \text{ d}^{-1}$ )

### *Estimation of $R_{ns}$*

The net short-wave radiation ( $R_{ns}$ ) can be estimated using the FAO (Smith, 1992) equation as:

$$R_{ns} = (1 - \alpha) R_s \quad (3.31)$$

where  $\alpha$  = albedo or canopy reflectance coefficient, for grass = 0.23

$R_s$  = incoming total solar radiation ( $\text{MJ m}^{-2} \text{ d}^{-1}$ )

In Eq. 3.31,  $R_s$  is a measured input climatic variable which can be measured using Pyranometer at the site under consideration. However, if Pyranometer measurements are not available,  $R_s$  can also be calculated (from daily measured sunshine hours) using the procedures as given in Smith (1992).

### *Estimation of $R_{nl}$*

$R_{nl}$  for use in Eq. 3.30 can be estimated using an equation given by Meyer (1994) as:

$$R_{nl} = \left[ \left( a \frac{R_s}{R_{so}} + b \right) \varepsilon' \sigma (T_m + 273)^4 \right] \quad (3.32)$$

where  $R_{so}$  = daily clear day (maximum) radiation ( $\text{MJ m}^{-2} \text{ d}^{-1}$ )

a, b = empirical coefficients

$\varepsilon'$  = net emissivity

$\sigma$  = Stefan-Boltzmann constant equal to  $4.896 \times 10^{-9}$  ( $\text{MJ m}^{-2} \text{ d}^{-1} \text{ }^\circ\text{K}^{-4}$ )

$T_m$  = daily mean temperature (°C)

Estimates of daily clear day (maximum) radiation ( $R_{so}$ ) for use in Eq. 3.32 can be estimated through procedures described in Section 3.2.1.

### *Estimation of 'a' and 'b' of Eq. 3.32*

For use in Eq. 3.32, FAO (Smith, 1992) recommended the general values of empirical coefficients 'a' and 'b' as 1.35 and -0.35 respectively. However, for reliable  $R_{nl}$  estimates, FAO emphasised the use of locally determined values of these coefficients. Meyer et al. (1993) derived the values of a and b coefficients as 0.92 and 0.08 respectively for Griffith (Australia). In this study, these locally derived Meyer et. al. (1993) values were used for all three sites.

### *Estimation of $\varepsilon'$*

This climatic parameter can be estimated as (Smith, 1992):

$$\varepsilon' = c + d\sqrt{e_a} \quad (3.33)$$

where c = empirical coefficient equal to 0.34  
d = empirical coefficient equal to - 0.139  
and all other symbols are as defined earlier.

This completes the procedure for estimating  $R_{nl}$ . The above procedure can give quite accurate  $R_{nl}$  estimates given the locally calibrated parameters are used (Smith, 1992; Meyer et al., 1995; and Allen, 1996). In this thesis, this aforementioned procedure for daily  $R_{nl}$  estimates (i.e. Eq. 3.30-3.33) was adopted. However, some researchers (e.g. Meyer, 1988; Jensen et al., 1990; and Amatya et al., 1995) suggested that if long-term daily measured (or reliably estimated)  $R_{nl}$  data are available, a linear relationship between  $R_{nl}$  and  $R_s$  can be established. This relationship can then be satisfactorily used for  $R_{nl}$  estimates when some of the required input data (e.g.  $T_{dew}$ ) for  $R_{nl}$  estimates is not available. According to this:

$$R_n = m R_s + c \quad (3.34)$$

where  $m, c$  = empirical regression coefficients  
and all other terms are as defined earlier.

As stated earlier, in the current study, the  $R_n$  estimates were made using the procedures as given by Eq. 3.30-3.33. However, the linear relationship given by Eq. 3.34 was also developed in this study. This is discussed in Section 3.6.2.

### *Estimation of soil heat flux density (G)*

Generally  $G$  is a measured input data on a daily basis. In case if measured  $G$  is not available, it can be estimated as (Meyer, 1994):

$$G = a(T_m - T_{av}) \quad (3.35)$$

where  $a$  = an experimentally determined coefficient ( $\text{MJ m}^{-2} \text{ } ^\circ\text{C}^{-1} \text{ d}^{-1}$ )

$T_m$  = mean daily temperature ( $^\circ\text{C}$ )

$T_{av}$  = average of the mean daily temperatures of the previous three days  
( $^\circ\text{C}$ )

Meyer (1994) estimated the coefficient  $a$  as 0.12 for Griffith (Australia). Since the magnitude of daily soil heat flux ( $G$ ) under a crop (grass) canopy over 10 to 30-day periods is relatively small, the daily values of  $G$  can be neglected for most practical purposes (Wright, 1982; Jensen et al., 1990; and Smith, 1992). Therefore, in this thesis, the daily values of  $G$  were adopted as zero.

### *Estimation of $f(u)$*

The  $f(u)$  term in Eq. 3.29, is a parameter which depends on the crop and the site, and needs to be determined experimentally under site-specific conditions (Chiew and McMahon, 1991). Meyer (1994), developed the locally calibrated  $f(u)$  (of the form  $f(u) = a + b u$ ) for use in Eq. 3.29 for Griffith (Australia) using lysimeter data. Meyer

et al. (1995) reported that with the introduction of locally calibrated  $f(u)$ , the M\_Y method provided the best estimates of  $ET_o$  on a daily basis. In the current study, the value of  $f(u)$  for Griffith was estimated using the Meyer (1994) relationship as:

$$f(u) = (17.86 + 3.80 u) \quad (3.36)$$

where all terms are as defined earlier.

As will be shown later (in Section 3.5.3), for the other two study sites (i.e., Tatura and Aspendale), the same  $f(u)$  relationship as given by Eq. 3.36 was adopted. The estimation procedure for  $a$  and  $b$  constants as given in Meyer (1994) is described below in three steps:

- (i) rearrange the M\_Y equation (i.e., Eq. 3.29) to compute the  $f(u)$  term.
- (ii) use the daily lysimeter values for  $ET_o$  and corresponding daily measured climatic data (for estimation of other parameters appearing in the M\_Y equation) to compute the  $f(u)$  value on a daily basis.
- (iii) values of  $a$  and  $b$  constants can then be obtained through simple linear regression analysis of daily  $f(u)$  data obtained from (ii) above and the corresponding measured wind speed ( $u$ ) data over the length of available record.

It is important to mention that the values of  $a$  and  $b$  constants for  $f(u)$  depend upon the method used to calculate the saturation vapour pressure ( $e_z^*$ ) in the M\_Y equation. For example, the  $e_z^*$  parameter can either be calculated as the average of saturation vapour pressure at maximum and minimum temperatures, or can be calculated at mean daily air temperature. Hence, depending upon the method used for estimation of  $e_z^*$ , the values of  $a$  and  $b$  obtained from (iii) above will be different. As stated earlier, locally calibrated  $f(u)$  was available for Griffith from Meyer (1994). In his calibration,  $e_z^*$  was estimated at mean daily air temperature.

### 3.2.8 Modified Penman-Watts&Hancock Method (W\_H)

As stated earlier (Section 2.3.4), this method is exactly the same as the M\_Y method (i.e. Eq. 3.29) except that the  $f(u)$  term used in this method was given by Watts and Hancock (1984). According to Chiew and McMahon (1991) and Hussein (1999), for reference grass the Watts and Hancock  $f(u)$  can be expressed as:

$$f(u) = 3600 N \lambda \frac{\rho \varepsilon}{P} \left\{ 2.173 \ln \left( \frac{z_w + 2.5 z_{om}}{z_{om}} \right) \right\}^{-2} (1 + 0.537 u) \quad (3.37)$$

where  $N$  = maximum number of sunshine hours

$\rho$  = air density ( $\text{kg m}^{-3}$ )

$\varepsilon$  = ratio of molecular weight of water to air and is equal to 0.622

$z_w$  = height at which wind speeds are measured, usually equal to 2 (m)

$z_{om}$  = roughness parameter for momentum (m)

and all other terms are as defined earlier (Section 3.2.2).

The parameters  $\lambda$  and  $P$  in Eq. 3.37 can be calculated as per methods described in Section 3.2.2. The estimation procedures for remaining climatic parameters of Eq. 3.37 are described below.

#### *Estimation of $N$*

This parameter can be estimated using the Stapper et al. (1986) computer software as recommended by Meyer (1994).

#### *Estimation $\rho$*

This parameter can be estimated using the equation given by Smith (1992) as:

$$\rho = \frac{3.486 P}{1.013 (T_m + 273)} \quad (3.38)$$

### ***Estimation of $z_{om}$***

According to Brutsaert (1975),  $z_{om}$  is related to the grass height ( $h_c$ ) as:

$$z_{om} = 0.123 h_c \quad (3.39)$$

where  $h_c$  is in meters.

### **3.2.9 McIlroy Method (McI)**

This is also a combination type formula, which uses the wet-bulb depression and the resistance of the air layer above the crop. This equation has been reported satisfactory for  $ET_o$  estimates on a daily basis by McIlroy and Angus (1964) and Dilley and Shepherd (1972). This equation in SI units can be expressed as:

$$ET_o = \frac{1}{\lambda} \left[ \frac{s}{s + c_{at}} (R_n - G) + h_a D_w \right] \quad (3.40)$$

where  $s/(s + c_{at})$  = wet-bulb temperature and atmospheric pressure dependent nomographic term

$h_a$  = atmospheric conductance for the air layer from surface to reference height (usually taken as 2m) ( $\text{MJ m}^{-2} \text{d}^{-1} \text{ } ^\circ\text{C}^{-1}$ )

$D_w$  = wet-bulb temperature depression ( $^\circ\text{C}$ )

and all other parameters are as defined earlier.

The estimation procedures for  $R_n$  and  $G$  were already been discussed in Section 3.2.7. The estimation procedures for remaining parameters of Eq. 3.40 are described below.

### ***Estimation of $s/(s + c_{at})$***

As stated earlier, the  $s/(s + c_{at})$  term in Eq. 3.40 depends on wet-bulb temperature and atmospheric pressure. For given wet-bulb temperature and atmospheric pressure, the

value of  $s/(s + c_{al})$  term can be obtained from the nomographs presented by Slatyer and McIlroy (1961). However, for computer based computations the values of this term can be estimated as follows.

According to Slatyer and McIlroy (1961), the  $s/(s + c_{al})$  term can be approximated using following relationship as:

$$\frac{s}{s + c_{al}} \approx \frac{S}{S + K} \quad (3.41)$$

where  $S$  = slope of saturation vapour pressure curve at mean wet-bulb temperature ( $\text{kPa } ^\circ\text{C}^{-1}$ )

$K$  = wet-bulb temperature and pressure dependent parameter ( $\text{kPa } ^\circ\text{C}^{-1}$ )

The slope of the saturation vapour pressure curve at mean daily wet-bulb temperature ( $S$ ) can be estimated using Dilley (1968) and Dilley (1995, personal communication) as:

$$S = \frac{25029.36}{(T_w + 237.3)^2} \exp\left(\frac{17.27 T_w}{T_w + 237.3}\right) \quad (3.42)$$

where  $T_w$  = mean daily wet-bulb temperature ( $^\circ\text{C}$ )

The wet-bulb temperature and atmospheric pressure dependent parameter,  $K$  ( $\text{kPa } ^\circ\text{C}^{-1}$ ) can be calculated using the Dilley (1968) equation as:

$$K = 6.60 \times 10^{-3} P (1 + 0.00115 T_w) \quad (3.43)$$

where  $P$  = atmospheric pressure ( $\text{kPa}$ ), estimated as per Section 3.2.2

For use with Eqs. 3.42 and 3.43,  $T_w$  is generally a measured input data item. However, if measured  $T_w$  is not available, it can be estimated as Jensen et al. (1990):

$$T_w = \frac{(\gamma T_d + \Delta T_{dew})}{(\Delta + \gamma)} \quad (3.43a)$$

where  $T_{\text{dew}}$  = dew point temperature ( $^{\circ}\text{C}$ )

and all other terms are as defined earlier.

It is important to note that for use in Eq. 3.43a, the  $\Delta$  parameter can be estimated using Eq. 3.14 at mean temperature estimated as  $0.5 (T_m + T_{\text{dew}})$ .

### ***Estimation of $h_a$***

In Eq. 3.40,  $h_a$  is a parameter which depends on the crop and the site, and is equivalent to the wind function term of other combination methods (e.g. Eq. 3.29; Section 3.2.7) of the form of  $h_a = (a + b u)$ . This parameter needs to be determined experimentally under site-specific conditions. Dilley and Shepherd (1972) developed the locally calibrated  $h_a$  for use in Eq. 3.40 for Aspendale (Australia) using grass lysimeter data. In the current study, the value of  $h_a$  for Aspendale was estimated using the Dilley and Shepherd (1972) relationship as:

$$h_a = (0.446 + 0.319 u) \quad (3.44)$$

where all terms are as defined earlier

As stated earlier, for each site a separate locally calibrated  $h_a$  is desired. However, as will be shown later (in Section 3.5.3), for the other two sites (i.e., Tatura and Griffith), the same  $h_a$  relationship as given by Eq. 3.44 was adopted.

### **3.2.10 Penman-Monteith Method (P\_M)**

This is also a combination type equation which includes aerodynamic and surface resistance terms, and is one of the most physically based evapotranspiration estimation methods. A comprehensive description of its derivation and applications was presented in Monteith (1965,1981). FAO (Smith, 1992) reported that the Penman-Monteith method is highly data extensive but the best method for  $ET_o$  estimates among all other existing methods. The general Penman-Monteith equation for daily  $ET_o$  estimates as given in Jensen et al. (1990) can be written as:

$$ET_o = \frac{1}{\lambda} \left[ \frac{\Delta(R_n - G) + \frac{\{0.622 K_1 \lambda \rho \gamma (e_z^* - e_d)\}}{P r_a}}{\Delta + \gamma \left(1 + \frac{r_c}{r_a}\right)} \right] \quad (3.45)$$

where  $ET_o$  = the grass reference evapotranspiration ( $\text{mm d}^{-1}$ )

$K_1$  = a dimension coefficient

$\rho$  = atmospheric density ( $\text{kg m}^{-3}$ )

$r_a$  = aerodynamic resistance ( $\text{s m}^{-1}$ )

$r_c$  = canopy resistance ( $\text{s m}^{-1}$ )

and all other terms are as defined earlier

It is important to mention that the  $e_z^*$  term in above Eq. 3.45 is calculated as the average of saturation vapour pressures estimated at maximum and minimum temperatures. The parameters  $\lambda$ ,  $\Delta$ ,  $R_n$ ,  $G$ ,  $\gamma$ ,  $e_z^*$ ,  $e_d$  and  $P$  of Eq. 3.45 can be calculated as per methods described in Sections 3.2.2 and 3.2.7. The estimation procedures for remaining climatic parameters of Eq. 3.45 are given below.

#### ***Estimation of $(0.622 K_1 \lambda \rho) / P$***

The value of the term  $(0.622 K_1 \lambda \rho) / P$  in Eq. 3.45 can be estimated from a generalised relationship as a function of mean daily temperature as presented by Jensen et al. (1990) as:

$$(0.622 K_1 \lambda \rho) / P = 1710 - 6.85 T_m \quad (3.46)$$

where all parameters are as defined earlier.

#### ***Estimation of $r_a$***

The aerodynamic resistance term ( $r_a$ ) in Eq. 3.45 is approximated by Garratt and Hicks (1973) relationship as given in Allen et al. (1989):

$$r_a = \frac{\left[ \ln \left( \frac{z_w - d}{z_{om}} \right) \right] \left[ \ln \left( \frac{z_h - d}{z_{oh}} \right) \right]}{k^2 u_z} \quad (3.47)$$

- where  $r_a$  = aerodynamic resistance ( $s\ m^{-1}$ )  
 $z_w$  = height at which wind speeds are measured (m)  
 $d$  = zero plane displacement of wind profile (m)  
 $z_{om}$  = roughness parameter for momentum (m)  
 $z_h$  = height at which humidity air temperatures are measured (m)  
 $z_{oh}$  = roughness parameter for heat and water vapour (m)  
 $k$  = Von Karman's constant which is equal to 0.41  
 $u_z$  = wind speed at height  $z$  ( $m\ s^{-1}$ )

For the Penman-Monteith method, the standard value of  $z$  is equal to 2 meters. Brutsaert (1975) reported that  $z_{om}$  is related to the mean height,  $h_c$  of a (grass) canopy as follows;

$$z_{om} = 0.123 h_c \quad (3.48)$$

where  $h_c$  is in meters.

Values of  $z_{oh}$  can be approximated by Brutsaert (1979,1982) as:

$$z_{oh} = 0.1 z_{om} \quad (3.49)$$

Several researchers (e.g. Monteith, 1981; Brutsaert, 1982; and Plate, 1971), as quoted in Jensen et al. (1990) have recommended the estimation of the zero plane displacement height ( $d$ ) using the relationship as follows:

$$d = 0.67 h_c \quad (3.50)$$

### Estimation of $r_c$

The average daily values of canopy resistance ( $r_c$ ) for well-watered, actively growing reference grass can be approximated using a relationship relating the average minimum day time value of stomatal resistance for a single leaf of grass and the leaf area index (LAI) given in Allen et al. (1989) as:

$$r_c = \frac{100.0}{0.5 LAI} \quad (3.51)$$

It is important to mention that in Eq. 3.51, the value 100.0 in the numerator represents an average leaf resistance ( $s\ m^{-1}$ ) for 24-hour duration, and the 0.5 LAI in the denominator indicates that generally only the upper half of a dense grass cover may be active in the evapotranspiration and energy exchange process.

LAI for a reference grass less than 0.15m in height can be approximated using the procedure of Allen et al. (1989) as follows:

$$LAI = 24 h_c \quad (3.52)$$

where  $h_c$  is in meters.

Allen et al. (1989) suggested a grass height of 0.12m and weather measurement height ( $z$ ) of 2m, for  $ET_o$  estimates from the Penman-Monteith equation. Based on this suggestion, Eq. 3.52 when combined with Eqs. 3.47 through 3.51 for  $r_a$  and  $r_c$  values with some simplifications can be written as (Allen et al., 1989):

$$ET_o = \frac{1}{\lambda} \left[ \frac{\Delta(R_n - G) + \left\{ u_z \gamma \left( \frac{2830}{T_m + 273} - 2.13 \right) (e_z^* - e_d) \right\}}{\Delta + \gamma(1 + 0.334u_z)} \right] \quad (3.53)$$

where all symbols are as defined earlier.

Later on, in order to standardise the Penman-Monteith equation for global use, the FAO (Smith, 1992) also recommended to adopt a grass height of 0.12m and weather measurement height (z) of 2m for use in Eq. 3.53. The FAO, in an attempt to further improve  $ET_o$  estimates, derived the radiation and aerodynamic components separately for use in the Penman-Monteith combination equation. Followed by the FAO recommendations, combining these components in the Penman-Monteith equation gives the following expression;

$$ET_o = \left[ \frac{0.408\Delta(R_n - G) + \left\{ u_z \gamma \left( \frac{900}{T + 273} \right) (e_z^* - e_d) \right\}}{\Delta + \gamma(1 + 0.34u_z)} \right] \quad (3.54)$$

Equation 3.54 is the improved version of Eq. 3.53 for daily  $ET_o$  calculations, and has been recommended by the International Commission on Irrigation and Drainage, ICID (Allen et al., 1994b) as the standard  $ET_o$  equation to calibrate other empirical  $ET_o$  methods where measured  $ET_o$  data are not available. In the current study described in this thesis, Eq. 3.54 has been adopted as the standardised Penman-Monteith (P\_M) method for  $ET_o$  estimates.

### 3.3 STUDY SITES

The  $ET_o$  estimation methods selected for this study were evaluated for their relative performance (in estimating  $ET_o$  values on a daily basis) using three study sites. One of the purposes of this study was to evaluate the performance of these methods for use in the Goulburn-Murray Irrigation Area (GMIA) in Victoria (Australia). First site selected was the site in Tatura, in the Central GIA. A site in Griffith (NSW, Australia) was also included in the study, since a climatic similarity exists between Griffith and the Northern area of Victoria which includes the GMIA (Meyer, 1994; personal communication with Angus, 1995). This site was primarily considered to make the best use of locally derived/calibrated parameters resulting from  $ET_o$  research carried out at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) lysimeter site by Meyer (1988,1994) and Meyer et al. (1993,1995). Both Tatura and Griffith sites represent semi-arid inland areas of Australia.

In order to compare the relative performance of  $ET_o$  estimation methods under completely different climatic conditions, the Aspendale (Southern Victoria, Australia) site was also included in the study. Aspendale is located near the Port Phillip Bay of Australia, and hence its climate is alternately influenced by winds from a dry land mass and the bay. Therefore, Aspendale has a different climatic pattern as compared to the aforementioned Tatura and Griffith sites. These three study sites are shown in Figure 3.1. The geographical descriptions of these study sites are given in Table 3.2. As can be observed from Table 3.2, the study sites cover a latitude range of  $34^\circ$  to  $38^\circ$ .

### 3.4 Data Collection

Normal climatic data requirements for estimating daily  $ET_o$  using the combination methods, include air temperature (such as maximum, minimum, dew point, wet bulb and dry bulb), solar radiation, relative humidity and wind speed measurements at the site under consideration. Estimates of  $ET_o$  are no better than the weather data upon which they are based. Therefore, an assessment of the weather data integrity and quality needs to be calculated if they are not available from reliable (data collection) agencies (Allen, 1996). The required data of the aforementioned three study sites were collected from publications, personal communications with investigators working at those locations, and the Bureau of Meteorology (BOM), Australia.

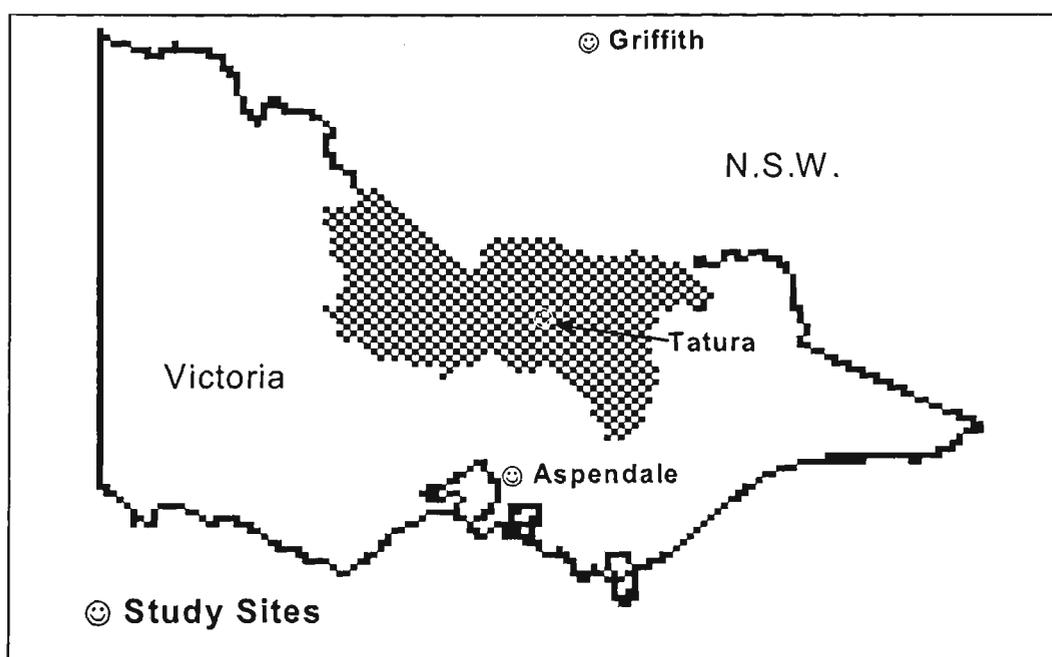


Figure 3.1 Study Sites Selected for Analysis of  $ET_o$  Methods

Table 3.2 Geographical Details of ET<sub>o</sub> Study Sites

Station	Southern Latitude	Eastern Longitude	Altitude (m)
Griffith	34.30°	146.05°	130.0
Tatura	36.44°	145.23°	101.3
Aspendale	38.00°	145.08°	3.0

In general, for evaluation/calibration of ET<sub>o</sub> methods, the lysimeter reference evapotranspiration measurements are used. However, in practice the lysimeter data are not generally available for most sites. In such situations, the use of an ET<sub>o</sub> method already calibrated (hereafter termed as the *base method*) against lysimeter data at some nearby climatically similar sites can also produce data for calibration (personal communication with Angus, 1995). The data collection for each of the three study sites is described as below.

### Griffith

For Griffith, the modified Penman (M<sub>P</sub>) method was locally calibrated against lysimeter measurements by Meyer (1994) and Meyer et al. (1995). However, the lysimeter data were not available to the candidate at the time of this study. Therefore, for Griffith the M<sub>P</sub> method calibrated by Meyer (1994) and Meyer et al. (1995), hereafter referred to as the modified Penman<sub>Meyer</sub> (M<sub>Y</sub>) method (Sections 2.3.4 and 3.2.7) was adopted as the *base method* for evaluation/calibration of other ET<sub>o</sub> methods. For the purpose of evaluation/calibration of other ET<sub>o</sub> methods at Griffith, the required daily climatic data were collected from the CSIRO Griffith weather station. The data collection was done for the available period of 1990-95 (six) years. R<sub>n</sub> was estimated using Eqs. 3.30-3.33 as given in Section 3.2.7. It is important to

note that for use with the McI method, measured wet-bulb temperature ( $T_w$ ) data at Griffith were not available. Hence, it was estimated using Eq. 3.43a.

### Tatura

No lysimeter study has been done in Tatura, and hence, there was no lysimeter data available for this site. However, as stated earlier (Section 3.3), there exists a climatic similarity between Griffith and Tatura. Keeping in view this similarity aspect, the  $M_Y$  method was adopted for Tatura as the base method for evaluation/calibration of other  $ET_o$  methods, since it was used for Griffith. It is important to mention that for use in the  $M_Y$  method, various climatic parameters (Section 3.2.7) locally developed for Griffith conditions, were also used for Tatura site.

For evaluation of other  $ET_o$  methods at Tatura, the required daily climatic data for 1990-92 were collected from the Tatura office of the Institute of Sustainable Irrigated Agriculture (ISIA). As stated earlier, the net radiation ( $R_n$ ) is an important input climatic data item for combination methods. At ISIA weather station,  $R_n$  measurements were not routinely made. However, the daily measured  $R_s$  data were available, hence  $R_n$  was estimated using Eqs. 3.30-3.33 as given in Section 3.2.7. It is important to mention that at this site many climatic data items were missing on many days. Therefore, in order to evaluate/calibrate all ten  $ET_o$  estimation methods selected in this study, only the days with complete data set were considered.

### Aspendale

At Aspendale, a lysimeter study was carried out by McIlroy and Angus (1963,1964). The daily lysimeter data available for this site were obtained from Angus (Personal communication, 1995) for the available period of six months, starting from January, 1965 to March, 1965. The  $R_n$  measurements corresponding to the lysimeter data were also available. The other required climatic data for this site were collected from the Bureau of Meteorology (BOM) and Melbourne office of Australian Archives. However, the climatic data were missing on some days. Hence, the days with incomplete data set were not included in the analysis.

The climatic data record together with its sources and the *base methods* used for evaluation of various  $ET_0$  methods at the three study sites are presented in Table 3.3.

### 3.5 METHODOLOGY FOR EVALUATION AND CALIBRATION OF $ET_0$ METHODS

As stated earlier (Section 3.1), irrigation scheduling requires  $ET_0$  estimates on a daily basis. Since the calculation of  $ET_0$  using monthly averages of weather data do not adequately represent daily  $ET_0$ , the estimation of daily  $ET_0$  using daily climatic data is required (Allen et al., 1989; and Jensen et al., 1990). Keeping in view of this aspect, the ten  $ET_0$  estimation methods that were described in Section 3.2 were primarily evaluated in this study in terms of their ability to estimate daily  $ET_0$  using daily climatic data.

Table 3.3 Description of Climatic Data used for Evaluation of  $ET_0$  Methods

Site	Method Used for Evaluation/Calibration	Data Used for Analysis	Principal References for Climatic Data & Parameters
Griffith	Modified Penman-Meyer (M_Y) Method	Jan, 1990 – Dec, 1995	Meyer (1988,1994) Meyer et al. (1993,1995) Meyer (1995, pers. comn.) Smith (1995, pers. comn.)
Tatura	Modified Penman-Meyer (M_Y) Method	Dec, 1990 – April, 1992	BOM-Melbourne; Prendergast and Bush (1995, pers. comn.); Wilson (1995, pers. comn.)
Aspendale	Lysimeter	Jan, 1965 – Mar, 1965	BOM and Australian Archives, Melbourne Dilley and Shepherd (1972); Angus and Dilley (1995, pers. comn.)

BOM-->Bureau of Meteorology

### 3.5.1 Evaluation of $ET_0$ Methods

Generally, the desirable characteristics sought in evaluating an  $ET_0$  estimation method are (Jensen et al., 1990) :

- accuracy in estimating peak  $ET_0$ .
- accuracy in estimating seasonal  $ET_0$ .
- ability to accurately estimate  $ET_0$  in a variety of climates and locations

In addition to the above criteria, another desirable attribute is that if an  $ET_0$  estimation method overestimates or underestimates  $ET_0$  within a specific climate, then the estimation error should be systematic and correctable using simple linear adjustments.

It is important to mention that in above criteria, the accuracy in estimating peak month  $ET_0$  has explicitly been considered, in addition to seasonal  $ET_0$ . The reason for this is that some  $ET_0$  methods have been observed to give  $ET_0$  predictions during the peak month which were significantly overestimated or underestimated as compared to the overall seasonal predictions (Allen et al., 1989).

Standard error of estimates (SEE) is commonly used to describe the goodness of fit between two variables X and Y (e.g. lysimeter or *base method*  $ET_0$  data and the data estimated from the  $ET_0$  method). Hence, SEE can be used to gauge the accuracy and consistency of  $ET_0$  methods in predicting daily  $ET_0$  estimates. This statistical parameter can also be used as the main parameter for ranking various  $ET_0$  methods that are in good agreement with the lysimeter (or base method) values. The parameters of slope ( $m$ ), intercept ( $c$ ) and coefficient of correlation ( $r$ ) of linear regression (as given later in Eq. 3.56) of the variables X and Y can also help to examine the performance of an  $ET_0$  estimation method at the site under consideration. It is important to note that SEE gives an indication of the closeness of the data points to the 1:1 line in the X-Y plot, where as  $r$  provides an indication of the closeness of the data points to the line of best fit. Therefore, the best method is the one with  $c$  value closest to zero,  $m$  value closest to 1.0, the smallest SEE (ideally close to zero),

and the highest  $r$  (Parmele and McGuinness, 1974; Allen et al., 1989; and Amatya et al., 1995).

With regards to the correlation coefficient ( $r$ ), Jensen et al. (1990) revealed that the correlation coefficient is not always a good indicator of accuracy of an  $ET_0$  estimation method. The reason they reported was that higher correlation coefficients generally are obtained as the range of data values increases. Hence, if the data set used in regression analysis has a small range of daily  $ET_0$  estimates (e.g.  $<4 \text{ mm d}^{-1}$ ), then the resulting correlation coefficient would be low. This is why they preferred the use of SEE to the correlation coefficient for evaluation of various  $ET_0$  methods. Since the SEE based evaluation approach has been widely used in the irrigation profession (e.g. Allen et al., 1989; Jensen et al., 1990; Smith, 1992; and Hussein, 1999), it has been adopted in the current study.

The standard error of estimates (mm/day), between the lysimeter (or base method) values and the  $ET_0$  method estimates can be calculated according to the equation:

$$SEE = \sqrt{\frac{\sum_{i=1}^n (Y_i - X_i)^2}{n - 1}} \quad (3.55)$$

where  $Y_i$  = the lysimeter (or base method)  $ET_0$  on  $i^{\text{th}}$  day (mm/day)  
 $X_i$  = the corresponding  $ET_0$  method estimate of  $ET_0$  on the  $i^{\text{th}}$  day  
 $n$  = the total number of days

The SEE gives an indication how well an  $ET_0$  method has compared with the lysimeter (or base method) measurements over the specified (e.g. peak month or entire season) length of record at the site under question. In addition, the SEE values also indicate the expected performance of an  $ET_0$  estimation method when used directly “off the shelf” (i.e. used without any adjustment). If the distribution of errors (or differences) between lysimeter (or base method) measurements and the  $ET_0$  method estimates follows a normal distribution, then the SEE represents the maximum error in  $\text{mm d}^{-1}$  for 68% percent of all estimates by that method.

Since the SEE indicates the goodness of fit of an  $ET_o$  method estimates and the lysimeter (or base method) measurements, it can be effectively used as the main parameter for ranking of various  $ET_o$  estimation methods at the site under question (Jensen et al., 1990). The procedure for ranking of various  $ET_o$  estimation methods based on the SEE parameter is detailed in Section 3.5.2.

### 3.5.2 Criteria for Ranking of $ET_o$ Methods

As stated earlier (Section 3.5.1), the SEE parameter can be effectively used as the basis for ranking of various  $ET_o$  estimation methods. Since the accuracy in estimating both peak month  $ET_o$  (e.g. in this study the January month) and seasonal  $ET_o$  (i.e. all months) are very important in selecting an  $ET_o$  estimation method, the weighted SEE is used for ranking purposes. In order to compute the weighted SEE, the following two types of SEE values are required (Jensen et al., 1990):

- (i) the SEE of unadjusted  $ET_o$  method estimates versus lysimeter (or base method) measurements, hereafter referred to as  $SEE_U$ .
- (ii) the SEE of calibrated  $ET_o$  method estimates (Section 3.5.3) versus lysimeter (or base method) measurements, hereafter referred to as  $SEE_A$ .

The use of above two SEEs provides information on both accuracy of unadjusted  $ET_o$  estimates and the ease with which an  $ET_o$  estimation method can be adjusted or corrected with a simple coefficient to fit local conditions. For both peak month (i.e. January) and the entire season, these two SEEs (i.e.  $SEE_U$  and  $SEE_A$ ) can be calculated using Eq. 3.55.

As per Jensen et al. (1990), the SEEs were weighted in this study by weighing seasonal values 70% and peak month values 30%. Within each of these two groupings, two-third (67%) weight was placed on the unadjusted SEE and one-third (33%) weight was placed on the SEE of calibrated estimates. Thus, the  $ET_o$  method which had the lowest weighted SEE ( $SEE_w$ ) was ranked first for its relative accuracy among the other methods at the site under question. It is worth mentioning that in this

thesis the terms *seasonal*  $ET_0$  and *all months*  $ET_0$  are interchangeably used to refer to the same thing.

### 3.5.3 Procedure Adopted for Calibration of $ET_0$ Methods

In order to achieve reliable  $ET_0$  estimates under site-specific conditions, local calibration of various  $ET_0$  methods is essential. As stated earlier, in this study either lysimeter (or base method) data were used to calibrate different  $ET_0$  estimation methods. The calibration bases for each of the three study sites are listed in Table 3.3. The justification for using M\_Y method as the base method for Griffith and Tatura sites is explained in Section 3.5.1. The calibration techniques that can be used for various  $ET_0$  estimation methods selected for this study are explained below. Not all calibration techniques described below have been used in this study.

#### *Modified Penman-Meyer (M\_Y) Combination Method*

In the modified Penman-Meyer (M\_Y) combination method, the wind function  $f(u)$  is the basic calibration parameter. Hence, the M\_Y method is usually calibrated by evaluating the constants  $a$  and  $b$  in the  $f(u)$  term given in Eqs. 3.29 and 3.36 (Jensen et al., 1990). The estimation procedure for  $a$  and  $b$  constants is described in Section 3.2.7. As described in Section 3.2.7, the values of  $a$  and  $b$  constants in  $f(u)$  differ depending upon the method used to calculate the saturation vapour pressure ( $e_z^*$ ), whether it is calculated as the average of saturation vapour pressures at maximum and minimum temperatures, or at mean daily air temperature. Hence, for locally derived  $a$  and  $b$  values of  $f(u)$ , the method of estimating  $e_z^*$  also needs to be specified.

As stated earlier (Section 3.2.7), locally calibrated  $f(u)$  was available for Griffith, from Meyer (1994). For the other two sites (i.e. Aspendale and Tatura), values of  $a$  and  $b$  can be developed from the procedure given in Section 3.2.7.

#### *McIlroy (McI) Combination Method*

Like the M\_Y method, the McIlroy combination method can be calibrated by computing the constants  $a$  and  $b$  in the atmospheric conductance ( $h_a$ ) term of Eq. 3.44.

The estimation procedure for  $a$  and  $b$  constants in  $h_a$  is same as for  $a$  and  $b$  constants of  $f(u)$  described in Section 3.2.7. As stated in Section 3.2.9, locally calibrated  $h_a$  was available for Aspendale in Dilley and Shepherd (1972). For the other two sites (i.e. Tatura and Griffith), values of  $a$  and  $b$  can be derived from the procedure described in Section 3.2.7.

### ***Improved Hargreaves (IHA) Method***

The IHA method can be calibrated by computing the empirical constant  $c$  of Eq. 3.13. The estimation procedure for this constant  $c$  is explained in Section 3.2.2.

### ***Alternative Approach to Estimation of Empirical Coefficients in M\_Y, McI and IHG Methods***

It is important to appreciate that instead of evaluating  $a$  and  $b$  coefficients in combination (e.g. M\_Y and McI) methods, and  $c$  coefficient in the IHA method, an alternative approach which can also be used is to adjust the entire equation with the calibration coefficients (Jensen et al., 1990). These calibration coefficients can be obtained through the linear regression analysis of lysimeter (or base method) and the  $ET_0$  method data sets.

### ***Other Methods***

Among the remaining five non-combination  $ET_0$  methods (i.e. HAR, RIT, RAD, PEV and SEV) and the two combination (i.e. W\_H and P\_M) methods selected for the current study, no method contains empirical terms such as above  $a$ ,  $b$  or  $c$  values described in M\_Y, McI and IHA methods. Therefore, the only option left for calibration of these seven methods is the second approach (i.e. to adjust the entire equation with the calibration coefficients).

### ***Final Procedure Adopted for Calibration of All Ten $ET_0$ Methods***

To be consistent with all ten  $ET_0$  methods, the second approach was adopted in the current study. Therefore, for use with the M\_Y method, the  $f(u)$  developed by Meyer (1994) for Griffith (i.e. Eq. 3.36) was used for all three sites. Similarly, for use with

the McI method the  $h_a$  developed by Dilley and Shepherd (1972) for Aspendale (i.e. Eq. 3.44) was used for all three sites. Although  $f(u)$  and  $h_a$  were available only for Griffith and Aspendale respectively, these values had to be used for the other sites since they were the best available. Any errors resulting because of this will be adjusted through calibration.

It is important to mention that in order to get the calibration coefficients from the regression analysis, lysimeter (or base method) data are taken as the dependent variable and  $ET_o$  method data are taken as the independent variable. In this case the linear regression equation can be written as:

$$ET_o(\text{lysimeter}) = m ET_o(\text{method}) + c \quad (3.56)$$

where  $m$  = slope of the regression line  
 $c$  = intercept of the regression line

The  $m$  and  $c$  parameters can be used as the adjustment coefficients for calibration of an  $ET_o$  estimation method. A good agreement between  $ET_o$  estimates using an  $ET_o$  method and those of lysimeter (or base method) measurements is clearly indicated by the values of these parameters. A value of  $m$  close to unity and the zero intercept indicate a high degree of correlation between the two  $ET_o$  data sets. The correlation coefficient ( $r$ ) indicates the degree of association between the two variables (i.e. lysimeter or base method measurements and the  $ET_o$  method estimates). The  $r$  value always ranges between 0 and 1. A value of  $r$  close to unity indicates a high degree of association between the  $ET_o$  method estimates and the lysimeter (or base method) values. A zero value of  $r$  indicates no correlation at all between the two data sets.

It is important to mention that for calibration purposes, many researchers (e.g. Allen et al., 1989; Jensen et al., 1990; Smith, 1992; Chiew et al., 1995; and Hussein, 1999) preferred the use of linear regression line forced through the origin to the line with an intercept. The reason for this was that the value of intercept  $c$  was not (statistically) significantly different from zero for daily  $ET_o$  estimates. Also, any consistent under- or over-prediction by the estimating method that might appear in the constant of the

regression line is offset (Katul et al., 1992) by forcing through the origin. This approach was followed in this study for calibration of other  $ET_o$  methods. Hence, the linear regression equation adopted in the current study was as follows:

$$ET_o(\text{lysimeter}) = m ET_o(\text{method}) \quad (3.57)$$

where all terms are as defined earlier.

The regression parameter,  $m$  was used to calibrate (or adjust) the  $ET_o$  method estimates. After the adjustment through calibration, the SEE were calculated using Eq. 3.55 for each of the  $ET_o$  methods to gauge the accuracy and consistency of the calibrated  $ET_o$  method for the site under consideration.

#### 3.5.4 $ET_o$ Estimates for Planning Purposes

It is important to mention that in many circumstances (e.g. for planning purposes), the farm manager likes to know the approximate total irrigation requirement (IR) of a certain crop of his/her farm before the actual season starts. In this thesis, IR computed before the start of an irrigation season is referred to as the *pre-season irrigation requirement*. The pre-season IR can help the farmer to decide how much area to be allocated for a specific crop among other crops to maximise his/her farm returns.

As will be shown later (in Section C.6), for pre-season IR the daily  $ET_o$  data are required before the start of an irrigation season. It is important to mention that in reality before the start of an irrigation season no information about the climatic variables (which are used for estimation of daily  $ET_o$ ) is available. Therefore, for pre-season IR estimation the only choice left is to use the long-term mean values of daily  $ET_o$  (Fereres et al., 1981; and Villalobos and Fereres, 1987,1989). The long-term mean values of daily  $ET_o$  (hereafter referred to as *mean daily  $ET_o$* ) can be estimated from historical daily  $ET_o$  data by simple average of each day over the number of available years. However, for use with computer based IR estimation programs, the mean daily  $ET_o$  needs to be translated into a mathematical equation. This can be done

using some commercially available computer software (e.g. Sigma Plot). This aspect is also discussed in Section 3.6.4.

It is also important to mention that in some irrigation systems (e.g. GMIA of Victoria), the predominant practice for IR estimates is to use the daily Class-A Pan evaporation measurements multiplied by locally derived empirical crop factors (Heslop et al., 1990; Heslop 1991; and Erlanger et al., 1992). This practice is generally used as an alternative to the FAO-24 (Doorenbos and Pruitt, 1977) practice of  $ET_o$  estimates multiplied by crop coefficients ( $K_c$ ) for IR estimation. Hence, in this case for pre-season IR estimates, instead of mean daily  $ET_o$ , the mean daily class-A pan evaporation would be required. The mean daily pan evaporation can be estimated using the same procedures as for mean daily  $ET_o$  estimates described in previous paragraph. This aspect is also discussed in Section 3.6.4.

### 3.6 RESULTS AND DISCUSSION

As shown in Table 3.1, the clear day solar radiation ( $R_{so}$ ) and net radiation ( $R_n$ ) are important input climatic data items which are required by all combination methods, and specifically  $R_{so}$  is also required by HAR and IHA methods.  $R_{so}$  and  $R_n$  can be estimated as per methods given in Sections 3.2.1 and 3.2.7 respectively. With regards to  $R_n$  estimates as stated earlier (Section 3.2.7), some researchers (e.g. Meyer, 1988; and Jensen et al., 1990) suggested to establish a linear relationship between  $R_n$  and  $R_s$  as given by Eq. 3.34. This relationship can be used if some input data items required for  $R_n$  estimates are not available. In this section, the results of analysis of  $R_{so}$  and  $R_n$  versus  $R_s$  relationship are discussed first. After this, the evaluation/calibration of ten  $ET_o$  estimation methods selected for this study are discussed. As stated earlier in Section 3.5.4, for pre-season planning mean daily  $ET_o$  estimates are required. The mean daily  $ET_o$  estimates are discussed after evaluation/calibration of ten  $ET_o$  methods. Finally, a summary of these results is presented at the end of this section. It is important to note that in this section, for discussion of various analysis at the three study sites the general order adopted is Aspendale, Tatura and Griffith, unless specified for certain reasons.

### 3.6.1 Clear Day (maximum) Solar Radiation ( $R_{so}$ ) Estimates

As discussed earlier (in Section 3.2.1), in the absence of long-term daily measured  $R_s$  data the equations of Angus (1980) (i.e. Eq. 3.6 to 3.12) can be used to obtain  $R_{so}$  on the 22<sup>nd</sup> day of each calendar month. The 13  $R_{so}$  data values (i.e. one for each month and an additional value for 22<sup>nd</sup> Dec to complete 366 days) obtained from these equations can then be used to construct an  $R_{so}$  envelope curve for the site under consideration. This envelope curve can subsequently be used to obtain  $R_{so}$  values for any day of the year at that site. However, for computer based calculations the envelope curve needs to be fitted with a mathematical equation. As stated earlier in Section 3.2.1, a polynomial equation for  $R_{so}$  envelope curve was developed for Griffith by Meyer (1994) using measured daily  $R_s$  data. Hence, for this part of the study, the discussion is started with the Griffith site in detail as below.

In order to evaluate the ability of the equations of Angus (1980) to provide an  $R_{so}$  envelope curve, these equations were checked against the above stated Meyer (1994) polynomial equation at Griffith. For this purpose, the 13  $R_{so}$  data values obtained from the Angus equations were plotted on Y-axis against the corresponding Angus\_day (i.e. 22<sup>nd</sup> Dec as 1, 22<sup>nd</sup> Jan as 31, 22<sup>nd</sup> Feb as 62 etc., and finally 22<sup>nd</sup> Dec of the following year as 366). The graphical representation of this  $R_{so}$  data set is shown in Figure 3.2(a). As can be seen from this figure, this data set followed a curvilinear pattern. The cubic spline method (Wold, 1974; Press et al., 1988), was then applied to interpolate the intermediate points corresponding to each day of the year. The cubic spline interpolated  $R_{so}$  values are also shown in Figure 3.2(a). As can be observed from this figure, the cubic spline method can successfully provide the  $R_{so}$  for any day of the year at Griffith.

#### *Comparison of Angus (1980) and Stapper et al. (1986) $R_{so}$ Estimates with Meyer (1994) Estimates*

In order to check the accuracy of aforementioned envelope curve resulting from the interpolation of Angus (1980)  $R_{so}$  data points, the cubic spline interpolated  $R_{so}$  values were compared with that of Meyer (1994) polynomial for Griffith. As stated in Section 3.2.1, Meyer (1994) recommended that if long-term daily measured  $R_s$  data

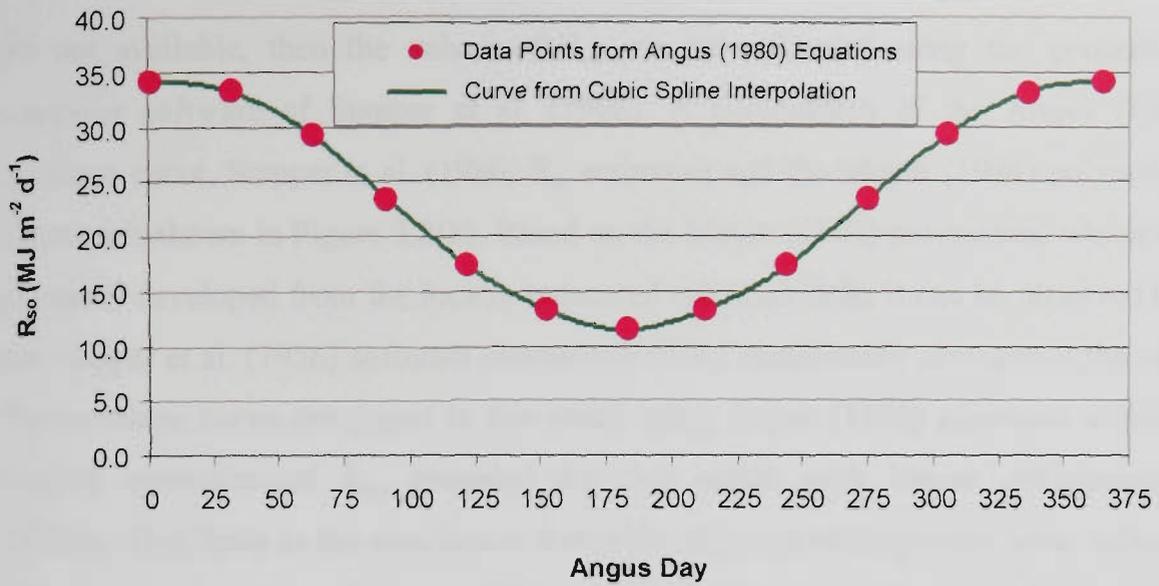


Figure 3.2(a)  $R_{so}$  Envelope Estimates from Angus (1980) Equations and Interpolation by Cubic Spline Method at Griffith

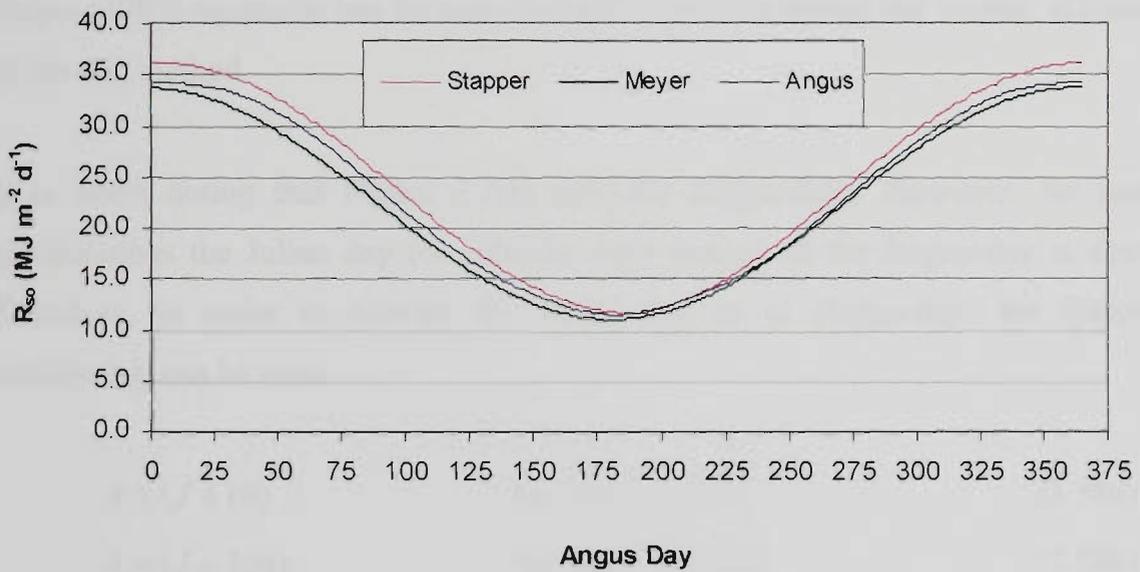


Figure 3.2(b)  $R_{so}$  Envelop Estimates at Griffith

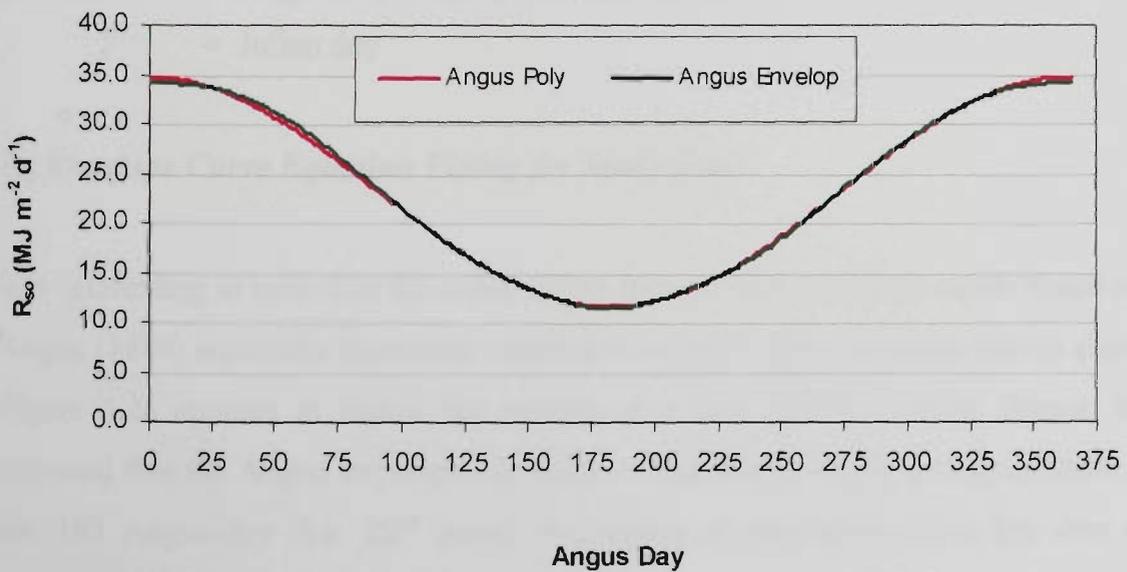


Figure 3.2(c) Angus  $R_{so}$  Polynomial-fit and Angus  $R_{so}$  Cubic Spline Interpolated Envelop Curve

are not available, then the values of  $R_{so}$  can be estimated using the generalised computer software of Stapper et al. (1986). A comparison of the Angus (1980) envelope curve, Stapper et al. (1986)  $R_{so}$  estimates and the Meyer (1994) polynomial equation is shown in Figure 3.2(b). Based on the Meyer (1994) polynomial which was primarily developed from the locally measured radiation data, it can be observed that the Stapper et al. (1986) software overestimated  $R_{so}$  consistently throughout the year. The envelope curve developed in this study using Angus (1980) equations although slightly overestimated  $R_{so}$ , provided the best match with Meyer polynomial at Griffith. This leads to the conclusion that in the absence of long-term solar radiation ( $R_s$ ) data, the equations of Angus (1980) can be preferred over the use of Stapper et al. (1986) software to construct the  $R_{so}$  envelope curve. The slight over-estimation by Angus (1980) equations can be automatically corrected during the overall calibration of the  $ET_o$  method.

It is worth noting that Figure 3.2(a) uses the Angus-days. However, for routine computations the Julian day (or calendar day) instead of the Angus-day is desired. Therefore, in order to convert the Julian day in to Angus-day, the following relationship can be used

$$A = (J + 10) \quad \text{for } 1 \leq J \leq 356 \quad (3.58a)$$

$$A = (J - 356) \quad \text{for } 356 < J \leq 366 \quad (3.58b)$$

where  $A$  = Angus-day ranging from 1 to 366

$J$  = Julian day

### ***$R_{so}$ Envelope Curve Equation Fitting for Study Sites***

It is interesting to note that the cubic spline interpolated envelope curve based on the Angus (1980) equations (hereafter referred to as the Angus envelope curve) shown in Figure 3.2a appears to follow the pattern of a sine function curve. Hence, it was assumed that the Angus envelope curve was a sine curve which was symmetric about the 183 Angus-day (i.e. 22<sup>nd</sup> June). According to this assumption the sine curve equation can be expressed as:

$$R_{so} = a + b \cos D \quad (3.59)$$

$$\text{and } D = 2\pi \left( \frac{A}{366} \right) \quad (3.60)$$

where  $R_{so}$  = clear day solar radiation from the Angus envelope curve ( $\text{MJ m}^{-2} \text{d}^{-1}$ )

a, b = empirical constants

A = Angus-day

$R_{so}$  values were computed at each study site (i.e. Griffith, Tatura and Aspendale) using the Angus (1980) equations and the cubic spline method. The input for Angus equations was the latitude of each study site. These values were then regressed against “ $\cos D$ ”. The fitted equations for the  $R_{so}$  envelope curve at three study sites are given as below.

**For Griffith:**

$$R_{so} = 23.22 + 11.55 \cos D \quad (r^2 = 0.99) \quad (3.62)$$

**For Tatura:**

$$R_{so} = 22.50 + 11.96 \cos D \quad (r^2 = 0.99) \quad (3.63)$$

**For Aspendale:**

$$R_{so} = 21.90 + 12.30 \cos D \quad (r^2 = 0.99) \quad (3.64)$$

Figure 3.2c shows a comparison of  $R_{so}$  values using polynomial Eq. 3.62 (hereafter referred to as the Angus Poly) and the cubic spline interpolated values (i.e. Angus envelope) for Griffith. It can be seen from this figure that the fitted curve follows the Angus envelope quite satisfactorily, confirming that the regression method adopted to fit the envelope curve with the sine curve was quite successful. The  $R_{so}$  envelope curves for three sites are shown in Figure 3.3 which use Eqs. 3.62 to 3.64. These  $R_{so}$

equations were used in this chapter for comparison of  $ET_0$  methods, when  $R_{s0}$  was required.

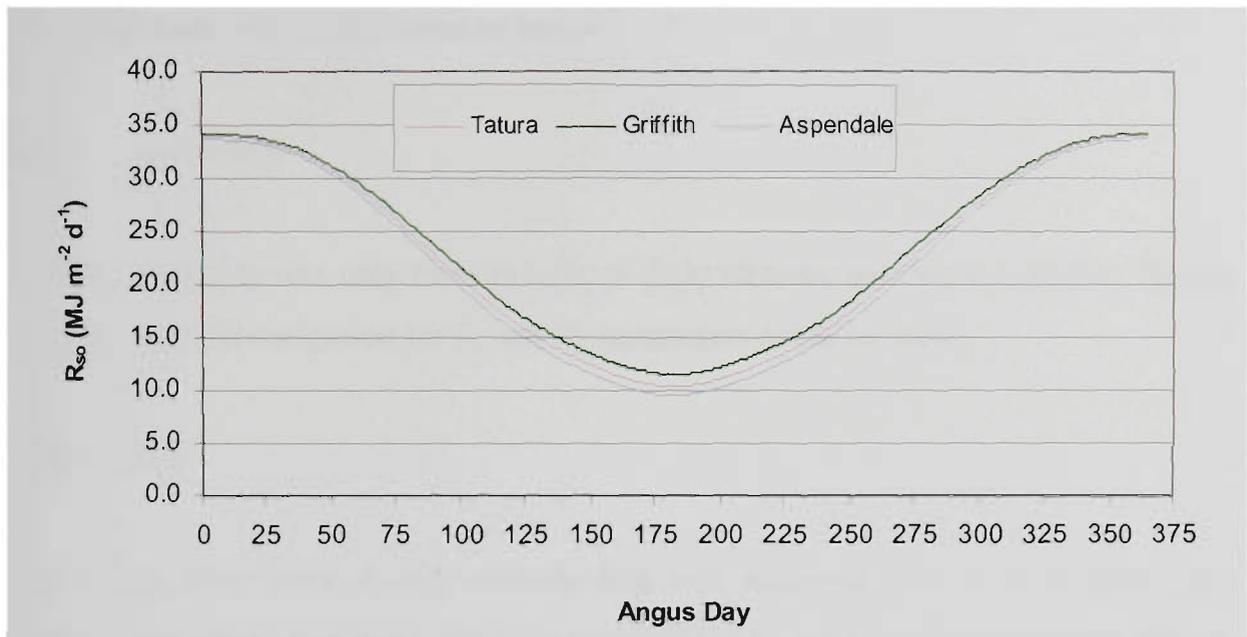


Figure 3.3 Angus  $R_{s0}$  Envelope Curve Fittings at Various Sites

It is important to note that the aforementioned  $R_{s0}$  envelope curve fitting technique requires a separate equation to be developed for each location. Although, Meyer et al. (1995) suggested that an  $R_{s0}$  envelope curve developed for a certain site can be safely used within  $\pm 2^\circ$  S latitudes, yet it is laborious even to develop such curves if a large number of sites are to be dealt with. Therefore, in order to overcome this limitation associated with the envelope curve fitting, and for more generalised use of the equations of Angus (1980), the cubic spline interpolation method was adopted in the IRrigation Planning, Scheduling and Evaluation (IRPSAEV) computer package developed in this study, since it does not require separate equations. The IRPSAEV package is described in Appendix C.

### 3.6.2 Net Radiation ( $R_n$ ) versus Solar Radiation ( $R_s$ ) Relationship

As shown in Table 3.1, the net radiation ( $R_n$ ) is also an important input climatic data item for all combination methods. In the current study,  $R_n$  was estimated using Eqs. 3.30-3.33 as given in Section 3.2.7. However, as stated earlier (Section 3.2.7) some researchers (e.g. Meyer, 1988; and Jensen et al., 1990) suggested to establish a linear

relationship between  $R_n$  and  $R_s$  as given in Eq. 3.34. This relationship can be used if some input data (e.g.  $T_{dew}$ ) required for  $R_n$  estimates are not available. In this section, the linear relationship between  $R_n$  (computed from Eq. 3.30-3.33) and measured  $R_s$  for three study sites is discussed as below.

### (I) Aspendale

At the Aspendale site, only three months of daily climatic data were available. Hence, at this site no investigation for  $R_s$  and  $R_n$  parameters could be made.

### (II) Tatura

At Tatura, three years of daily climatic data were available. However, on most days either  $R_s$  or some other input data item required for  $R_n$  estimates were missing. Hence, the days which had complete data were used in the regression analysis. For the available data  $R_n$  was estimated using Eq. 3.30 - 3.33. Then, a linear regression was performed for the two data sets (i.e.  $R_n$  and  $R_s$ ) using Eq. 3.34. The graphical representation of this data set is given in Figure 3.4a. As can be seen from this figure, a strong correlation exists between these two climatic parameters. After regression, the regression parameters  $m$  and  $c$  can be used in Eq. 3.34 to compute  $R_n$  from measured  $R_s$ . The linear relationship resulting from the regression analysis for Tatura is given below:

$$R_n = 0.642 R_s - 2.304 \quad (\text{no. of observations} = 321; r^2 = 0.96) \quad (3.65)$$

The  $R_n$  estimates using Eq. 3.65 were plotted against original  $R_n$  estimates (i.e. Eq. 3.30-3.33) which is shown in Figure 3.4 b. This figure shows how good the regression relationship is.

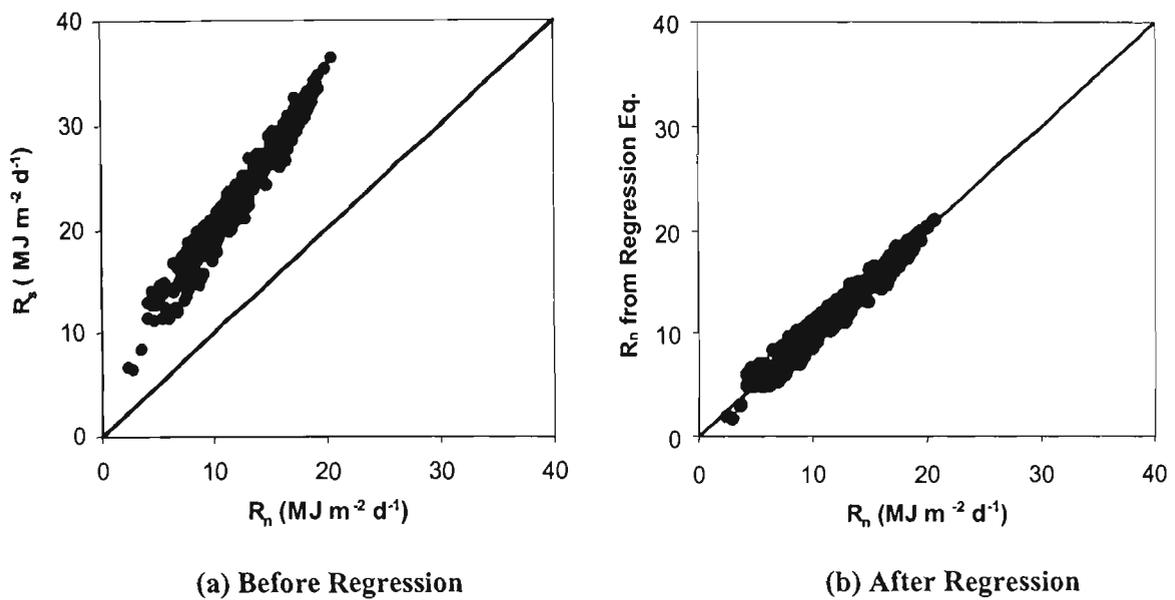


Figure 3.4  $R_n$  and  $R_s$  Relationship at Tatura

### (III) Griffith

At Griffith, six years of daily measured  $R_s$  data were available. For this period, the analysis was performed. The graphical representation of this data is shown in Figure 3.5. Like Tatura, there is a strong correlation between the  $R_s$  and  $R_n$  parameters at this site. The linear relationship resulting from the regression analysis at Griffith is given below:

$$R_n = 0.646 R_s - 2.966 \quad (\text{no. of observations.} = 2191; r^2 = 0.96) \quad (3.66)$$

It is important to mention that in this chapter for comparison of  $ET_o$  methods,  $R_n$  estimates were made using Eq. 3.30-3.33, and not from equations 3.65 and 3.66. This was because  $R_n$  estimates given by Eq. 3.30-3.33 were more accurate.

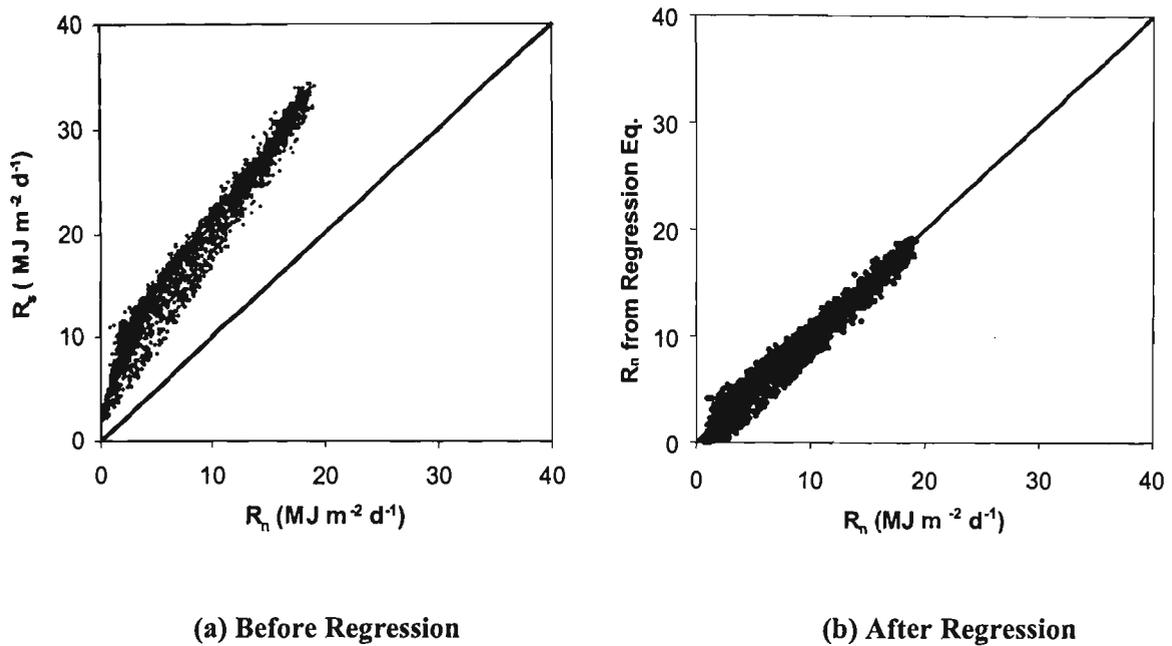


Figure 3.5  $R_n$  and  $R_s$  Relationship at Griffith

### 3.6.3 Analysis of $ET_o$ Methods

The ten  $ET_o$  estimation methods as outlined in Section 3.2 were investigated for their suitability to estimate daily  $ET_o$  for use in short-term irrigation planning and operational studies under conditions in Victoria (Australia). For this purpose, various statistical parameters such as standard error of estimate (SEE) as described in Sections 3.5.1 and 3.5.2, and the correlation coefficient ( $r$ ), and slope term ( $m$ ) of the regression line between lysimeter (or base method) and  $ET_o$  method data as described in Section 3.5.3 were calculated for  $ET_o$  method estimates at each of the three study sites. However, the standard error of estimate (SEE) parameter was used as the basic parameter to gauge the accuracy and consistency of  $ET_o$  estimation method in estimating daily  $ET_o$  values at each site. The reason for selecting SEE is given in Section 3.5.1. Sections 3.6.3.1 to 3.6.3.3 describe the analysis for Aspendale, Tatura and Griffith respectively. Aspendale was described first, since it was the only site with lysimeter data available.

#### 3.6.3.1 Aspendale

At Aspendale, the daily lysimeter measurements were used for evaluation of various  $ET_o$  methods. The statistical parameters of daily  $ET_o$  estimates using the ten  $ET_o$

methods are presented in Table 3.4. As can be seen from Table 3.4, for each  $ET_o$  method the statistical parameters are computed for two groups. The first group is based on the *all months* or *entire season* daily data, whereas the second group used only the *peak month* (i.e. January) data. The reason for two groupings is already given in Sections 3.5.1 and 3.5.2. The statistical parameters given in various columns of Table 3.4 are briefly described below.

Column (1): This column gives the names of various  $ET_o$  methods evaluated at the site.

Column (2): This column shows the estimates from the  $ET_o$  method expressed as a percentage of the corresponding lysimeter measured  $ET_o$  during the entire season. This parameter indicates the over or under-estimation characteristic of an  $ET_o$  method. A value of 100 indicates that over the entire season, on average, the method estimates are in perfect agreement with lysimeter. If the value is less than 100, it indicates an under-estimation, while a value above 100 indicates an over-estimation.

Column (3): This column gives the standard error of estimate for  $ET_o$  estimates obtained from the  $ET_o$  method in  $\text{mm d}^{-1}$  that have not been adjusted by regression.

Column (4): This column gives the slope of the regression line of lysimeter versus  $ET_o$  method estimates with y-intercept as zero. As stated earlier in Section 3.5.3, the lysimeter values were used as the dependent variable and the  $ET_o$  method estimates as the independent variable for regression analysis.

Column (5): This column indicates the correlation coefficient of the regression line of lysimeter versus  $ET_o$  method estimates.

Table 3.4 Summary of Statistics for Evaluation and Calibration of Various ET<sub>o</sub> Methods at Aspendale

Category of Methods	Method (1)	ET%	SEE <sub>u</sub>	m	r	SEE <sub>a</sub>	ET%	SEE <sub>u</sub>	m	r	SEE <sub>a</sub>
		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		All Months					Peak Month				
Combination	McIlroy (McI)	101	0.87	0.99	0.79	0.86	101	0.84	0.98	0.58	0.84
	Penman_Watts&Hancock (W_H)	93	1.15	1.09	0.68	1.06	98	0.89	1.02	0.53	0.89
	Penman_Meyer (M_Y)	110	1.14	0.92	0.70	1.04	112	1.16	0.88	0.49	0.92
	Penman_Monteith (P_M)	79	1.45	1.27	0.74	0.96	79	1.39	1.25	0.53	0.88
	Ritchie (RIT)	96	1.24	1.04	0.58	1.23	99	0.89	0.99	0.53	0.89
Non-Combination	Simplified Pan Evaporation (SEV)	104	1.26	0.96	0.57	1.24	101	0.87	0.99	0.54	0.87
	FAO-24 Pan (PEV)	81	1.57	1.22	0.55	1.26	78	1.45	1.29	0.62	0.80
	FAO-24 Radiation (RAD)	116	1.59	0.86	0.49	1.35	124	1.71	0.79	0.50	0.92
	Improved Hargreaves (IHA)	73	1.81	1.33	0.53	1.30	69	2.04	1.36	0.34	1.50
	Hargreaves (HAR)	62	2.39	1.51	0.28	1.63	61	2.71	1.48	0.34	2.02

Column (6): This column gives the standard error of estimates for  $ET_0$  estimates in  $\text{mm d}^{-1}$  that have been adjusted with the regression coefficient (Col. 4) using Eq. 3.57.

Columns (7) to (11) are similar to columns (2) to (6), but for the *peak month*. The various statistical parameters given in Table 3.4 are discussed as follows.

**(i) Over/under-estimation by  $ET_0$  methods**

The ET% parameter given in Col. 2 indicates the over/under-estimation characteristic of various  $ET_0$  methods over *all months*. As can be observed, majority of the methods (i.e. 6 out of 10) tended to under-estimate daily  $ET_0$  estimates. This under-estimation ranged from 4-38%. The highly under-estimating (38%) method was the HAR method. The over-estimation (by four methods) ranged from 1-16% with the highest over-estimation (16%) by the RAD method. It is important to note that both the highest under-estimating and over-estimating methods were among the non-combination methods.

Among the four combination (i.e. McI, W\_H, M\_Y and P\_M) methods tested, two methods over-estimated and two under-estimated the daily  $ET_0$  estimates. The excellent ET% given by the McI method was expected because the atmospheric conductance ( $h_a$ ) parameter adopted in this method was developed by Dilley and Shepherd (1972) for Aspendale. The 10% over-estimation by the M\_Y combination method was not surprising, because the  $f(u)$  parameter used in this method was not basically developed for Aspendale but for Griffith.

The 7% under-estimation by the W\_H method could be attributed to the fact that the  $f(u)$  given by Watts and Hancock was a generalised  $f(u)$  rather than specifically calibrated for Aspendale. However, the 21% under-estimation by the P\_M method at Aspendale was quite surprising because in recent literature (e.g. Smith, 1992; Allen et al., 1994a,1994b; Chiew et al., 1995; ASCE, 1996; and Hussein 1999), this method has been strongly advocated as the most accurate method for daily  $ET_0$  estimates for global use. However, as revealed by Jensen et al. (1990), this method did under-

estimate monthly  $ET_0$  estimates at some locations in the world including Aspendale. The under-estimation for monthly estimates reported by Jensen et al. (1990) was 7%. Meyer et al. (1995) also reported a 30% consistent under-estimation by the P\_M method for daily  $ET_0$  estimates at Griffith.

Among the six non-combination (i.e. HAR, IHA, RIT, RAD, PEV and SEV) methods investigated in this study, two methods over-estimated and the remaining four under-estimated the  $ET_0$  estimates. The over-estimation ranged from 4% by SEV to 16% by the RAD method. The very good ET% value given by SEV method (i.e. 104%) at Aspendale was quite encouraging although some studies (e.g. Watts and Hancock, 1984; Thivianathan et al., 1991; and Amatya et al., 1996) has disfavoured the use of pan data. This value is comparable with physically-based combination methods tested in this study, which are generally considered as more accurate than the non-combination methods. The 16% over-estimation by the RAD method was mainly due to the fact that this method used only the radiation term of the combination method.

The under-estimation by four non-combination (i.e. HAR, IHA, RIT and PEV) methods ranged from 4% (RIT) to 38% (HAR). The 4% under-estimation by the RIT method was also encouraging because this method used only two measured climatic variables (i.e. radiation and temperature) for  $ET_0$  estimates. The 19% under-estimation by the PEV method can be mainly attributed to the inaccuracies involved in the estimation of correct pan coefficients from a wide range of climatic variables of wind speed and relative humidity (Jensen et al., 1990). The very high under-estimation of 27% and 38% by the IHA and HAR methods was not surprising, and can simply be attributed to the fact that these methods are only temperature-based methods and hence expected to be less accurate.

With regards to the over/under-estimation of daily  $ET_0$  during *peak month* by various  $ET_0$  methods, the corresponding ET% parameter is given in Col. 8. As can be observed, the response of all  $ET_0$  methods towards the over/under-estimation for this case was similar to what was observed for the case of *all months*, but within  $\pm 5\%$  of *all months* values. The exception was the RAD method which gave an over-estimation of 24% during *peak month* as compared to 16% over-estimation during *all months*.

## (ii) Goodness-of-fit of $ET_0$ Method Estimates with Lysimeter Measurements

As discussed above, the  $ET\%$  parameter mimics the overall under/over-estimation characteristic of an  $ET_0$  method. It does not give any information about how well an  $ET_0$  method compares with the daily lysimeter measurements over the specified period. Therefore, in order to see the goodness-of-fit of  $ET_0$  method estimates with daily lysimeter measurements over the specified (i.e. *peak month* and *all months*) length of record, the SEE parameter was calculated. It is important to note that in Table 3.4, two types of SEE viz.  $SEE_u$  (Col. 3) and  $SEE_a$  (Col. 6) are given. These two sets of SEE give information on both accuracy of unadjusted and adjusted  $ET_0$  estimates.

Looking at  $SEE_u$  values of *all months* presented in Col. 3, it can be observed that SEE values for unadjusted  $ET_0$  estimates ranged from 0.87-2.39  $\text{mm d}^{-1}$  for  $ET_0$  methods tested. Among the four combination (i.e. McI, W\_H, M\_Y and P\_M) methods, McI method had the lowest  $SEE_u$  value (equal to 0.87) followed by M\_Y, W\_H and P\_M methods respectively. The lowest  $SEE_u$  value for the McI method was again due to the reason as stated earlier under *over/under-estimation*. The values of  $SEE_u$  for M\_Y and W\_H methods were quite comparable. The highest value of  $SEE_u$  among the four combination methods was observed for P\_M method.

With regards to the  $SEE_u$  during *peak month* (Col. 8), it can be observed that during *peak month* the performance of each combination method was relatively better as compared to *all months* case. However, the performance of the M\_Y method during *peak month* was slightly reduced.

For the six non-combination (i.e. HAR, IHA, RIT, RAD, PEV and SEV) methods investigated, it can be observed that  $SEE_u$  values for these methods ranged from 1.24-2.39  $\text{mm d}^{-1}$ . Among these six methods, RIT had the lowest  $SEE_u$  equal to 1.23. The highest value of  $SEE_u$  among the six non-combination methods tested was observed for the HAR method. This highest  $SEE_u$  value for the HAR method indicates the poor performance of this method among other methods at the Aspendale site. This poor

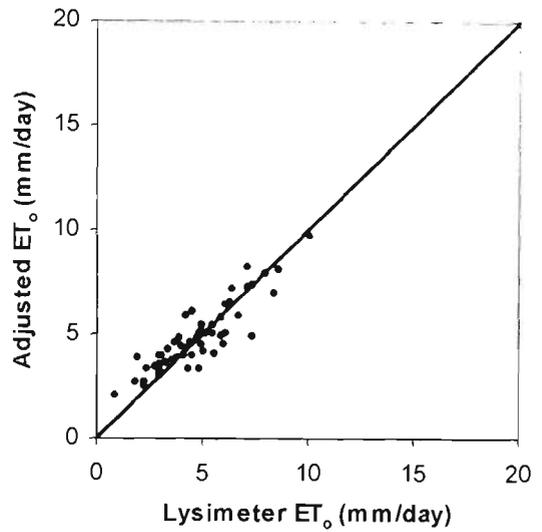
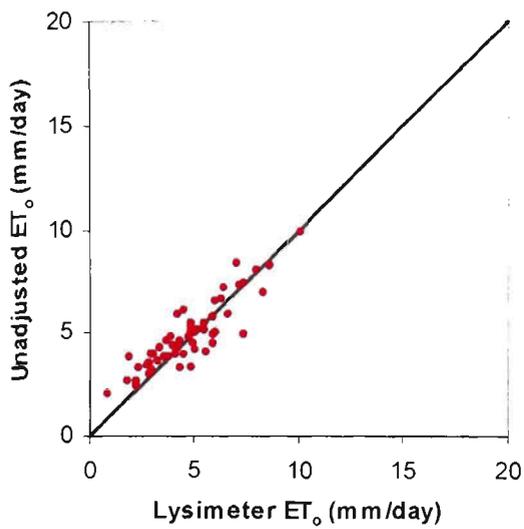
performance of the HAR method can be attributed to the reason stated earlier under *over/under-estimation*.

With regards to the performance of the six non-combination methods during the *peak month*, the Col. (8) indicates that during *peak month* the performance of RIT, PEV and SEV method was relatively better as compared with *all months*. However, the performance of RAD, IHA and HAR methods during *peak month* was reduced.

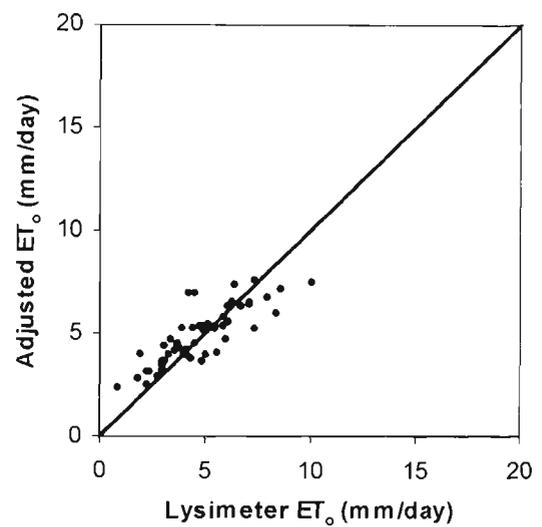
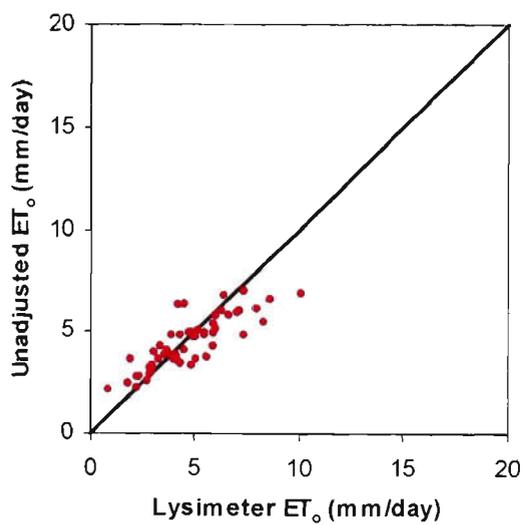
### (iii) *Calibration of ET<sub>o</sub> Methods*

In order to improve the performance of ET<sub>o</sub> methods, the calibration of various ET<sub>o</sub> methods was performed. As stated earlier in Section 3.5.3, the linear regression was performed for calibration between the lysimeter and the ET<sub>o</sub> method data sets. The slope (*m*) term of the linear regression line for various ET<sub>o</sub> methods is given in Col. 4. The corresponding correlation coefficient (*r*) of the linear regression is given in Col. 5. The *m* value (i.e. Col. 4) of the respective method was then used to adjust the ET<sub>o</sub> method estimates using Eq. 3.57. In order to see the performance of these “*adjusted or calibrated*” ET<sub>o</sub> estimates, the SEEs were recalculated. The SEE for *adjusted/calibrated* ET<sub>o</sub> estimates (SEE<sub>a</sub>) are given in Col. 6. The two sets of SEE (i.e. SEE<sub>u</sub> and SEE<sub>a</sub>) give information on both accuracy of unadjusted ET<sub>o</sub> estimates and ease with which these methods can be corrected to suite local conditions.

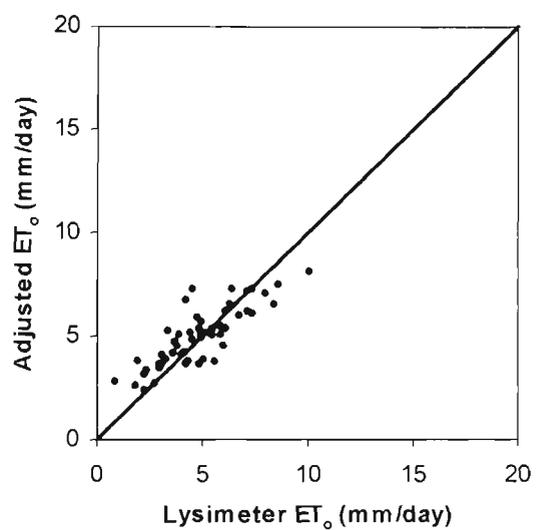
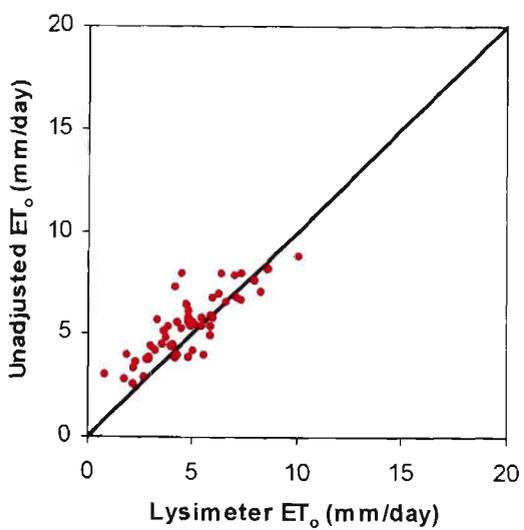
Looking at the two sets of SEE (i.e. SEE<sub>u</sub> and SEE<sub>a</sub>) for *all months* presented in Col. 3 and Col. 6, it is clear that SEEs were improved (i.e. SEEs were decreased) for all methods, but for most methods the SEE values were significantly improved after the adjustment. This aspect showed the need for calibration of various ET<sub>o</sub> methods under local conditions. The graphical representation of daily ET<sub>o</sub> estimates computed by various ET<sub>o</sub> methods before and after the adjustment/calibration is shown in Figure 3.6. It is important to mention that in Figure 3.6 the sequence of various ET<sub>o</sub> methods is given according to their ranking at the Aspendale site. The ranking aspect of these methods is discussed in Sub-section (iv) below.



(a) Mcl Method

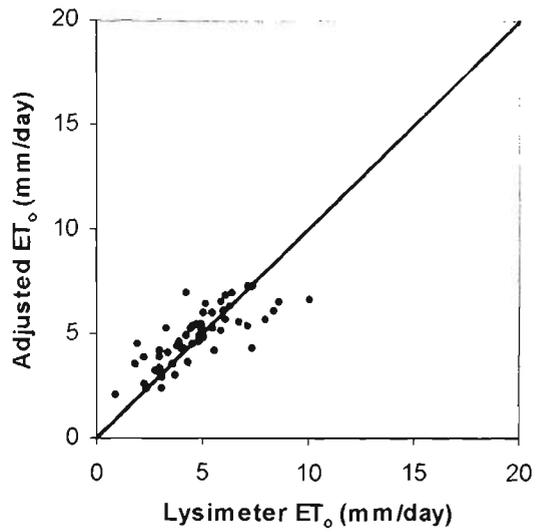
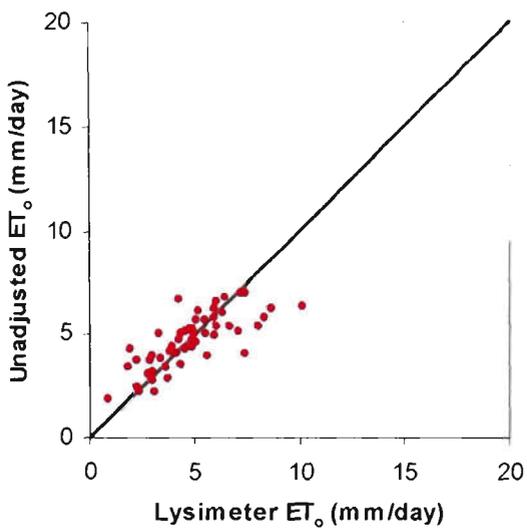


(b) W\_H Method

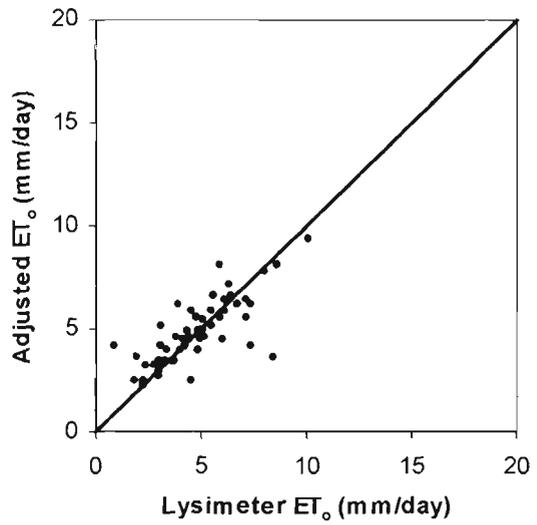
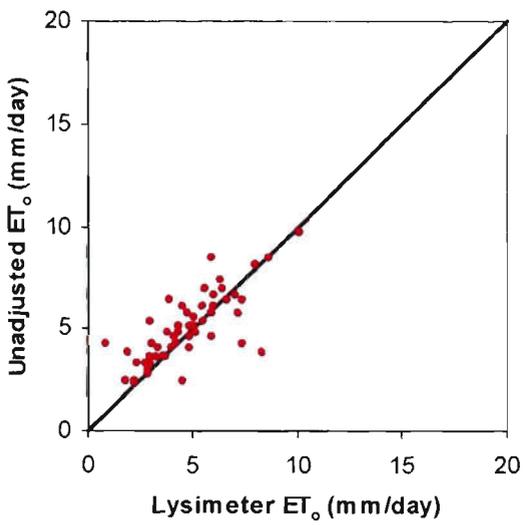


(c) M\_Y Method

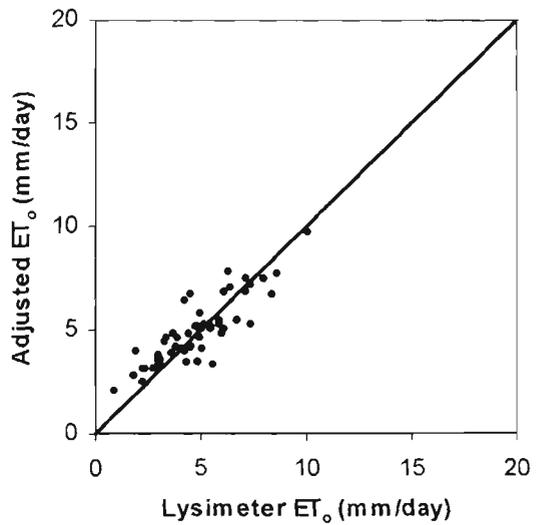
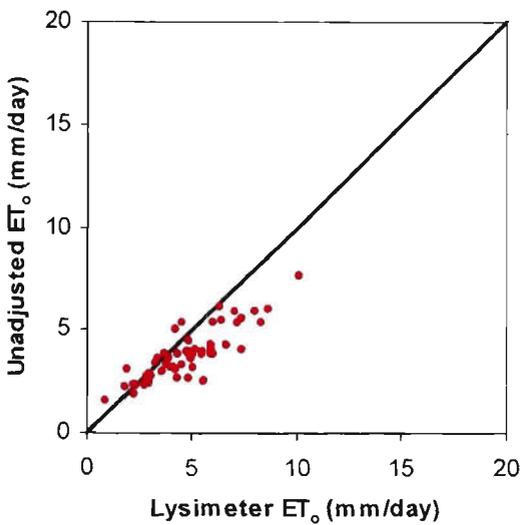
Figure 3.6  $ET_o$  Method Estimates Vs. Lysimeter Measurements at Aspendale



**(d) RIT Method**

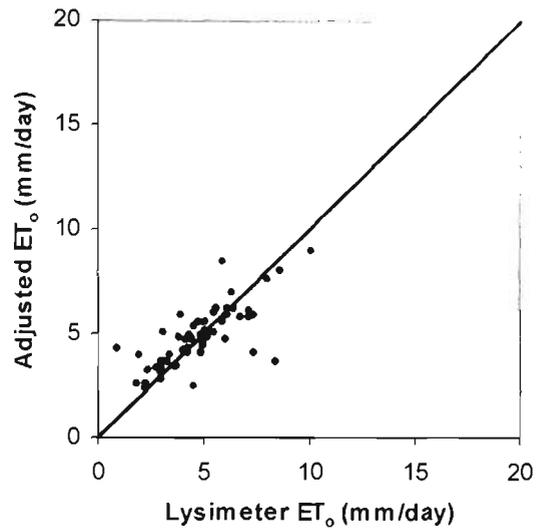
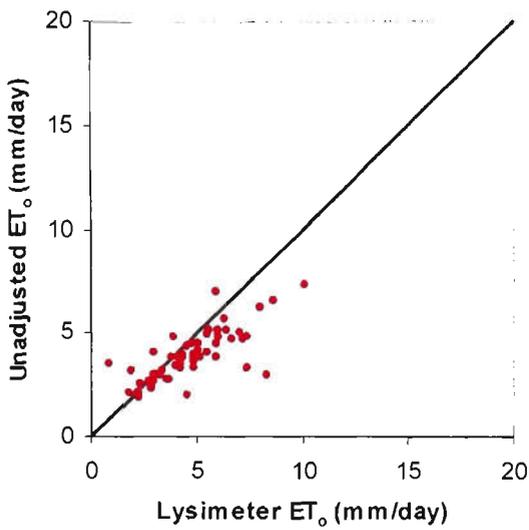


**(e) SEV Method**

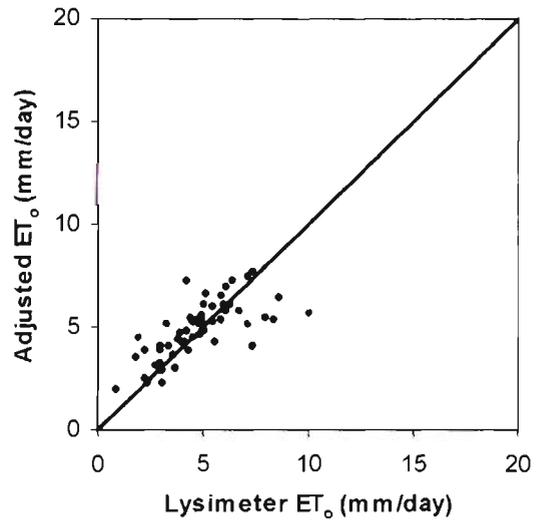
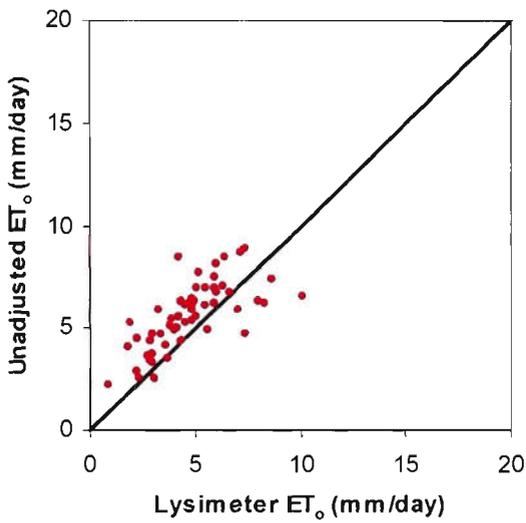


**(f) P\_M Method**

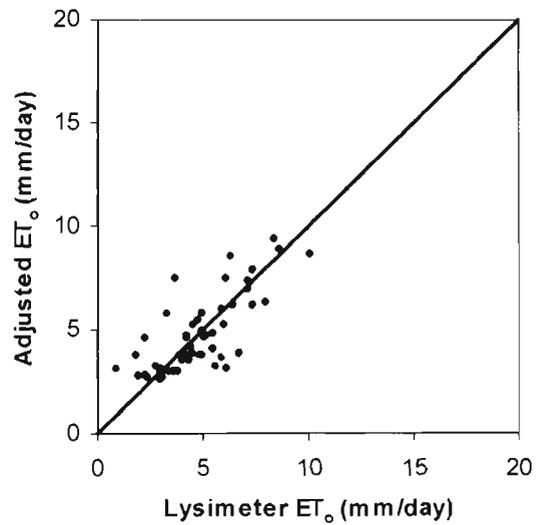
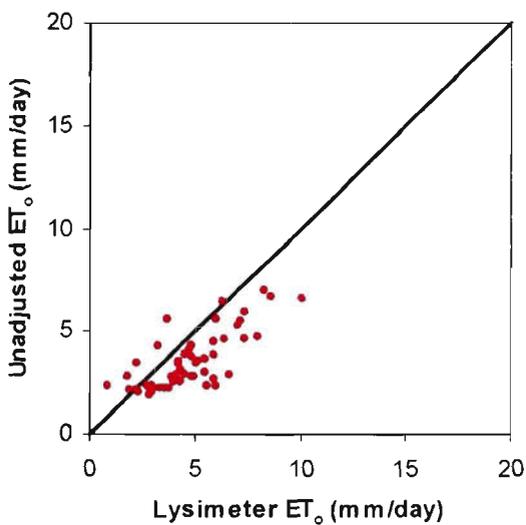
Figure 3.6  $ET_o$  Method Estimates Vs. Lysimeter Measurements at Aspendale (Continued)



(g) PEV Method

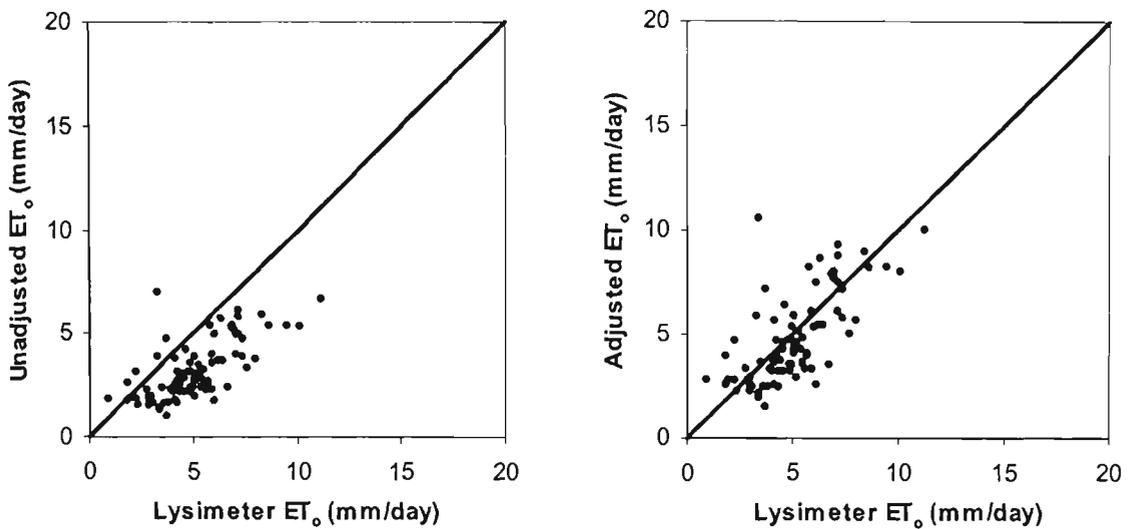


(h) RAD Method



(i) IHA Method

Figure 3.6  $ET_o$  Method Estimates Vs. Lysimeter Measurements at Aspendale (Continued)



(j) HAR Method

Figure 3.6  $ET_0$  Method Estimates Vs. Lysimeter Measurements at Aspendale  
(Continued)

(iv) *Ranking of  $ET_0$  methods*

As stated earlier (Section 3.5.2), when evaluating an  $ET_0$  estimation method, the accuracy in estimating both *peak month*  $ET_0$  and *all months*  $ET_0$  are very important. Hence, for ranking the relative performance of various  $ET_0$  methods, the weighted standard error of estimate ( $SEE_w$ ) parameter was used. This parameter was calculated as  $[0.7\{0.67(\text{Col. 3})+0.33(\text{Col. 6})\} + 0.3\{0.67(\text{Col. 8})+0.33(\text{Col. 11})\}]$ . The detail of this parameter is already given in Section 3.5.2. It is worth mentioning that for the estimation of  $SEE_w$  parameter, the column numbers referred here are those of Table 3.4. The summary of ranking of various  $ET_0$  methods for estimating daily  $ET_0$  are presented in Table 3.5. It is important to mention that the  $m$  and  $r$  columns (i.e. Col. 3 and Col. 4) in Table 3.5 are the same as given in Table 3.4 for *all months* case. The  $m$  and  $r$  values in Table 3.5 indicate the relative consistency of each  $ET_0$  estimation method in estimating daily  $ET_0$  estimates after the calibration.

Table 3.5 Ranking of Various ET<sub>o</sub> Methods for Daily ET<sub>o</sub> Estimates at Aspendale

Rank (1)	Method (2)	m (3)	r (4)	SEE <sub>w</sub> (5)
1	McIlroy (McI)	0.99	0.79	0.86
2	Penman_Watts&Hancock (W_H)	1.09	0.68	0.89
3	Penman_Meyer (M_Y)	0.92	0.70	1.10
4	Ritchie (RIT)	1.04	0.58	1.13
5	Simplified Pan Evaporation (SEV)	0.96	0.57	1.14
6	Penman_Monteith (P_M)	1.27	0.74	1.27
7	FAO-24 Pan (PEV)	1.22	0.55	1.40
8	FAO-24 Radiation (RAD)	0.86	0.49	1.45
9	Improved Hargreaves (IHA)	1.33	0.53	1.71
10	Hargreaves (HAR)	1.51	0.28	2.24

The column (1) of Table 3.5 shows the rank of an ET<sub>o</sub> method. This rank represents the relative performance of the ET<sub>o</sub> method in terms of estimating daily ET<sub>o</sub> values from climatic data at the site under consideration. As stated earlier, this rank is based on the SEE<sub>w</sub> parameter. The best method is with minimum SEE<sub>w</sub>, and *m* and *r* values close to 1. Hence, the method with the lowest SEE<sub>w</sub> value was given the highest rank (i.e. 1). The second lowest SEE<sub>w</sub> value dictated the second highest rank (i.e. 2). Similarly the method with the highest SEE<sub>w</sub> was given the lowest rank (i.e. 10 in this case) at this site.

As can be observed from Table 3.5, the McI method had the lowest SEE<sub>w</sub> and the highest correlation coefficient of all methods evaluated. It also had the lowest SEE for *all months* (0.87 mm d<sup>-1</sup>) and *peak month* (0.84 mm d<sup>-1</sup>) prior to the adjustment based on the linear regression coefficients through the origin.

The top three methods were among combination type, with RIT and SEV methods placing fourth and fifth. The W\_H was ranked second overall, with a standard error of estimate for *peak month* of 0.89 mm d<sup>-1</sup> and SEE for *all months* of 1.15 mm d<sup>-1</sup>. The M\_Y method, in which the values of *a* and *b* coefficients of the empirical *f(u)* term were adopted from that of Griffith, was ranked third overall.

As can be seen from Col. 5, weighted SEE were quite close to each other for the third through fifth ranks i.e. within  $0.04 \text{ mm d}^{-1}$ , which indicates fairly equal performance by these three methods in estimating both *peak month* and *all months*  $ET_0$  at Aspendale.

This aspect highlights how an empirical and less data requiring  $ET_0$  method (such as RIT and SEV) if calibrated can also perform equally well as physically based combination methods.

The RIT method, a temperature-radiation based method was ranked fourth, ahead of the P\_M combination method. The RIT method estimated daily  $ET_0$  during *peak month* more accurately (i.e.  $m = 0.99$ ) than the M\_Y method ( $m=0.88$ ), although the *all months* deviation of its estimates from the lysimeter measurements was greater.

The P\_M method ranked below not only other forms of the combination equation but also below the RIT and SEV methods due to consistent under-estimation. This was due to the fact that this method under-estimated  $ET_0$  by an average of 21% over *all months*, which reduced its ranking. Although, the SEE of this method was significantly improved after adjustment from  $1.45$  to  $0.96 \text{ mm d}^{-1}$ , the high under-estimation in *peak month* also resulted in having a ranking of sixth place overall. This aspect gives a concern to evaluate the other  $ET_0$  methods using the P\_M method as the base method without testing/calibrating it under local conditions.

The FAO-24 Pan (PEV) method had relatively larger SEE for *peak month* and *all months* ( $SEE_u = 1.45$  and  $1.57$ ) than the SEV method ( $SEE_u = 0.87$  and  $1.26$ ), which employed simple measurement of pan evaporation multiplied by a factor. The reason for higher SEE for the PEV method is due to the inaccuracies involved in the estimation of correct pan coefficients from wide range of climatic variables of wind speed and relative humidity as given in sub-section (i).

The FAO-radiation (RAD) method was ranked eighth. The poor performance of this method was due to the over-estimation during both *peak month* and *all months*. As stated earlier, the over-estimation by this method during *all months* was 16% which

was 6% more higher than that reported by Jensen et al., 1990 based on the 11 locations lysimeter data around the world.

The poorest performing methods overall were the HAR and IHA methods, which significantly under-estimated  $ET_0$  at Aspendale. The under-estimation by HAR and IHA was 38% and 27% for *all months*, and 39% and 31% for *peak month* respectively.

It is important to note that in spite of the best performance by the McI method at Aspendale, its correlation coefficient ( $r$ ) value was relatively low although it is the highest in comparison to other methods. Higher correlation coefficients are generally obtained as the range of data used increases (Allen et. al., 1990). At the Aspendale site, relatively lower correlation values for most  $ET_0$  methods was due primarily to the small range in  $ET_0$  values because only three months of data were available for use in the analysis. Another reason for this could be the climatic variability of Aspendale, being located near the Port Phillip Bay of Australia whose climate is influenced alternatively by winds from a dry land mass and the bay, and by the diurnal variation in wind direction.

### **Summary of Aspendale Analysis**

The above analysis revealed that if measured lysimeter data are available, various  $ET_0$  estimation methods must first be evaluated and then if required be locally calibrated against these data. Combination methods generally provide the most accurate  $ET_0$  estimates because they are based on physical laws and rational relationships. However, depending upon the climatological situation of a specific site, a locally calibrated less data requiring simple  $ET_0$  method may produce better results than a data extensive complicated  $ET_0$  estimation method. The SEV method can provide accurate results, provided that pan is properly maintained. Keeping in view of the relative performance of the ten  $ET_0$  methods tested, five (three combination and two non-combination) methods namely McI, W\_H, M\_Y, RIT and SEV are recommended for daily  $ET_0$  estimates for use in irrigation scheduling studies at the Aspendale site.

### 3.6.3.2 Tatura

As stated earlier (Section 3.4), lysimeter data were not available at Tatura. Hence, the M\_Y method was used at this site as the base method for evaluation/calibration of other nine  $ET_0$  methods. Justification for using the M\_Y method as the base method at Tatura has already been discussed under Section 3.4. Following the same format as adopted for Aspendale, the statistical parameters of daily  $ET_0$  estimates using nine  $ET_0$  methods at Tatura were also calculated. They are presented in Table 3.6. Various statistical parameters given in Table 3.6 are discussed as follows.

#### (i) *Over/under-estimation by $ET_0$ methods*

The ET% parameter given in Col. 2 indicates the over/under-estimation characteristic of various  $ET_0$  methods over *all months* at the Tatura site. As can be seen from this column, unlike Aspendale almost all (i.e. 8 out of 9) methods under-estimated the daily  $ET_0$  estimates. The only over-estimation by the RAD method was of the order of 2%. A similar trend of over/under-estimation during the *peak month* can also be observed from Col. 7. It is important to note that at Tatura, the under-estimation by the P\_M combination method was further increased by 8% as compared with the Aspendale site.

#### (ii) *Goodness-of-fit of $ET_0$ method estimates with base method estimates*

In order to see the goodness-of-fit of  $ET_0$  method estimates with those of the base method, the SEE parameter was calculated. This is shown in Col. 3. Looking at *all months*  $SEE_u$  presented in Col. 3, it can be observed that among all methods the temperature-radiation RAD method had the lowest SEE value. This is in contrast with Aspendale where the combination McI method had the lowest  $SEE_u$ . It is also important to note that at Tatura, the McI method had relatively higher  $SEE_u$  compared to Aspendale. This relatively higher  $SEE_u$  value at Tatura can be attributed to the fact that the atmospheric conductance ( $h_a$ ) parameter used in the McI method at Tatura was basically developed for Aspendale and not for Tatura.

Table 3.6 Summary of Statistics for Evaluation and Calibration of Various ET<sub>o</sub> Methods at Tatura

Category of Methods	Method (1)	ET%	SEE <sub>u</sub>	m	r	SEE <sub>a</sub>	ET%	SEE <sub>u</sub>	m	r	SEE <sub>a</sub>
		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		All Months					Peak Month				
Combination	McIlroy (Mcl)	88	0.93	1.13	0.93	0.53	87	1.12	1.15	0.89	0.49
	Penman_Watts&Hancock (W_H)	82	1.22	1.21	0.97	0.36	84	1.29	1.19	0.96	0.30
	Penman_Monteith (P_M)	71	1.96	1.40	0.96	0.41	72	2.24	1.39	0.95	0.34
Non-combination	Ritchie (RJT)	82	1.45	1.22	0.82	0.82	80	1.67	1.25	0.84	0.59
	Simplified Pan Evaporation (SEV)	88	1.25	1.10	0.67	1.11	91	1.30	1.08	0.37	1.17
Non-combination	FAO-24 Pan (PEV)	69	2.16	1.40	0.71	1.05	71	2.40	1.37	0.41	1.13
	FAO-24 Radiation (RAD)	102	0.86	0.97	0.81	0.85	102	0.81	0.97	0.72	0.78
	Improved Hargreaves (IHA)	73	2.06	1.36	0.68	1.10	71	2.52	1.39	0.26	1.26
	Hargreaves (HAR)	60	2.84	1.63	0.58	1.26	59	3.39	1.66	0.13	1.37

With regards to the  $SEE_u$  values during *peak month* (Col. 8), it can be seen that during *peak month* the performance of almost all methods was relatively poorer as compared with *all months* case. However, the performance of the RAD method during *peak month* was slightly better as compared to the *all months* case.

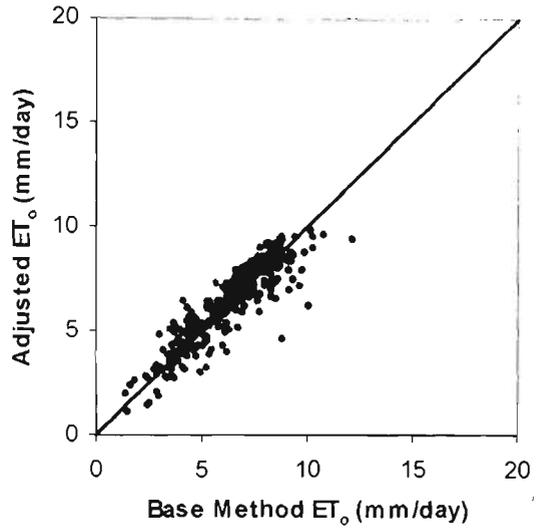
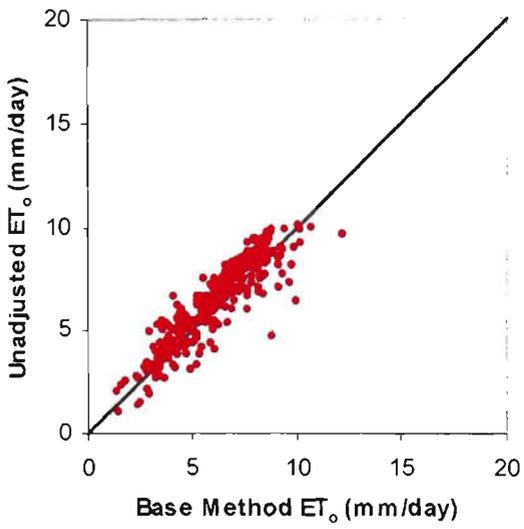
The above discussion based on the SEE of Col. (3) and Col. (8) revealed that the performance of various  $ET_o$  methods at Tatura was not good. Hence, for improved  $ET_o$  estimates, calibration of these methods was desirable. The calibration aspect is described in next sub-section.

### **(iii) Calibration of $ET_o$ methods**

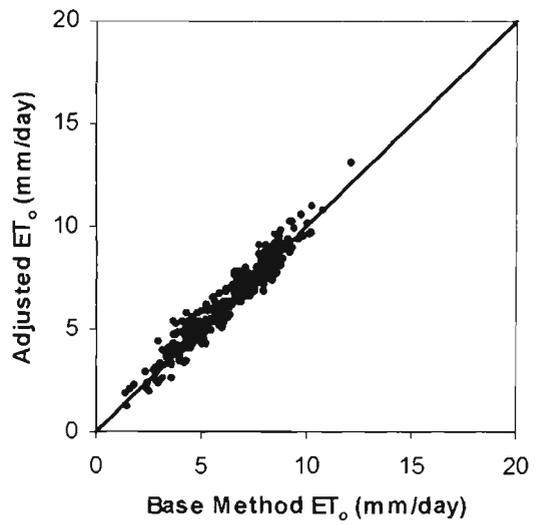
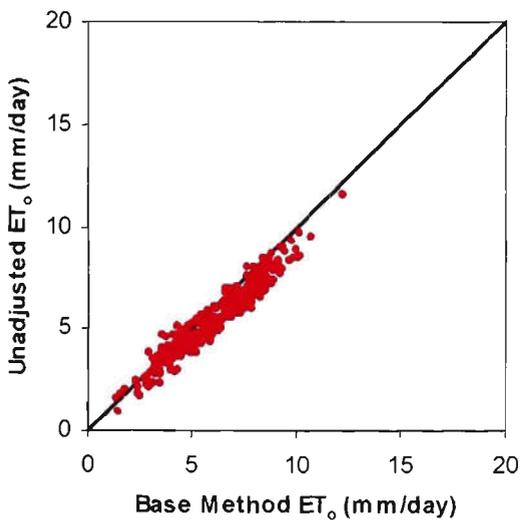
In order to improve the performance of various  $ET_o$  methods, the calibration of  $ET_o$  methods was performed. The same procedure as described for Aspendale was used for calibration. The SEE for *adjusted (or calibrated)*  $ET_o$  estimates ( $SEE_a$ ) are given in Col. 6.

Looking at the two sets of SEE (i.e.  $SEE_u$  and  $SEE_a$ ) for *all months* presented in Col. 3 and Col. 6, it is immediately evident that for all methods the SEE values were significantly improved (i.e. SEE was decreased) after the adjustment. For *peak month*, the two sets of SEE (Col. 8 and Col.11) also showed a significantly improved performance of various methods after the adjustment. Thus, the need for calibration under local conditions is supported by this analysis, as found with the Aspendale analysis.

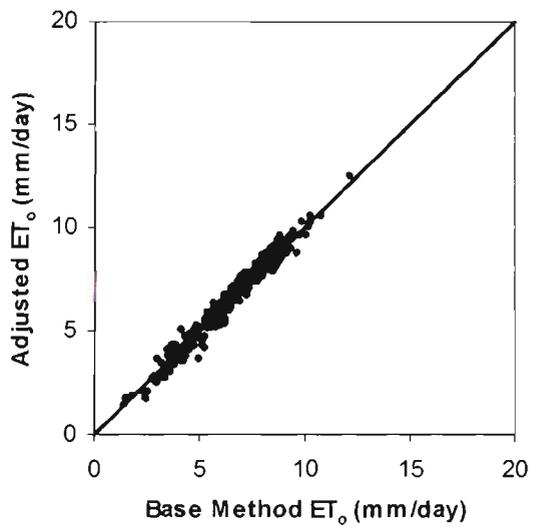
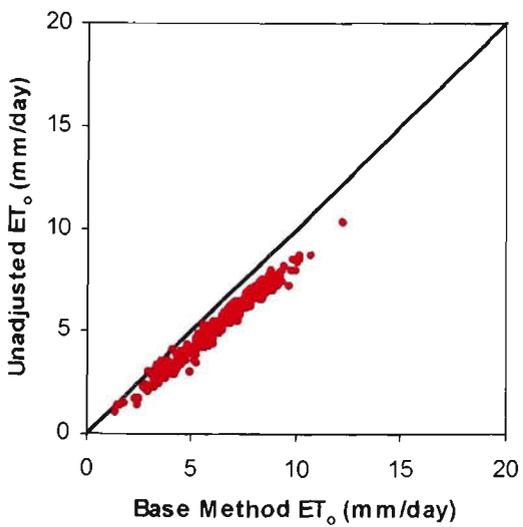
As shown in Col. 6, after the adjustment, the combination methods were the leading methods in performance as compared with the other methods. The graphical representation of daily  $ET_o$  estimates at Tatura computed by various  $ET_o$  methods is given in Figure 3.7. This figure shows the estimates before and after the adjustment/calibration. The sequence of various  $ET_o$  methods in Figure 3.7 is given according to their ranking at the Tatura site.



(a) RAD Method

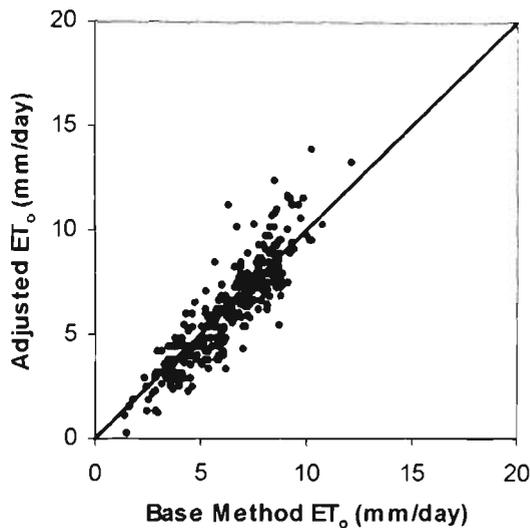
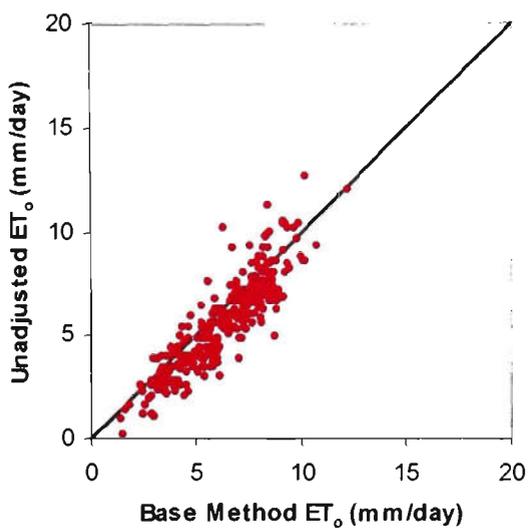


(b) Mcl Method

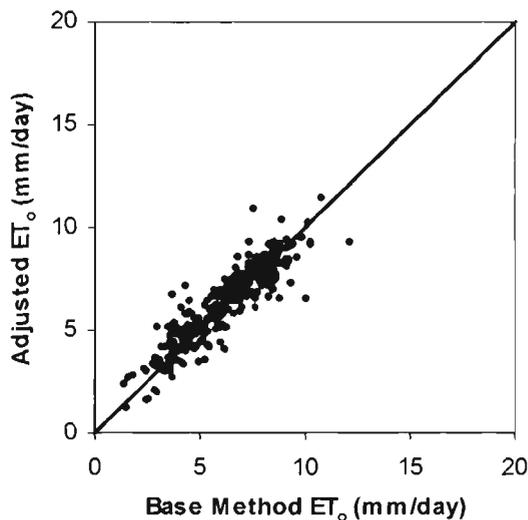
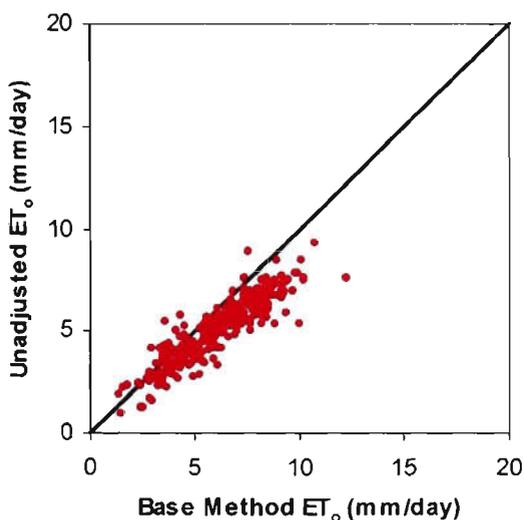


(c) W\_H Method

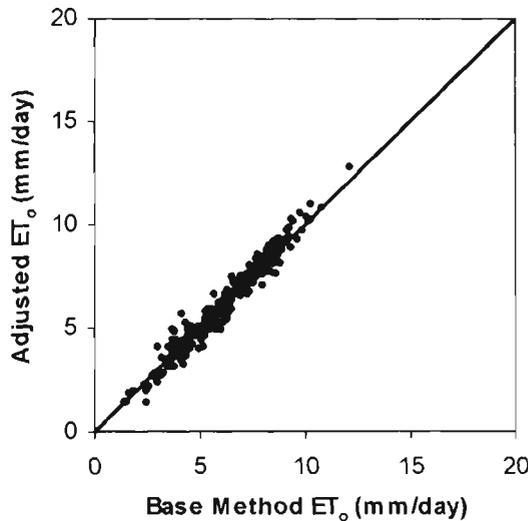
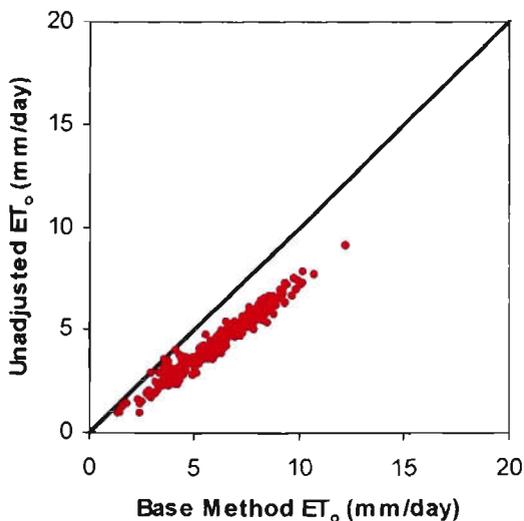
Figure 3.7  $ET_0$  Method Estimates Vs. Base Method Estimates at Tatura



**(d) SEV Method**

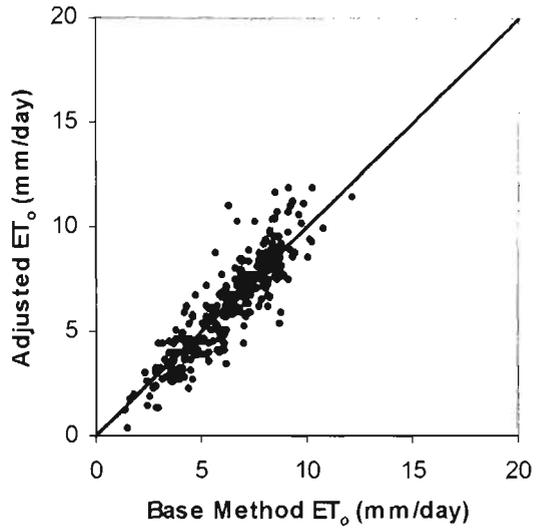
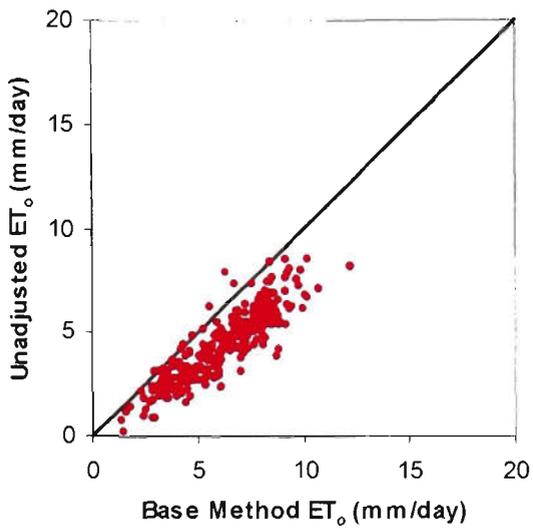


**(e) RIT Method**

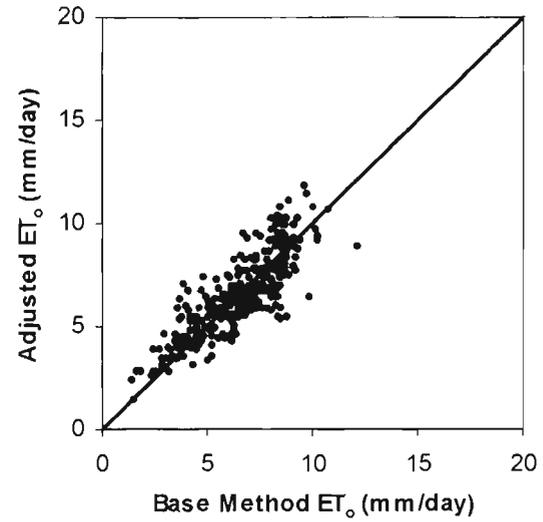
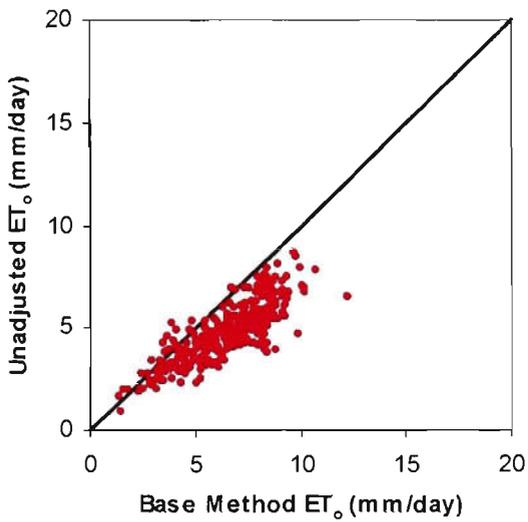


**(f) P\_M Method**

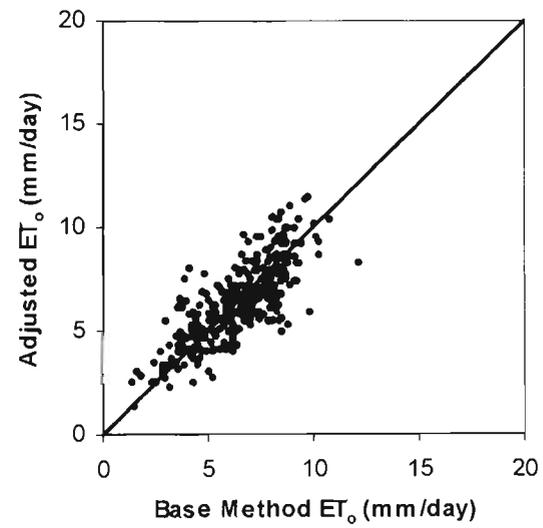
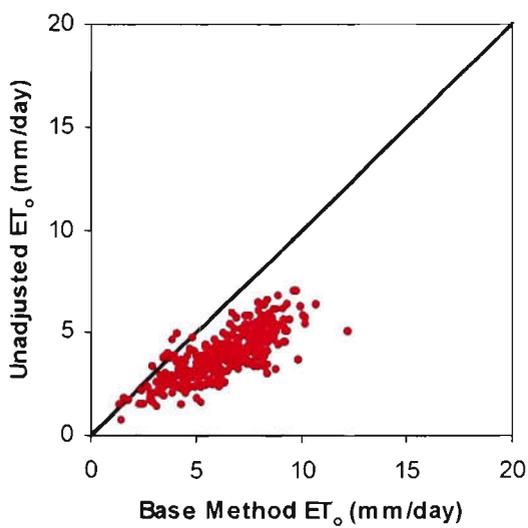
Figure 3.7  $ET_0$  Method Estimates Vs. Base Method Estimates at Tatura (Continued)



(g) PEV Method



(h) IHG Method



(i) HAR Method

Figure 3.7  $ET_o$  Method Estimates Vs. Base Method Estimates at Tatura (Continued)

(iv) *Ranking of  $ET_o$  methods*

A summary of ranking of various  $ET_o$  methods at Tatura is presented in Table 3.7. The parameters  $m$ ,  $r$  and  $SEE_w$  in Table 3.7 are as in Table 3.5 for Aspendale. As stated earlier, the  $M_Y$  method was used as the base method for evaluation/calibration of other nine methods. Being the base method,  $M_Y$  was given the rank 1 in Table 3.7. The remaining nine methods were assigned the rank based on the  $SEE_w$  criteria as for Aspendale.

Table 3.7 Ranking of Various  $ET_o$  Methods for Daily  $ET_o$  Estimates at Tatura

Rank (1)	Method (2)	$m$ (3)	$r$ (4)	$SEE_w$ (5)
1	Penman_Meyer ( $M_Y$ )	Base	Method	
2	FAO-24 Radiation (RAD)	0.97	0.81	0.80
3	McIlroy (McI)	1.13	0.93	0.91
4	Penman_Watts&Hancock ( $W_H$ )	1.21	0.97	0.97
5	Simplified Pan Evaporation (SEV)	1.10	0.67	1.26
6	Ritchie (RIT)	1.22	0.82	1.32
7	Penman_Monteith ( $P_M$ )	1.40	0.96	1.61
8	FAO-24 Pan (PEV)	1.40	0.71	1.98
9	Improved Hargreaves (IHA)	1.36	0.68	2.10
10	Hargreaves (HAR)	1.63	0.58	2.73

As can be observed from Table 3.7, the RAD method had the lowest  $SEE_w$ , and hence, was given the highest rank among the methods tested. Following the RAD method, next top two methods were among combination type, with McI and  $W_H$  methods placing third and fourth. The reason for the McI method ranked lower than the non-combination RAD method can be attributed to the fact that the  $h_a$  parameter adopted in the McI method for Tatura was basically developed for Aspendale as stated in sub-section (ii). The climate of Aspendale being located near the Port Phillip Bay of Australia is influenced alternatively by winds from a dry land mass and the bay, and by the diurnal variation in wind direction, and hence is significantly different from the inland semi-arid climatic environment experienced at Tatura. Therefore,  $h_a$

developed for Aspendale may not be representative of Tatura. As can be seen from Col. 5, the weighted SEE were quite close to each other for the third (McI) and fourth (W\_H) ranks (i.e. within  $0.06\text{mm d}^{-1}$ ), which indicates fairly equal performance by these two methods in estimating both peak-month and *all months*  $ET_0$  at Tatura.

The temperature-radiation RAD method being ahead of the combination methods at Tatura again indicates how a less data requiring  $ET_0$  method, if calibrated, can perform even better than a physically based combination method. In addition, the RAD and the McI methods being the highest ranked methods at Tatura and Aspendale respectively, indicate that no single method can be regarded as the superior method for daily  $ET_0$  estimates at different locations. The ranking of other methods is self explanatory, and hence need not to be discussed in detail.

#### Scatter and Ranking of $ET_0$ Methods

It is important to note that in Figure 3.7a the RAD method is showing more scatter than the McI (Figure 3.7b) method, and the McI method is showing more scatter than the W\_H (Figure 3.7c) method. By considering this scatter from general view point, the Figures 3.7a, 3.7b and 3.7c should have the ranking 3, 2 and 1 respectively (i.e. less scatter, superior rank). However, the statistical analysis presented in Table 3.7 revealed that the ranking order is RAD (i.e. Figure 3.7a), McI (i.e. Figure 3.7b) and W\_H (i.e. Figure 3.7c). Although, from common sense it seems to be strange, yet it is statistically correct. The reason for this is that the W\_H method although having relatively less scatter shows consistent under-estimation before calibration, where as the RAD method does not show any consistent under-estimation. Similarly, the McI method shows relatively less under-estimation as compared to the W\_H method, and hence is having relatively higher (i.e. better) rank than the W\_H method, but still lower rank as compared to the RAD method.

Similarly, the P\_M method (Figure 3.7f) although shows the less scatter, was highly under-estimating  $ET_0$  before the calibration, and hence was ranked below the other five (i.e. RAD, McI, W\_H, SEV and RIT) methods. This leads to the conclusion that scatter alone is not sufficient to compare or evaluate  $ET_0$  methods. These findings agree with Jacovides and Kontoyiannis (1995).

### Effect of Data Range on Correlation Coefficient (r)

It is important to note that at Tatura the values of correlation coefficient (r) for various methods were significantly higher compared to Aspendale. At Tatura, relatively higher correlation values for most ET<sub>o</sub> methods was due primarily to the large range in ET<sub>o</sub> values, since three years (i.e. 1990-92) of data were used in the analysis. This is in line with the findings of Jensen et al. (1990).

### **Summary of Tatura Analysis**

Similar observations to Aspendale were found at Tatura. However, comparing the ranking of various ET<sub>o</sub> methods at the two sites gave another additional finding that no single ET<sub>o</sub> estimation method was superior for both sites. Keeping in view of the relative performance of various ET<sub>o</sub> methods tested, one non-combination and two combination methods namely RAD, McI and W\_H were recommended for daily ET<sub>o</sub> estimates at the Tatura site. It is important to mention that the M\_Y method which was used as the *base method*, was by default included in this recommendation as the top ranking method.

#### **3.6.3.3 Griffith**

As stated earlier (Section 3.4), the modified Penman method was locally calibrated against lysimeter data at Griffith by Meyer et al. (1995). However, these lysimeter data were not available to the candidate at the time of this study. Hence, the modified Penman method calibrated by Meyer (M\_Y) was used as the base method at this site for evaluation/calibration of other nine ET<sub>o</sub> methods. Following the same format as adopted for Aspendale and Tatura, the statistical parameters of the nine ET<sub>o</sub> methods for Griffith are presented in Table 3.8. The various statistical parameters in Table 3.8 are briefly discussed as follows.

Table 3.8 Summary of Statistics for Evaluation and Calibration of Various ET<sub>o</sub> Methods at Griffith

Category of Methods	Method (1)	ET% (2)	SEE <sub>u</sub> (3)	m (4)	r (5)	SEE <sub>a</sub> (6)	ET% (7)	SEE <sub>u</sub> (8)	m (9)	r (10)	SEE <sub>a</sub> (11)
		All Months					Peak Month				
Combination	McIlroy (McI)	73	1.46	1.26	0.95	0.74	80	1.87	1.23	0.91	0.65
	Penman_Watts&Hancock (W_H)	78	1.29	1.25	0.98	0.44	82	1.75	1.22	0.98	0.32
	Penman_Monteith (P_M)	71	1.74	1.39	0.99	0.36	73	2.60	1.37	0.96	0.45
	Ritchie (RIT)	75	1.83	1.32	0.88	1.10	71	2.80	1.38	0.78	1.02
Non-combination	Simplified Pan Evaporation (SEV)	100	1.18	0.94	0.87	1.13	105	1.70	0.91	0.54	1.48
	FAO-24 Pan (PEV)	76	1.61	1.28	0.89	1.03	78	2.20	1.25	0.66	1.27
	FAO-24 Radiation (RAD)	89	1.25	1.10	0.88	1.12	90	1.47	1.11	0.72	1.16
	Improved Hargreaves (IHA)	71	2.03	1.43	0.92	0.92	70	3.09	1.43	0.65	1.28
	Hargreaves (HAR)	57	2.84	1.77	0.88	1.13	57	4.31	1.76	0.52	1.51

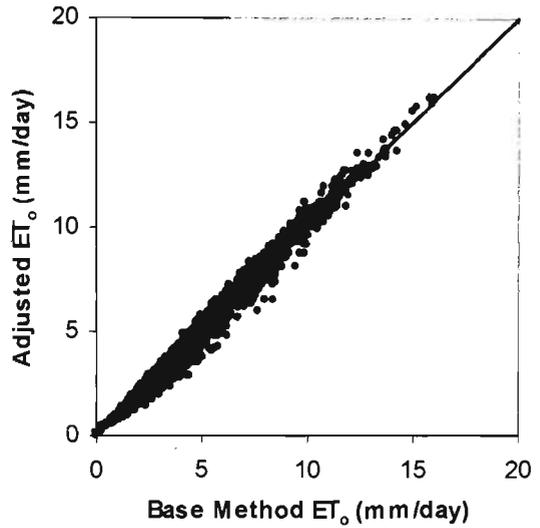
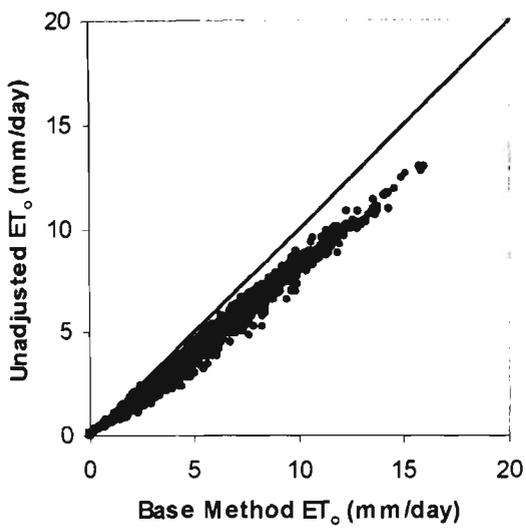
The ET% parameter given in Col. 2 indicates that at Griffith like Tatura almost all methods (i.e. 8 out of 9) underestimated daily  $ET_0$  estimates. The exception was the SEV method which gave ET% equal to 100% for *all months*, indicating an excellent agreement with the base method estimates. However, a 5% over-estimation during the *peak month* can also be observed.

A comparison of under/over-estimation at the three sites indicated that: at Aspendale four methods namely SEV, RAD, McI and M\_Y over-estimated the  $ET_0$  estimates; at Tatura only the RAD method where as at Griffith no method over-estimated  $ET_0$ . This aspect indicated the variant nature of  $ET_0$  methods in terms of daily  $ET_0$  estimates under different climatic conditions. Like the other two sites, the  $SEE_u$  and  $SEE_a$  for Griffith given in Table 3.8 also supported the need for calibration of various  $ET_0$  methods under local conditions.

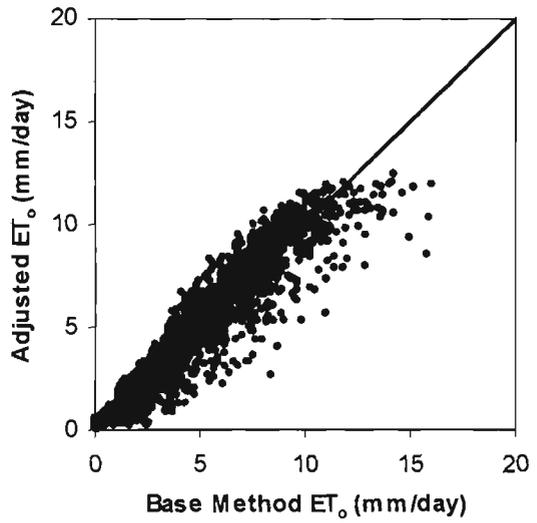
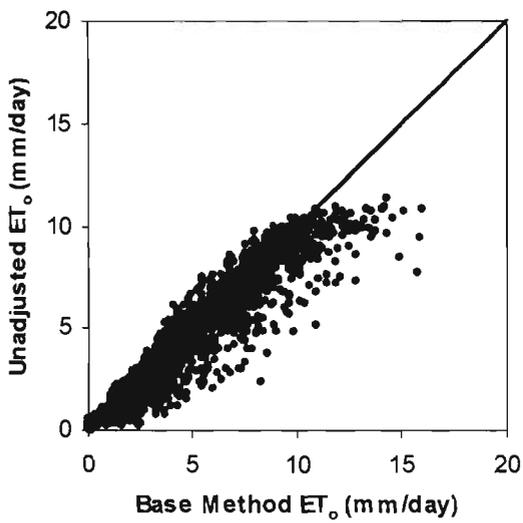
The graphical representation of daily  $ET_0$  estimates at Griffith computed by various  $ET_0$  methods is given in Figure 3.8. The figure shows estimates before and after the adjustment/calibration. Similar to Aspendale and Tatura, the sequence of various  $ET_0$  methods is given according to their ranking at the Griffith site.

A summary of ranking of various  $ET_0$  methods for Griffith is presented in Table 3.9. The parameters  $m$ ,  $r$  and  $SEE_w$  in Table 3.9 are as in Table 3.5 for Aspendale. At Griffith, different ranking of  $ET_0$  methods as compared to the other two sites again confirmed the fact that no single method can be regarded as the superior method for daily  $ET_0$  estimates at different locations. Furthermore, it can be seen from the results at the Griffith site that a less data requiring  $ET_0$  method (e.g. in this case RAD method), when calibrated, can perform even better than a physically based combination (McI) method.

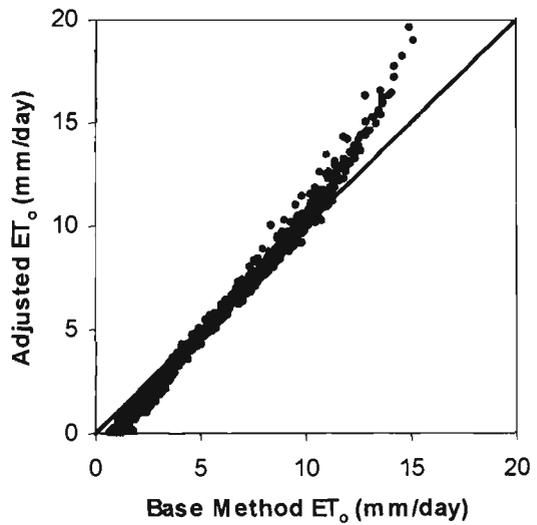
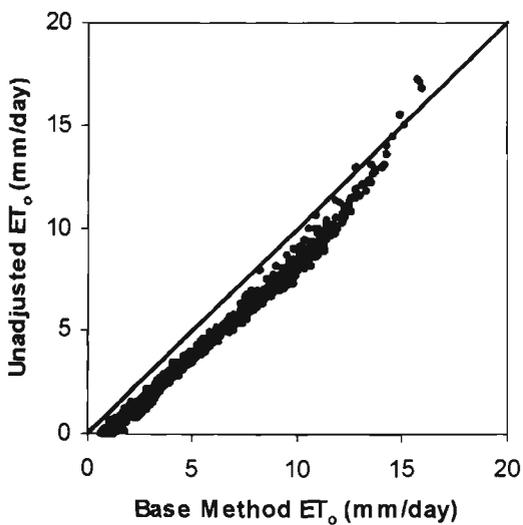
As stated earlier in Section 3.4, measured wet-bulb temperature data at Griffith were not available but they were estimated using Eq. 3.43a. As can be observed from Table 3.9, the McI method (in which estimated wet-bulb temperatures were used) was ahead of the P\_M combination method which uses available measured data. This aspect indicated that availability of climatic data alone should not be the sole criterion in selecting an  $ET_0$  estimation method because some of the needed data can also be



(a) W\_H Method

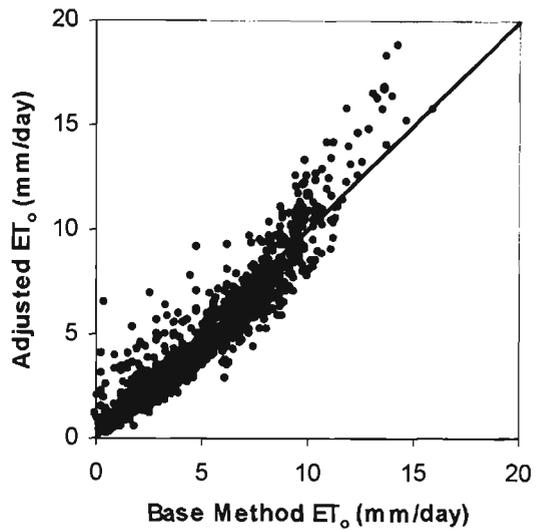
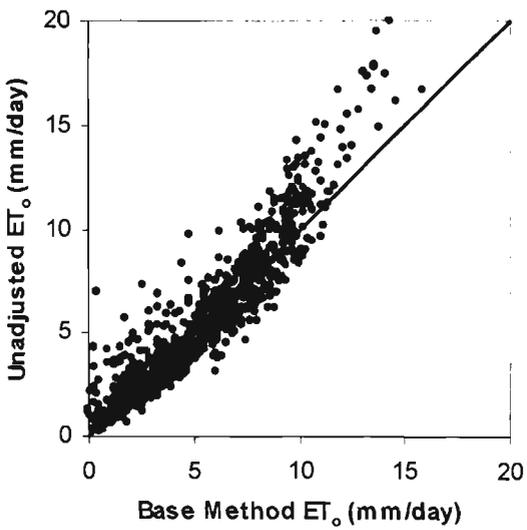


(b) RAD Method

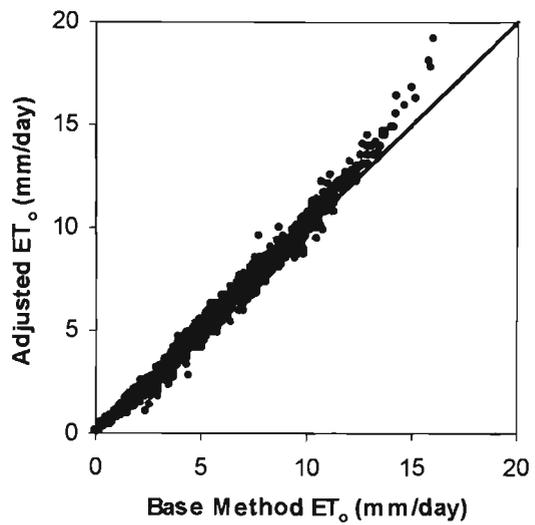
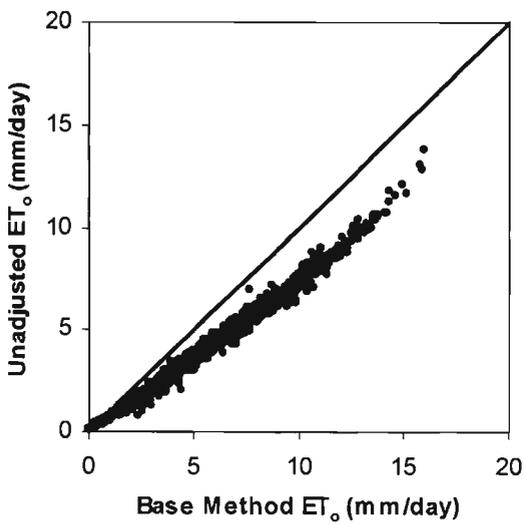


(c) Mcl Method

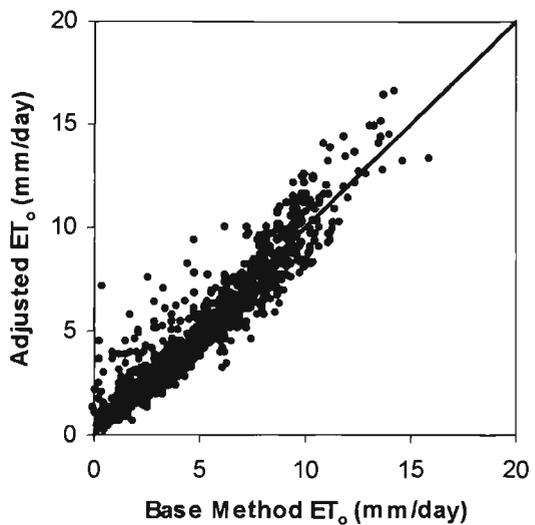
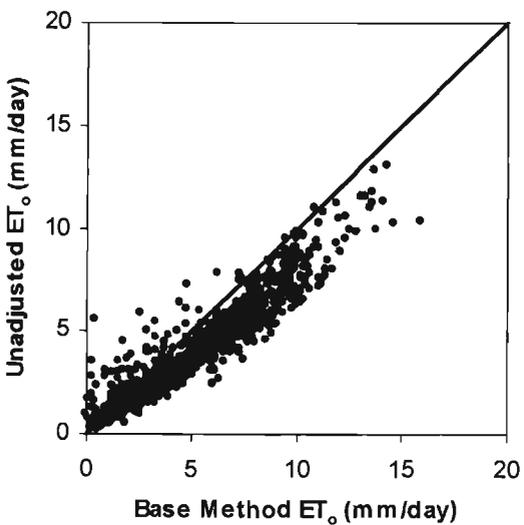
Figure 3.8  $ET_o$  Method Estimates Vs. Base Method Estimates at Griffith



(d) SEV Method

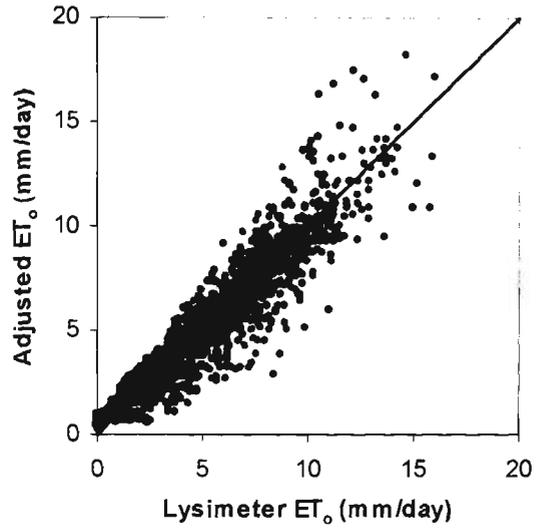
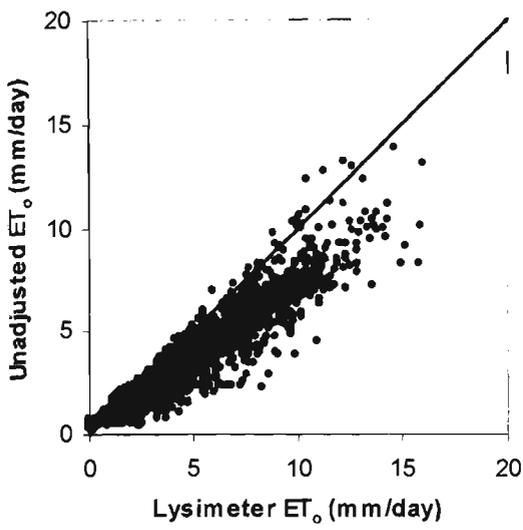


(e) P\_M Method

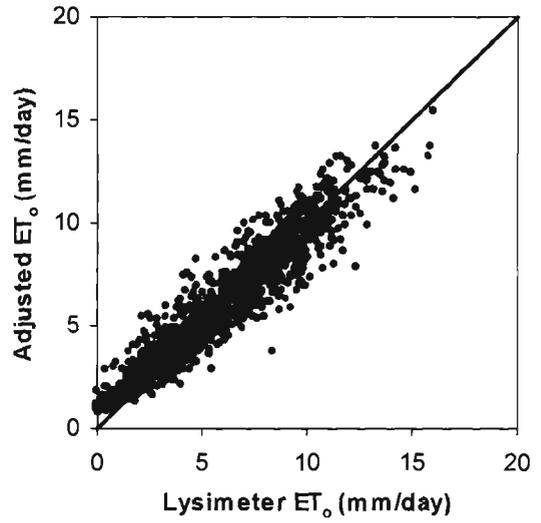
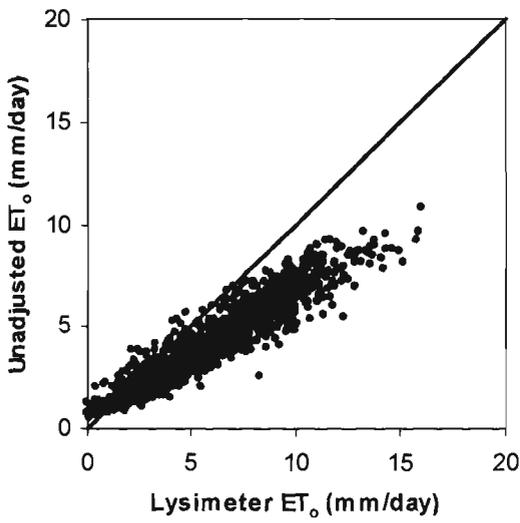


(f) PEV Method

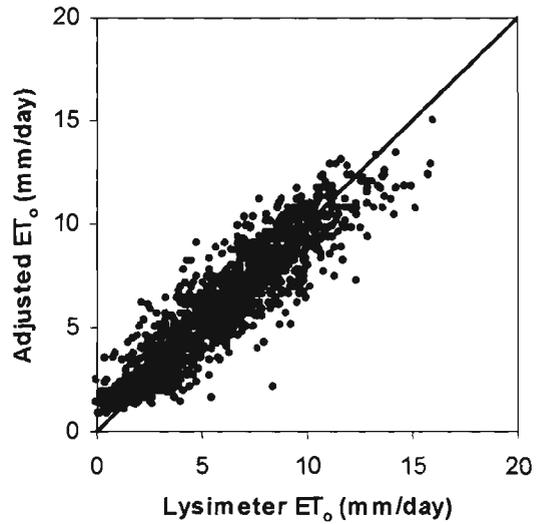
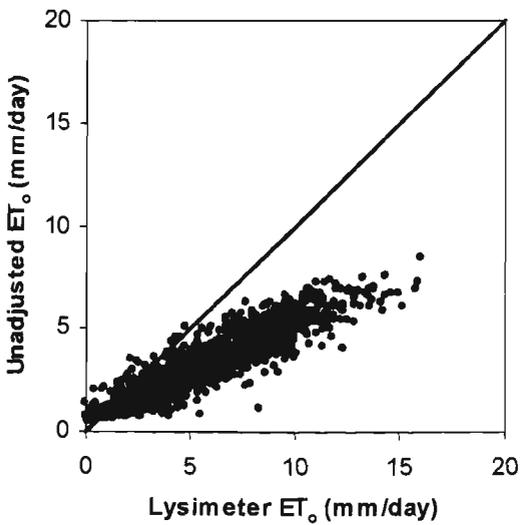
Figure 3.8  $ET_0$  Method Estimates Vs. Base Method Estimates at Griffith (Continued)



**(g) RIT Method**



**(h) IHA Method**



**(i) HAR Method**

Figure 3.8  $ET_o$  Method Estimates Vs. Base Method Estimates at Griffith (Continued)

estimated from other variables with sufficient accuracy to permit the usage of better  $ET_0$  estimating methods.

Table 3.9 Ranking of Various  $ET_0$  Methods for Daily  $ET_0$  Estimates at Griffith

Rank (1)	Method (2)	m (3)	r (4)	$SEE_w$ (5)
1	Penman_Meyer (M_Y)	Base	Method	
2	Penman_Watts&Hancock (W_H)	1.25	0.98	1.28
3	FAO-24 Radiation (RAD)	1.10	0.88	1.37
4	McIlroy (McI)	1.26	0.95	1.47
5	Simplified Pan Evaporation (SEV)	0.94	0.87	1.63
6	Penman_Monteith (P_M)	1.39	0.99	1.89
7	FAO-24 Pan (PEV)	1.28	0.89	1.89
8	Ritchie (RIT)	1.32	0.88	2.21
9	Improved Hargreaves (IHA)	1.43	0.92	2.49
10	Hargreaves (HAR)	1.77	0.88	3.39

It is important to note that at Griffith the values of correlation coefficient ( $r$ ) for various methods were higher as compared to the other two sites. The reason for these higher  $r$  values was that the use of six years data at Griffith provided a large range in  $ET_0$  values as compared to the other two sites. This is again in line with the findings of Jensen et al. (1990). It can also be observed that at Griffith, the values of  $SEE_w$  for various methods was relatively higher as compared to the other two sites. This aspect indicates that  $r$  alone is not always a good indicator of the performance of an  $ET_0$  method, and hence its use for ranking of  $ET_0$  methods should be made with scepticism. This is also in line with the findings of Jensen et al. (1990).

### Summary of Griffith Analysis

The analysis at Griffith confirmed the findings of the other two sites. Hence, the summary for this site is same as for Aspendale and Tatura.

### 3.6.4 ET<sub>o</sub> Estimates for Planning Purposes

As stated earlier (in Section 3.5.4), mean daily ET<sub>o</sub> estimates are required for pre-season irrigation planning. If historical daily ET<sub>o</sub> data are available, the mean daily ET<sub>o</sub> can be estimated by simple average for each day over the historical period (Villalobos and Fereres, 1987,1989). However, for computer oriented irrigation management software the mean daily ET<sub>o</sub> need to be translated into an equation. In this section, this aspect is described. It is important to note that for this part of the study, Griffith is considered first, since it had the most data, followed by Tatura and Aspendale.

At **Griffith**, six years (1990-95) of daily ET<sub>o</sub> data by the M\_Y method were available. These six years of daily ET<sub>o</sub> data were used to compute the mean daily ET<sub>o</sub> for each day of the calendar year. Then, this set of 365 ET<sub>o</sub> data values was used to derive an equation fit. For this purpose, Sigma Plot computer software (Sigma Plot, 1997) was used. The equation (or curve) fit investigation by Sigma Plot revealed that the mean daily ET<sub>o</sub> at Griffith could best be fitted by an equation which is known as the Modified Gaussian 5-Parameters equation. This was done by trial and error considering many different forms of equations. This equation is expressed as:

$$\bar{ET}_o = \left[ y_o + a \exp \left\{ -0.5 \left| \frac{J - x_o}{b} \right|^c \right\} \right] \quad (3.65)$$

where  $\bar{ET}_o$  = mean daily reference evapotranspiration (mm/day)

J = Julian day

$y_o$ ,  $a$ ,  $x_o$ ,  $b$  and  $c$  = empirical parameters of the equation which are obtained by the equation fit.

The curve-fit analysis gave the  $r^2$  value equal to 0.99, which revealed that at Griffith the mean daily ET<sub>o</sub> can be successfully represented by this equation. The graphical representation of original (or historical) and curve-fit mean daily ET<sub>o</sub> is shown in Figure 3.9. As can be seen from Figure 3.9, there are deviations between the original and curve-fit ET<sub>o</sub> values. Since the entire season is considered in pre-season irrigation

planning, these daily deviations will automatically be smoothed out over the entire season. A similar analysis was done for Tatura yielding results similar to Figure 3.9. It is important to mention that for Aspendale only three months of data were available, therefore no investigation was made on the computation of mean daily  $ET_0$  estimates from historical daily  $ET_0$  data. The curve-fit parameters of mean daily  $ET_0$  estimates for Griffith and Tatura for 5-parameters Gaussian equation are given in Table 3.10.

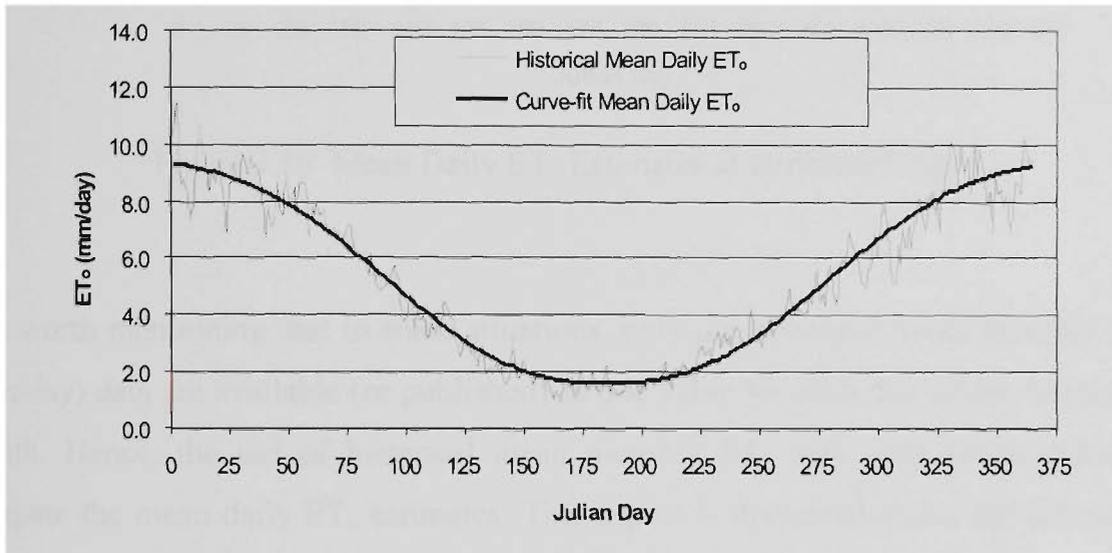


Figure 3.9 Historical and Curve-fit Mean Daily  $ET_0$  Estimates at Griffith

Table 3.10 Curve-fit Parameters for Mean Daily  $ET_0$  Estimates

Data Type	Equation Parameters	Griffith	Tatura	Aspendale
Mean daily $ET_0$	$y_0$	9.61	8.45	7.61
	$a$	-8.02	-7.45	6.16
	$x_0$	185.40	189.17	188.18
	$b$	86.36	83.84	97.55
	$c$	2.49	2.16	2.22

It is important to note that in Table 3.10, curve-fit parameters for Aspendale site are also presented. The estimation procedure for these curve-fit parameters for the Aspendale site is described later in sub-section (ii). The graphical representation for mean daily  $ET_0$  estimates for all three study sites is shown in Figure 3.10.

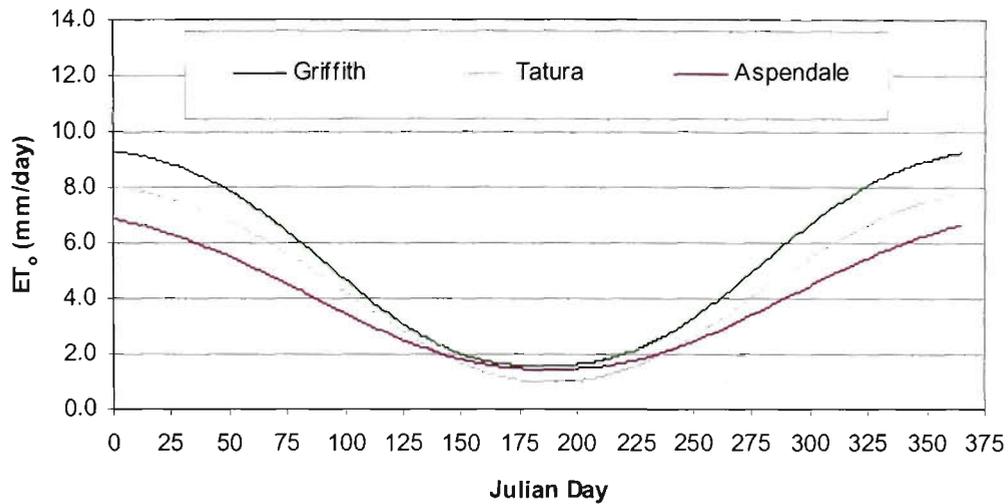


Figure 3.10 Mean Daily  $ET_0$  Estimates at Different Sites

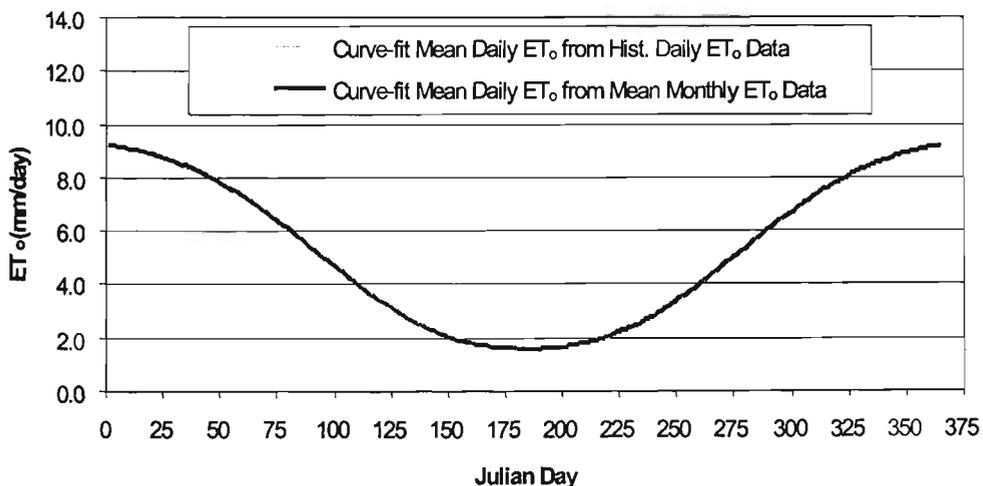
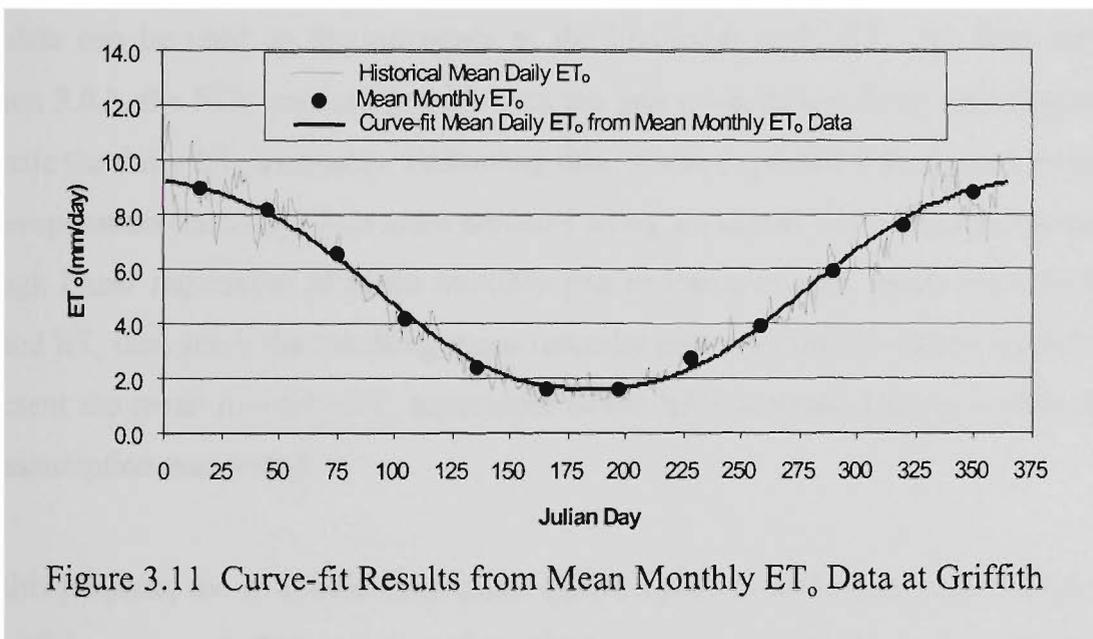
It is worth mentioning that in some situations, only the historical mean monthly  $ET_0$  (mm/day) data are available (or published) as one value for each day of the respective month. Hence, the use of historical mean monthly  $ET_0$  data were investigated to compute the mean daily  $ET_0$  estimates. This aspect is discussed under the following sub-section (i).

**(i) Mean daily  $ET_0$  estimates from historical mean monthly  $ET_0$  data**

As stated earlier, in some situations the historical daily  $ET_0$  data are not available, instead historical mean monthly  $ET_0$  (mm/day) data are available. With regards to the use of mean monthly  $ET_0$  for mean daily  $ET_0$  estimates, six years of daily  $ET_0$  data at Griffith were used. The historical mean monthly  $ET_0$  data set was obtained from the above data, which is referred to as *mean monthly  $ET_0$* .

For mean daily  $ET_0$  estimates, each value of mean monthly  $ET_0$  data set was assumed to fall in the middle (i.e. 15<sup>th</sup> date) of the respective month. Following this assumption, the twelve mean monthly  $ET_0$  data values were subjected to an equation fit. Again, the Sigma Plot computer software was used and the results revealed that this data set was also best-fitted by the Modified Gaussian 5-Parameters equation with  $r^2$  value equal to 0.99. In this thesis, the mean daily  $ET_0$  estimates obtained from

the curve-fit of mean monthly  $ET_0$  data are referred to as the *curve-fit mean daily  $ET_0$  from mean monthly  $ET_0$* . The graphical representation of original (or historical) mean daily  $ET_0$ , mean monthly  $ET_0$  and curve-fit mean daily  $ET_0$  from mean monthly  $ET_0$  data is given in Figure 3.11. As can be seen from this figure, the mean daily  $ET_0$  obtained from the mean monthly  $ET_0$  data follows the same pattern as in Figure 3.9. Figure 3.12 compares the curve-fitted mean daily  $ET_0$  estimates obtained from historical daily  $ET_0$  data and historical mean monthly  $ET_0$  data. The excellent agreement between the two mean daily  $ET_0$  curves (i.e. two curves coincide in this case) clearly indicates that in the absence of historical daily  $ET_0$  data, the mean monthly  $ET_0$  data can be successfully used to derive mean daily  $ET_0$  estimates for use in pre-season irrigation planning.



It is important to appreciate that in most irrigation systems the historical  $ET_o$  data are not available, instead mean monthly pan evaporation (mm/day) data are easily available. Hence, a study was conducted to investigate whether the historical mean monthly pan evaporation data can be used to compute the mean daily  $ET_o$  estimates. The use of mean monthly pan evaporation data to compute the mean daily  $ET_o$  estimates is discussed in the sub-section (ii).

**(ii) *Mean daily  $ET_o$  estimates from historical mean monthly pan evaporation data***

As indicated above, for computation of mean daily  $ET_o$  estimates, the mean monthly  $ET_o$  data can be used as the surrogate to the historical daily  $ET_o$ . As discussed in Section 3.6.3, the SEV method (which uses the pan evaporation data) can adequately estimate the daily  $ET_o$  estimates. Following this, it was expected that if mean monthly pan evaporation (mm/day) data were adjusted using a calibration coefficient (obtained through linear regression of mean monthly pan evaporation and mean monthly base method  $ET_o$  data sets), the resulting mean monthly pan evaporation values would then represent the mean monthly  $ET_o$  equivalent to the SEV method. Hence, in this study this assumption was tested.

For this purpose, the available three years (1991-1993) of daily pan evaporation data of Griffith were used. The corresponding three years of daily M\_Y (base method)  $ET_o$  data were also used. Based on these data, the mean monthly values for both (i.e. pan and  $ET_o$ ) data sets were obtained. The calibration coefficient ( $m$ ) was then obtained through the regression of these two mean monthly data sets. Thus, the coefficient  $m$  obtained in this case was equal to 0.99. The long term mean monthly pan evaporation for Griffith (based on an historical record of 30 years) was available from BOM. These BOM mean monthly pan evaporation data were adjusted using  $m$  value (to give SEV method  $ET_o$ ), and then were subjected to curve fit as per the technique described in subsection (i). Again, in this case, the Gaussian 5-parameters equation was found to best-fit this data set.

The graphical representation of the resulting mean daily  $ET_0$  estimates by SEV and the M\_Y methods is given in Figure 3.13(a) for Griffith. As can be observed from this figure, there was little under-estimation by the SEV method. This under-estimation was due to the reason that for derivation of  $m$  only three years data were used that were not enough to represent the long 30 years historical records of BOM. However, the pattern of the SEV method  $ET_0$  in this figure revealed that mean monthly pan evaporation data can also be successfully used for mean daily  $ET_0$  estimates. Hence, this leads to the conclusion that in the absence of historical  $ET_0$  data, the mean monthly pan evaporation data can also be used for mean daily  $ET_0$  estimates provided a representative  $m$  value is used.

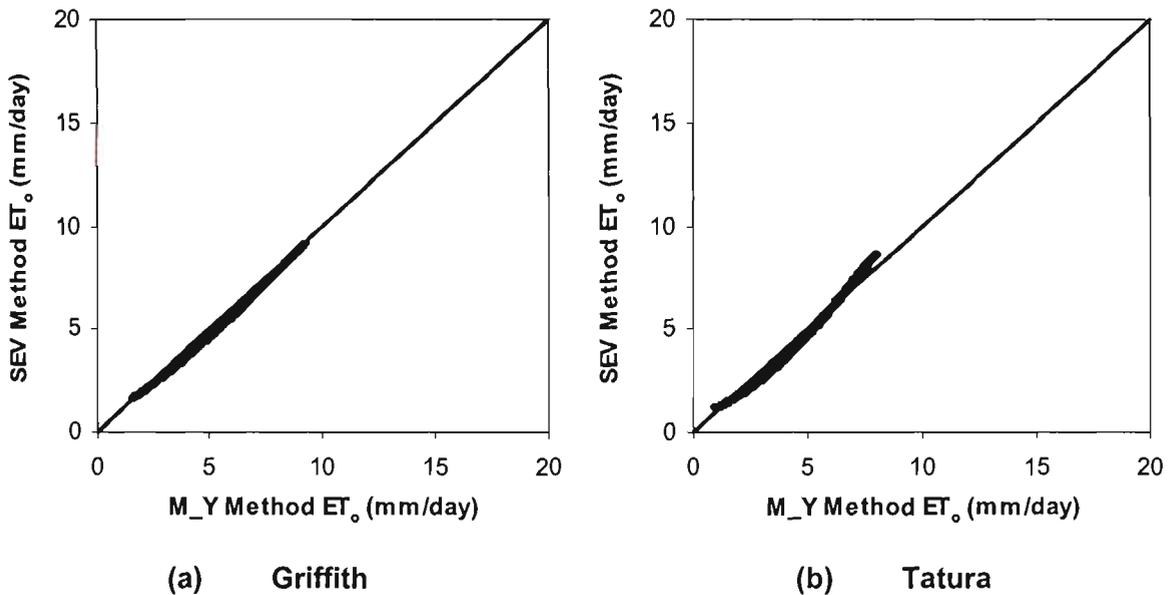


Figure 3.13 Mean Daily  $ET_0$  Estimates by M\_Y and SEV Methods

In order to substantiate the above aspect, the Tatura site was also investigated. The  $m$  value obtained in this case was 1.14. The graphical representation for Tatura is shown in Figure 3.13(b). This figure also supports the fact that in the absence of historical  $ET_0$  data, the mean monthly pan evaporation data can be used for mean daily  $ET_0$  estimates. This information is very useful for the pre-season irrigation planning of farms for which pan evaporation data are available at a nearby site as the only available data. In such cases, the  $m$  value from the nearby site can be used for mean daily  $ET_0$  estimates. As stated earlier, for Aspendale only three months data were

available, therefore no separate investigation was made on the use of mean monthly pan data for mean daily  $ET_0$  estimate.

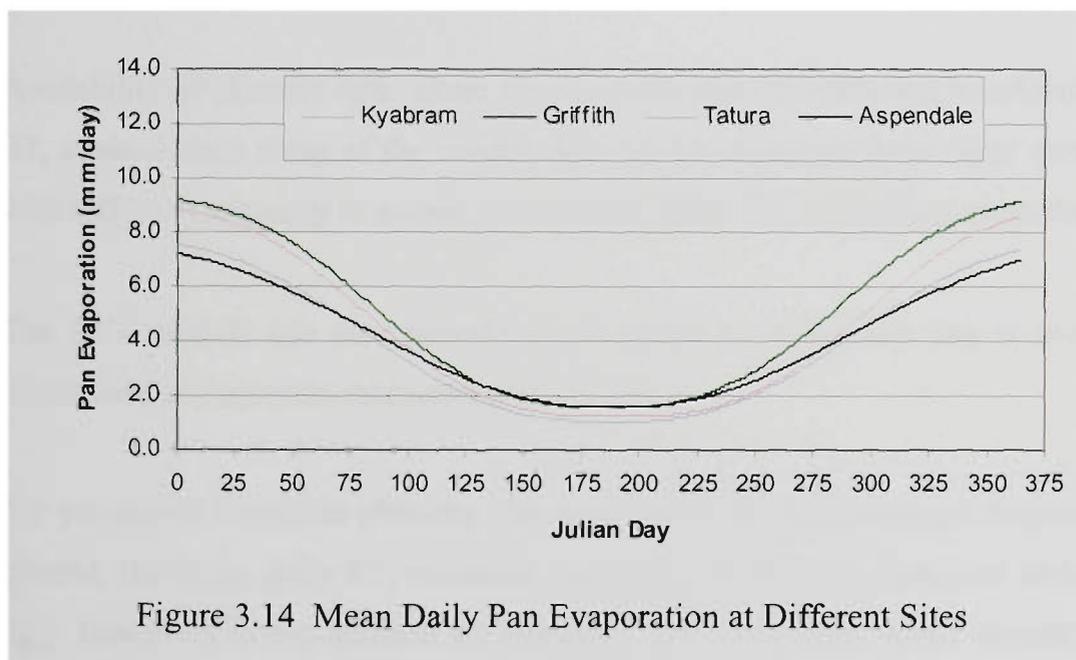
It is interesting to note that the aforementioned  $m$  values (for use with mean monthly SEV method) at both Griffith and Tatura are very similar to the over/under-estimation information shown by the daily SEV method at respective site. For example, at Griffith for SEV in Col. (2) of Table 3.8 the actual  $ET\%$  value of 100.1 (rounded to an integer value of 100) represents a slight over-estimation by the SEV method over *all months* period, indicating an adjustment factor of 0.99 (i.e.  $100/100.1$ ). Similarly, at Tatura for SEV in Col. (2) of Table 3.6, the  $ET\%$  value of 88 represents an under-estimation of 12% by SEV method, indicating an adjustment factor of 1.14 (i.e.  $100/88$ ). This leads to the conclusion that for mean daily  $ET_0$  estimates,  $m$  values can be approximated by  $100/ET\%$ . Hence, based on this concept the  $m$  value for Aspendale was estimated to be 0.96 (i.e.  $100/104$ ). This  $m$  value was then used for curve fitting at Aspendale, and subsequently for mean daily  $ET_0$  estimates. The resulting curve-fit parameters of mean daily  $ET_0$  estimates for Aspendale are given in Table 3.10.

**(iii) Mean daily pan evaporation for planning purpose**

As stated earlier in Section 3.5.4, in some irrigation systems the predominant practice for irrigation requirement (IR) estimates is to use the daily pan evaporation measurements instead of  $ET_0$  estimates. Hence, in this case for pre-season IR estimates, the mean daily pan evaporation is required. However, for most of the sites, the only easily accessible available data are mean monthly pan evaporation data from BOM. Therefore, following the same procedure as described earlier in sub-section (i) for  $ET_0$  estimates, the mean daily pan evaporation was estimated by curve fitting to the BOM historical mean monthly pan evaporation data. The curve fit parameters of mean daily pan evaporation for various sites are given in Table 3.11, where as the graphical representation of this is given in Figure 3.14. It is important to note that in Table 3.11 and Figure 3.14 an additional site namely Kyabram is also included. The reason for this is that the climatic data of Kyabram were used for validation of the irrigation scheduling model for a farm in Tongala (Victoria, Australia). The irrigation scheduling model is described in Chapter 5.

Table 3.11 Curve-fit Parameters for Mean Daily Pan Evaporation

Data Type	Equation Parameters	Aspendale	Tatura	Griffith	Kyabram
Mean Daily Pan Evaporation	$y_0$	7.88	7.88	9.44	9.11
	$a$	-6.32	-6.84	-7.86	-7.87
	$x_0$	188.28	187.65	185.40	189.61
	$b$	97.87	96.15	92.24	98.19
	$c$	2.30	2.68	2.78	2.94



### 3.6.5 Summary of Analysis

The study described in this chapter evaluated ten  $ET_0$  estimation methods commonly used to estimate daily reference evapotranspiration for use in short term irrigation planning and scheduling studies. Based on the analyses of the ten  $ET_0$  estimation methods at three sites in Victoria and NSW (Australia), the following conclusions were drawn:

- No single daily  $ET_0$  estimation method using meteorological data is satisfactory for all climatic regimes.
- Combination methods generally provide the most accurate  $ET_0$  estimates because they are based on physical laws and rational relationships.
- If measured lysimeter (or base method)  $ET_0$  data are available, the  $ET_0$  estimation methods must be locally calibrated against these data before they are used in irrigation scheduling studies.
- Depending upon the climatological situation of a specific site, a locally calibrated less data requiring simple  $ET_0$  estimation method may produce better results than a data extensive complicated  $ET_0$  estimation method.
- Availability of climatic data alone should not be the sole criterion in selecting an  $ET_0$  method since some of the needed data can be estimated from other variables with sufficient accuracy to permit the usage of better  $ET_0$  estimating methods.
- The SEV method can also provide good results provided that pan is properly maintained and accurate measurements are taken.
- For pre-season irrigation planning, the mean daily  $ET_0$  estimates are required. In general, the mean daily  $ET_0$  estimates can be obtained from historical daily  $ET_0$  data. However, in the absence of historical daily  $ET_0$  data, mean monthly pan evaporation data can also be safely used for computation of mean daily  $ET_0$  estimates.

### **3.7 REFERENCE CROP EVAPOTRANSPIRATION ESTIMATION COMPUTER SOFTWARE**

As found in Section 3.6.5, the combination methods generally provided the most accurate  $ET_0$  estimates, because they were based on physical laws and rational relationships. However, it was also found that no single daily  $ET_0$  estimation method

using meteorological data was satisfactory for all climatic regimes. Depending upon the climatic situation of a specific site, a locally calibrated less data requiring simple  $ET_0$  estimation method may also produce even better results than the data extensive combination methods. Furthermore, the availability of measured climatic data can also dictate the selection of an  $ET_0$  estimation method to be employed at the site under consideration. Thus, there is a need to develop a computer software to compute  $ET_0$  estimates with multiple choice of  $ET_0$  estimation methods to suit local conditions. Therefore, based on this concept, an  $ET_0$  estimation computer software (REF\_ET) was developed, as part of this thesis.

In this section, a brief description of REF\_ET package encompassing its salient features is described. The detailed description of the package including its installation, inputs, use and application is given in Appendix-A.

### **3.7.1 General Description of REF\_ET Computer Software**

The REF\_ET package was developed to compute daily  $ET_0$  estimates with multiple choice from ten different  $ET_0$  estimation methods. These methods range from simple temperature-based methods to complicated data extensive combination methods, as described in Section 3.2. These methods were evaluated using data from three different sites in Victoria and NSW (Australia) as described in Sections 3.3 to 3.6. While developing this package, a special consideration was given to its robustness, efficient computation, and user-friendliness. To achieve the above considerations, the ten  $ET_0$  estimation methods considered in the package were first coded in FORTRAN-77 to facilitate faster computations, and then menu-driven user interfaces developed to run under both DOS and Window environments.

The REF\_ET software is composed of a single computational component (ETO) written in FORTRAN-77 code, which is supported by a number of subroutines. The source codes of ETO and its supporting subroutines can be requested from the candidate. The flow chart of ETO is given in Appendix A.

The software requires measured climatic data on a daily basis as its major input. Since the availability of the measured climatic data can force the user to use specific  $ET_0$

estimation methods, a user-specified “priority order” option to use the desired  $ET_o$  estimation methods among the ten available was incorporated in this package. The package first attempts to compute  $ET_o$  estimates using the user-specified highest priority (i.e. highest ranked)  $ET_o$  estimation method. However, if the climatic data required for this method are not available, then the software uses the method having second highest priority, and so on. In this way, all ten  $ET_o$  methods are considered. Therefore, with this user-specified priority order option, there is a high likelihood that an  $ET_o$  estimate is computed for each day of the study period based on the user-specified  $ET_o$  estimation method subject to availability of data. However, if data are not available for a particular day for all preferred  $ET_o$  estimation methods, then  $ET_o$  estimation is not made for this day. It is important to note that in addition to this above stated “priority order” option, there is another option available in the package. Under this option, the REF\_ET package computes daily  $ET_o$  estimates for the study period using all ten  $ET_o$  methods at the same time, ignoring the user-specified priority order.

As stated earlier,  $ET_o$  methods also require local calibration for best performance under site specific conditions. Therefore, in order to make the package compatible under wide range of climatic conditions, the package was also provided with an option to accept a “local calibration coefficient” for each of these ten  $ET_o$  estimation methods. Therefore, the package is comprehensive to estimate daily  $ET_o$  for any climatic region.

### **3.8 CONCLUSIONS**

The reference crop evapotranspiration ( $ET_o$ ) is required to model the actual crop evapotranspiration or crop water use ( $ET_a$ ) for use in irrigation planning and scheduling studies, which are important in planning the short-term (i.e. 7-14 day) operation of irrigation systems. Empirical  $ET_o$  methods have been popular in recent times for these studies compared to direct lysimeter measurements because of high expense, laboriousness and complex instrumentations. However, these empirical  $ET_o$  methods should be evaluated at a site before their use.

There are numerous empirical methods available for estimating  $ET_0$  using climatic data. A study of ten  $ET_0$  estimation methods ranging from simple temperature-based to data extensive combination methods at three locations in Victoria and New South Wales, NSW (Australia) was carried out in terms of their performance for daily  $ET_0$  estimates under local conditions. The standard error of estimates (SEE) parameter was used as the evaluation parameter. An  $ET_0$  estimation method with lowest SEE was regarded as the best method. Based on the SEE parameter, the study revealed that combination methods generally provided the most accurate  $ET_0$  estimates. These methods are based on physical laws and rational relationships. However, the analyses also revealed that no single daily  $ET_0$  estimation method using meteorological data was satisfactory for all sites.

It was observed that all  $ET_0$  methods required local calibration against measured lysimeter (or base method)  $ET_0$  data for better performance. Depending upon the climatic situation of a specific site, a locally calibrated less data requiring simple  $ET_0$  estimation method can produce even better results than the data extensive combination method. The results also revealed that availability of climatic data alone should not be the sole criterion in selecting an  $ET_0$  method since some of the needed data can be estimated from other variables with sufficient accuracy to permit usage of better  $ET_0$  estimating methods. It was also observed that the simplified Class-A pan evaporation (SEV) method can provide good results provided that pan is properly maintained and accurate measurements are taken.

In some cases, the farm manager likes to know the approximate total irrigation requirement of a certain crop before the season starts, so that he/she can decide on the area to be cultivated. This is termed as pre-season planning in this thesis. For pre-season irrigation planning, the mean daily estimates of  $ET_0$  are required. In general, the mean daily  $ET_0$  estimates can be obtained from historical daily  $ET_0$  data. However, in the absence of historical daily  $ET_0$  data, mean monthly pan evaporation data can also be used to compute the mean daily  $ET_0$  estimates.

Based on the conclusion that no single daily  $ET_0$  estimation method using meteorological data was satisfactory for all sites, a user-friendly menu driven computer software (REF\_ET) was developed to compute daily  $ET_0$  estimates with

multiple choice from ten different  $ET_0$  estimation methods. These were the methods that were evaluated using data from three different sites in Victoria and NSW. An option to accept a “local calibration coefficient” for each of the ten  $ET_0$  estimation methods enables the REF\_ET package to estimate daily  $ET_0$  for any climatic region.

The  $ET_0$  estimates given by REF\_ET software can be effectively used for irrigation scheduling to save significant amount of irrigation water at a farm level. The package is also useful for extension agencies and other irrigation/research professionals.

## CHAPTER 4

### RAINFALL PREDICTION

#### 4.1 INTRODUCTION

As stated earlier (Section 2.1), the short-term (i.e. 7-14 day) planning and operation of irrigation systems via irrigation scheduling requires an estimate of irrigation water requirement (IWR). Since IWR is significantly influenced by rainfall, a reliable estimate of the expected rainfall in any irrigation period of the crop growing season is of fundamental importance. Efficient utilisation of rainfall during the rainy season will help in saving water in the storage reservoir that could be used in the dry season. This chapter deals with the prediction of short-term rainfalls.

The most common approach employed for predicting the expected amount of rainfall has been to fit an appropriate statistical distribution to the historical rainfall records. Fitting the series by an appropriate distribution has been researched quite extensively. The current standard practice is to use several distributions (e.g. log normal, log Pearson type-3, etc) to fit the data series (in most cases transforming the data series to fit a normal distribution using standard transformation functions), and then to use the statistical techniques such as chi-square test and/or Kolmogorov-Smirnov's test to study the adequacy of these fitting techniques. After fitting the series by an appropriate distribution, the expected rainfall is then predicted with a certain probability of exceedance (Buishand, 1978). A study of rainfall records at many locations in Thailand indicated that the short-term rainfall series were positively skewed and that there could be considerable number of non-rainy periods giving zero values in the data series (Phien et al., 1978). In Victoria, Australia (as will be shown later in Section 4.6.1), a similar pattern is observed.

In statistical analysis, difficulties arise in fitting a distribution to such data series which have zero values. There are three possible ways to resolve these difficulties:

- (i) Analyse non-zero values and fit the distribution
- (ii) Add a small constant to all observations and fit the distribution
- (iii) Use the methods that account for zero values

Among the three options listed above, option (i) appears to be illogical because it biases the results as the zeros are essentially ignored. Hence it was rejected from further consideration in this study.

The option (ii) although seems sound, also biases the results theoretically because the original data are modified (Haan, 1977). However, if the value of the constant added to the original data series is very small, then it would not bias the data significantly. If 0.2 mm rainfall is added to the original rainfall data series, it would not have any appreciable impact on the data series and subsequently in IWR. Therefore, in this study, this option (i.e. adding 0.2 mm to all observations of the series) was also tested.

With regards to option (iii), as discussed in Section 2.4.2, there is no clearly superior probability distribution that is regarded as the best distribution for rainfall series having zeros. However, the total probability theorem (TPT) and leaky law (LL) methods hold the most promise to fit the short-term rainfall series having zero values (Section 2.5.3). Therefore, these two methods were selected for this study. These methods were tested for their suitability to predict the short-term rainfall of 7-14 day duration under Victorian (Australia) conditions.

The first part of this chapter describes the theoretical details of the above two statistical methods selected for this study. This is followed by a discussion of the analysis of short-term rainfall data series at three selected sites in Victoria, Australia, using these two methods. A rainfall prediction computer software (RAIN\_PRE) developed as part of this

study based on the aforementioned two methods is presented at the end of this chapter. The operational details of RAIN\_PRE package are given in Appendix B.

## 4.2 Total Probability Theorem (TPT)

Haan (1977) proposed the total probability theorem (TPT) approach for the analysis of data series having zero values. In this approach, zero and non-zero values are analysed separately, and then combined together through a joint/conditional probability function. According to the TPT

$$P(X \geq x) = [ \{P(X = 0) P(X \geq x | X = 0)\} + \{P(X \neq 0) P(X \geq x | X \neq 0)\} ] \quad (4.1)$$

In Eq. 4.1, the series is broken into two parts viz.: zero and non-zero. The first term on the right hand side of this equation represents the zero data, and the second term represents the non-zero portion of the data series.

Since  $P(X \geq x | X = 0)$  is zero, Eq. 4.1 becomes

$$P(X \geq x) = P(X \neq 0) P(X \geq x | X \neq 0) \quad (4.2)$$

The standard notation of probability applies to Eqs. 4.1 and 4.2, in which  $X$  is the rainfall variable.  $P(X \neq 0)$  can be estimated by the fraction of non-zero values, and  $P(X \geq x | X \neq 0)$  can be estimated by a standard statistical analysis of the non-zero values, with the sample size taken to be equal to the number of non-zero values.

As a function of cumulative probability distribution, Eq. 4.2 can be rewritten as:

$$1 - P_x(X) = N [1 - P_x^*(X)] \quad (4.3a)$$

or

$$P_x(X) = 1 - N [1 - P_x^*(X)] \quad (4.3b)$$

where  $P_x(X)$  = cumulative probability distribution of all X (including zeros)  
 [i.e.  $P(X \leq x | X \geq 0)$ ].

N = probability that X is not zero.

$P_x^*(X)$  = cumulative probability distribution of non-zero values of X  
 [i.e.  $P(X \leq x | X \neq 0)$ ].

The best results using Eq. 4.3 can only be obtained if a sound probability distribution is selected for non-zero values. This aspect is briefly discussed in the following section.

#### 4.2.1 Probability Distribution of Non-Zero Data Series

Most non-zero hydrological data are highly skewed especially in Australia because of high climatic variability, and the normal distribution does not provide a good fit for these data. The popular approach adopted to overcome this problem is either to fit the available distributions to obtain a good fit or to transform the variable values to fit a normal distribution. Various distributions and transformations (e.g. power, and log) have been suggested by Yevjevich (1972) and other hydrologists for this purpose. However, there is no clearly a superior distribution to fit a data series with non-zero values to suit all applications (Benson, 1968; and Khaliq, 1995). Hence, it is often convenient to seek the normalisation by transformation in order to utilise the simple properties of normal distribution function (Aldabagh et al., 1982). Therefore, two commonly used normalising transformations namely power and log were employed in this study. Since square root transformation appears to satisfactorily model the short-term rainfall data series, it was also used in this study. These three transformations are given below.

(i) **Power Transformation**

This transformation (Box and Cox, 1964) transforms the data into a normal distribution as follows:

$$y = (x^\lambda - 1)/\lambda \quad \text{for} \quad \lambda \neq 0, \quad x > 0 \quad (4.4)$$

$$y = \ln x \quad \text{for} \quad \lambda = 0, \quad x > 0 \quad (4.5)$$

- where  $x$  = variable of the given data series  
 $y$  = transformed variable, which has a normal distribution  
 $\lambda$  = a constant of transformation

The proper value of  $\lambda$  is the that value producing a transformed sample with skewness coefficient ( $C_s$ ) and excess coefficient ( $\varepsilon$ ) equal to zero. The maximum likelihood method or iterative process may be used to estimate the desired value of  $\lambda$ . Once  $\lambda$  is determined for the data set, for a given probability level  $\alpha$ , the transformed variable  $y_\alpha$  can be determined, and then the corresponding probable value of  $x_\alpha$ , i.e.  $P(X \leq x_\alpha) = \alpha$ , can be determined by the following procedure:

Considering  $P(Y \leq y_\alpha) = P[(x^\lambda - 1)/\lambda \leq y_\alpha] = \alpha$ , it follows that

$$P[X \leq (\lambda y + 1)^{1/\lambda}] = \alpha \quad (4.6)$$

Hence, for the given probability level  $\alpha$ , the probable value of  $x_\alpha = (\lambda y_\alpha + 1)^{1/\lambda}$ , where  $y_\alpha$  = probable value for the normal variable  $Y$  at the given probability level  $\alpha$ .

**(ii) Log Transformation**

This transformation is essentially a sub-set of the power transformation for which  $\lambda = 0$ . According to this:

$$y = \ln x \tag{4.7}$$

where  $x$  = variable of the given data series

$y$  = transformed variable

For a given probability level ( $\alpha$ ) of  $y$  variable ( $y_\alpha$ ), the corresponding probable value of  $x$  variable ( $x_\alpha$ ) can be found as:

$$x_\alpha = \exp(y_\alpha) \tag{4.8}$$

**(iii) Square Root Transformation**

This transformation considers the square root of the original variable values to produce the transformed variables as follows:

$$y = \sqrt{x} \tag{4.9}$$

where  $x$  = variable of the given data series

$y$  = transformed variable

If the square root transformation fits a certain data set, then for the specified probability level ( $\alpha$ ), the transformed variable  $y_\alpha$  can be determined. Then, the value of  $x_\alpha$  of the original series for the same probability level can be determined from:

$$x_\alpha = y_\alpha^2 \tag{4.10}$$

## 4.2.2 Normality Criteria

Once a transformation function is used to normalise data, it is necessary to check that the transformed data are normal. In order to test the normality of a data series, the skewness coefficient ( $C_s$ ) and excess coefficient ( $\varepsilon$ ) have been used in the past (Aldabagh et al., 1982). For a completely normalised data set both  $C_s$  and  $\varepsilon$  should be equal to zero. However, Yevjevich (1972) proposed the values of tolerance  $\pm 0.05$  from zero for  $C_s$ . Bowman (1973) recommended that if a data set with size  $n$  falls within the range of  $\pm 1.96\sqrt{6/n}$  and  $\pm 1.96\sqrt{24/n}$  for  $C_s$  and  $\varepsilon$  respectively, then the normality assumption holds for that data set. Phien et al. (1982) proved that Bowman's recommendations could be used with 95% confidence level. In this study, Bowman's recommendations were adopted. The aforementioned  $C_s$  and  $\varepsilon$  statistical parameters required for testing the normality criteria can be estimated by using the following equations, which are given in standard statistical text books (e.g. Haan, 1977).

### *Coefficient of Skewness ( $C_s$ )*

$C_s$  defines the extent of symmetry of a probability distribution. For a sample with  $n$  observations:

$$C_s = \frac{n^2 M_3}{(n-1)(n-2) S^3} \quad (4.11)$$

where  $M_3 = \frac{\sum_{i=1}^n (x_i - \bar{x})^3}{n}$

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n}$$

$n$  = no. of observations

The sample variance ( $S^2$ ) statistical parameter for use in Eq. 4.11 can be estimated as:

$$S^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)} \quad (4.12)$$

### ***Coefficient of Excess ( $\varepsilon$ )***

It is defined as:

$$\varepsilon = (C_k - 3) \quad (4.13)$$

where  $C_k$  = coefficient of kurtosis.

$C_k$  refers to the extent of peakedness (or flatness) of a probability distribution. For a normal distribution  $C_k = 3.0$ . An unbiased estimate of  $C_k$  can be estimated as:

$$C_k = \frac{n^3 M_4}{(n-1)(n-2)(n-3) S^4} \quad (4.14)$$

where  $M_4 = \frac{\sum_{i=1}^n (x_i - \bar{x})^4}{n}$

### **4.2.3 Normal Distribution**

With a transformation function, as discussed in Sections 4.2.1 and 4.2.2, the data set can be fitted with a normal distribution. The characteristic of the normal distribution is briefly discussed below.

If  $X$  is continuous random variable, which can be fitted with a normal distribution, then its probability density function (pdf) is defined as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \quad \text{for } -\infty < x < \infty \quad \text{and} \quad \sigma > 0 \quad (4.15)$$

where  $\mu$  = mean

$\sigma^2$  = variance

For computational convenience, it is usually customary to standardise every normally distributed random variable  $X$  (with mean =  $\mu$  and variance =  $\sigma^2$ ), into a new normal random variable with zero mean and unit variance by using the following expression:

$$Z = (x - \mu)/\sigma \quad Z : N(0,1) \quad (4.16)$$

where pdf of  $Z$  is defined as:

$$f(z) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-z^2}{2}\right) \quad \text{for } -\infty < z < \infty \quad (4.17)$$

Thus,

$$P(Z \leq z) = F(z) = \frac{1}{2\pi} \int_{-\infty}^z \exp\left(-t^2/2\right) dt \quad (4.18)$$

where  $F(z)$  = cumulative probability distribution function of  $Z$ .

Values of  $F(z)$  can be found in many statistical books in tabular form. However, for computerised calculations, Moran (1980) presented the following formula for estimation of  $F(z)$ :

$$F(z) = \frac{1}{2} + \frac{1}{\pi} \left\{ \frac{z}{3\sqrt{2}} + \sum_{n=1}^{\infty} n^{-1} e^{-n^2/9} \sin\left(\frac{nz\sqrt{2}}{3}\right) \right\} \quad (4.19)$$

In this study, Moran (1980) formula has been adopted while fitting the normal distribution.

#### 4.2.4 High Outliers

In statistical analysis, difficulty often arises in fitting a distribution to a certain data series that has outliers in it. Outliers are defined as those extreme events that depart significantly from the trend of the remaining observed data. The retention or deletion of these values can appreciably affect the fitted distribution and estimates made from it (Pilgrim and Doran, 1987). As will be shown later in Section 4.6.3, the short-term rainfall data series used in this study contain high outliers (hereafter referred to as outliers) in them. Thus, the identification and treatment of these outliers are very important, and hence are discussed below.

A wide variety of procedures for identifying and treating outliers involving statistical tests was reviewed by Barnett and Lewis (1980) and Thomas (1985). According to Barnett and Lewis, the test presented by Walsh (1959) to identify the outliers (i.e. exceptionally high rainfall events) has the advantage of being easy to apply among other tests and its acceptable accuracy. Therefore, in this study this test was employed to check the presence of outliers in the short-term rainfall data series. Thus if an outlier is detected, it would be removed before transforming and/or fitting a distribution to that data series. Justification for removing outliers can be explained by the fact that in irrigation scheduling studies, one is not interested in the extremely high rainfall events, since high rainfall events result in heavy surface runoff after the soil has been saturated. This surface runoff is of no use for the crops. In addition, for irrigation scheduling, the exceedance probability adopted for rainfall predictions is usually above 40% (Siddeek et al., 1989). Since in most cases the exceedance probability possessed by outliers is less than 10% (as

will be shown later in Section 4.6.4), the rainfall predictions made at exceedance probability of 50% and above would not be significantly affected if the outliers are removed. The Walsh outliers test is described below in steps.

(i) If  $X$  represents a data series of sample size  $n$  in descending order, then assume a certain number of outliers ( $k$ ) for this sample. Start  $k$  with a high value for outliers.

(ii) Use Eq. 4.20 to compute  $K$  for a given significance level ( $\alpha$ ):

$$K = \frac{1}{\sqrt{\alpha}} \quad (4.20)$$

(iii) Compute  $A$  from Eq. 4.21 as:

$$A = \frac{1 + K \sqrt{\frac{(\sqrt{2n} - K^2)}{(\sqrt{2n} - 1)}}}{(\sqrt{2n} - K^2 - 1)} \quad (4.21)$$

(iv) Compute  $s$  from Eq. 4.22 as:

$$s = k + \sqrt{2n} \quad (4.22)$$

(v) Use Eq. 4.23 to compute the Walsh test parameter ( $S$ ) as:

$$S = x_{(n+1-k)} - (1 + A) x_{(n-k)} + A x_{(n+1-s)} \quad (4.23)$$

(vi) Finally:

- if  $S > 0$ , then the assumed  $k$  is correct, i.e., the top  $k$  data values are declared as the outliers. Hence, those data values are removed from the original data series.

- if  $S \leq 0$ , then assumed- $k$  is not correct. Hence, reduce the assumed- $k$  value by one, and repeat the above steps (i) – (vi) until  $S > 0$ .

It is important to note that in the Walsh (1959) test, it is desired to specify the number of suspected outliers before the test is applied. Thus in this study, an arbitrary value of  $k$  was specified as input, and the test was programmed to come up with a correct value of  $k$ .

### 4.3 LEAKY LAW (LL)

The leaky law (LL) is a mixed distribution to analyse data series having zero values with a finite probability of occurrence. This distribution consists of a probability mass at zero and a continuous distribution for positive values (Buishand, 1977).

If  $X$  is a mixed variable (with zero and non-zero values) that follows a leaky law with parameters  $\rho$  and  $\Theta$ , then its probability distribution can be written as:

$$P(X \leq x) = \exp(-\Theta) + \exp(-\Theta) \int_0^x \sum_{k=1}^{\infty} \frac{(\rho\Theta)^k t^{k-1}}{(k-1)!} \frac{\exp(-\rho t)}{k!} dt, \quad x \geq 0 \quad (4.24)$$

In Eq. 4.24, the first term on the right hand side represents the probability of zero values in the data series, and the second term represents the probability of non-zero values. Equation 4.24 can be expressed in terms of the modified Bessel function of order 1 ( $I_1$ ) as:

$$P(X \leq x) = \exp(-\Theta) + \int_0^x \exp(-\Theta - \rho t) \sqrt{\frac{\rho\Theta}{t}} I_1(2\sqrt{\rho\Theta t}) dt, \quad x \geq 0 \quad (4.25)$$

After integration, Eq. 4.25 yields the probability density function (pdf) as:

$$f(x) = \exp(-\Theta - \rho x) \sqrt{\frac{\rho \Theta}{x}} I_1(2\sqrt{\rho \Theta x}), \quad x \geq 0 \quad (4.26)$$

There are two techniques available for estimating the  $\rho$  and  $\Theta$  parameters of leaky law. These techniques are the method of maximum likelihood and the method of moments. The method of maximum likelihood is generally accepted as the most efficient procedure for estimation of the parameters. However, the estimation of these parameters by this method is generally complex. The method of moments is a relatively simpler procedure than the method of likelihood. This method estimates the values of LL parameters with reasonable accuracy (Phien et al., 1978). Hence, this method was selected for this study. The details of the leaky law distribution and the parameter estimation procedures are presented in Buishand (1977).

Based on the method of moments, the parameters  $\rho$  and  $\Theta$  can be estimated as follows:

$$\rho = 2\bar{X}/S^2 \quad (4.27)$$

$$\Theta = \rho\bar{X} \quad (4.28)$$

where  $S^2$  = sample variance

$\bar{X}$  = sample mean.

$S^2$  can be estimated using Eq. 4.12.

#### 4.4 SELECTION OF AN APPROPRIATE DISTRIBUTION METHOD

As discussed earlier, TPT (with multiple choice of transformations for modelling non-zero data values) and LL methods were selected in this study for the analysis of short-

term rainfall data series. When several probability distributions are used to model certain data series, it is possible that more than one distributions adequately fit the data series. As shown later in Section 4.6.5, this was the case with the data series analysed in this study. Therefore, it is necessary to choose the best method for the particular data series carefully.

Yevjevich (1972) suggested that the evaluation of distribution functions should be done using some objective goodness-of-fit criteria, such as the chi-square and Kolmogorov-Smirnov tests. Law and Kelton (1991) reported that the Kolmogorov-Smirnov (K-S) test is more powerful than the chi-square test for many distributions. Another feature of the K-S test is that it can be effectively applied to continuous random variables. The short-term rainfall data series mimic a continuous random variable. For these reasons, the K-S test was adopted in this study for the selection of an appropriate distribution method (TPT & LL). This test is described in Section 4.4.2.

It is important to mention that in the K-S test, it is usually customary to compare the non-exceedance probability of each rainfall observation (including zeros) using the selected distribution method  $[F(x_i)]$  with that of calculated from an empirical plotting position formula ( $p_i$ ). Many plotting position formulae have been proposed in the past. A useful review of these formulae is given in Benson (1969) and Viessman et al., (1972). Although each plotting position formula has some theoretical interpretation, the choice of which to use appears to be largely a matter of personal taste (Nathan, 1990). For the analysis of hydrological data, the Weibull plotting position formula has been widely used (McMahon and Mein, 1986). Therefore, in this study, the Weibull plotting position was adopted. This is described in Section 4.4.1.

#### **4.4.1 Weibull Plotting Position**

In this method, data are arranged in the order of magnitude in ascending order, and the non-exceedance probability of each observation is computed from Eq. 4.29 as:

$$p_i = \frac{i}{(n+1)} \quad (4.29)$$

where  $p_i$  = non-exceedance probability of observation with rank  $i$  (fraction, between 0 and 1)  
 $i$  = rank number  
 $n$  = total number of data

#### 4.4.2 Kolmogorov-Smirnov (K-S) Test

For the selection of the best suited distribution method (among various distribution methods), the methodology followed in this study is given below:

- Arrange the sample rainfall data series ( $X$ ) of size  $n$  in ascending order.
- Assign the rank  $i$  to observation  $x_i$ .
- Compute the non-exceedance probability ( $p_i$ ) of each observation with rank  $i$  using the Weibull formula as given in Eq. 4.29.
- Compute the non-exceedance probability,  $F(x_i)$  of each observation with rank  $i$  using the selected distribution method.
- Compute the D-statistic of the K-S test considering all observations from:

$$D = \max |F(x_i) - p_i| \quad \text{for } i = 1, 2, 3, \dots, n \quad (4.30)$$

- Compare the calculated D-statistic with the tabulated value. If the calculated D-statistic is less than the tabulated value, then the selected distribution method is qualified to fit the rainfall data series under consideration. Otherwise, the selected distribution method is rejected.

- In case if more than one distribution method qualify to fit the same rainfall data series, then the distribution method with the lowest value of D-statistic is selected as the best suited method for that data series in this study (Personal communication with Neil Diamond, 1998).

## **4.5 STUDY SITES AND ANALYSIS OF DATA**

### **4.5.1 Study Sites**

The theoretical considerations outlined in Section 4.2 through 4.4 were employed for the analysis of short-term rainfall data series at three rainfall stations in the Goulburn-Murray Irrigation Area (GMIA) of Victoria (Australia), which is one of the largest irrigation development projects in Australia. A brief introduction of this area has already been given in Chapter 1. The three rainfall stations considered were Tongala, Tatura and Pyramid Hill. These rainfall stations are shown in Figure 4.1, with their geographical details in Table 4.1. The rainfall stations studied in this chapter are marked by “\*” in Figure 4.1. As shown in Table 4.1, long records of rainfall records were available at the stations and these rainfall data were collected from the Bureau of Meteorology (BOM), Australia.

### **4.5.2 Irrigation Season and Rainfall Series**

In GMIA, the irrigation season normally starts on mid-August (say 15-Aug) of a year and terminates on mid-May (say 15-May) in the following year. During this irrigation season, three climatic seasons viz., spring (Sep-Nov), summer (Dec-Feb) and autumn (Mar-May) are observed. A regional scale study of rainfall records of this area revealed that the average annual rainfall of GIA ranged between 345-509 mm (RWC, 1988). Among the three climatic seasons, the maximum rainfall occurs during the spring season, relatively less during the autumn and least during the summer season. A typical rainfall pattern in the GIA during the irrigation season is shown in Figure 4.2. Rainfall in this figure is expressed as a percentage of average seasonal rainfall to the average rainfall of the

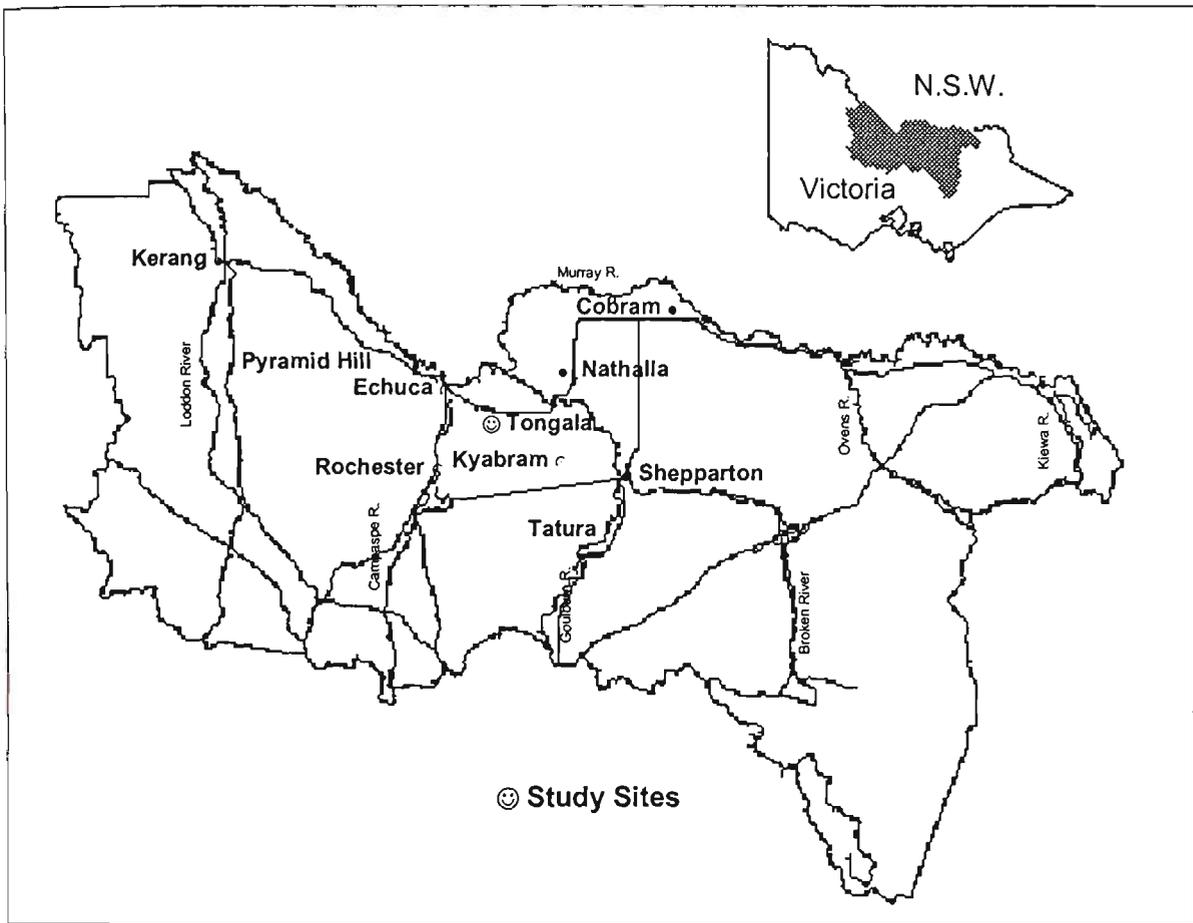


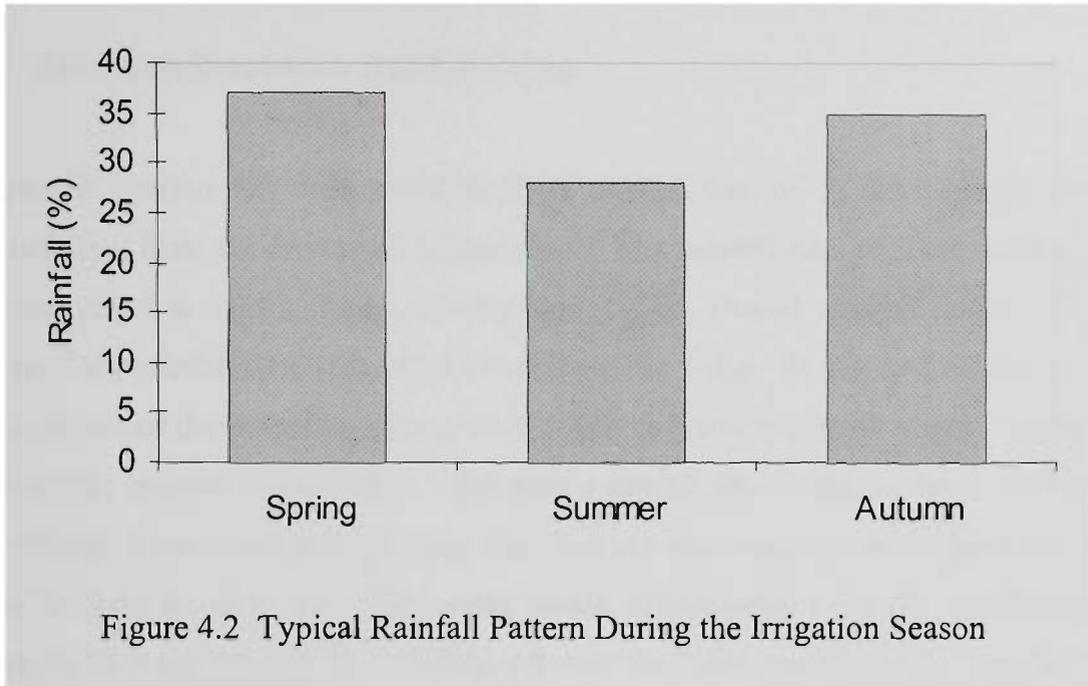
Figure 4.1 Rainfall Stations Selected for Analysis

Table 4.1 Geographical Details of Rainfall Stations

Station	Southern Latitude	Eastern Longitude	Altitude (m)	Rainfall Record
Tongala	36° 15'	144° 57'	100.1	1929 – 1987 (59 Years)
Tatura	36° 26'	145° 16'	114.0	1884 – 1992 (109 Years)
Pyramid Hill	36° 04'	144° 08'	90.0	1941 – 1992 (52 Years)

Source: Bureau of Meteorology, Australia.

irrigation season. Here, the irrigation season consists of all three climatic seasons (i.e. spring, summer and autumn).



Traditionally, the irrigation interval ranges from 7-14 days in the GIA depending on the local soil, crop and climatic conditions. If the irrigation interval is 14 days, then the entire irrigation season is comprised of approximately twenty 14-day irrigation periods. Since irrigation can begin any time after 15-Aug depending on the rainfall conditions before the start of the irrigation season, the proposed rainfall prediction methodology should be flexible enough to predict rainfalls for various irrigation periods starting from any day of the irrigation season. Depending upon the distribution of rainfall, the rainfall predictions (and therefore the irrigation requirements) will vary for different irrigation periods beginning on different days. For instance, the rainfall prediction for the irrigation period beginning on Aug-15 would differ from that of the period beginning on Aug-16. Predictions of rainfall should therefore, be made for all possible periods of irrigation season starting from Aug-15. Through this approach, there would be approximately two hundred and eighty 14-day series to be analysed for rainfall predictions, covering the irrigation season between 15-Aug and 15-May. In order to cover the reasonable range of

irrigation intervals observed in the study area in terms of rainfall predictions, 7-day, 10-day and 14-day rainfall series were analysed in this study.

## **4.6 ANALYSIS, RESULTS AND DISCUSSION**

### **4.6.1 Zeros and Short-term Rainfall Series**

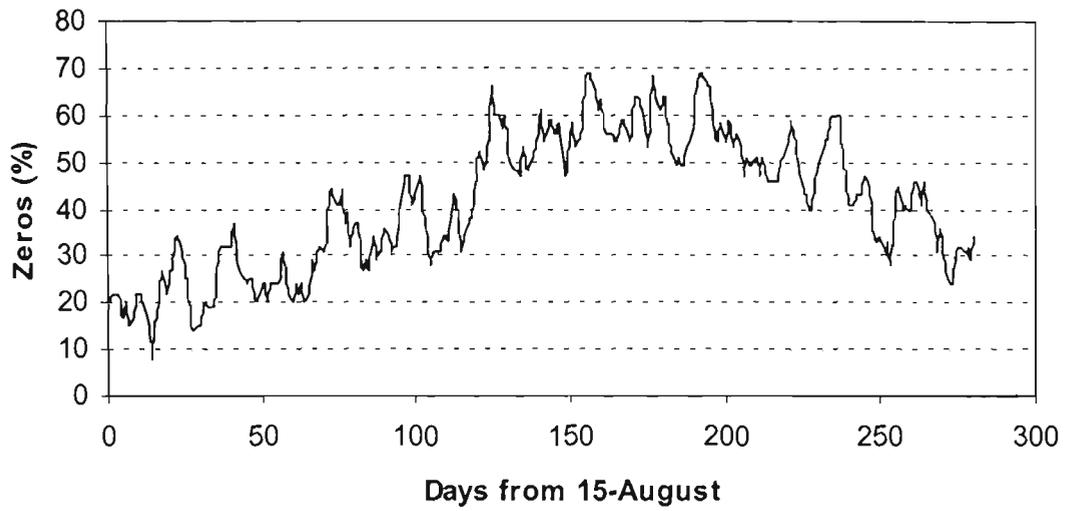
As stated in Section 4.5.1, the available daily rainfall data of all three rainfall stations were collected from the Bureau of Meteorology. The rainfall data of these three stations were processed to create 7-day, 10-day and 14-day period rainfall series. For this purpose, daily rainfall data were used to compute the 7-day, 10-day and 14-day rainfalls for all periods of the irrigation season with 1-day shift starting from Aug-15 to May-15. For example, in order to create the 7-day period rainfall series starting from 15-Aug, the daily rainfall from 15-Aug to 21-Aug (i.e. 7-days) was summed up to give the 7-day rainfall total for the first year of historical record. This rainfall value (i.e. rainfall sum of 15-Aug to 21-Aug) formed the first data value of the 7-day rainfall series. Similarly, for second data value, the daily rainfall of the same period (i.e. from 15-Aug to 21-Aug) was summed up using the second year. This process was repeated for all available historical records of the respective station. Hence, in this way the 7-day rainfall series starting from 15-Aug was created at the respective station. Similarly, the next 7-day rainfall series (starting from 16-Aug) was obtained by summing up the daily rainfall from 16-Aug to 22-Aug (i.e. 7-days) for all available years. Following this procedure (i.e. with 1-day shift starting from Aug-15 to May-15), the 7-day rainfall series for all periods of the irrigation season were computed at the respective station. Through this approach approximately two hundred and eighty 7-day rainfall series were created for each station. For other short-term (i.e. 10-day and 14-day period) rainfall series, the same approach was adopted, and 280 and 266 series were obtained for 10-day and 14-day series respectively.

It is worth mentioning that in this analysis, an irrigation period (i.e. 7-, 10- or 14-day period) with zero rainfall in one year was referred to as a dry-period. Furthermore, a rainfall series with equal or greater than 60% of dry periods (i.e. zero values) was

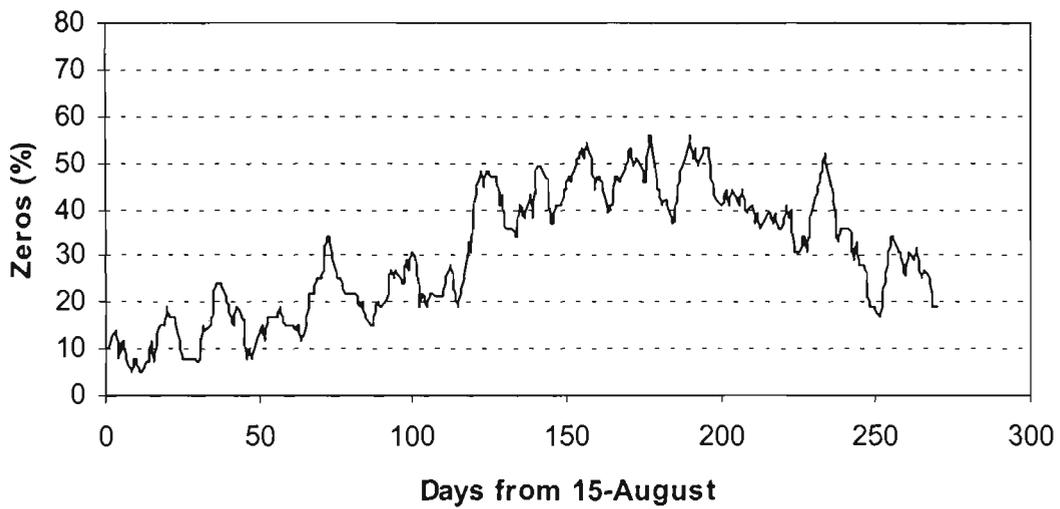
considered as a dry series. The 60% zero value was an arbitrary criterion, used in this study to declare a rainfall series as a dry series. For a dry series, zero rainfall prediction was assumed in this study. Based on these definitions, it was observed that almost all data series had zero values ranging from 1-69%. The number of zeros in various short-term rainfall data series at the Tongala station are shown in Figure 4.3. The zeros in Figure 4.3 are presented as a percentage of total number of years of rainfall records at the site.

As can be observed from Figure 4.3, the distribution of zeros at Tongala during the irrigation season is variable. At the beginning of the irrigation season, the zeros are less, which then gradually increase to high values, and then again start to decline as the season progresses. Figure 4.3 reveals that the 7-day rainfall data series have relatively more zeros than the 10-days series, and the 10-day series have relatively more zeros than the 14-day data series. This is not surprising because as the period length (in days) increases, the probability of having zeros also decreases. The range of zeros for 7-day, 10-day and 14-day data series was 9-69%, 5-55% and 1-43% respectively.

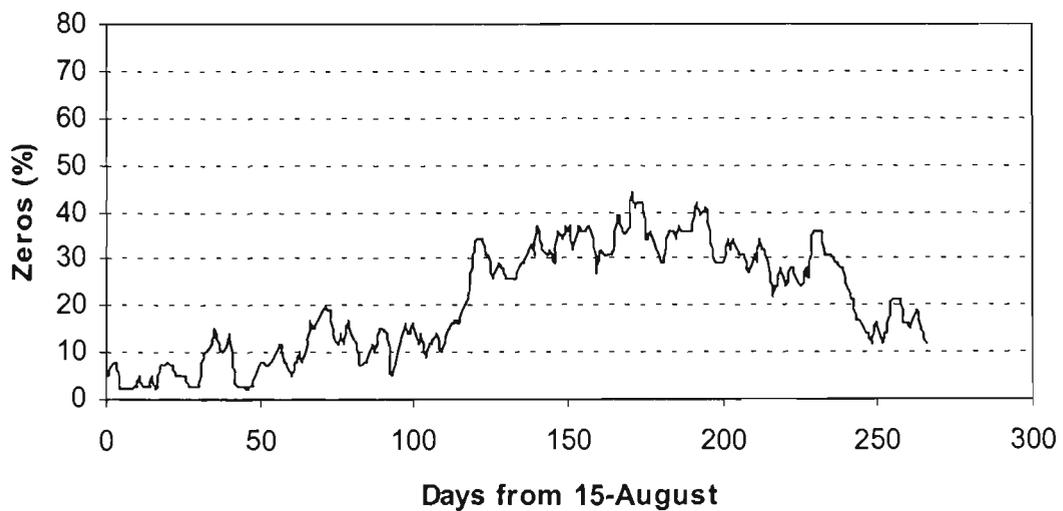
The trend of zeros shown in Figure 4.3 for Tongala mimics the overall pattern of rainfall distribution during the irrigation season which is shown in Figure 4.4. This figure shows the average 7-day, 10-day and 14-day rainfalls for various days of the irrigation season starting from 15-August. As shown in this figure, the short-term rainfall is relatively high at the beginning of the season, and then becomes lesser as the season reaches approximately 120-days from 15-August. This 120-days corresponds to mid-December, which is close to the start of the summer season and is characterised with the least amount of rainfall in the Tongala area. Followed by the end of summer season (i.e. approximately 210-days from 15-August), which is the start of autumn, an increasing trend of rainfall distribution can also be observed from this figure. A similar pattern of zeros and the rainfall distribution exists for Tatura and Pyramid Hill. This is shown in Figures 4.5 - 4.8. It is important to note that in Figures 4.4, 4.6 and 4.8 some of the rainfall distribution graphical lines are not continuous. This is due to the reason that on these occasions the daily rainfall data were not available (i.e. missing).



(a) 7-day Series



(b) 10-day Series



(c) 14-day Series

Figure 4.3 Number of Zeros in Various Short-term Rainfall Data Series at Tongala

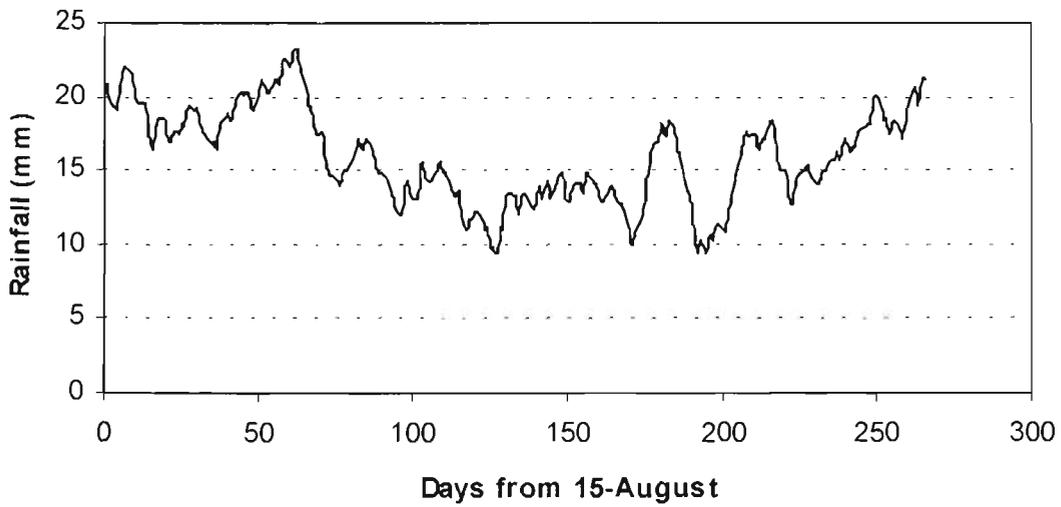
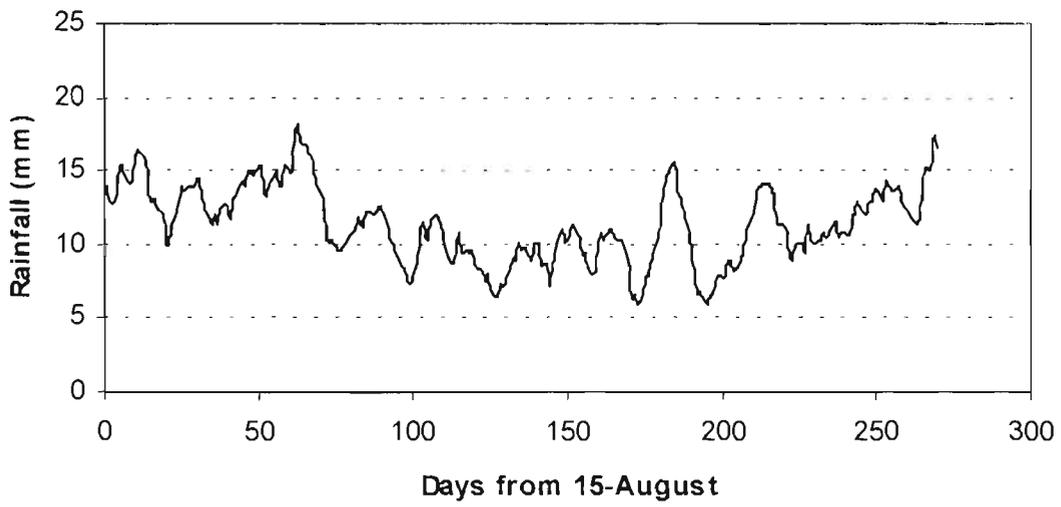
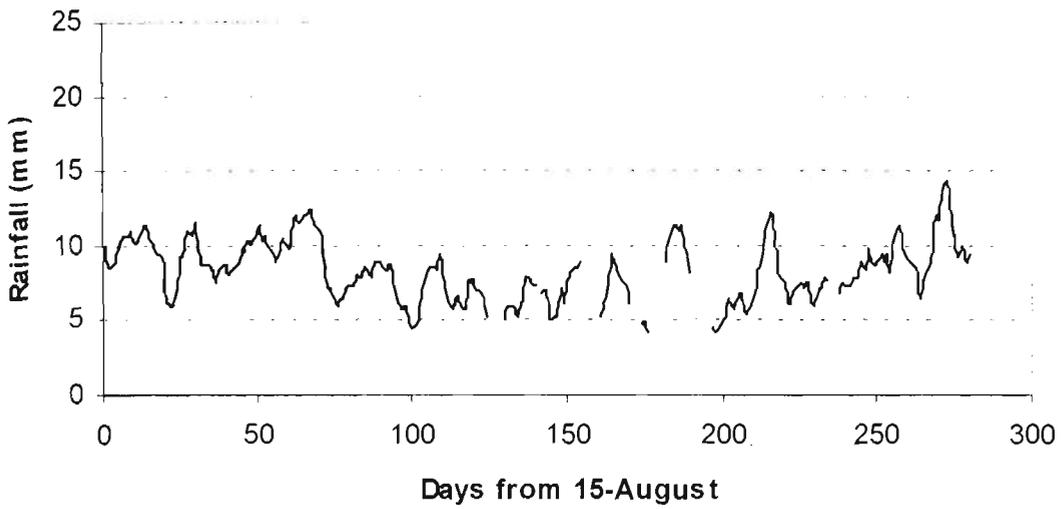
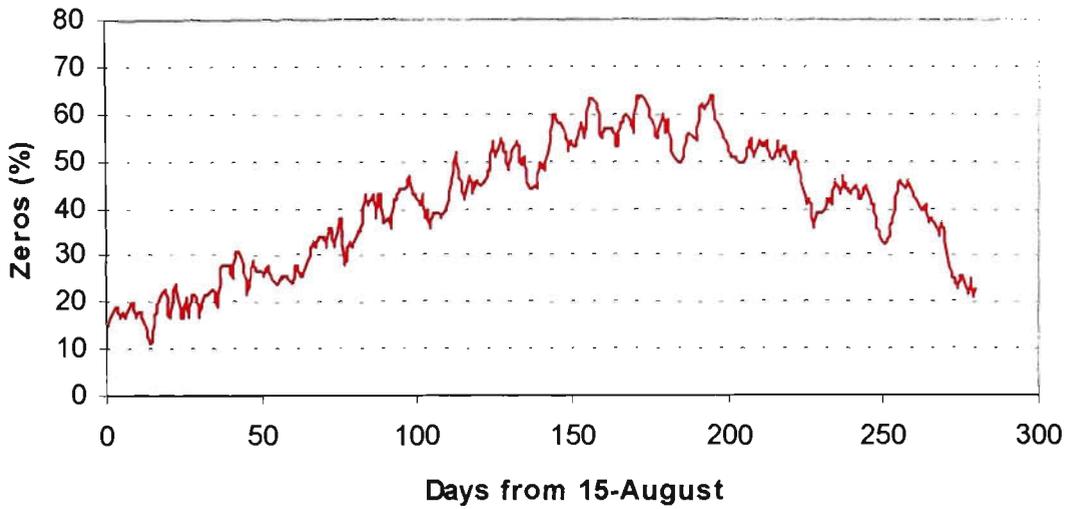
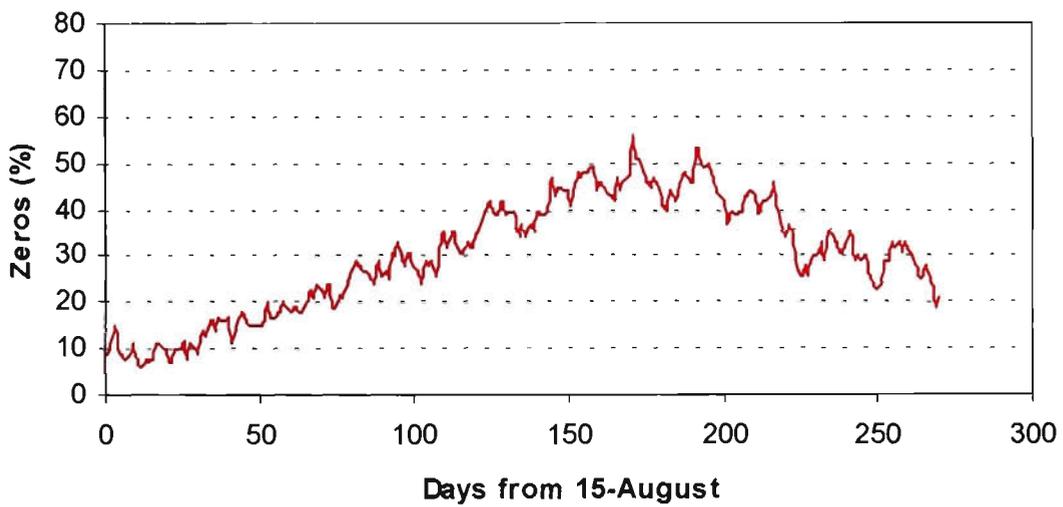


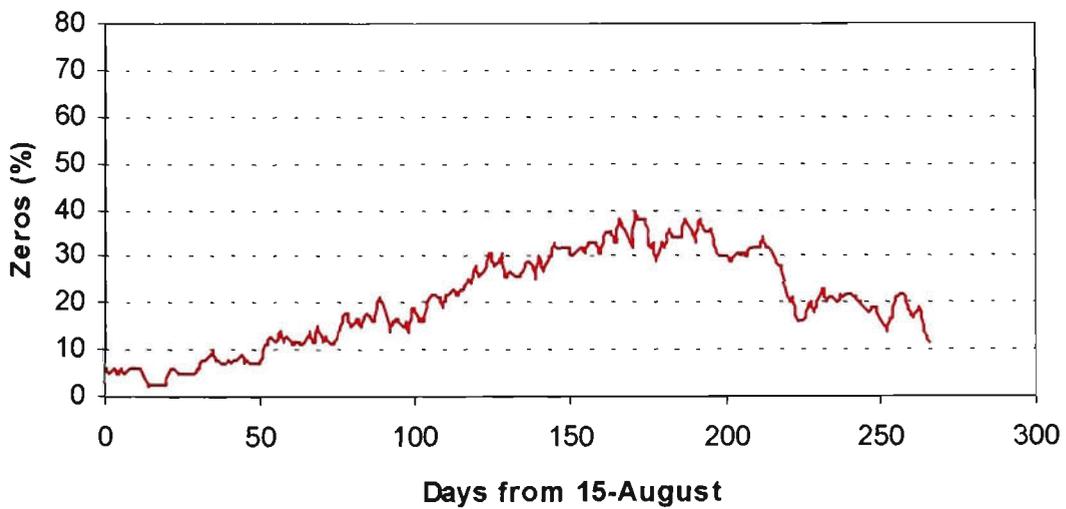
Figure 4.4 Short-term Rainfall Series at Tongala



(a) 7-day Series

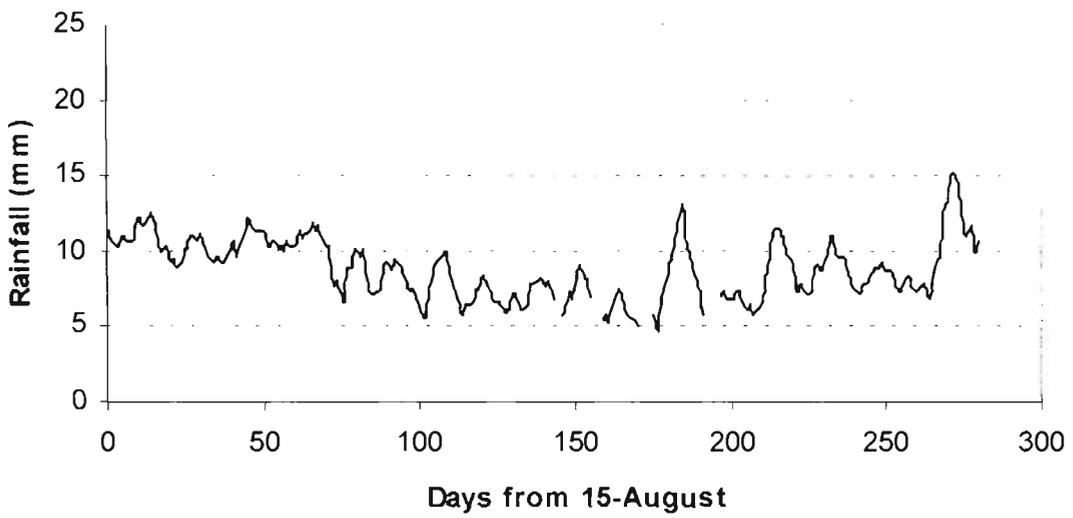


(b) 10-day Series

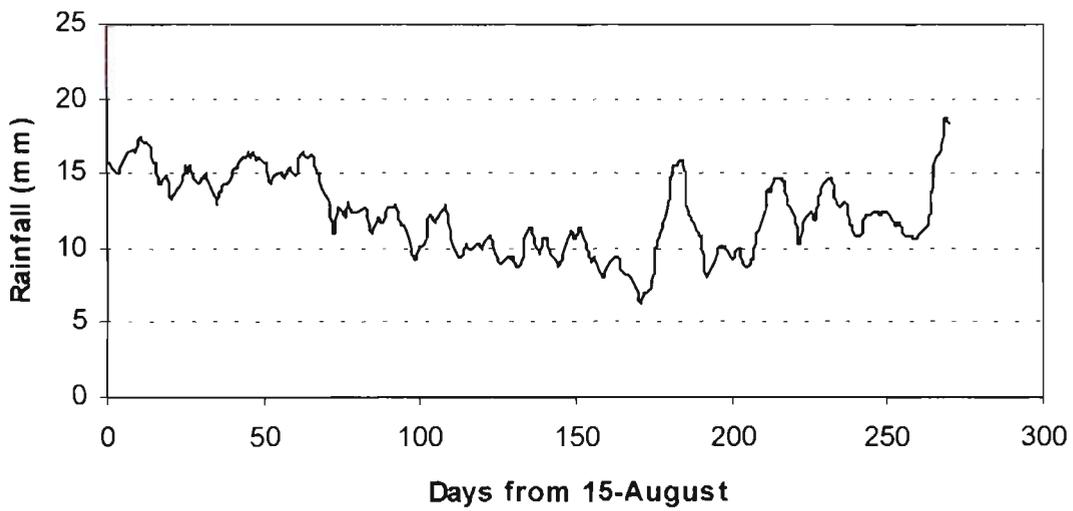


(c) 14-day Series

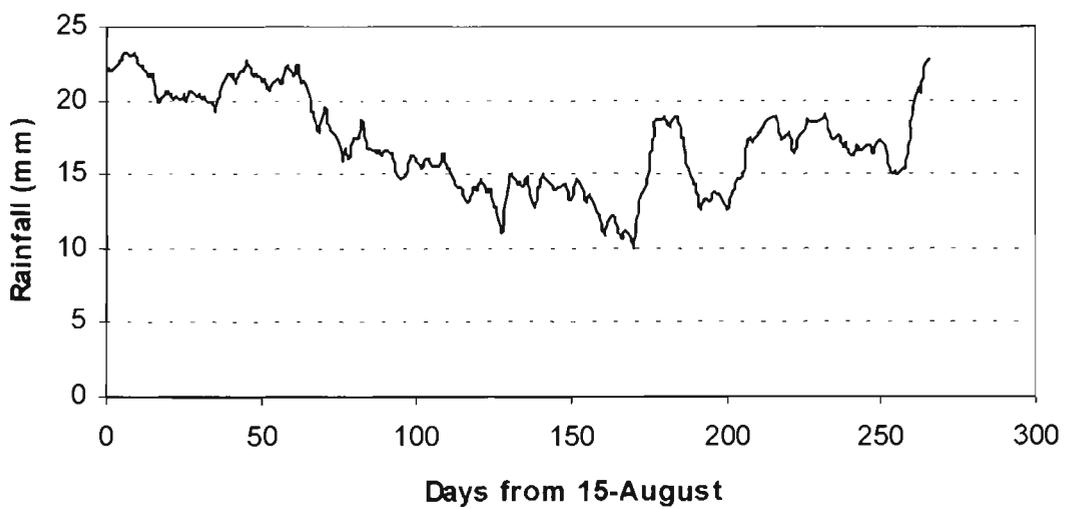
Figure 4.5 Number of Zeros in Various Short-term Rainfall Data Series at Tatura



(a) 7-day Series

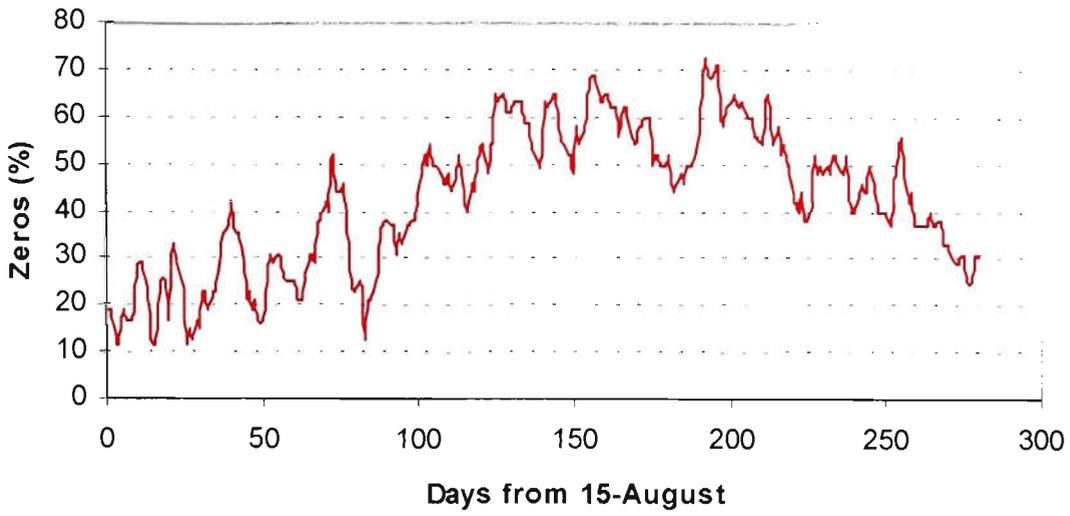


(b) 10-day Series

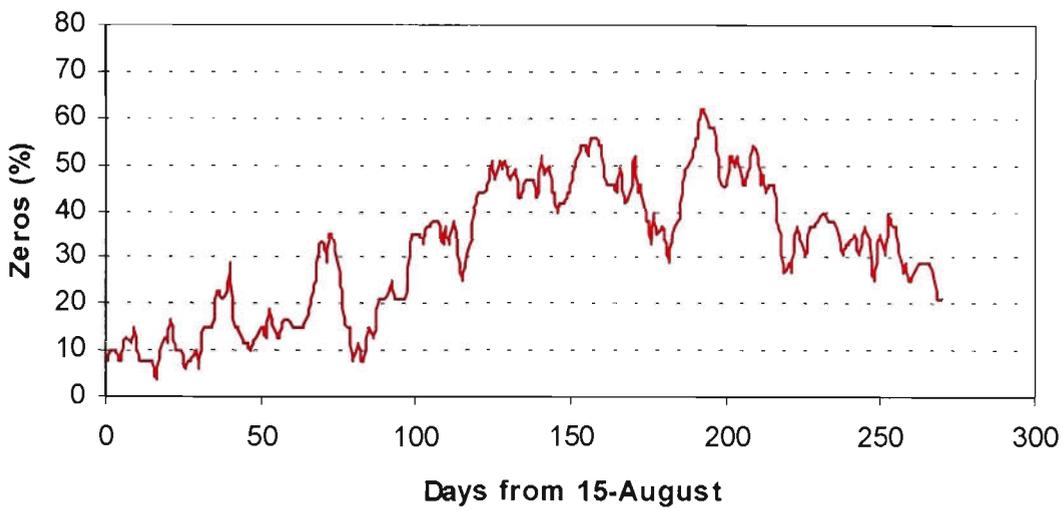


(c) 14-day Series

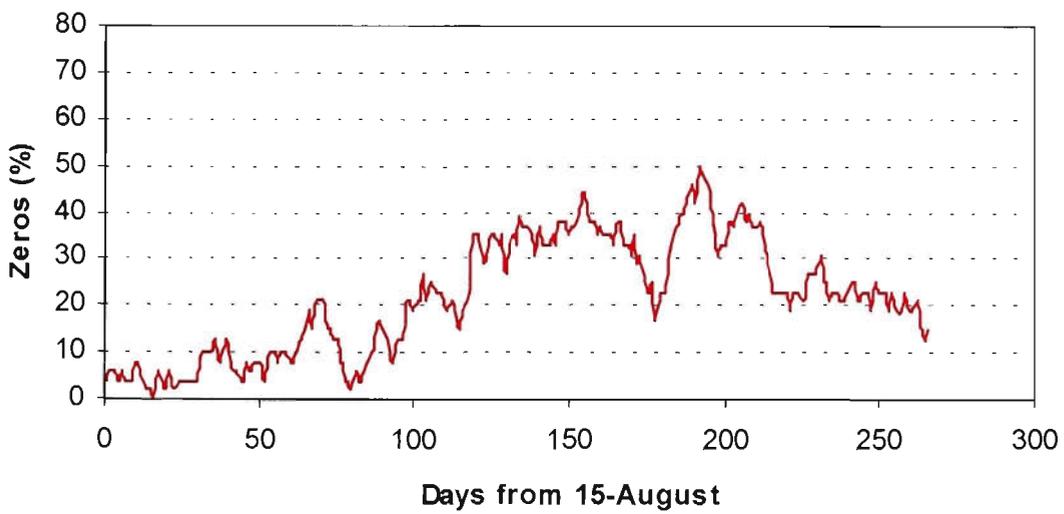
Figure 4.6 Short-term Rainfall Series at Tatura



(a) 7-day Series

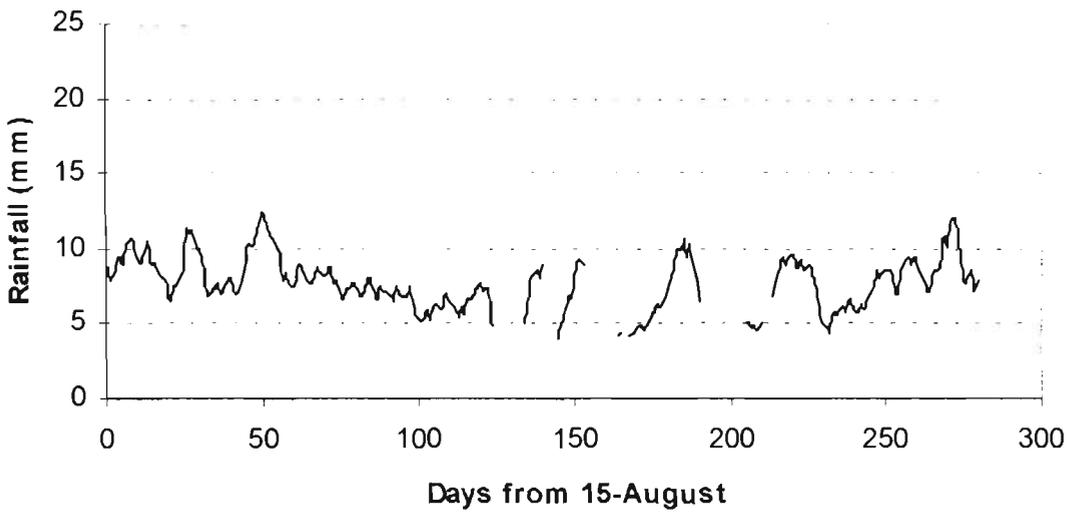


(b) 10-day Series

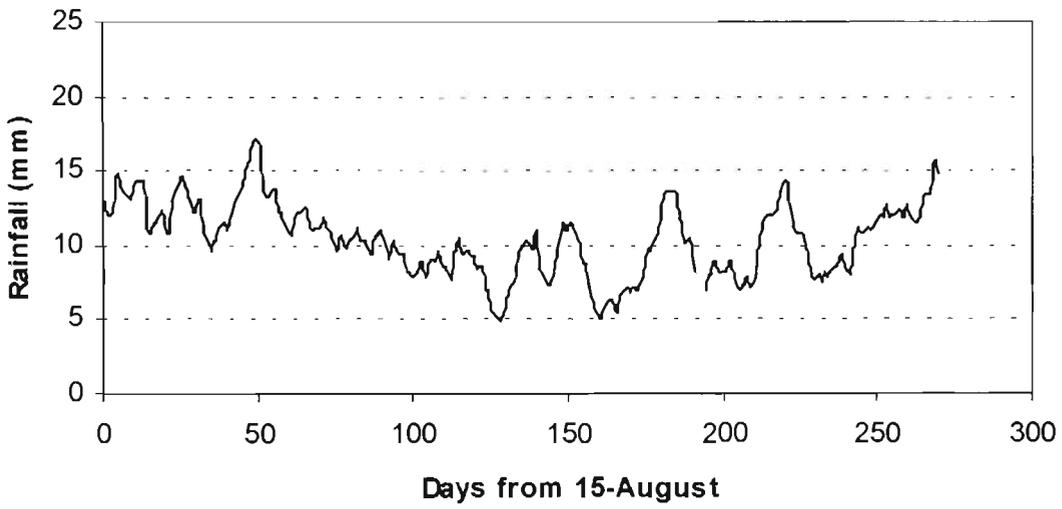


(c) 14-day Series

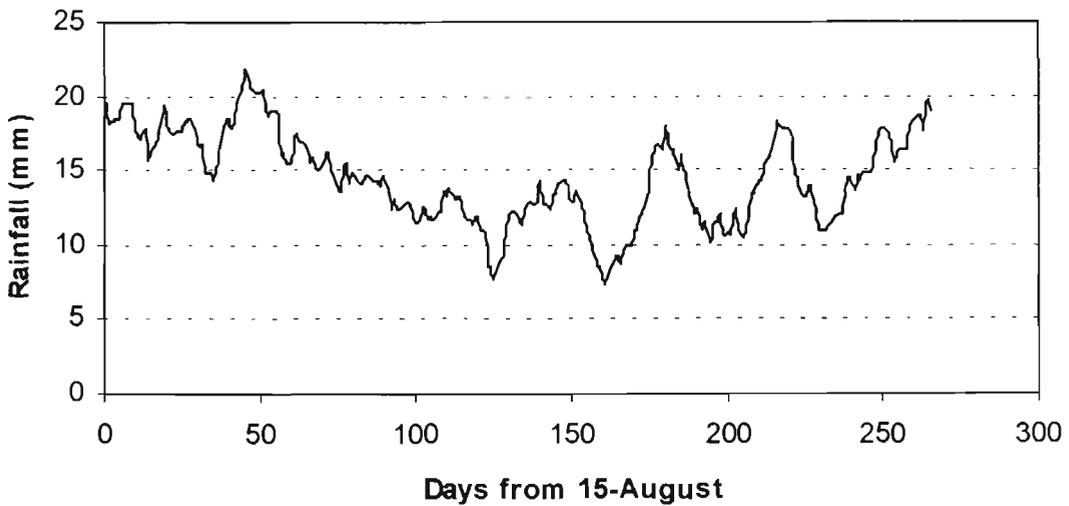
Figure 4.7 Number of Zeros in Various Short-term Rainfall Data Series at Pyramid Hill



(a) 7-day Series



(b) 10-day Series



(c) 14-day Series

Figure 4.8 Short-term Rainfall Series at Pyramid Hill

#### 4.6.2 Characteristics of Short-term Rainfall Series

In order to investigate the general characteristics of the short-term rainfall series, these data series were analysed. The data series included both zero and non-zero values. The statistical descriptors of these series at the three stations are given in Table 4.2. This table shows that the series are highly skewed. The  $C_s$  and  $\epsilon$  values in Table 4.2 are significantly different to the Bowman (1973) tolerance limits of normality assumption outlined in Section 4.2.2. Hence, it was concluded that the normal distribution could not be used for modelling these short-term rainfall data series at all three sites.

Table 4.2 General Statistics of Short-term Rainfall Series at Various Stations

Station	Series	Coeff. of Skewness ( $C_s$ )		Coeff. of Excess ( $\epsilon$ )	
		Range	Mean	Range	Mean
Tongala	7-day	0.80 - 5.87	2.35	-0.70 - 38.06	6.80
	10-day	0.64 - 5.11	2.11	-0.62 - 30.30	5.66
	14-day	0.68 - 3.90	1.92	-0.98 - 19.77	4.84
Tatura	7-day	1.15 - 7.89	2.68	0.09 - 70.23	10.23
	10-day	0.69 - 7.63	2.43	-0.28 - 67.10	8.89
	14-day	0.44 - 6.74	2.20	-0.77 - 55.77	7.64
Pyramid Hill	7-day	1.18 - 7.30	2.50	-0.21 - 64.32	9.12
	10-day	0.85 - 6.36	2.31	-0.16 - 49.71	7.99
	14-day	0.56 - 5.01	2.02	-0.25 - 54.16	6.96

#### 4.6.3 Normalising Transformations and Normality Assumption

In order to utilise the simple properties of the normal distribution, the original data series were transformed. For this purpose, three normalising transformations as outlined in Section 4.2.1 were tested for their ability to normalise the original rainfall data series.

In this analysis, in line with option (ii) of Section 4.1, firstly a dummy constant (0.2) was added to all observations to model the zero values of the data series. Then, the three transformations (i.e. power, log and square-root) were employed to normalise these series based on Bowman (1973) criterion. It was observed that none of the series could be normalised by either square root or log transformations at the three stations. When tested, the power transformation provided better results by normalising 16% of the total data series. Poor normalising behaviour may be due to zeros in the original data series and hence, it was decided to use the methods which handle zeros separately. These methods were the use of total probability theorem (TPT) and the leaky law (LL) distribution, which were discussed in Section 4.6.4 and 4.6.5 respectively.

#### **4.6.4 Total Probability Theorem (TPT)**

To overcome the difficulty arising from the presence of zeros in the original data series, the total probability theorem (TPT) was employed. In this approach (Section 4.2), the zero values were treated separately. The remaining non-zero series were then tested for normality. It was found that only less than 9% of the total non-zero data series were normally distributed at all three stations. Therefore, all three normalising transformations were used to normalise the non-zero data series. A detailed discussion of each of the three stations is given below.

##### **Tongala:**

At the Tongala station, it was observed that only 72% of the total non-zero short-term rainfall data series considered in this study could be normalised by either of the three (i.e. power, log and square root) transformations based on the Bowman (1973) criterion.

The analysis revealed that 6%, 62% and 51% of 14-day non-zero rainfall series were transformed to fit a normal distribution by power, log and square-root transformations respectively. It was found that the high failure (94%) of the power transformation in the 14-day non-zero data series was due to values that were less than 1mm in the original series. Such values in power transformation resulted in negative transformed values that

posed problems in converging the solution to meet the normality assumption (i.e. Bowman criterion). This was also the case with log transformation.

For the 10-day data series, the analysis revealed that 9%, 87% and 58% of non-zero data series were transformed to fit a normal distribution by power, log and square-root transformations respectively, while for the 7-day rainfall data series, 11%, 93% and 61% of the series were transformed respectively. The failure of power and log transformations was again due to rainfall values less than 1mm.

Considering the aforementioned difficulties associated with the power and log transformations, an adjustment was made to the original non-zero data items of the series which were less than 1 mm. That is, they were considered as zero values. This adjustment was done for all three transformations. Since in irrigation scheduling studies, the rainfall values less than 2mm are generally ignored (Hedditch, 1985, Heslop, 1991), and therefore, this adjustment would not have any significant impact on short-term rainfall predictions for use in irrigation planning. It was observed that after this adjustment the number of non-zero series transformed by power and log transformations was significantly improved. In case of the 14-day series, power and log transformations were found to transform 100% and 88% of the non-zero data series satisfactorily. The 10-day non-zero rainfall data series transformed by power and log transformations were 100% and 99% of the total series. In case of the 7-day series, power and log transformations were found to transform 100% and 100% of the total series. The number of non-zero data series normalised by various transformations before and after the <1 mm rainfall adjustment, at the Tongala site are shown in Figure 4.9.

It is important to note that the behaviour of the square-root transformation was quite different to the other two transformations. As can be observed from Figure 4.9 in case of the 14-day series, the number of series transformed by this transformation was reduced from 51% to 48% after the <1mm rainfall adjustment was made. A similar behaviour of this transformation can be observed with 10-day and 7-day data series. The reason for this reduction in the transformed data series satisfying the normality criteria cannot be

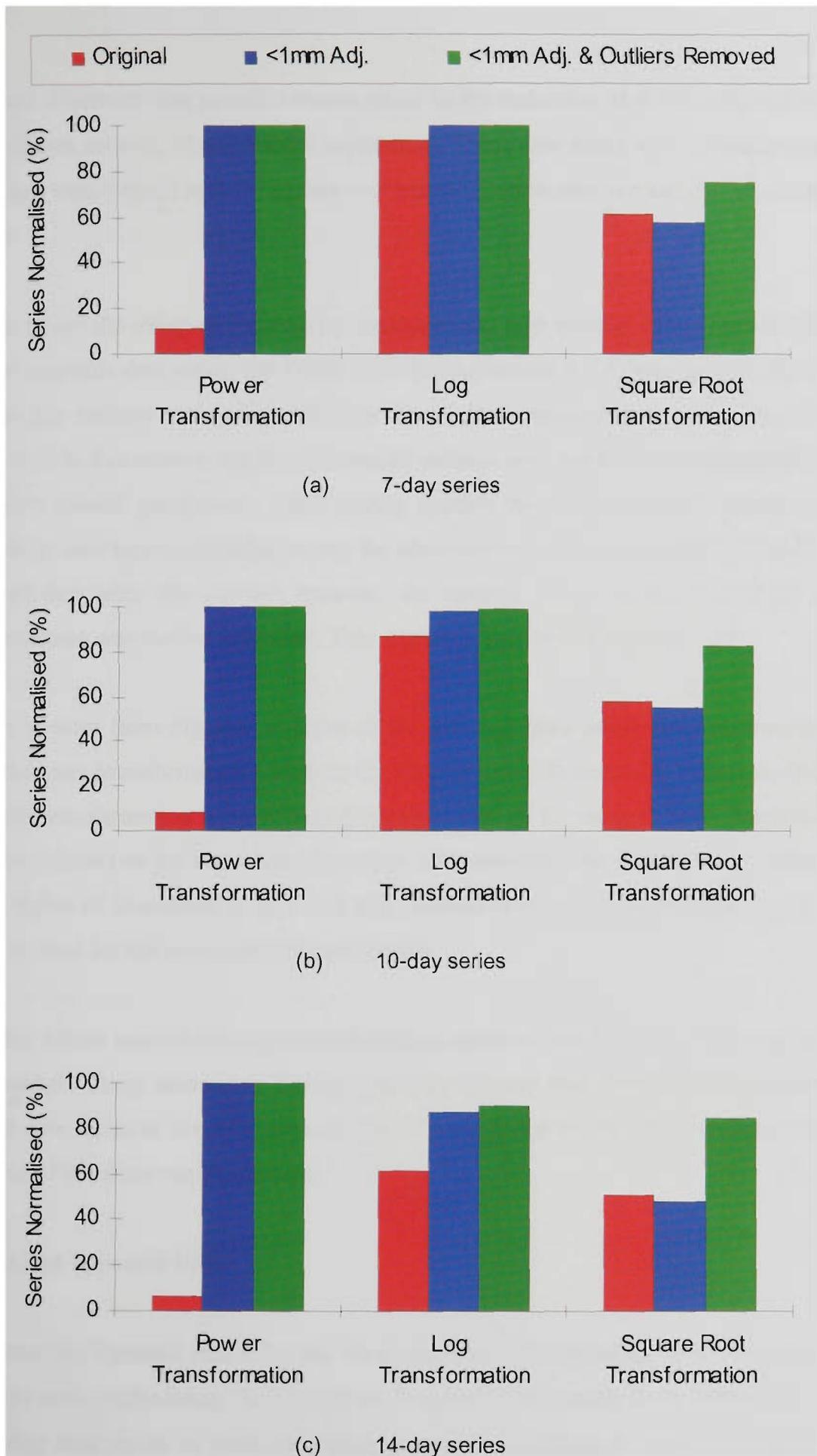


Figure 4.9 Rainfall Series Normalised by Various Transformations Before & After <1mm Rainfall Adjustment and Outliers Removal at Tongala.

explained. However, one possible reason could be the reduction of the sample size of the non-zero data set with <1mm rainfall adjustment. These new series with a smaller sample size, when transformed with the square-root transformation may not satisfy the normality criteria.

In order to see the effect of outliers (i.e. exceptionally high rainfall values) present in the original non-zero data series, the Walsh (1959) test (Section 4.2.4) was applied. By using this test, the outliers were removed from the original non-zero data series. As will be shown later in this section that the removal of outliers does not have significant effect on short-term rainfall predictions. After having applied the outlier test, all non-zero data series were once again normalised using the aforementioned three transformations. It was observed that after the outliers removal, the number of series normalised by each transformation was further increased. This aspect is also shown in Figure 4.9.

As can be seen from Figure 4.9, some of the non-zero data series were normalised by more than one transformation based on the Bowman (1973) normality criterion. In such case, the transformation method that gives the value of  $C_s$  close to zero (Section 4.2) could be selected as the better transformation. Alternatively, the method which gives the lowest value of D-statistic of the K-S test (Section 4.4) could be adopted as the best suited method for the series under consideration.

After the <1mm rainfall adjustment and outliers removal, the K-S test (when applied to TPT method using alternative transformations) showed that 100% of the short-term rainfall data series at the Tongala site could be modelled by the TPT method using at least one of the three transformations.

#### **Tatura and Pyramid Hill:**

At Tatura and Pyramid Hill sites, the short-term rainfall data series were also analysed using the same methodology as adopted for Tongala. With regards to the behaviour of the short-term data series at these two sites, a similar behaviour to that of Tongala was

observed. The K-S test revealed that at Tatura and Pyramid Hill sites 100% of the short-term rainfall data series could be modelled by the TPT method using at least one of the three transformations. The graphical representations of this analysis at Tatura and Pyramid Hill sites are given in Figures 4.10 and 4.11 respectively.

### ***Implication of <1mm Rainfall Adjustment and Outliers Removal***

To illustrate the implication of <1mm rainfall adjustment and outliers removal on short-term rainfall predictions using the TPT method, two 14-day rainfall data series are used here as examples. Two data series had to be used in this case, since no single series was modelled by all three transformations in its original form (i.e. without the <1mm adjustment or outliers removal).

The **first data series** was comprised of 107 data values, among these there were 31 zero values. The remaining 76 non-zero data values arranged in an ascending order can be expressed as 0.3, 0.5, 0.5, 1.0, 1.4, 1.5, 1.8 ..... 79.0, 88.1, **216.7**. As can be seen, there were three data values which were less than 1. It can also be noted that the highest value of this data series (i.e. 216.7) was highly departing from the remaining non-zero data values.

When this data series was tested for the TPT method with power transformation, it was observed that the non-zero part of the series could not be normalised by power transformation based on the Bowman (1973) criteria. Hence, the TPT method using power transformation (TPTP) failed to model the original data series. However, based on the *<1mm rainfall adjustment* criteria, when the three data values of original data series which were less than 1 (i.e. 0.3, 0.5, and 0.5) were replaced as zero values, it was found that the non-zero part of the data series was normalised by power transformation. In this thesis, the data series after the <1mm rainfall adjustment is referred to as the *adjusted* data series. The K-S test revealed that this adjusted data series was successfully modelled by TPTP.

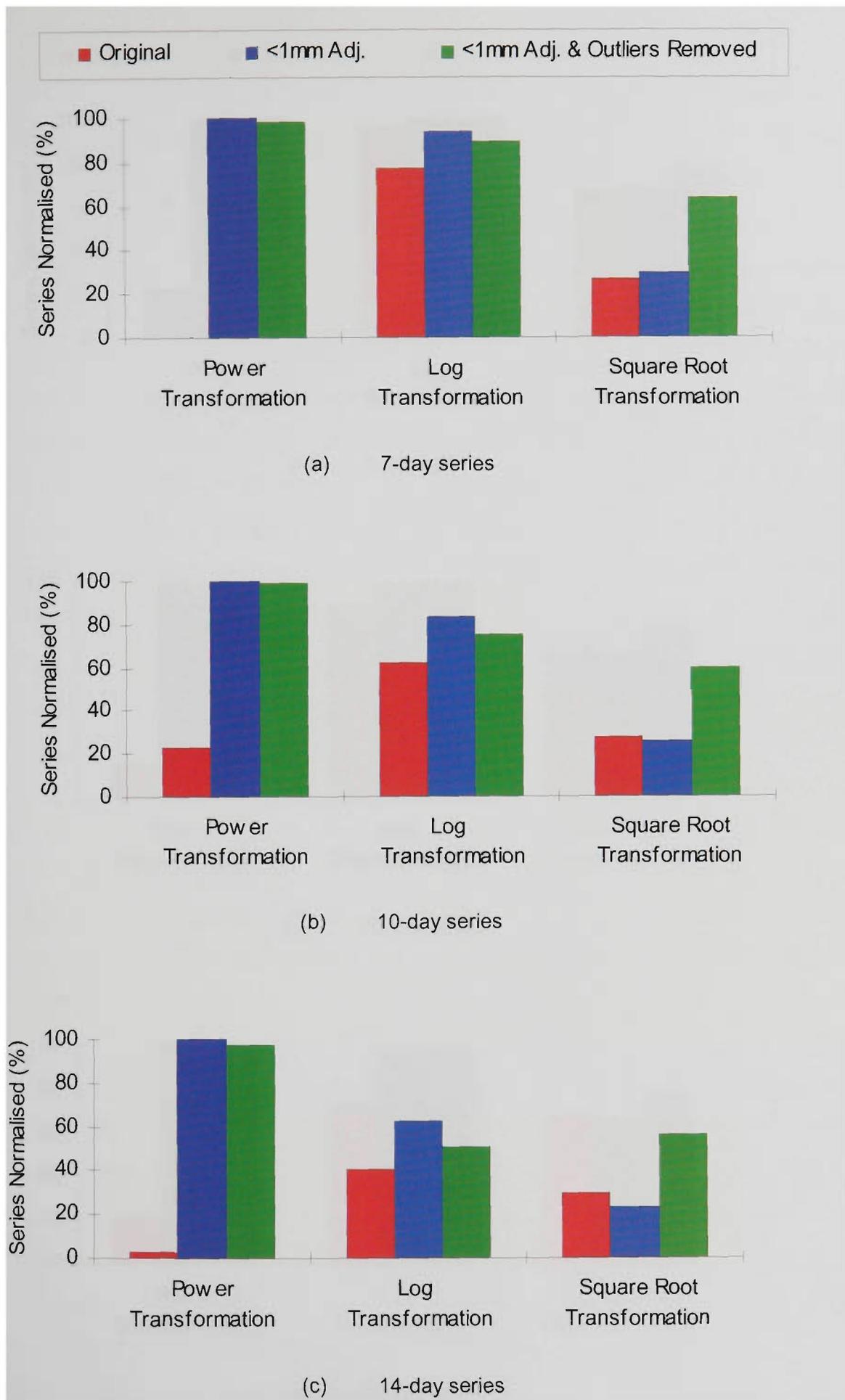


Figure 4.10 Rainfall Series Normalised by Various Transformations Before & After <1mm Rainfall Adjustment and Outliers Removal at Tatura.

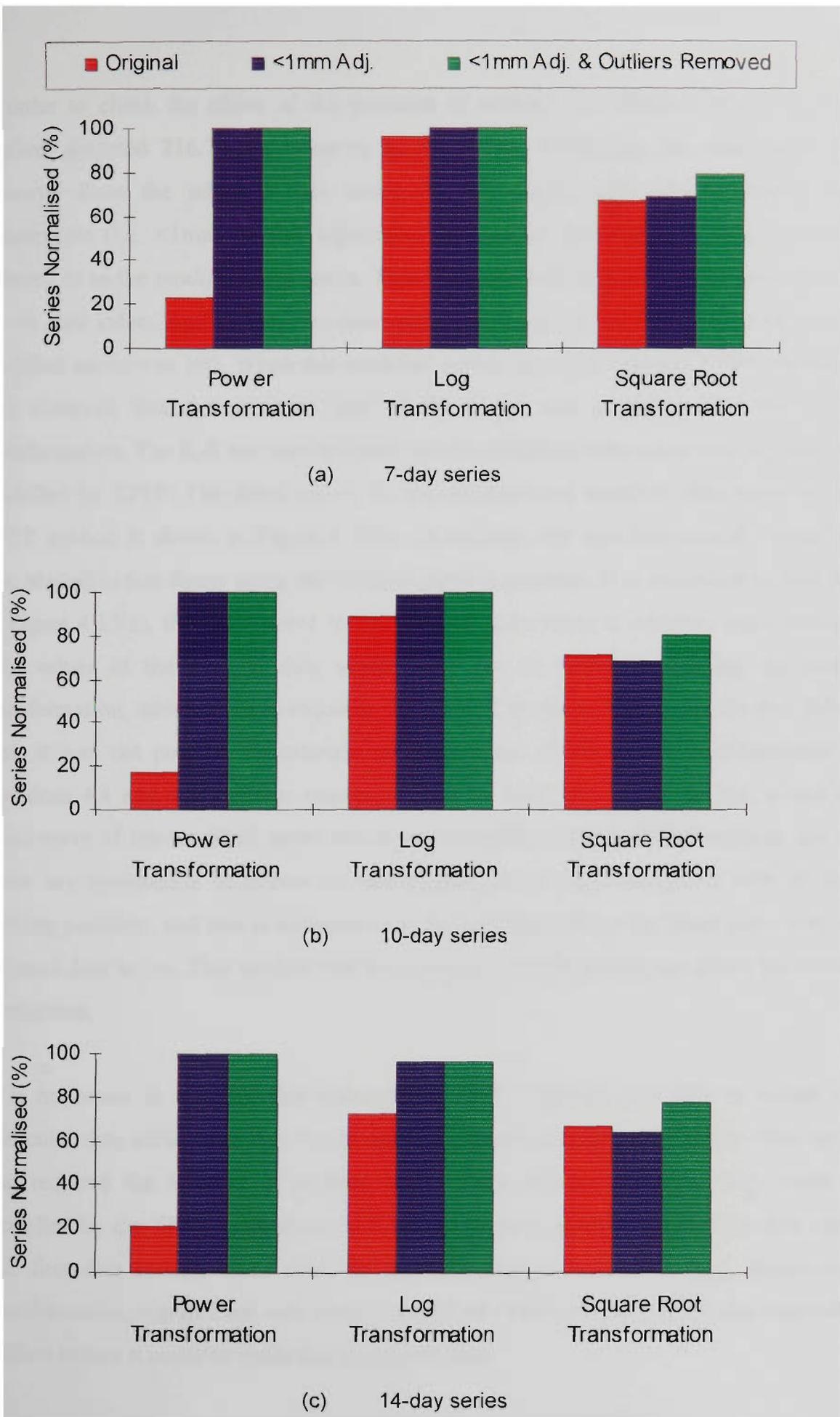


Figure 4.11 Rainfall Series Normalised by Various Transformations Before & After <1mm Rainfall Adjustment and Outliers Removal at Pyramid Hill.

In order to check the effect of the presence of outliers, the Walsh (1959) test when applied, detected 216.7 data value to be an outlier. Therefore, this data value was removed from the adjusted data series. In this thesis, after aforementioned two adjustments (i.e. <1mm rainfall adjustment and outlier removal), the data series is referred to as the *modified* data series. Thus, the modified data series contained 34 (i.e. 31+3) zero values, and 72 non-zero data values ranging from 1.0 to 88.1. The size of the modified series was 106. When this modified series was used with the TPTP method, it was observed that the non-zero part of the series was normalised by the power transformation. The K-S test also revealed that the modified data series was successfully modelled by TPTP. The fitted curves for the adjusted and modified data series by the TPTP method is shown in Figure 4.12(a). In addition, the non-zero rainfall values are also plotted in this figure using the Weibull plotting position. It is important to note that in Figure 4.12(a), the fitted curve for the original data series is missing, since the non-zero values of the original data series could not be transformed using the power transformation, which is a pre-requisite for the TPT method. The reason for this failure was, it was not possible to estimate the  $\lambda$  parameter of the power transformation of equations 4.4 and 4.5. Another important point to note from Figure 4.12(a) is that the fitted curve of the modified series which was modelled with the TPTP method, did not show any appreciable difference in rainfall predictions when compared with Weibull plotting positions, and also in comparison to the predictions from the fitted curve with the adjusted data series. This implies that the removal of outliers does not affect the rainfall predictions.

It is important to mention that although the TPTP method was able to model this particular data series after the <1mm rainfall adjustment, there were many other series that required the removal of outliers after <1mm adjustment before they could be modelled by the TPTP method. As will be shown later, even this particular data series (i.e. first data series), when fitted by the TPT method with other (e.g. square-root) transformation, required not only the adjustment of <1mm rainfall but also the removal of outliers before it could be modelled by this method.

● Weibull   
 — Original   
 - - - <1mm Adj.   
 — <1mm Adj. & Outliers Removed

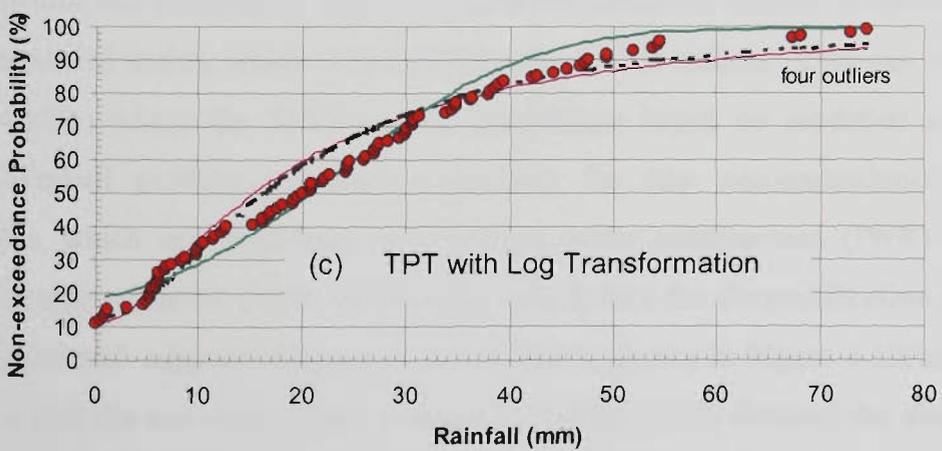
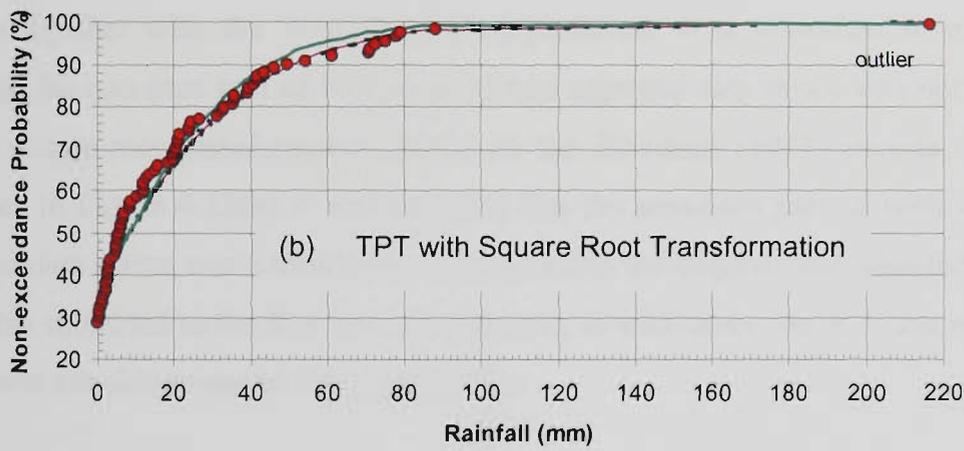
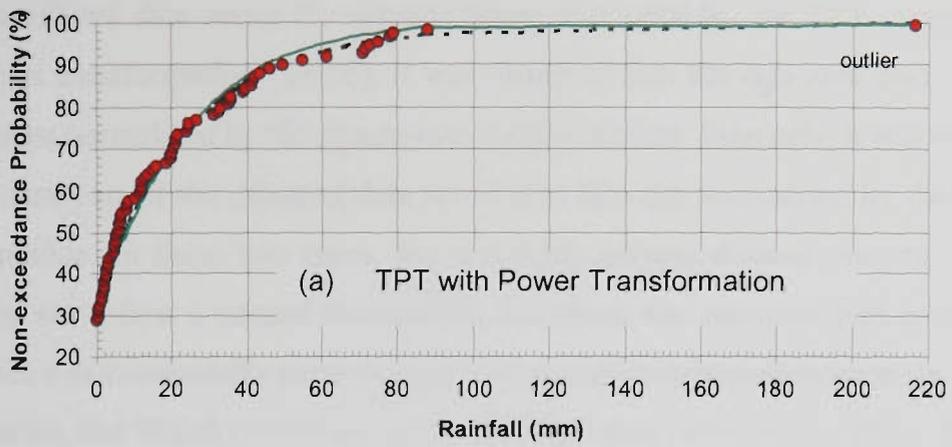


Figure 4.12 Fit by TPT Method for 14-day Rainfall Series

When the above data series (in original form) was used by the TPT method with the square-root transformation (TPTS), it was observed that the non-zero part of the series could not be normalised by the square-root transformation. Similarly, it was observed that the non-zero part of the *adjusted* data series was also not normalised by the square-root transformation. In these two cases, the normality criteria showed that the transformed series did not follow a normal distribution. However, the non-zero part of the *modified* data series was successfully normalised by the square-root transformation. In this case, as stated earlier, the Walsh (1959) test detected 216.7 data value as an outlier. The K-S test also confirmed that the modified data series was successfully modelled by TPTS. The fitted curve for this modified data series with the TPTS method is shown in Figure 4.12(b) together with the Weibull plotting positions. It is important to mention that although the non-zero part of both original and adjusted data series was not normalised by the square-root transformation based on the Bowman (1973) criteria, for plotting purposes in Figure 4.12(b) it was assumed that the non-zero part of both original and adjusted data series was normalised. Consequently, the original and adjusted data series were also subjected to the K-S test. As expected, in both cases, the K-S test revealed that TPTS was not able to model these data series.

It is important to note that although the adjusted data series was not modelled by the TPTS method, the removal of outlier also did not affect the rainfall predictions as given by the modified series, which was fitted by the TPTS method. This can be seen from Figure 4.12(b) where the TPTS rainfall predictions based on modified series closely follow Weibull plotting positions, especially for low non-exceedance probability predictions which are important in irrigation water requirement (IWR) estimations. Another important point worth mentioning here is that the disqualification of TPTS for both original and adjusted data series is not clearly shown in Figure 4.12(b). The reason for this is that the non-exceedance probability values which dictated the disqualification of TPTS method based on Weibull formula (for both original and adjusted series), are hiding behind the Weibull plotting points in Figure 4.12(b). In order to show this point

clearly, another data series (hereafter referred to as the 2<sup>nd</sup> data series) was employed. This is explained below.

Before explaining the second data series, it is important to mention that the above referred first data series was also tested for the TPT method using log transformation (TPTL). It was observed that the non-zero part of the original data series was normalised by log transformation without requiring any adjustment (i.e. <1mm adjustment and/or removal of outlier) in the original data series. The K-S test revealed that TPTL successfully modelled the original data series.

The second data series like the first series was also comprised of 107 data values. However, in this series there were only 12 zero values. The remaining 95 non-zero data values of this series arranged in an ascending order can be expressed as 0.5, 0.8, 1.0, 1.2, 3.0, 4.6 ..... 54.4, 54.5, **67.3, 68.1, 73.0, 74.6**. As can be observed, there were two data values which were less than 1. The Walsh (1959) test when applied, detected that there were four outliers in this data series. These outlier values are shown in bold. Based on the aforementioned details, the adjusted series had 14 (i.e. 12+2) zero values, and 93 non-zero data values ranging from 1.0 to 74.6. Hence, the size of adjusted data series was 107. The modified data series had 14 zero values, and 89 non-zero values ranging from 1.0 to 54.4. Thus, the size of the modified series was 103.

When this original data series was tested for the TPT method with log transformation, it was observed that non-zero part of the series could not be normalised by the log transformation based on the Bowman (1973) criteria. Hence, the TPT method using the log transformation (TPTL) failed to model the original data series based on the K-S test. When the adjusted series was tested, it was observed that the non-zero part of the adjusted data series was also not normalised by log transformation. Therefore, it was decided to investigate the presence of outliers in the data series.

As stated earlier, the Walsh (1959) test detected four outliers in this data series. After the removal of the four outliers, the modified series was once again tested for TPTL. It was

revealed that now the non-zero part of the modified data series was normalised by the log transformation. The K-S test also confirmed that TPTL successfully fitted this modified data series. The graphical presentation of this data series with the TPTL method is also shown in Figure 4.12(c). It is important to mention that although the original and adjusted data series were not modelled by the TPTL method, these series are also shown with the modified data series for TPTL method in Figure 4.12(c). The reason for this is already stated under the first data series for the TPTS method in Figure 4.12(b).

As can be seen from Figure 4.12(c), the pattern of the fitted curve with the original data series significantly deviates from the Weibull plotting position. A similar pattern is also shown for the adjusted series. This high deviation depicts the fact that the TPTL method was not able to model these data series. The same was revealed in the K-S test. However, as can be seen from Figure 4.12(c), the fitted curve of the modified data series closely followed the pattern of Weibull plotting positions. This shows the capability of the TPTL method to model the modified data series. As stated earlier, the K-S test also confirmed that TPTL successfully fitted this modified data series.

### **Summary of TPT Analysis**

As shown in Figures 4.4-4.12, the above analysis revealed that the short-term non-zero rainfall data series can successfully be normalised using at least one of the three transformations considered in this study (i.e. power, log and square-root transformations), provided that the series are adjusted for less than 1mm rainfall values, and the outliers are also removed using the Wlash (1959) outliers test. Hence, these results showed good promise to adopt the TPT method for predicting the short-term rainfall of various durations such as 7-14 day periods at a required probability level. The equations that can be used for rainfall prediction using different probability distributions were discussed in Section 4.2.1. The rainfall prediction software using these equations is described in Section 4.7, whereas an example of rainfall prediction by this software is described in Appendix B.

#### 4.6.5 Leaky Law

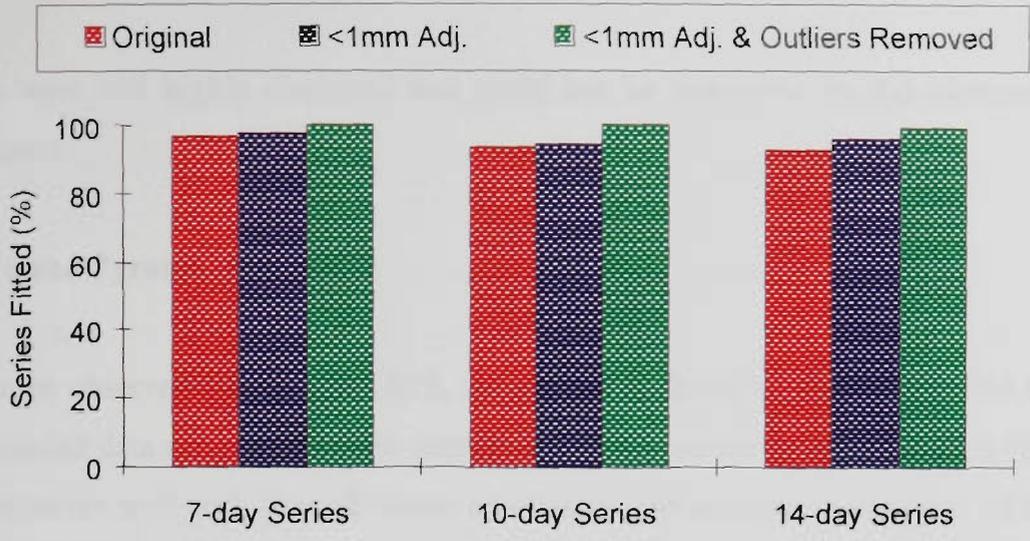
The Leaky Law (LL) method which also accounts directly for zeros present in the original data, provided good results when the short-term rainfall data series at the three sites were fitted. Same data sets that were used in Section 4.6.4 were used in fitting the LL method. Similar to the TPT method, the original series, the adjusted series and the modified series were considered. The success rate in fitting the LL method for these data series is shown in Figure 4.13. The success rate was determined by the K-S test as described in Section 4.4.2. The analysis at the three sites considered is discussed below.

##### **Tongala:**

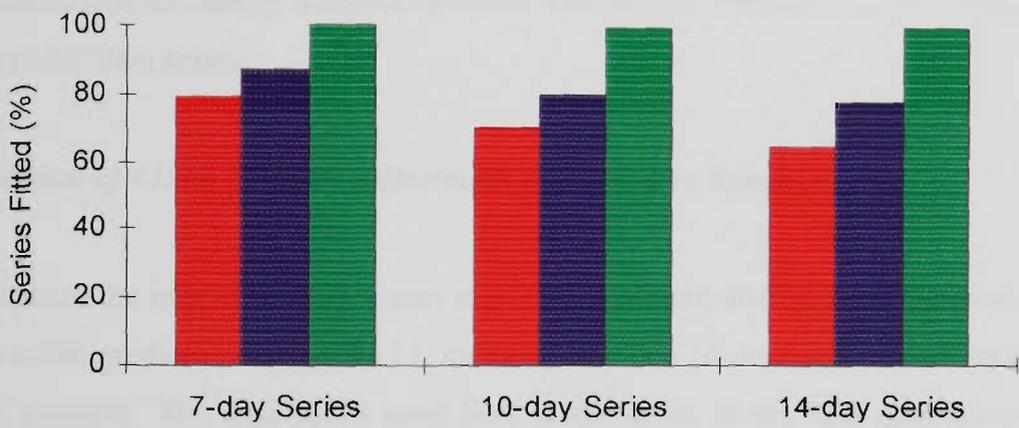
At the Tongala station, it was observed that 96, 93 and 92% of the 7-day, 10-day and 14-day data series respectively were fitted by the LL method (Figure 4.13). The failure of the LL method in the remaining series was due to the fact that those series were highly dispersed with a high coefficient of variance. This high dispersion of data series was due to the combined effect of large variation among non-zero values and the outliers present in the original data series.

In order to partially mitigate the problem of dispersion, the <1mm rainfall adjustment (i.e. less than 1mm rainfall considered to be equal to zero as in Section 4.6.4) was made in the original data series. When this adjustment was made, the number of series fitted by the LL method at this site was increased. However, this increase was not significant. The increase achieved was only of the order of 1%, 1.1% and 4% for 7-day, 10-day and 14-day data series respectively.

The outliers were then removed from the adjusted data series, using the Walsh (1959) test as in Section 4.6.4. After removing the outliers (and the <1mm rainfall adjustment), the LL method was once again fitted to the short-term rainfall data series. The K-S test then revealed that LL fitted 99% of the modified short-term rainfall series at the Tongala site. The remaining 1% of the series could not be fitted by the LL method, because those



(a) Tongala Station



(b) Tatura Station



(c) Pyramid Hill Station

Figure 4.13 Number of Series Fitted by LL Method

series were still highly dispersed and could not be overcome by the aforementioned techniques.

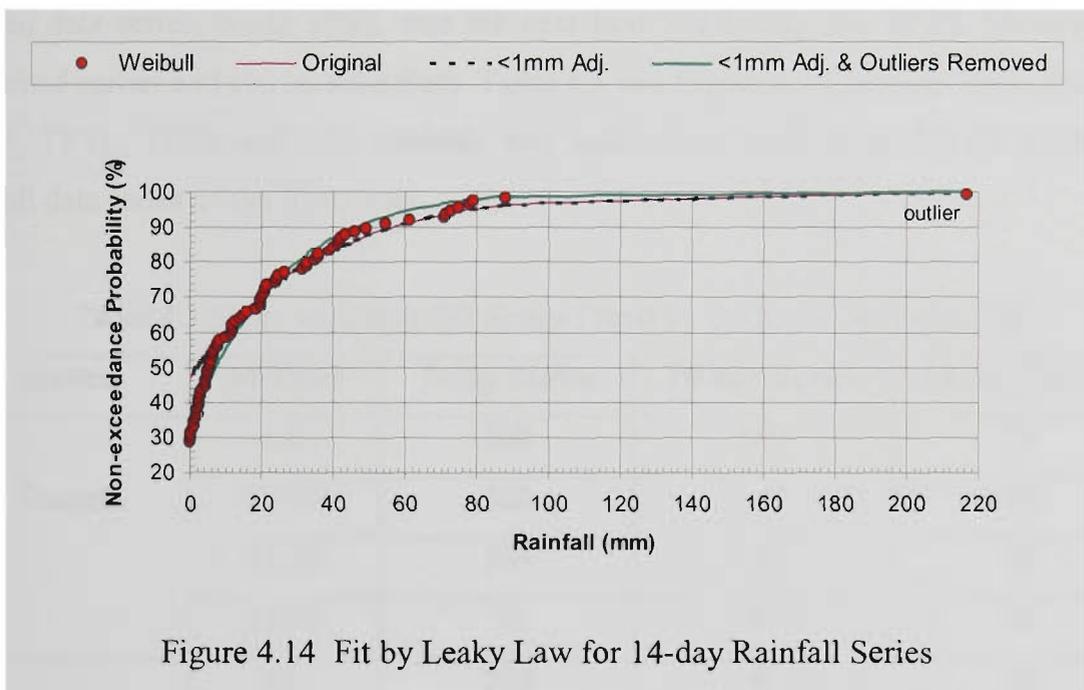
### **Tatura and Pyramid Hill:**

As can be observed from Figure 4.13, the pattern of fitting by the LL method to short-term rainfall data series at all three stations is almost similar in the sense that the fitting rate improves with inclusion of <1mm adjustment and removal of outliers. At Pyramid Hill, all 7-day and 10-day series (i.e. 100%) were fitted by the LL method, whereas 14-day series fitted by LL were 99%. At Tatura, fitting has been significantly improved by the LL method after the <1mm adjustment and removal of outliers. Nevertheless, the aforementioned LL fitting analysis revealed that the LL method cannot fit all the short-term rainfall data series.

### ***Implication of <1mm Rainfall Adjustment and Outliers Removal***

To illustrate the implication of <1mm rainfall adjustment and outliers removal on short-term rainfall predictions using the LL method, only one 14-day rainfall data series is used as the example. The data series used here is the same as the first data series used in Section 4.6.4 for TPTP and TPTS methods. As stated earlier, the size of the original data series was 107 with 31 zeros and one outlier. When the original data series was modelled by the LL method, the K-S test revealed that LL failed to model the original data series. Even the adjusted series was also not modelled by the LL method. As stated earlier in Section 4.6.4, the Walsh (1959) test detected one outlier for this data series. After the removal of this outlier, the modified series was modelled with the LL method. The K-S test revealed that LL successfully modelled this modified data series. The fitted curve of this data series by the LL method is shown in Figure 4.14 together with Weibull plotting positions. It is important to mention that although the original and adjusted data series were not modelled by the LL method based on the K-S test, solely for comparison purposes, the fitted curves of these series are also shown with the modified series in Figure 4.14.

As can be seen from Figure 4.14, the pattern of the original data series deviates from the Weibull plotting positions, especially near the zero-rainfall data values. A similar pattern is also shown by the adjusted series. This deviation depicts the fact that the LL method was not able to model these data series. The same was revealed by the K-S test. Nevertheless, as can be seen from Figure 4.14, the modified data series closely followed the pattern of Weibull plotting positions. This shows the capability of the LL method to model the modified data series. The K-S test also confirmed that LL successfully modelled this modified data series.



#### 4.6.6 Joint Use of TPT and LL Methods

As revealed in the preceding discussion (i.e. Sections 4.6.4 and 4.6.5), none of the two distribution methods (i.e. TPT using any single transformation and LL) were individually able to fit all the short-term rainfall data series in the area studied, although at least one method fits each data series. Therefore, it was decided to employ the TPT (with three transformations) and LL methods simultaneously to fit the short-term data series at the three stations. As in Section 4.6.4, the TPT method using three transformations namely

power, log and square root are referred to as TPTP, TPTL and TPTS methods respectively.

The simultaneous use of TPT and LL methods revealed that most of the series were satisfactorily modelled by both methods, while the remaining series were modelled by at least either of these two methods. Therefore, all these series can be modelled at least by one of the methods. Table 4.3 shows the capability of each of the TPTP, TPTL, TPTS and LL methods to fit the short-term rainfall data series at the three sites, while its graphical representation is given in Figure 4.15. As can be observed from Table 4.3 and Figure 4.15, the LL and TPTP methods fitted the maximum percentage of the short-term rainfall data series, while TPTL was the next best and finally the TPTS. However, as explained earlier and can be seen from Table 4.3 and Figure 4.15, none of these four (i.e. TPTP, TPTL, TPTS and LL) methods was individually able to model all short-term rainfall data series of the three sites.

Table 4.3 Short-term Rainfall Series Fitted by Different Methods (%)

Station	Method	7-day Series	10-day Series	14-day Series
Tongala	LL	100	100	99
	TPTP	100	100	100
	TPTL	100	99	90
	TPTS	75	82	85
Tatura	LL	100	99	99
	TPTP	99	99	97
	TPTL	89	76	51
	TPTS	63	60	56
Pyramid Hill	LL	100	100	99
	TPTP	100	100	100
	TPTL	100	100	96
	TPTS	79	81	78

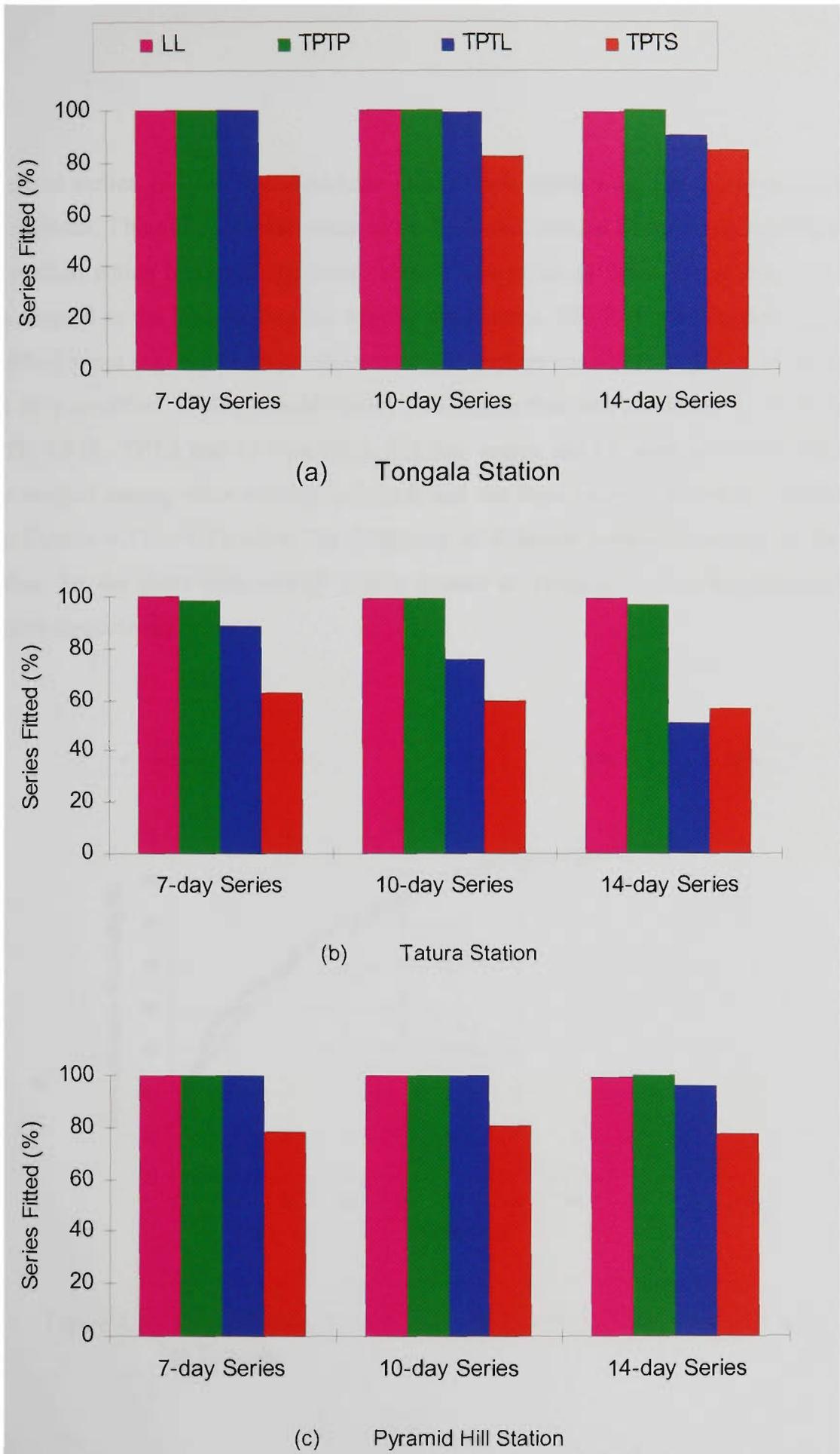


Figure 4.15 Short-term Rainfall Series Fitted by Various Distribution Methods

As stated earlier, most of the short-term rainfall data series were fitted by both TPT and LL methods. Therefore, in case when more than one method fit a certain rainfall series, the method which produced the least value of D-statistic of the K-S test (Section 4.4.1) was adopted as the best method for reliable predictions. The K-S test was done using the modified series (i.e. with <1mm adjustment and outliers removed). Figure 4.16 shows the plot of a modified 14-day rainfall series at Tongala that was modelled by all four (i.e. TPTP, TPTL, TPTS and LL) methods. For this series, the LL method was found to be best method among other methods, since it had the least value of D-statistic of the K-S test. Figures 4.17 – 4.19 show the frequency of different methods adopted as the best method for the short-term rainfall series studied at Tongala, Tatura and Pyramid Hill stations respectively.

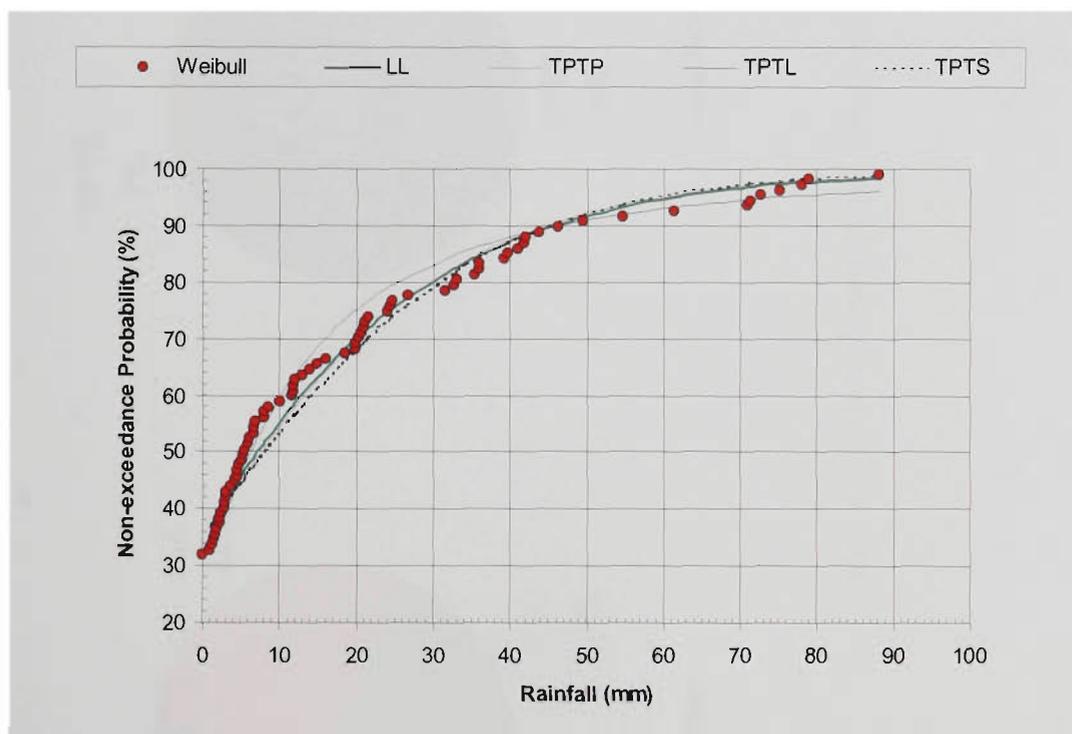
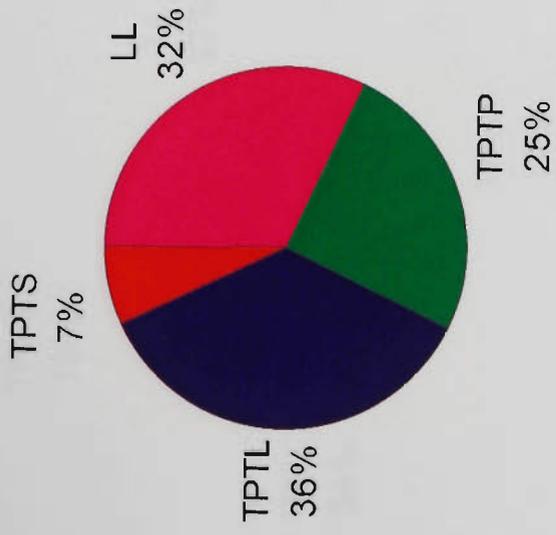
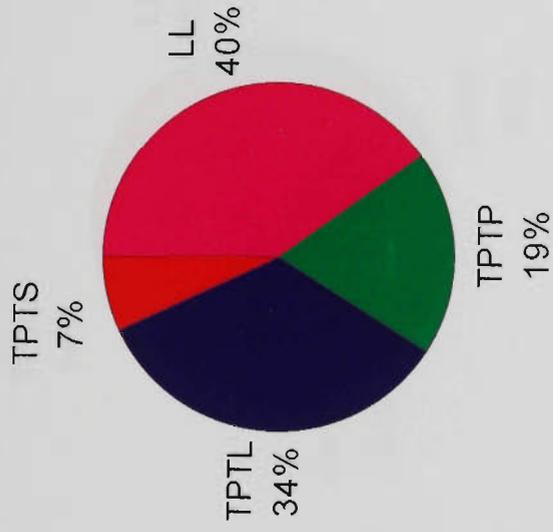


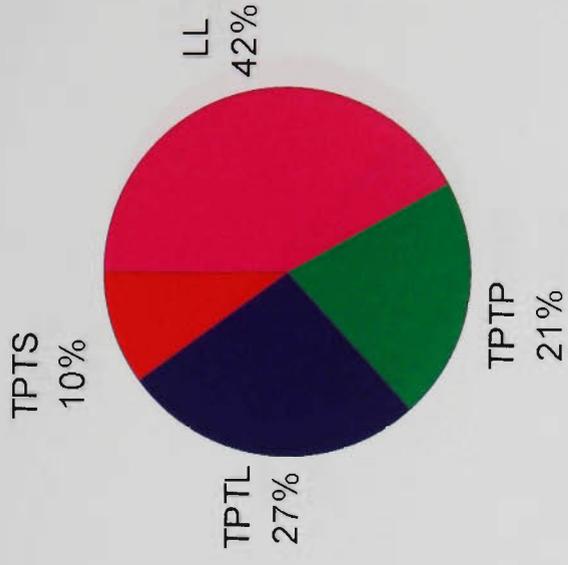
Figure 4.16 Fit by Various Distribution Methods for a 14-day Rainfall Series at Tongala.



7-day Series



10-day Series



14-day Series

Figure 4.17 Overall Best-Fitted Series by LL and TPT Methods at Tongala

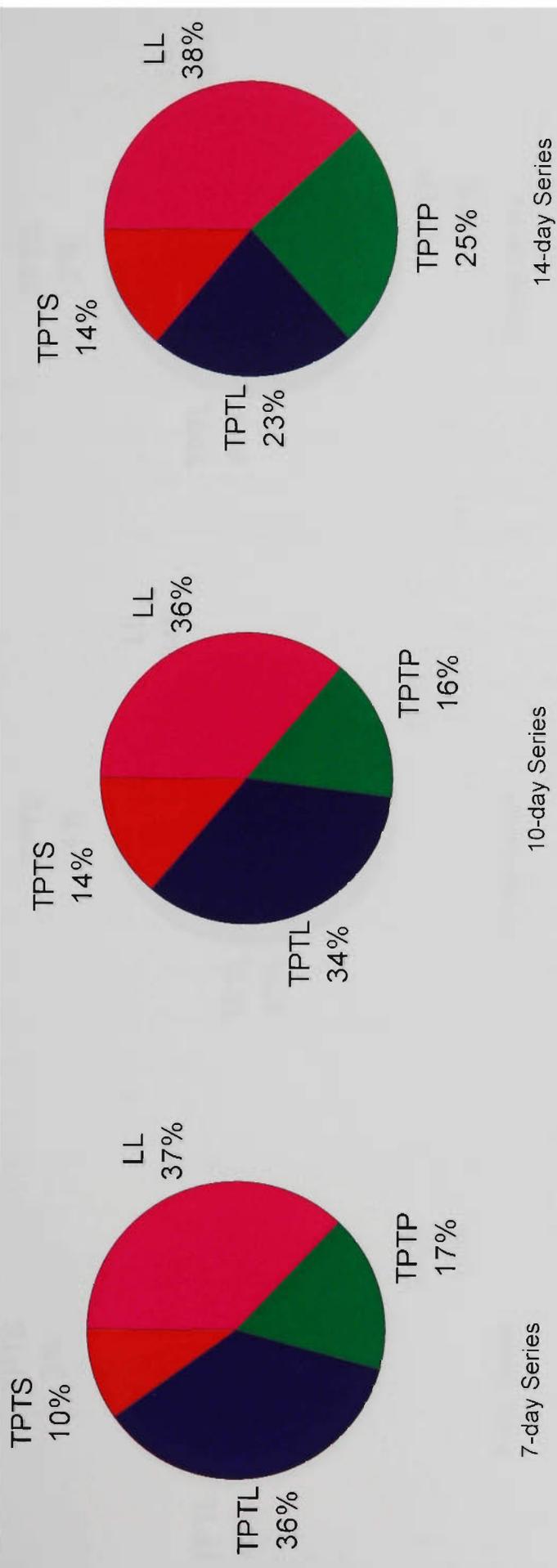


Figure 4.18 Overall Best-Fitted Series by LL and TPT Methods at Tatura

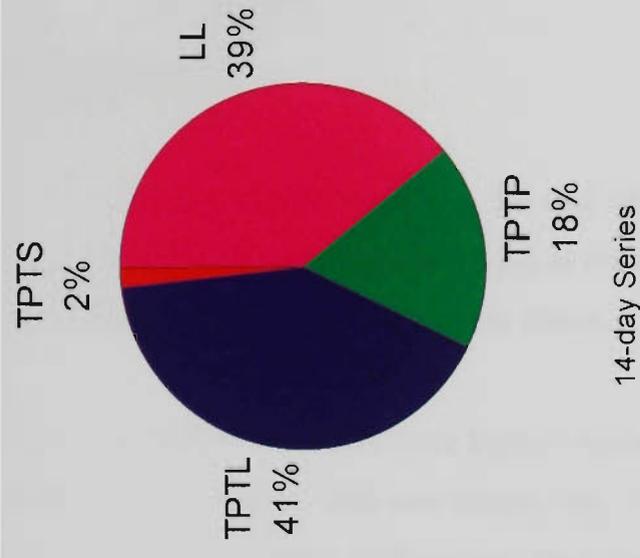
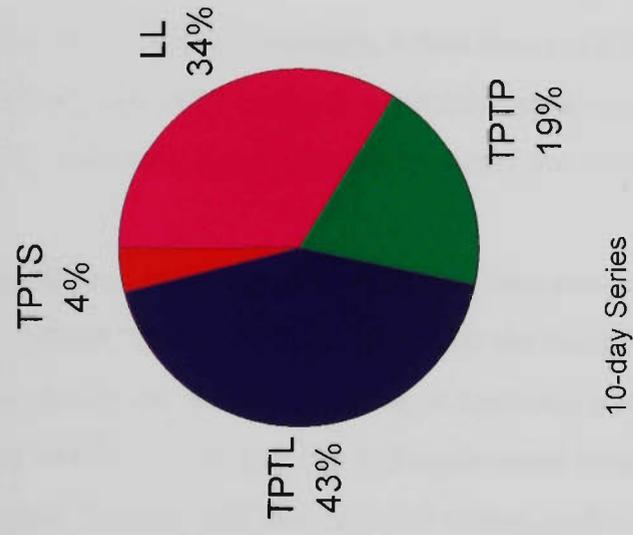
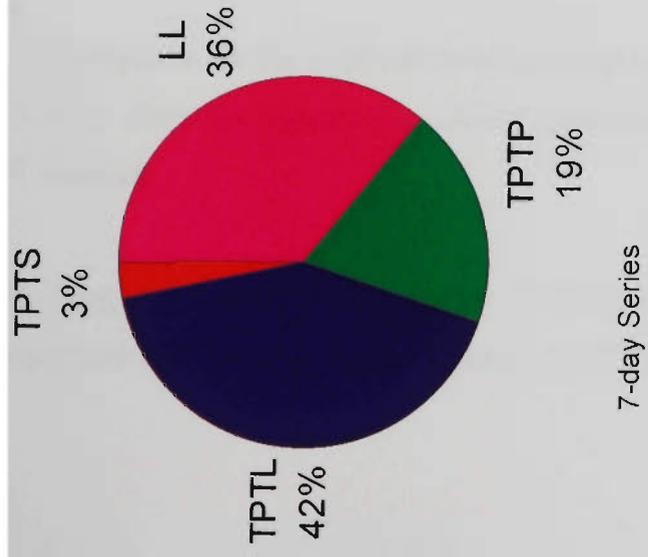


Figure 4.19 Overall Best-Fitted Series by LL and TPT Methods at Pyramid Hill

## Summary of Analysis

Based on the analyses of short-term (7-, 10- and 14-day) rainfall data series at the three sites (i.e. Tongala, Tatura and Pyramid Hill) in the Goulburn Irrigation Area in Victoria (Australia), the following conclusions were drawn:

- Short-term rainfall data series were highly skewed and hence posed difficulties to fit theoretical distributions. This was mainly due to considerable number of no-rainfall (or zeros) and high outliers in the series. Therefore, a separate treatment for zeros and high outliers was essential before fitting a distribution to these data series.
- Based on the literature review, it was found that the Total Probability Theorem (TPT) and leaky law (LL) methods explicitly account for zero values in the data series, and hence, they hold good promise to model the short-term rainfall data series.
- In order to adopt the TPT method, non-zero part of the data series needs to be normalised. The analysis revealed that the short-term non-zero rainfall data series can successfully be normalised using at least one of the three transformations considered in this study (i.e. power, log and square-root transformations), provided the series are adjusted for less than 1mm rainfall values, and the outliers are also removed using the Walsh (1959) outlier test.
- An investigation on the implication of removal of outliers indicated that the removal of outliers does not significantly affect short-term rainfall predictions given by the TPT method.
- TPT using the power transformation (TPTP) was found to be more effective in comparison with log (TPTL) and square root (TPTS) transformations.

- Fitting the short-term rainfall data series by the LL method is significantly improved after <1mm adjustment and removal of outliers. However, the LL fitting analysis revealed that the LL method cannot model all short-term rainfall data series.
- TPT and LL were satisfactory methods to model the short-term rainfall data series having zeros. However, none of these two methods was individually able to fit all short-term rainfall data series at the three sites.
- Since there is no single distribution method to fit all short-term rainfall data series, the joint use of TPT and LL methods can be used as the best choice for reliable rainfall predictions.
- Many short-term rainfall data series were observed to be satisfactorily fitted by at least either of the TPT or LL methods.
- In case when more than one method fit a certain rainfall series, the method which produces the least value of the D-statistic of the K-S test (Section 4.4.1) can be adopted as the best method for reliable predictions.

#### **4.7 RAINFALL PREDICTION COMPUTER SOFTWARE**

As stated earlier (Section 4.6.6), the joint use of TPT and LL methods provides the best solution for reliable short-term rainfall predictions for data series with both zero and non-zero values. Therefore, a computer software package (RAIN\_PRE) was developed to predict short duration (7-14 days) rainfall at specified probability of exceedance. In this section, a brief description of RAIN\_PRE package encompassing its salient features is described. The detailed description of this package including installation, inputs, use and application is given in Appendix B.

#### 4.7.1 General Description of RAIN\_PRE Computer Software

The RAIN\_PRE package was developed aiming at saving irrigation water by making the best use of expected future rainfall during the next irrigation period. While developing this package, a special consideration was given to its robustness, efficient computation, and user-friendliness. To achieve the above considerations, both the TPT (with three transformations outlined in Section 4.2.1) and LL methods were considered in the package, coded them with FORTRAN-77 to facilitate faster computations, and then menu-driven user interfaces developed, to run under both DOS and Window environments.

The RAIN\_PRE software is composed of two computational components. The first component (PROG1) computes the necessary parameters for the TPT and LL methods, and the second component (PROG2) calculates the rainfall predictions. Both components are written in FORTRAN-77 code, each of which is supported by a number of subroutines. The source codes of PROG1 and PROG2, and their supporting subroutines can be requested from the candidate. The flow chart of PROG1 and PROG2 are given in Appendix B.

The package predicts the expected rainfall with a certain probability of exceedance over a pre-specified prediction period. In order to make the rainfall predictions compatible with various irrigation intervals of wide range of crops, a user-specified 5-30 day prediction period (which is also the irrigation interval) was incorporated in this package.

The software requires the historical rainfall record on a daily basis as its major input, and prediction period in days and exceedance probability (%). The other required information is entered through menus of the package. The details of these input data items are given in Section B.4.1 of Appendix B. After entering the required input data, the package can be run to predict the expected rainfall at the specified exceedance probability level over given prediction period. The structure of RAIN\_PRE package is shown in Appendix B.

## 4.8 CONCLUSIONS

In planning the short-term (i.e. 7-14 day) operation (i.e. irrigation scheduling) of irrigation systems, an estimate of irrigation water requirement is of major concern. Since the irrigation water requirement is significantly influenced by rainfall, a reliable estimate of the expected rainfall in any irrigation period of the crop growing season is of fundamental importance. Efficient utilisation of rainfall during the rainy season will help in saving water in the storage reservoir that could be used in the dry season.

The most common approach employed for predicting the expected amount of rainfall has been to fit an appropriate statistical distribution to the historical rainfall records. The rainfall is then predicted with a certain probability of exceedance. A study of rainfall records at three locations in the GIA of Victoria (Australia) revealed that the short-term rainfall data series were positively skewed, and that there were considerable number of non-rainy periods giving zero values in the data series. In addition, high outliers were also found in most data series. The initial analysis revealed that the presence of zeros and outliers in the data series posed problems in fitting conventional statistical distributions (which do not explicitly account for zeros) to these data series. Hence, a method that accounts for the zero values was required to model them.

The total probability theorem (TPT) and leaky-law (LL) methods that account for the zeros were tested for their ability to model the short-term rainfall data series at the three sites. In order to adopt the TPT method with normal distribution, the non-zero part of the data series first needs to be normalised. For this purpose, three transformations (namely power, log and square root) were considered in the TPT method to model the non-zero values of the data series. The analysis revealed that the short-term non-zero rainfall data series could successfully be normalised using at least one of the three aforementioned transformations considered in this study, provided the series were adjusted for less than 1mm rainfall values, and the outliers removed using the Walsh (1959) outlier test. It was observed that TPT using the power transformation (TPTP) was more effective to model

the short-term data series in comparison with log (TPTL) and square root (TPTS) transformations.

Fitting the short-term rainfall data series by the LL method was significantly improved after <1mm adjustment and removal of outliers. However, the LL fitting analysis revealed that the LL method could not model all short-term rainfall data series, as was the case with TPT with all three transformations.

An investigation on the implication of the removal of outliers on short-term rainfall predictions indicated that the removal of outliers does not significantly affect the short-term rainfall predictions given by TPT and LL methods at the three study sites.

The analysis of short-term rainfall data series at the three sites revealed that although TPT and LL were satisfactory methods to model rainfall series with zeros, none of these two methods was individually able to fit all short-term rainfall data series at the three sites. Since there was no single distribution method available to fit all short-term rainfall data series, the joint use of TPT and LL methods was investigated to fit these data series. The joint use of TPT and LL methods revealed that various short-term rainfall data series were successfully modelled by at least either of these two methods. Hence, for reliable rainfall predictions, the joint use of TPT and LL methods was found to be the best choice.

Based on the concept of the joint use of TPT and LL methods, a user-friendly menu driven computer software (RAIN\_PRE) was developed to predict the expected rainfall for a given irrigation interval at a site for various user-specified probabilities of exceedance. The package is comprehensive to predict the rainfall for various irrigation intervals between 5-30 days. The rainfall predictions given by the RAIN\_PRE software can be effectively used to save irrigation water at a farm level.

## CHAPTER 5

### IRRIGATION SCHEDULING – MODEL DEVELOPMENT

#### 5.1 INTRODUCTION

Increasing concern of the limited water supplies as well as farmer concern about maintaining high quality produce has forced the farmers to adopt effective on-farm water management techniques to use available water more efficiently at farm level. Sound irrigation scheduling which deals with the frequency and dosage of irrigation water applications has been demonstrated as one of these potential on-farm management techniques.

In many situations, the problems faced by the farmers are to estimate when the crop needs water and how much water to apply in order to meet the crop requirements, while minimising drainage and other on-farm losses. The typical practices used by farmers for irrigation scheduling on the farm in most irrigation systems include observing early signs of plant wilting or soil drying, or when the neighbouring farm is irrigated, or at fixed schedules. These practices which could be regarded as ad-hoc methods involving guesswork, are subjected to chances of misjudgement, and hence could result in poor water use efficiencies at farm level.

The advances in irrigation science and technology have provided the break-through required to quantify the effects of plant, soil and climate on irrigation scheduling. Therefore, the on-farm irrigation scheduling techniques have been improved significantly in the last two decades. In particular, with the development of personal computers, irrigation scheduling based on accounting of the soil water budget components has become popular around the world (Hess, 1996).

Several computer programs with varying degree of sophistication have been evolved in the literature during the last two decades. However, these computer based scheduling programs are not yet widely practised by the farmers. In USA, even though some of the scheduling programs were offered free of charge, the acceptance of these programs among farmers has been reported to be low. The limited use of these irrigation scheduling programs among farmers could be attributed to one (or more) of the following reasons (Pleban and Israeli, 1989; and Adoum, 1993):

- (i) The computer programs were not user-friendly, but were research-oriented tools for use by professionals only.
- (ii) The programs considered the scheduling problem from the point of view of the crop and academic research, and not particularly from the viewpoint of the farmers.
- (iii) Some computer programs employed complex algorithms for modelling of water movement through the root zone, and required the measurement of a large number of soil, plant and climatic parameters, which are not routinely available in most irrigation systems.

An efficient irrigation scheduling computer program must at a minimum provide information on the timing of the next irrigation and the amount of water to apply so as to serve as a real-time operational tool. In addition, the program should also be able to predict the expected irrigation schedules as well as the estimates of total expected irrigation water requirements for the entire season (before the actual season starts), to render itself as a planning tool.

A farmer survey conducted in Northern Victoria in Australia (Maskie, 1995) revealed that farmers had shown an interest in automation to improve water use efficiencies at farm level, provided the automation techniques were simple and compatible with their needs. The irrigation scheduling programs can serve to enhance such automation.

Farmers are generally busy in making different management decisions during the irrigation season. Consequently, any aid for improving irrigation decisions should minimise the efforts required to obtain input data and should provide output that is easy to understand and use. If farmers perceive that the required data are too difficult to obtain or that a considerable time is required to obtain and process the required data, then they are unlikely to use the irrigation scheduling computer programs (Buchleiter, 1995).

In the spirit of the above stated desirable features, the development of a simple model for efficient scheduling and forecasting of irrigation water requirements at an on-farm level is presented in this chapter. The model employs simple algorithms for simulating the soil-plant-atmosphere system. An effort was made to develop the model with minimum and readily available inputs (e.g. general soil physical properties such as saturation level, field capacity, wilting point, and other crop related parameters such as crop coefficients, root zone depth), so that the model can be calibrated without the need for extensive field measurements, for use in actual field situations.

First, this chapter describes the fundamental concepts of the irrigation scheduling process including various soil moisture related definitions. Then, it discusses different components of the irrigation scheduling model, which uses soil water balance approach. Theoretical details as well as the estimation procedures of various components are presented, after reviewing related previous research work. After this, a summary of the algorithms used in the developed irrigation scheduling model is outlined. The computations of irrigation scheduling model are described then. The performance evaluation of the irrigation scheduling model under Victorian (Australian) conditions is presented at the end of the chapter.

## **5.2 FUNDAMENTAL CONCEPTS**

As stated earlier, the main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor quality of harvest (Haise and Hagan, 1967). Irrigated crops suffer production losses when they are over-watered or

under-watered. Proper irrigation scheduling could assure fulfilling the maximum yield requirements whilst making an efficient use of the available water at farm level.

Since irrigation scheduling process deals with deciding when to irrigate, and how much water to apply, it integrates many complex interactions of water, soil and crop as well as climate related physical factors. Thus, it is necessary to consider the fundamental concepts related to these interactions. Some of these fundamental concepts are explained in the following sub-sections.

### **5.2.1 Soil-Plant-Atmosphere Continuum**

In modelling irrigation scheduling accurately, the soil-plant-atmosphere continuum needs to be considered as a physically-integrated, dynamic system in which transport processes occur interactively (Hoffman and Martin, 1993). The plant in this continuum, acts as an interface between its source (i.e. soil) and sink (i.e. atmosphere), to support the transport process. Soil water, which fills the pores between individual soil particles and soil aggregates, is one of the most important ingredients of this system. The water in soil constantly moves by percolation, evaporation, transpiration, irrigation, infiltration, and other processes, and therefore plays a vital role in the transport processes of the soil-plant-atmosphere continuum. Thus, an understanding of the behaviour of soil water, and the relationship between the water content and air content in the soil is also of great importance. Hence, various soil moisture related terminologies employed in irrigation scheduling are discussed in this section. In this study, the terms soil water and soil moisture are interchangeably used.

#### ***Soil moisture volume/mass relationship***

Generally, a unit volume of soil consists of three components namely solids, water and air, as shown in Figure 5.1. Therefore, based on Figure 5.1, the soil moisture content (SMC) can be expressed on a volume basis ( $\theta$ ) also referred to as volumetric units, or on a mass basis ( $M$ ), with units of  $\text{cm}^3 \text{ cm}^{-3}$  and  $\text{gm gm}^{-1}$  respectively, or both in percent.

Mathematically it could be expressed as:

$$\theta = \frac{V_w}{V_t} \quad (5.1)$$

$$M = \frac{M_w}{M_s} \quad (5.2)$$

where  $V_w$  = volume of water (cm<sup>3</sup>)

$V_t$  = total volume of soil unit (cm<sup>3</sup>) =  $V_a + V_w + V_s$

$M_w$  = mass of water (gm)

$M_s$  = mass of oven dried soil at 105 °C (gm)

and all other terms are as defined earlier.

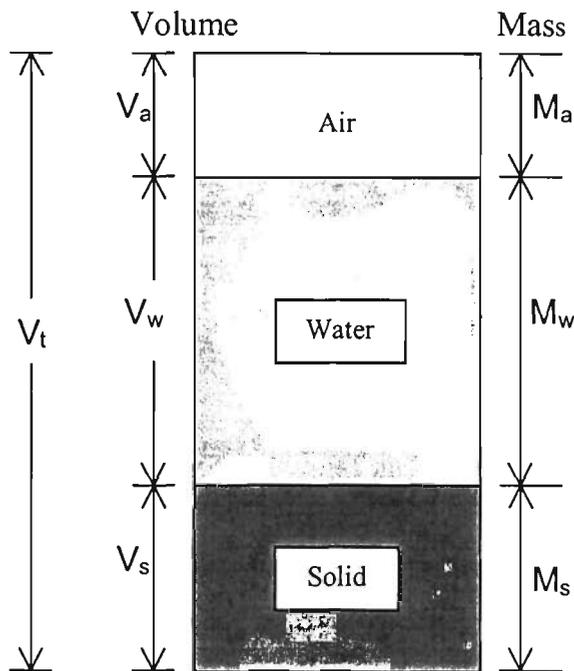


Figure 5.1 Soil Mass-Volume Relationship

The conversion of SMC from a mass basis to a volumetric basis can be achieved as:

$$\theta = M \frac{\rho_b}{\rho_w} \quad (5.3a)$$

$$\rho_b = \frac{M_s}{V_t} \quad (5.3b)$$

where  $\rho_b$  = dry bulk density of soil ( $\text{gm cm}^{-3}$ )  
 $\rho_w$  = density of liquid water ( $\text{gm cm}^{-3}$ )  
and all other terms are as defined earlier.

The volumetric SMC in Eqs. 5.1 and 5.3 represents the equivalent depth of water per unit of soil profile/depth. Prior to the use of neutron moisture probe, which is calibrated to indicate  $\theta$ , most field studies used gravimetric determination of M. Hence to determine SMC in volumetric units, Eq. 5.3 was used.

With regards to  $\rho_b$  parameter for use in Eq. 5.3, in most cases  $\rho_b$  once determined during a study, was assumed to remain constant at a given depth throughout the season or study. This assumption is reasonable below the plow depth, but could result in substantial measurement error in the total soil water in the plowed layer. Although the error is not great for determining SMC changes over 5 to 15-day periods,  $\rho_b$  must be adjusted for SMC changes in swelling and cracking soils (ASCE, 1996).

It is important to note that all soil moisture retained in the soil profile is not available for plant use. There are certain limits which are explained through the terms (e.g. saturation point, field capacity, permanent wilting point, available water and hygroscopic water) described below. These terms are also shown in Figure 5.2. All these soil moisture terminologies described in this sub-section are used to estimate the irrigation water requirement for use in the Irrigation Scheduling model of this study.

### ***Saturation point***

When all voids between individual soil particles and soil aggregates are filled with water and there is no air in the soil profile, the moisture content is termed as the saturation

point. Thus, the saturation point represents the maximum water holding capacity of the soil.

In field conditions, the soil profile becomes saturated temporarily after an irrigation, flooding, or a heavy rainfall. The water which drains out of the saturated soil under the influence of gravity is known as gravitational water. In sand, it may drain out within an hour, and in heavier agricultural soils it may take up to 1 to 3 days. The gravitational water is generally considered unavailable to the plants, and most root systems suffer or die when surrounded by gravitational water for any length of time because of lack of aeration (Finkel, 1982). In this study, the notation  $\theta_{sat}$  was used to represent the volumetric *SMC* at saturation point of the soil.

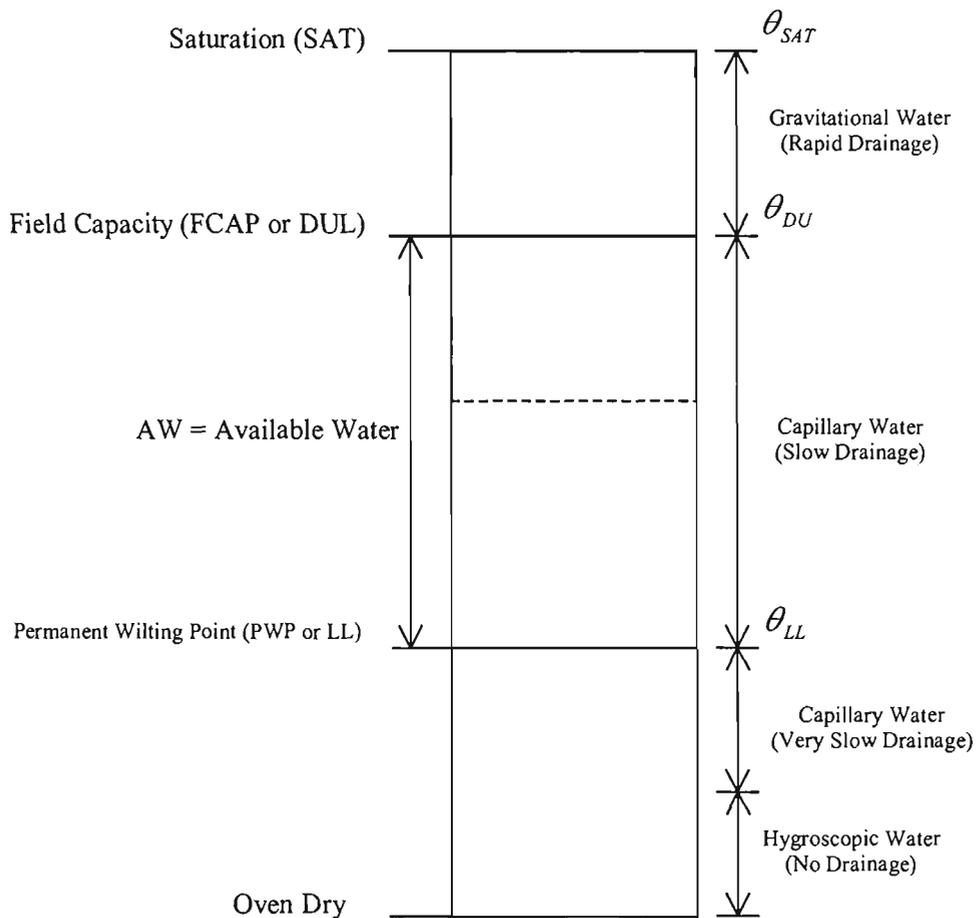


Figure 5.2 Schematic Representation Soil Water

### ***Field capacity (FCAP)***

The moisture content after the gravitational water has drained out is termed as the field capacity (FCAP), and is considered as the upper limit of the moisture available to plants under normal field conditions. FCAP is the maximum amount of water that a well-drained soil can hold against the gravitational force by capillary, and is also the point at which maximum plant growth occurs.

It should be noted that the field capacity is not a unique value that always occurs in a given soil, since it is not a true equilibrium state. This is because the downward movement of water does not cease when soil reaches field capacity, but continues at a reduced rate for a long time even after the field capacity. However, this later-drainage rate is very small. If growing plants are present, the change in moisture content of the root zone due to this later-drainage is negligible compared with the water use by plants. Therefore, for operational purposes, FCAP for a given soil can be expressed with a specific value (McIntyre, 1974a).

Since FCAP represents the drained upper limit of the soil after a major precipitation (irrigation and/or rainfall) event for maximum plant growth to occur, more recent equivalent term called *Drained Upper Limit (DUL)* has also been synonymously used for FCAP (e.g. Wood et al., 1997; ASCE, 1996). To be consistent with the latest standard terminologies,  $\theta_{DU}$  is used to represent the volumetric SMC at FCAP conditions. The values of  $\theta_{DU}$  parameter for various soil textures are available in the literature stated under *Available Water* sub-heading below.

### ***Permanent wilting point (PWP)***

As the plant roots begin to use water held within the soil by capillary, the soil dries out. Eventually, the soil reaches a condition what is known as the permanent wilting point (PWP). Thus, the moisture content at which plants will wilt and not recover with further irrigation, is termed as PWP. At PWP, there is still some moisture left in the soil but it is

so tightly held to the soil particles that the plant roots cannot extract it for their use. The PWP for different plant species varies within the same soil type. Since PWP represents the lower limit of moisture extraction by plant roots, the volumetric *SMC* at *PWP* is expressed by another synonymous recent symbol as  $\theta_{LL}$ , where LL refers to the Lower Limit.

***Available water (AW)***

The soil moisture which is available for plant use is known as the available water. By definition, it is the amount of water stored in the soil profile between DUL and PWP. Mathematically it can be expressed as:

$$AW = (\theta_{DU} - \theta_{LL}) Z \tag{5.4}$$

where *AW* = available water in depth units (cm)

*Z* = root zone depth (cm)

and all other terms are as defined earlier.

In practice, the soil is never allowed to dry out to PWP, but is kept above a certain soil moisture (hereafter referred to as *critical soil moisture*) level to avoid yield losses. This *critical soil moisture* ( $\theta_{crit}$ ) determines when to irrigate the field, and hence, is also referred to as the *refill point* of the soil profile.

ASCE (1996) reported that even though the values for  $\theta_{DU}$  and  $\theta_{LL}$  could vary widely with the soil texture, the values for available water (AW) vary relatively little, especially for moderately coarse to fine textured soils. Therefore, for operational purposes if  $\theta_{DU}$  can be determined from field observations of soil moisture one to three days following significant rain or irrigation, then  $\theta_{LL}$  can be approximated as  $(\theta_{DU} - AW)$ , where AW can be taken from the literature (e.g. RWC, 1988; and ASCE, 1996) for the corresponding soil textural class. However, if possible, both specific values of  $\theta_{DU}$  and

$\theta_{LL}$  should be determined from field studies for accurate results.

It is important to mention that in this thesis, the notations FCAP (or DUL), PWP (or LL), and AW etc. when appear in normal flow of the text, represent the corresponding SMC in depth units, and when appearing as subscripts with  $\theta$  refer to corresponding SMC in volumetric units. Figure 5.2 shows the relation between FCAP (or DUL), PWP (or LL), and AW.

The average values and ranges of  $\theta_{DU}$  ( $\sim FCAP$ ),  $\theta_{LL}$  ( $\sim PWP$ ), and  $AW$  parameters for different soils are given in literature (e.g. Blaikie and Mason, 1993; Lattimore et al., 1994; ASCE, 1996; and Wood et al., 1997).

### ***Hygroscopic water***

The soil moisture below PWP may leave the soil through direct evaporation (i.e. capillary water - very slow drainage) from the soil surface, until it reaches at an air-dried level. The moisture which remains in the soil after drying in air is termed as hygroscopic water. This moisture is adsorbed on the surface of the soil particles and can only be removed by drying in an oven at 105 °C. The hygroscopic water is of no value to the plants.

It should be noted that all of the above stated moisture quantities are determined and expressed either in terms of percentage by mass of an oven-dry soil, or in terms of percentage by volume of the soil matrix (i.e. volumetric units), as stated earlier. However, for irrigation scheduling studies, it is usually desirable to express these moisture contents in terms of equivalent depth of water in the soil profile, which is obtained as:

$$d = \theta Z \tag{5.5}$$

where  $d$  = depth of water (cm)  
 $\theta$  = volumetric soil moisture content ( $\text{cm}^3 \text{cm}^{-3}$ )  
 $Z$  = depth of soil profile (cm)

### 5.2.2 Division of Root Zone Profile into Sub-layers

It is worthwhile to note that some of the soil hydraulic characteristics such as soil water holding capacity, wilting point, field capacity, plant available water, etc. vary throughout the root zone profile depth from the soil surface. In addition, the upper (or surface) portion of the root zone profile exhibits special features in terms of its contribution towards the evapotranspiration (ET) process, since the soil evaporation component of ET is supported only by this upper layer. The variability of soil hydraulic properties throughout the root zone and soil evaporation through surface layer necessitates that the entire root zone depth ( $Z$ ) should be divided into a number of discrete sub-layers or stratifications, with homogeneous hydraulic characteristics. The soil moisture must then be estimated separately in each sub-layer and summed up over the entire root zone (Cuenca, 1988; Tracy and Marino, 1989; De Faria et al., 1994; and Singh and Singh, 1996). This method would produce reliable SMC estimates than those resulting from assuming the entire root zone as a single store with average values for hydraulic parameters. However, the latter method has been used by Armstrong et al. (1993), Walker et al. (1993) and Buchleiter (1995). This method gives acceptable results for homogeneous soil profiles or even for shallow-rooted crops growing in heterogeneous soil profiles, but could lead to substantial errors in deep-rooted crops in heterogeneous soils, especially in swelling and cracking soils such as those of Northern Victorian soils (McIntyre, 1974b).

Therefore, considering the critical aspect of heterogeneous soil profiles and the importance of minimum data requirements, the entire root zone ( $Z$ ) is divided into four workable sub-layers of equal thickness in this study. This aspect is further discussed in Section 5.4.3.

Considering the discrete sub-layers as described above in the root zone, the total soil moisture content in the entire root zone can be estimated by the following:

$$d_z = \int_0^Z \theta_z dz = \sum_{i=1}^n \theta_i \cdot z_i \quad (5.6)$$

where  $d_z$  = soil moisture content of entire root zone in depth units (cm)  
 $\theta_i$  = volumetric soil moisture content of sub-layer  $i$  ( $\text{cm}^3 \text{ cm}^{-3}$ )  
 $z_i$  = depth (or thickness) of  $i^{\text{th}}$  sub-layer (cm)  
 $n$  = total number of discrete sub-layers in the entire root zone divided between 0 and  $Z$ , where  $Z$  is the entire root zone.

In addition, this study follows a simple cascade type approach to redistribute soil moisture among the sub-layers for every precipitation (rainfall and/or irrigation) event. This aspect is discussed in Section 5.2.3.

### 5.2.3 Soil Moisture Redistribution Among Sub-Layers

According to the approach adopted in this study, any water (rainfall and/or irrigation) applied to the field will be distributed among sub-layers starting from the surface sub-layer to the subsequent lower sub-layers. This implies that if the depth of applied water is greater than the storage capacity of surface sub-layer, firstly the surface sub-layer is recharged to its FCAP or  $\theta_{DU}$  level and then excess water is distributed to the second (lower) sub-layer to recharge it to its FCAP level, and so on until all applied water is distributed among all sub-layers. After having recharged all root zone sub-layers at FCAP level, if there is some excess water still left, this excess water is considered as deep percolation losses. This approach is in line with the previous studies of Saxton et al. (1974), Cuenca (1988), and Tracy and Marino (1989).

Morton (1991) quoted that the soil moisture movement from an upper sub-layer to the adjacent (lower) sub-layer may start even if the SMC of the upper sub-layer has not reached its FCAP level. However, this movement has been reported insignificant to affect the overall model simulation results (Cuenca, 1991; and De Faria et al., 1994).

### 5.3 COMPONENTS OF THE IRRIGATION SCHEDULING MODEL

As mentioned earlier, the irrigation scheduling process considers many complex interactions of water, soil, crop as well as climate related physical factors which influence irrigation decisions. Since irrigation scheduling deals with a complex soil-plant-atmosphere system, the accuracy of an irrigation scheduling model primarily depends on how accurately this system is modelled. Comprehensive modelling of all processes involved in the soil-plant-atmosphere continuum requires many complex data requirements which are not only costly but also laborious and time consuming to collect. Hence, the comprehensive modelling of these processes is not practically feasible under normal irrigated field conditions.

Correct irrigation scheduling requires a knowledge of the soil moisture content. Since the measurement of SMC in the root zone is often costly, time consuming and complicated due to endemic variability in the soil, there has been a continuing effort in developing mathematical models for SMC estimates which use readily available meteorological, soil and plant data (Baier and Robertson, 1966; De Jong and Cameron, 1978; and De Jong and Hayhoe, 1984).

Various approaches have evolved to describe the movement of moisture in the soil-plant-atmosphere system. Empirical as well as physically based mathematical models have been developed to describe unsaturated flow in the root zone and to predict crop water requirements, as discussed in Chapter 2. In the empirical models, simple empirical algorithms based on field observations to transfer water in and out of the soil profile are adopted. These models vary in their use of infiltration and redistribution procedures as well as of techniques to describe actual evapotranspiration as a function of available soil water. This modelling approach has proven quite versatile since many simple assumptions appear to have a wide range of applicability (Baier and Robertson 1966). In general, however, reliable predictions at individual sites require some calibration using observed soil moisture data.

The physically based models, on the other hand, use the principle of continuity and Darcy's law to derive a general soil-water flow equation with water moving through the soil in response to water potential or water content gradients. Water uptake by plant roots is then simulated by adding a volumetric sink term to this soil-water flow equation. A major advantage of these physically based models is that they are process-oriented, distinguishing (for example) between transpiration, soil evaporation and free water evaporation processes, and that they use measured parameters. Although this approach has sound theoretical foundations, it can still only be considered as a first-order approximation to what is happening under actual field conditions (De Jong and Hayhoe, 1984). In addition, the main problem with the use of these physically based models is that they are data extensive. The input parameters (such as soil hydraulic conductivity  $K(\theta)$ , soil moisture diffusivity,  $D(\theta)$  required by these models are either time variant or spatially variable, and need to be determined experimentally under local conditions, which are routinely not feasible in most irrigation systems.

In between these two extremes (i.e. empirical and physically-based models), there can be hybrid (or semi-empirical) models which use best features of both types of models. These models may produce reasonable accuracy for irrigation scheduling, which require less amount of data. Such a hybrid approach is adopted in this study. In this study, an irrigation scheduling model was developed using the water balance approach and includes a dynamic moisture extraction function for modelling the plant root system to mimic the actual field conditions. This model can be considered as hybrid (i.e. semi-empirical) of empirical and physically-based mathematical models, where the water balance components are estimated using semi-empirical methods.

### 5.3.1 Water Balance Model of Irrigated Crops

For most irrigated crops, the soil-water balance can be expressed as follows:

$$SMC_j = SMC_{j-1} + IR_j + RF_j + CR_j - ET_j - DP_j - DR_j \quad (5.7)$$

- where  $SMC_j$  = soil moisture content at the end of  $j^{th}$  period (cm)
- $IR_j$  = net irrigation during period  $j$  (cm), as described in section 5.3.2.
- $RF_j$  = effective rainfall during period  $j$  (cm), as described in section 5.3.3.
- $CR_j$  = capillary rise from the lower boundary of the soil profile during period  $j$  (cm), as described in section 5.3.4.
- $ET_j$  = crop evapotranspiration during period  $j$  (cm), as described in section 5.3.5.
- $DP_j$  = deep percolation from the lower boundary of the soil profile during period  $j$  (cm), as described in section 5.3.5.
- $DR_j$  = surface runoff/drainage out of the field during period  $j$  (cm)

Equation 5.7 represents the water balance of the entire soil profile over a specified time period. For irrigation scheduling, the soil profile of interest is only the zone in which plant roots expand to support the ET process. Therefore, when Eq. 5.7 is employed for the root zone of a crop, it predicts the moisture content of the entire root zone depth ( $Z$ ) resulting from the interaction of various water balance components which influence moisture movement in the root zone.

For computation of SMC in the root zone on the basis of a time step of one day, Eq. 5.7 can be rewritten as:

$$\int_0^Z \theta_{2,z} dz = \int_0^Z \theta_{1,z} dz + IR_1 + RF_1 + CR_1 - ET_1 - DP_1 - DR_1 \quad (5.8)$$

- where  $\theta_{2,z}$  = volumetric soil moisture content of root zone depth  $Z$  at the end of day 2 ( $cm^3 cm^{-3}$ )
- $\theta_{1,z}$  = volumetric soil moisture content of entire root zone depth  $Z$  at the end of previous day 1 ( $cm^3 cm^{-3}$ )
- $Z$  = root zone depth (cm)
- and all other terms are as defined earlier.

In most agricultural situations, especially where the surface is flat (e.g. laser levelled), surface runoff (DR) is negligible (Curwen and Massie, 1985). Also, in situations where the ground-water table is significantly well beneath the root zone of the crop, ground water contribution through capillary rise (CR) in comparison with daily ET is negligible. However, the inter sub-layers CR (Section 5.3.4) resulting from an irrigation event is an important factor even though the ground-water table is significantly well beneath the root zone of the crop. Equation 5.8 can then be simplified as follows:

$$\int_0^z \theta_{2,z} dz = \int_0^z \theta_{1,z} dz + IR_1 + RF_1 + CR_1 - ET_1 - DP_1 \quad (5.9)$$

This soil water balance model (Eq. 5.9) has been previously used as a basis in various irrigation scheduling studies by several researchers (e.g. Cuenca, 1988; Clarke et al., 1992; Boisvert et al., 1992; Singh et al., 1995; and Hess, 1996) under various soil, crop and climatic conditions. However, the algorithms adopted in modelling various components of the water balance model varied depending on the purpose and desired degree of accuracy under prevailing field conditions. The same water balance model (i.e. Eq. 5.9) also forms the basis of the irrigation scheduling model of this study. The detailed description of the estimation procedures adopted in this study for each component of the water balance model is presented below.

### 5.3.2 Net Irrigation (IR)

The net irrigation (*IR*) term of the water balance model (Eq. 5.9) refers to the amount of water which is actually available to the crop for evapotranspiration. In actual practice, the amount of irrigation water that is applied to the crop is greater by an amount depending on the efficiency of the irrigation system in use, and is termed as the gross irrigation (*IR<sub>gross</sub>*). Net irrigation (*IR*) is thus the amount of water remaining after direct evaporative loss to the atmosphere (such as from spray mist or flooded surfaces), interception loss from wet canopy cover, surface runoff, and in some instances unavoidable deep percolation and/or leaching loss below the root zone.

Since an irrigation application is associated with the interactions of several soil, crop and climate related parameters, adequate modelling of these interactions essentially increases the complexity and input data requirements, which is beyond the capabilities of most farmers to provide in normal irrigation systems. Therefore, based on an irrigator's experience, a suitable application efficiency figure can be used to approximate the value of gross irrigation applied for use in the model. In this study, a user-specified application efficiency factor is included in the model. The application efficiency values can be found in the literature (e.g. Doorenbos and Pruitt, 1977; and Wolters, 1992).

### 5.3.3 Effective Rainfall (*RF*)

The effective rainfall term (*RF*) in the above water balance model (Eq. 5.9) refers to the amount of rain that reaches the root zone in meeting the ET requirement of the crop, after it has been intercepted and evaporated directly from the crop foliage. An extensive review of models for estimating effective rainfall from measured rainfall has been published by the FAO of the United Nations (Dastane, 1974). Rainfall interception losses are usually derived from experimental measurements for various growth stages of specific crops (Theiveyanathan et al., 1998). Interception losses are generally greater during summer months when evaporative demand is high. To account for these losses, the actual measured rainfall is adjusted by a correction factor to derive the effective rainfall value for a given crop (Burman et al., 1983). The effective rainfall correction factors are given by Doorenbos and Pruitt (1977), Burman et al. (1980), Hedditch, (1985) and Heslop (1991). The estimated effective rainfall can then be used in the water balance model.

It should be noted that after having allowed for interception losses, not all of the remaining rainfall is essentially available for plant use, especially if it exceeds the DUL of the root zone or if it falls soon after an irrigation event. In these cases, further losses occur as surface runoff and/or deep percolation loss. Deep percolation is discussed in

detail in Section 5.3.4. The surface runoff is ignored in this study for the reasons stated in Section 5.3.1.

#### **5.3.4 Capillary Rise (CR)**

The capillary rise (CR) term in the water balance model of Eq. 5.9 represents the amount of moisture which is contributed by the lower sub-layers to the upper adjacent sub-layers (through the capillary rise action), when there is a deficit in SMC of the upper sub-layers. Ignoring CR can result in underestimation of the SMC available for plant evapotranspiration. Feddes et al. (1978) reported that the inclusion of upward moisture movement through capillary rise between the adjacent sub-layers could yield more accurate results of soil moisture simulation in irrigated crops. This approach requires the parameters, such as hydraulic conductivity ( $K(\theta)$ ) and soil moisture diffusivity ( $D(\theta)$ ), which are seldom available in most irrigation systems. Even if they are available, the spatial variability of these parameters affect the results. For these reasons, the capillary rise (or diffusivity) aspect of soil moisture has not been included in this study. Nevertheless, this aspect can be indirectly accounted for through the  $\theta_{DU}$  calibration process, while considering the excess water of deep percolation, as described in Section 5.3.5.

#### **5.3.5 Deep Percolation (DP)**

The deep percolation (DP) term in the water balance model of Eq. 5.9 represents the amount of excess water which goes beyond the root zone and is not available for plant  $ET$ , but contributes to the sub-surface drainage. Deep percolation usually occurs when rainfall follows an adequate irrigation event where root zone is already wet, or when an irrigation event itself overfills the root zone above its water holding capacity.

Since deep percolation from an irrigated field is associated with its overfilled conditions beyond the water holding capacity, it can be estimated from the drained upper limit

(*DUL*) or field capacity (*FCAP*) of the soil. Therefore, for the purpose of this study, it is stipulated that *DP* is generated when the SMC exceeds drained upper limit  $\theta_{DU}$  or field capacity of the root zone.

It is worthwhile to note that in actual field conditions, if the SMC of the root zone is already at its *DUL* following an irrigation event, and moderate rainfall occurs, the deep percolation does not take place instantaneously soon after the rainfall (McIntyre, 1974a). In fact, field capacity is generally attained after one to four days of the rainfall event depending upon the type of the soil. In addition, some of this gradually percolating water (hereafter referred to as *excess water*) becomes readily available to satisfy the crop ET (or plant water use) requirements, before actually contributing to deep percolation losses. However, the fraction of this excess water available for crop use depends on the prevailing crop, soil type and climatic conditions. For the same soil type, during relatively higher evaporative demand periods, this fraction is greater than during the less evaporative demand periods. During the same evaporative demand periods, a coarse soil has a higher fraction compared to that of a fine soil.

In most previous irrigation scheduling studies that are based on the water balance approach (e.g. Jensen et al., 1971; and Heerman et al., 1976), the *excess water* was considered as “*all lost*” water, and hence totally discarded from the water balance calculations whenever an overfilled conditions beyond the *FCAP* is occurred. This can lead to significant discrepancies between the actual and predicted soil moisture contents in the root zone. By virtue of these under-estimated SMC predictions of the root zone, the above assumption can result in more frequent and/or premature (or earlier) irrigation recommendations. Therefore, for operational purposes, to account for this extra moisture availability for plant use, an adjustment needs to be made in the model to reduce the deep percolation loss figure as computed by the model.

Accurate modelling of the above stated transient excess water component requires many crop and soil related parameters such as tillage practices, soil hydraulic conductivity, diffusivity, infiltration parameters, etc. However, it is unrealistic to expect from the

farmers to provide these information for irrigation scheduling purposes. Buchleiter (1993) suggested an exponential function based on the water holding capacity of the soil to determine the fraction of the transient excess water component available for crop use. However, this function assumes a single root zone layer which is valid only in homogenous soil profiles, and could give misleading results in heterogeneous root zone soil profiles. Hence, in order to model the heterogeneous soil profiles and to maintain a reasonable accuracy, a simplified approximation was adopted in this study. In this approach, the value of  $\theta_{DU}$  used in water balance model was set a few percentage points above the normal values as obtained from the literature to account for the transient extra moisture available for crop use. However, this needs to be calibrated (or adjusted) for each soil type under local field conditions. In this study, this extra allowance to be made in  $\theta_{DU}$  value was limited to 25% of total available water of the respective root zone sub-layer. This is in line with the suggestion of Buchleiter (1995).

In situations, where impervious heavy clay barriers underlay the top soil or the root zone, these barriers restrict the downward drainage of the soil moisture. Hence,  $DP$  losses in these cases can be replaced by surface runoff losses when modelling the actual field conditions. However, this has not been considered in this study. Hence, in this study any excess water above the field capacity (FCAP) was considered as loss, except the above stated extra allowance made through the  $\theta_{DU}$ .

### 5.3.6 Evapotranspiration (ET)

Evapotranspiration or water uptake by plants is the major ‘sink’ term of the water balance model given by Eq. 5.9. It refers to the amount of soil moisture which is utilised through the consumptive use of the crop. The daily potential crop evapotranspiration ( $ET_c$ ) can be estimated using the reference evapotranspiration ( $ET_o$ ) and crop coefficient ( $K_c$ ) through the following relation as:

$$ET_c = K_c ET_o \tag{5.10}$$

It should be noted that because of the two “reference crop” definitions (grass and alfalfa) used, two types of crop coefficients namely grass-based (Doorenbos and Pruitt, 1977) and alfalfa-based (Wright, 1981,1982) have been developed. Therefore, caution must be exercised in not mixing these two types of crop coefficients. Hence, both the reference evapotranspiration and crop coefficient values in Eq. 5.10 must be based on the same reference crop to avoid errors in  $ET_c$  estimates. In this study, the grass-based  $K_c$  along with grass-based reference evapotranspiration were adopted due to its wide spread use around the globe for agricultural crops as compared with alfalfa-based coefficients (ASCE, 1996). The grass-based crop coefficients for various crops are given by Doorenbos and Pruitt (1977), Thomas and Rendell (1985), Heslop (1995) and ASCE (1996).

With regards to the reference crop evapotranspiration estimates, there are numerous empirical methods available for estimating  $ET_o$  with varying accuracy levels depending upon the availability of meteorological data for the site under consideration. However, as mentioned earlier (in Section 3.1), these methods need to be calibrated under local conditions before they are employed for crop water use ( $ET_c$ ) estimates. A detailed discussion of their merits, relative accuracy and calibration techniques is given in Chapter 3.

It is important to note that the  $ET_c$  estimates obtained from Eq. 5.10 represent the potential (or maximum) rate, which occurs only if SMC of the root zone remains close to the DUL (or FCAP) moisture level. However, in real life field conditions, this situation lasts only for a few days (following an adequate irrigation and/or heavy rainfall event) depending upon the prevalent climatic conditions. After this, the actual crop evapotranspiration ( $ET_a$ ) rate decreases day by day as moisture reserve depletes from the root zone until it reaches to a minimum value. This aspect of water uptake by plants through the process of evapotranspiration and the modelling techniques used are discussed in detail in Section 5.4.

## 5.4 MODELLING OF WATER UPTAKE BY PLANTS

Water uptake (or moisture extraction) by plant roots through the process of ET is one of the most difficult modelling components of the soil water balance model due to spatially variable and time-variant nature of the root system. Nevertheless, this subject has been investigated by a number of researchers and several mathematical models were developed to describe the moisture uptake by the plant root system. A review of these moisture extraction models is given in Molz (1981).

The studies carried out in this area can be classified under three major categories (Corapcioglu, 1992). The first category termed as *microscopic models* includes the studies dealing with the radial flow of water to a single plant root (Molz, 1976; and Cushman, 1982). In the microscopic approach, an individual plant root is considered as an infinitely long cylindrical sink of uniform radius. The soil water flow equation is then written in cylindrical co-ordinates and solved with appropriate boundary conditions at the root surface and at some distance from the root. This approach, in general, does not include interpretation of field data which are collected under heterogeneous conditions over a period of time during which the root system development progresses. The second category termed as *macroscopic models*, considers the moisture removal by the root system from each differential volume of the root zone at some rate as a whole without considering explicitly the effects of individual roots. This approach recognises the fact that the geometry of the root system is practically impossible to measure as it is time-dependent. Studies in this category combine the Richard (1931) equation for soil water flow in the unsaturated zone with a sink term representing water extraction by plant roots (Feddes and Rijtema, 1972; and Raats, 1976). The third category called *hybrid approach*, incorporates time-specific plant root and soil parameters, such as root density, root permeability, and root water potential into the extraction function for accurate water uptake predictions (Taylor and Klipper, 1978; Federer, 1979; and Marino and Tracy, 1988).

Even the hybrid approach requires a detailed knowledge of both the plant root and the soil parameters. However, such input information is both time-consuming and expensive to obtain. Therefore, in the interest of practicality and minimum input data

requirements for an operation-oriented irrigation scheduling model, an alternative simple approach was adopted in this study. This approach not only eliminates the use of data extensive Richard (1931) equation, but also is practicable to work in the real life field conditions, and produces acceptable accuracy. This approach employs the guidelines of some previous studies such as Denmead and Shaw (1962), Boughton (1966,1968), Hayhoe and De Jong (1988), Wesseling and Van De Broek (1988), Wesseling et al. (1989,1994), Boisvert et al. (1992) and Singh et al. (1995). The adopted approach is described below.

In this approach, the moisture extraction or water uptake by crop through the process of ET is considered as a diffuse volumetric “sink” controlled by a sink term specified in the water balance model. This so called sink term,  $S(\theta, z)$  represents the moisture extraction (or uptake) rate by plant roots in volumetric units of moisture per unit volume of the root zone profile per day ( $\text{cm}^3 \text{ cm}^{-3} \text{ d}^{-1}$ ). Alternatively, this can be expressed in depth units of moisture per unit depth of root zone profile per day ( $\text{cm cm}^{-1} \text{ d}^{-1}$ ). If the entire root zone is considered in the model, it could be simply expressed in depth units of moisture per day ( $\text{cm d}^{-1}$ ). The sink term,  $S(\theta, z)$  itself is a function of maximum extraction rate ( $S_{\max}$ ) by plant roots ( $\text{cm d}^{-1}$ ), and the soil matrix moisture content ( $\theta$ ), which could be described by the model of Feddes et al. (1978) as:

$$S(\theta, z) = \alpha(\theta) S_{\max} \quad (5.11)$$

where  $\alpha(\theta)$  = dimensionless moisture availability reduction factor varying between 0 and 1.

As per above discussion and Eq. 5.11, the water uptake by plants is affected by the soil moisture content of the root zone. This aspect is discussed in detail in Section 5.4.1.

#### 5.4.1 Estimation of Soil Moisture Availability Reduction Factor $\alpha(\theta)$

As mentioned earlier, the water uptake rate is influenced by the soil moisture availability in the root zone. Water uptake or moisture extraction by plant occurs at its maximum or potential rate ( $S_{\max}$ ), only if the soil moisture content is not limiting in

the root zone. However, under non-optimal conditions (i.e. either too dry or too wet), the actual water uptake rate  $S(\theta, z)$  is reduced by means of the moisture content dependent  $\alpha(\theta)$  factor of Eq. 5.11.

Many researchers (e.g. Denmead and Shaw, 1962; Wesseling et al., 1989; Wyseure et al., 1994; and Singh and Singh, 1996) assumed the moisture extraction rate to be at its maximum or potential rate between  $\theta_{DU}$  and certain threshold soil moisture ( $\theta_{thrs}$ ) levels, then declining linearly outside the  $\theta_{DU}$  and  $\theta_{thrs}$  bounds, ceasing completely at both complete saturation ( $\theta_{SAT}$ ) and permanent wilting point ( $\theta_{LL}$ ) soil moisture levels. As per this approach, the shape of the  $\alpha(\theta)$  factor, is schematically shown in Figure 5.3, and described by Eq. 5.12. Thus, for this approach, the values of this dimensionless moisture availability reduction factor ( $\alpha(\theta)$ ) which vary between 0 and 1 can be interpolated as follows:

$$\alpha(\theta) = 0 \quad \text{for} \quad \theta_{SAT} < \theta_i < \theta_{LL} \quad (5.12a)$$

$$\alpha(\theta) = 1 - (\theta_i - \theta_{DU}) / (\theta_{SAT} - \theta_{DU}) \quad \text{for} \quad \theta_{DU} < \theta_i \leq \theta_{SAT} \quad (5.12b)$$

$$\alpha(\theta) = 1 \quad \text{for} \quad \theta_{thrs} \leq \theta_i \leq \theta_{DU} \quad (5.12c)$$

$$\alpha(\theta) = (\theta_i - \theta_{LL}) / (\theta_{thrs} - \theta_{LL}) \quad \text{for} \quad \theta_{LL} \leq \theta_i < \theta_{thrs} \quad (5.12d)$$

where  $\theta_i$  = volumetric SMC on a particular day (%)

$\theta_{thrs}$  = threshold volumetric SMC at which the ET rate falls below potential rate (%)

and all other terms are as defined earlier.

It is important to mention that the value of  $\theta_{thrs}$  not only varies with the prevailing climatic conditions (e.g. high or low evaporative demands), but also throughout the growth period of the crop under given soil conditions. For general range of agricultural crops, it lies above the 50% of available water (Singh et al., 1995; and ASCE, 1996). Figure 5.3 also shows the effect of prevailing climatic conditions (i.e. high or low evaporative demands) on the  $\alpha(\theta)$  factor. As can be observed from this figure, under higher evaporative demand conditions, relatively lower values of  $\theta_{thrs}$

parameter exist. Since the  $\theta_{thrs}$  value is time variant as well as sensitive to the prevailing climatic conditions, it is virtually difficult to accurately specify an operational value of this  $\theta_{thrs}$  parameter for a crop under field conditions.

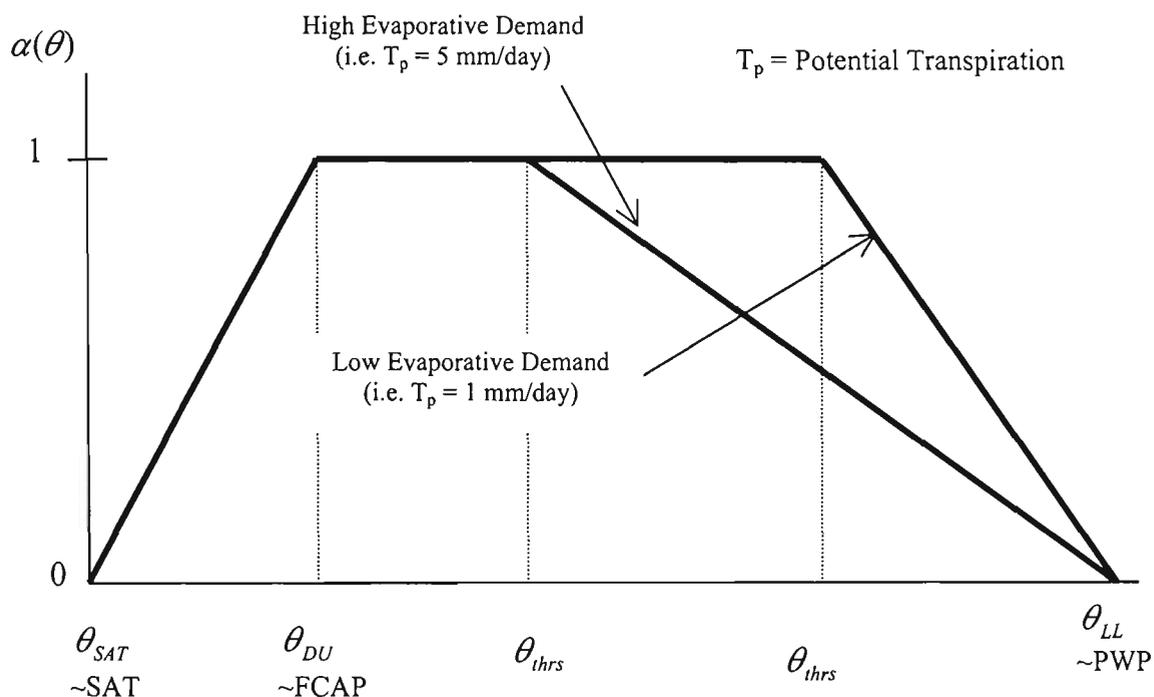


Figure 5.3 Schematic of Moisture Availability Reduction Factor  $\alpha(\theta)$  as a Function of SMC

Keeping in view the aspect of minimum input data requirements, a simpler approach that could avoid the use of this  $\theta_{thrs}$  parameter is preferable. Therefore, in order to avoid the use of  $\theta_{thrs}$  parameter for  $\alpha(\theta)$  factor, in this study several empirical (yet operational and field compatible) assumptions were incorporated in Figure 5.3. The empirical assumptions and the resulting modified shape of the above stated  $\alpha(\theta)$  factor adopted in this study is given in Section 5.4.6.

#### 5.4.2 Estimation of Maximum Extraction Rate ( $S_{max}$ )

Quantifying the maximum extraction rate ( $S_{max}$ ) term in Eq. 5.11 has been attempted by various researchers. Taylor and Klepper (1975) reported that the maximum

moisture extraction by plant was proportional to the plant rooting density. Since the plant rooting density (or root distribution) is difficult to measure, Feddes et al. (1978) proposed a single distribution of  $S_{max}$  with the rooting depth throughout the growing season. Hoogland et al. (1981) suggested an empirical model linearly decreasing with the rooting depth for  $S_{max}$ . However, in their model the values of empirical constants used need to be determined experimentally. Prasad (1988) reported that  $S_{max}$  is dependent on a root distribution function that needs to be determined experimentally depending on the plant type and its vegetative stage.

Antonopoulos (1997) tested the Feddes et al. (1978), Hoogland et al. (1981) and Prasad (1988)  $S_{max}$  models against field measured SMC data of Babajimopoulos et al., (1995,1996). He reported that the empirical model of Hoogland et al. (1981) with some prefixed values of  $S_{max}$  for a given rooting-depth range of a crop gave the best results. This result is in line with De Jong and Hayhoe (1984) who used the root density measurements of Coupland (1974), which reported that the root distribution generally show little systematic variation with season, presumably due to the large mass of dead or inactive roots compared to new active roots. Therefore, the use of a constant root density value at different root zone depths throughout the growing season is quite reasonable. However, both these findings proposed discrete root density and/or  $S_{max}$  values that need to be estimated experimentally under each set of soil and crop conditions. In contrast, the Chang and Corapcioglu (1997) study based on Taylor and Klepper (1975) measured data revealed that the root density distribution (and hence the moisture extraction) throughout the root zone did show a significant variation during the growing season until the maximum rooting depth was achieved. This emphasises the need for a dynamic root depth (and hence the root density distribution) dependent  $S_{max}$  model for use in Eq. 5.11.

Hayhoe and De Jong (1988), while recognising the complexity and dynamics of the geometry of the plant root system, presented a modified version of the Feddes et al. (1978)  $S_{max}$  model. In this modified model, the moisture uptake is limited by a function of potential transpiration ( $T_p$ ) which decreases linearly with depth as follows:

$$S_{\max} = \frac{2T_p (Z_e - z_r)}{Z_e^2} \quad (5.13)$$

where  $Z_e$  = effective root zone depth, defined as that portion of the root zone, which actually contributes to the evapotranspiration process (cm)

$z_r$  = vertical distance from the soil surface (cm)

In the above stated Hayhoe and De Jong (1988) model,  $S_{\max}$  was defined as a function of the root depth. Recognising the simple nature of the Hayhoe and De Jong (1988)  $S_{\max}$  model in simulating the actual field conditions, this model was selected for use in this study. A procedure to estimate the effective rooting depth (which varies with time) for use in Eq. 5.13 is described in Section 5.4.3.

### 5.4.3 Root Growth Model

To utilise the Hayhoe and De Jong (1988)  $S_{\max}$  model for moisture extraction by plants, the information about the rooting depth as a function of time is required. Simulation of root growth rate has received considerable attention from a number of researchers (e.g. Hanks and Hill, 1980; Fereres et al., 1981; Huck and Hillel, 1983; Borg and Grimes, 1986; Arora et al., 1987; and Schouwenaars, 1988), and as a result many empirical sigmoidal as well as exponential root growth models have been developed. However, most of these empirical models require the maximum rooting depth ( $RD_{\max}$ ) and the time at which the crop attains its maximum rooting depth ( $t_{\max}$ ) as input data. Both of these parameters are highly dependent on soil, crop, climate and other management practices, and hence are not routinely available in terms of their true field representative values in most irrigation systems. Even if they are available, the empirical models in which they are utilised, because of their assumptions, do not yield realistic output in predicting the root depth in actual field conditions (Subbaiah and Rao, 1993).

A comparative study of various root growth simulation models (using measured field data) conducted by Subbaiah and Rao (1993) discussed the limitations and operational difficulties of most commonly used empirical root growth models under actual field

conditions. Based on the results of their comparison, the candidate observed that the Borg and Grimes (1986) sigmoidal root growth model was to be superior to the other models because of its practicality under field conditions, and therefore it was employed in this study. As per this model for given  $RD_{max}$  and  $t_{max}$  values, the rooting depth of any crop on a particular day can be computed as follows:

$$RD_t = RD_{max} \left[ 0.5 + 0.5 \sin \left\{ 3.303 \left( \frac{t}{t_{max}} \right) - 1.47 \right\} \right] \quad (5.14)$$

where  $RD_t$  = current rooting depth (cm)

$RD_{max}$  = maximum rooting depth to be achieved at  $t = t_{max}$

$t_{max}$  = time to plant maturity (days)

$t$  = time (days) from germination

It is interesting to note that in the above Borg and Grimes (1986) root growth model, if  $t=0$  then the root depth is also zero. Thus, according to this model, the root depth increases only if the days after planting elapse. This implies that the plant seed is laid on the soil surface, which is not actually true for any agricultural crop. Therefore, Arora et al. (1987) reported that this model was not valid for measuring the root depth when time from germination was less than 10 days. Since the sole interest of an efficient irrigation scheduling lies in determining the depth of an active soil reservoir which needs replenishment through irrigation for sustaining agricultural productivity without any moisture stress, the aforementioned limitation of the Borg and Grimes models of great concern and needs to be rectified. Therefore, in order to overcome this limitation while considering the dynamics of root development and be compatible with actual field conditions, the following approach was used in this study.

As per this approach, the  $RD_t$  on a particular day is modelled in equal depth increments ( $\Delta Z$ ) which define several sub-layers (as referred in Section 5.2.2), with a minimum of one depth increment. This implies that on any day the rooting depth ( $RD_t$ ) of a crop would always be a multiple of  $\Delta Z$ . Furthermore, on any day, if  $RD_t$  (estimated from Eq. 5.14) is less than  $\Delta Z$ , the effective rooting depth ( $Z_e$ ) value for use in Eq. 5.13 is taken as  $\Delta Z$ . Similarly, if the estimated  $RD_t$  is between  $\Delta Z$  and  $2\Delta Z$ , the corresponding  $Z$  value to be adopted for that day would be equal to  $2\Delta Z$ .

This process is adopted until the  $RD_{max}$  is achieved. For use in this approach, the  $\Delta Z$  value would be decided according to the physical characteristics of the soil profile under consideration. For simplicity, maximum of four sub-layers were considered in this study. Hence, a value of  $\Delta Z=15\text{cm}$  can be adopted for shallow rooted (i.e.  $RD_{max} \leq 60\text{ cm}$ ) crops. Similarly,  $\Delta Z=30\text{cm}$  and  $RD_{max} /4$  could be adopted for medium rooted (i.e.  $60\text{cm} < RD_{max} \leq 120\text{cm}$ ) and deep rooted (i.e.  $RD_{max} > 120\text{cm}$ ) crops respectively.

Justification for having several depth increments in this approach is that after germination under favourable soil, plant and other environmental conditions, the roots of a crop continue to grow and/or proliferate daily at relatively faster rate and explore moisture even from beyond their actual root depths or rhizospheres. This is the case especially when the upper zone is depleted and the moisture from adjacent lower zone becomes available through capillary rise (Hayhoe and De Jong, 1988; and De Faria et al., 1994). From practical point of view, it is very difficult, if not impossible, to irrigate a crop precisely up to its actual daily root growth rate based root zone depths as it requires quite frequent irrigations such as almost every day. This is not possible with flood irrigated systems that are considered in this study. Also through this approach, a buffer soil moisture reserve would be available to plants for their newly developing roots to help avoiding any possible risk of moisture stress leading to an increased productivity (Plant et al., 1992).

It is worth mentioning that the rooting depth of a well established perennial crop does not change significantly during one growing season. Therefore, for all perennials such as perennial pastures and sugarcane ratoon crops, the rooting depth can be considered as constant throughout the growing season (Burman et al., 1983). However, for all other annual growing crops, root development with time can be estimated as per above procedure, until some local root growth information based on experimental measurements are available.

It is important to appreciate that water uptake by plants through the *ET* process is not only influenced by the soil moisture availability in the root zone, but also by the root density distribution throughout the root zone (Belmans et. al., 1979). Thus, in order to generate reliable irrigation schedules, a good irrigation scheduling model should also

consider the effect of the root density distribution. The effect of root density distribution on water uptake by plants is discussed in Section 5.4.4.

#### **5.4.4 Modelling the Effect of Root Density Distribution on Water Uptake by Plants**

The moisture extraction or water uptake by plants is affected by root density distribution throughout the root zone. The upper zones can extract relatively more water than the lower zones due to higher root densities near the soil surface (presumably where plant nutrients are usually higher), regardless of actual moisture availability in each zone (Taylor and Klepper, 1975). Traditionally, when the initial soil moisture content is uniform in the root zone, the root zone is divided equally into four sub-layers, and the moisture extraction pattern is assumed to be 40%, 30%, 20%, and 10% per quarter of root zone depth from top to the bottom of the root zone (Bradford and Letey, 1992). This is satisfactory for homogeneous soil profiles in which the effective root zone of a crop is well established. However, in actual field conditions, the rooting depth may range from 5cm to 250cm throughout the growing season depending upon the local soil, crop and climatic conditions (Blaikie and Mason, 1993; and ASCE, 1996). In case of annual crops (such as wheat, cotton, vegetables and green fodder), the effective rooting depth varies initially from a very small (say 5cm) value to some large values with time. Therefore, it is practically difficult to adopt the aforementioned per quarter fixed moisture extraction pattern for these small root depths. Under these circumstances, it is desirable to model a variable moisture extraction pattern that will be experienced under actual dynamic field conditions. This soil moisture extraction pattern should vary with the rooting depth as a function of time. A procedure to derive such a variable moisture extraction pattern for use in the water uptake model (Eq. 5.11) is described in Section 5.4.5.

#### **5.4.5 Derivation of Variable Moisture Extraction Pattern**

A close examination of the Hayhoe and De Jong (1988) model for  $S_{\max}$  (Eq. 5.13) shows the moisture extraction pattern as a function of root depth with an implicit dependence on root distribution for which only the effective rooting depth parameter is required. Therefore, this model which is schematically shown in Figure 5.4 was

adopted in this study as a basis to derive a variable moisture extraction pattern for multiple root zone sub-layers experienced during the growing season of a crop.

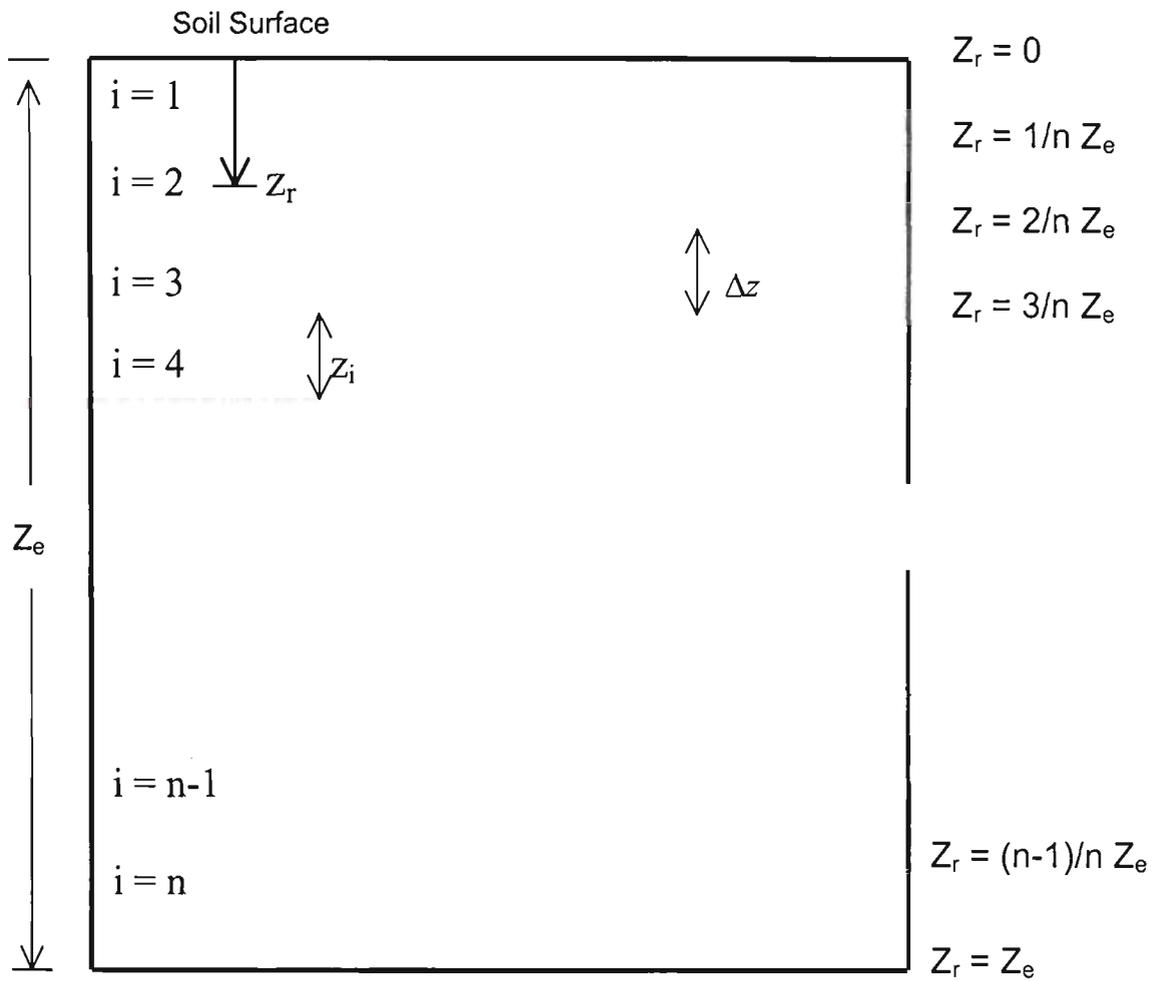


Figure 5.4 Effective Root Zone Depth ( $Z_e$ ) Subdivision into “n” sub-layers

As shown in Figure 5.4, the effective root zone depth ( $Z_e$ ) of a crop is divided into “n” sub-layers of equal thickness. They are the same sub-layers as described in Section 5.4.3. In this study, “n” sub-layers were considered to present a general formulation for the variable moisture extraction pattern, although four sub-layers were used in this study. For each sub-layer, the contribution towards  $S_{max}$ , can be computed from Eq. 5.13, which can be rewritten as

$$S_{max,i} = \frac{2T_p (Z_e - z_{ri})}{Z_e^2} \quad (5.15a)$$

where  $S_{max,i}$  = partial contribution to  $S_{max}$  from  $i^{th}$  sub-layer ( $cm\ d^{-1}$ )

$z_{ri}$  = vertical distance from soil surface to the mid-point of sub-layer  $i$   
(cm)

and all other symbols are as defined earlier

Again by following the same set of notations for  $S_{max}$  as given in Eq. 5.13, and by substituting  $z_{ri}$  in terms of  $Z_e$  for sub-layer  $i$  in Eq. 5.15a, the  $S_{max,i}$  on any day can be estimated as

$$S_{max,i} = 2T_p \left[ Z_e - \left\{ \frac{(\frac{i-1}{n})Z_e + (\frac{i}{n})Z_e}{2} \right\} \right] / Z_e^2$$

$$= \frac{T_p}{Z_e} \left\{ \frac{(2n - 2i + 1)}{n} \right\} \quad (5.15b)$$

and

$$S_{max} = \sum_{i=1}^n S_{max,i} \quad (5.15c)$$

In Eq. 5.15b, the term  $\left\{ \frac{(\frac{i-1}{n})Z_e + (\frac{i}{n})Z_e}{2} \right\}$  represents the distance from the soil surface to the middle point of sub-layer  $i$  expressed in terms of  $Z_e$  (i.e.  $z_{ri}$ ).

Now, the root density dependent moisture extraction factor ( $\Gamma$ ), which by definition represents the relative proportion of  $S_{max}$  from an individual sub-layer  $i$  (in percent) can be calculated as follows

$$\Gamma_i = 100 \times \frac{S_{max,i}}{\sum_{i=1}^n S_{max,i}} \quad (5.16a)$$

and

$$\sum_{i=1}^n \Gamma_i = 100\% \quad (5.16b)$$

where  $\Gamma_i$  = root density dependent moisture extraction factor for  $i^{\text{th}}$  sub-layer (%).

The above derived expression (Eq. 5.16a) is a general model to compute the variable moisture extraction pattern for any number of root zone sub-layers in a given effective root zone depth ( $Z_e$ ) on a particular day during the growing season of a crop. As per this model, if the root zone is divided into four equal sub-layers (i.e.  $n = 4$ ), then a moisture extraction pattern of 44%, 31%, 19% and 6% per quarter depth from top to bottom of the root zone is achieved from Eqs. 5.15 and 5.16. This pattern is quite close to the aforementioned commonly used per quarter assumption of 40%, 30%, 20% and 10%. Similarly, if the root zone is divided into three equal-sub layers (i.e.  $n = 3$ ), a pattern of 55%, 33% and 12% per one third depth from top to bottom of the root zone is achieved.

It is important to note that the use of Eq. 5.11 through Eq. 5.16 models the total moisture extraction or water uptake by plant system over the entire root zone in  $\text{cm cm}^{-1} \text{ d}^{-1}$  units. This water uptake by plants through roots represents the actual transpiration ( $T_a$ ) on any day, which cannot exceed the potential transpiration ( $T_p$ ) value of the corresponding day. Therefore, it is stipulated that

$$\sum_{i=1}^n S(\theta, z)_i \leq T_p \quad \text{for } z_r \leq Z_e \quad (5.17a)$$

and

$$S(\theta, z)_i = \frac{\alpha(\theta)_i \Gamma_i T_p \Delta z_i S_{\max, i}}{100} \quad (5.17b)$$

where  $S(\theta, z)_i$  = partial moisture extraction by plant from sub-layer  $i$  ( $\text{cm d}^{-1}$ )

$\alpha(\theta)_i$  = moisture reduction factor of sub-layer  $i$

and all other terms are as defined earlier

The term  $\alpha(\theta)_i$  can be determined using Eq. 5.12 for respective sub-layer against its current  $SMC$  level for the day under consideration.

The potential transpiration ( $T_p$ ), being one of the complementary components of potential crop evapotranspiration ( $ET_c$ ), can be determined through partitioning of  $ET_c$  (Eq. 5.10) between the potential plant transpiration ( $T_p$ ) and the potential soil surface evaporation ( $E_s$ ), using the procedures proposed by Belmans et al. (1983) and Mahey et al. (1984). In case the  $ET_c$  partitioning approach is employed, the partitioned  $T_p$  would be used in Eq. 5.17b to model the plant transpiration component of the water balance model alone. Hence, the partitioned  $E_s$  as such would still need to be considered to model the soil surface evaporation component of the water balance model using a separate technique. This would make the model complicated. In addition, the  $ET_c$  partitioning procedures require certain dynamic site-specific soil and crop parameters such as leaf area index (LAI), crop cover, and some other soil related empirical coefficients which are difficult to obtain in most irrigation systems. Even if they are available, their spatial variability can affect the accuracy of the results. Heterogeneous and/or cracking soil profiles lead to further complications. Therefore,  $ET_c$  was not partitioned in this study. Instead  $ET_c$  was computed using Eq. 5.10 to mimic the combined effect of evaporation from the soil surface and the plant transpiration in actual field conditions for use in Eqs. 5.13 - 5.17. This is in line with the suggestions of that of Bradford and Letey (1992) and Armstrong et al. (1993). Thus, in this study, the estimates of  $S(\theta, z)$  obtained from Eqs. 5.11 and 5.17b would in fact mirror the actual crop evapotranspiration ( $ET_a$ ) estimates under prevailing climatic conditions. This approach uses less input data.

One important factor to be highlighted here is that Eq. 5.16a gives a variable moisture extraction pattern under normal well-watered conditions in field with homogeneous soil profile. However, in heterogeneous soil profiles such as Northern Victoria's red-earth, the root growth as well as the root density distribution (and hence the moisture extraction) do not follow any systematic pattern, but are entirely dependent on the local soil, climate and other management practices (Blaikie et al., 1988). Hence, in order to account for these conditions and practices, local information about the rooting depth and the moisture extraction pattern is required based on actual field measurements and/or irrigator's experience. Therefore, to allow for these actual field conditions, it was considered necessary for the user to provide information on root

depth and moisture extraction pattern, as an option in the irrigation scheduling model to be developed in this study. Nevertheless, this user-defined input option for root depth and moisture extraction pattern was limited for a maximum of four sub-layers. This limit of four sub-layers was to keep the computer model inputs simple and workable under actual field conditions. In case if local information on the moisture extraction pattern of different layers is not available, the computer model would automatically compute the  $L_i$  parameter from Eqs. 5.15 and 5.16 for use in Eq. 5.17b.

#### 5.4.6 Evapotranspiration Rate after a Precipitation Event

The water uptake by crop computed by Eq. 5.17, assumes normal well-watered field conditions which are generally obtained only when the field is at its field capacity level. However, in reality, when a field is recharged through a precipitation (irrigation and/or rainfall) event, it takes a few (1 to 3 ) days for the root zone to reach its field capacity level depending upon the prevailing crop, soil and climatic conditions. Therefore, the additional considerations discussed below modify the water uptake model given in Section 5.4.1.

During the transient period, the evapotranspiration (ET) rate is highly variable in time and space. As water starts infiltrating into the soil profile, the transpiration component starts building up from its reduced rate (i.e. rate just before the start of the precipitation event) to a certain increased rate, after which it decreases until it approaches to zero due to anaerobic (complete saturation) conditions. After saturation, as the soil profile begins to return towards its field capacity under gravity drainage, the transpiration component again starts building up with time and ultimately attains its potential rate at field capacity. As shown in Figure 5.3, transpiration component continues at its potential rate until a certain threshold SMC ( $\theta_{thrs}$ ) is reached, which indicates an onset of the plant moisture stress. After  $\theta_{thrs}$ , the transpiration component starts decreasing linearly and subsequently becomes zero at PWP.

The surface evaporation component of  $ET$  at the same time builds up to its maximum (or potential) rate and continues at this potential rate until the upper surface sub-layer starts becoming dry. At the onset of drying of surface sub-layer, the evaporation

component also begins to decline and ultimately reaches to almost zero value at some limiting (air-dried) SMC value of the upper sub-layer.

The transient nature of these transpiration and surface evaporation components is dependent on the interactions of many soil, crop and climate related variables. These interactions are highly complex and hence are very difficult to model, if not impossible at all. Therefore, certain reasonable assumptions as given below were used in this study. As per these assumptions, it is stipulated that:

- (i) the SMC of the entire root zone reaches its SAT level (e.g. if a heavy rainfall occurs), or DUL level (e.g. if a normal irrigation is applied to recharge the root zone just up to DUL) by the end of the same day on which precipitation (i.e. irrigation and/or rainfall) event occurs.
- (ii) the water uptake by crop through the ET process attains its potential rate on the next day after the precipitation event, unless specified by the user ET as zero for a certain number of days (hereafter referred to as *ZeroET days*; Sections C.4.1 and C.10.1) to model anaerobic conditions after a heavy precipitation event. In case of heavy precipitation, the potential rate of ET is attained after *ZeroET days*. The water uptake then remains at its potential rate until the soil moisture level reaches a certain pre-specified DUL level. Then, it starts to decline linearly and subsequently approaching to almost zero at PWP (or LL) soil moisture level. The variation of  $\alpha(\theta)$  factor as per above two assumptions is shown in Figure 5.5, which is used in this study instead of Figure 5.3.

It is important to note that these two assumptions may cause some discrepancies between the actual and computed SMC estimates soon after the precipitation event. However, this problem would ultimately be settled down by itself (as will be shown later in Section 5.8) after a few days after the precipitation event when a steady state is reached. In irrigation scheduling studies, the major concern is about the SMC towards the end of the current irrigation period, and hence, these two assumptions

would not have any significant impact on the predicted irrigation schedules. Additionally, the aforementioned discrepancy would also be mitigated through the calibration process where the *ZeroET days* parameter (Section 5.9) is adjusted for local conditions.

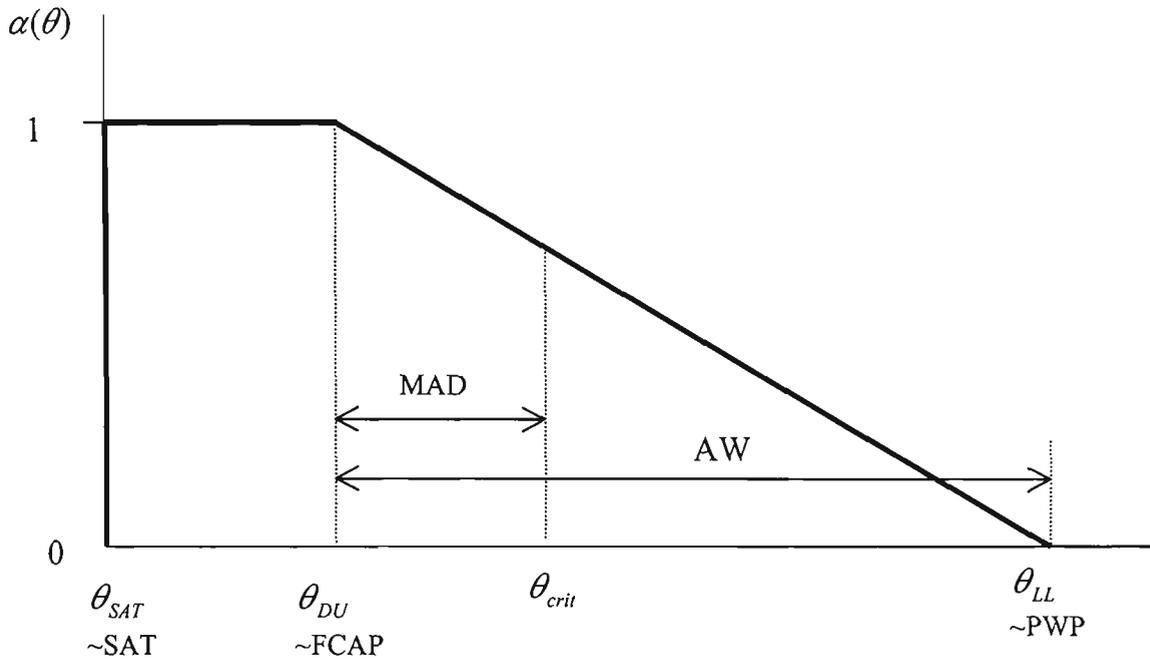


Figure 5.5 Schematic of Moisture Availability Reduction Factor  $\alpha(\theta)$  as a Function of SMC Used in this study

As stated in assumption (ii), the crop evapotranspiration (ET) would be at its maximum (or potential) rate when  $SMC \geq \theta_{DU}$ . This rate would decline with the decrease in SMC below  $\theta_{DU}$  and eventually approaching to a minimum value (equivalent to soil-evaporation) when  $SMC \leq \theta_{LL}$ . However, in general practice, the soil is never allowed to deplete to this (i.e.  $\theta_{LL}$ ) level, but is always kept fairly above  $\theta_{LL}$  level to avoid yield losses. Nevertheless, in order to model the occasional situation when  $SMC \leq \theta_{LL}$ , in continuation with the aforementioned two assumptions, a third assumption is also incorporated in this study:

- (iii) if  $SMC \leq \theta_{LL}$ , only the soil evaporation ( $E_s$ ) component of the ET continues and it is supported by the surface sub-layer ( $z_I$ ) of the root zone alone. It also virtually ceases when SMC of surface sub-layer

( $SMC_{z1}$ ) approaches a certain air-dried limiting value. For convenience, in this study it was assumed that  $E_s$  component ceases completely when  $SMC_{z1}$  falls below  $0.5 \theta_{LL(z1)}$ . This implies that when  $SMC_{z1} \leq 0.5 \theta_{LL(z1)}$ , then ET is zero. This assumption has been supported in literature (e.g. Cuenca, 1988) for use in irrigation scheduling studies.

The above assumptions (i) – (iii) were incorporated in the irrigation scheduling model of this study to model actual field conditions after a precipitation (rainfall and/or irrigation) event.

## 5.5 IRRIGATION TIMING APPROACHES

The timing of irrigation is one of the major management decisions repeatedly made by the farmer during an irrigation season. In order to determine the timing of next irrigation, mainly three approaches viz.; i) fixed irrigation interval, ii) target moisture level, and iii) fixed irrigation amount, are used (Pleban and Israeli, 1989). The choice of the irrigation timing approach is usually dictated by the objective (e.g. maximum crop yield) and the capacity constraints of the main supply system. These approaches are explained as follows.

### (i) *Fixed Irrigation Interval Approach*

In this approach, an irrigation event is scheduled according to a fixed interval (e.g. once every 7- day). This approach is generally adopted in those irrigation systems where irrigation deliveries are available at fixed intervals/rotations. These fixed intervals/rotations are generally imposed by the water authorities due to supply and/or capacity constraints of the infrastructure. Sometimes, the on-farm activities other than irrigating the field force the farmers to schedule irrigations at fixed intervals

When irrigation deliveries are scheduled at fixed intervals, the farmers have access to flexible water amounts. Hence, the amount of water can be specified by the farmer several days in advance. The amount can be variant depending on the requirement of

the crop. This method is practised by many farmers in the Goulburn-Murray Irrigation Area (GMIA) in Victoria (Australia) to irrigate their pasture crops.

In order to use this approach, the exact amount of water depleted from the root zone needs to be estimated and then replenished to avoid the crop stress. However, a general problem inherent with this approach is that the SMC might reach certain stress levels due to severe climatic conditions that could cause crop yield reduction, before the irrigation water becomes available for application because of fixed interval. Therefore, a good irrigation-scheduling model should issue a warning message whenever the SMC falls below the critical level that reduces yield (Pleban and Israelie, 1989). This was considered in the irrigation scheduling computer model (Appendix C) developed in this study.

It is important to mention that in some cases, the irrigation deliveries are also specified with fixed amounts of water available for application (by the water authorities) in addition to the fixed irrigation rotation. Hence, in this case no choice is left with the farmer except to adjust his field size for a specific crop to accommodate these rigid deliveries. This system of water deliveries is termed as Warabandi system. This is dominating in the Indian sub-continent, and is generally characterised with very low water use efficiencies due to its rigid nature (Hill and Allen, 1996).

### *(ii) Target Moisture Level Approach*

In this approach, an irrigation event is scheduled when the SMC of root zone reaches a certain predetermined target moisture level. The rationale behind this approach is that there is no reduction in the crop yield, provided that the SMC of root zone remains above this target moisture level. This target moisture level is known as the refill point or the critical moisture content (CRIT) of the soil, which represents the driest level of the soil profile prior to irrigation and in volumetric units it is expressed as  $\theta_{crit}$  (Smith, 1993; and Stricevic and Caki, 1997).

The refill point varies with both the type of crop and soil under consideration. The choice of the refill value to be used in particular situation depends also on other

economic factors. For instance, for cash crops generally the refill point with high value is desirable to avoid the yield losses while for other crops relatively lower values could be adopted. Also, for a crop, sometimes depending upon the growth stage of that crop, the refill point needs to be changed during the growing season to maximise the net farm returns (Hedditch, 1985). Additionally, sometimes due to high evaporative demand climatic conditions, some sensitive crops (e.g. white clover pasture) might exhibit moisture stress signs at certain SMC level, which they otherwise would not show in normal climatic conditions. Hence, these considerations necessitate the use of a variable refill point during the growing season for the crop under field conditions depending upon the prevailing climatic conditions.

Since it is practically difficult to exactly identify the refill point of a soil for various crops, it is usually customary to relate it to some proportion of the available water (AW - Section 5.2.1) of the soil profile. This proportion of AW is termed as the Management Allowable Deficit (MAD), and represents the average fraction of AW that is extracted by the plant before the moisture stress causes damage to the crop (James, 1988).

Mathematically, the critical moisture content in depth units (CRIT) can be expressed as follows:

$$CRIT = (DU - AW * MAD) \tag{5.18a}$$

$$AW = (DU - PWP) \tag{5.18b}$$

- where CRIT = critical SMC in depth units at which an irrigation is desirable (cm)
- DU = moisture content at drained upper limit (or field capacity) in depth units (cm)
- AW = plant available water (cm)
- MAD = management allowable deficit of plant available water (fraction)
- PWP = moisture content at permanent wilting point (cm)

The critical moisture content or refill point in volumetric units ( $\theta_{crit}$ ) can then be estimated as

$$\theta_{crit} = CRIT / Z_e \quad (5.19)$$

where  $Z_e$  = effective root zone.

As indicated above, the MAD parameter used in Eq. 5.18a refers to the average fraction of available water that is depleted before an irrigation is applied. Since MAD is a function of the crop, it needs to be specified for each crop under consideration. MAD value usually ranges from 20% depletion of available moisture to 70% depending on the type of crop, and a value of 50% for MAD is common (Turner, 1990; and ASCE, 1996). The MAD values for use in Eq. 5.18a for various agricultural crops can be obtained from the literature (e.g. Hedditch, 1985; Plant et al., 1992; and ASCE, 1996).

In continuation with the need of a variable refill point for certain crops as pointed out earlier, some recent studies (e.g. Tripathi, 1992; and Buchlieter, 1995) also suggest the use of a variable MAD value during the crop growing season for more efficient use of available irrigation water. Higher MAD values can be used when the crop is at a less sensitive stage and relatively lower MAD values during the critical growth stages of the crop. This aspect especially is of paramount importance where either irrigation supplies are limited or other energy related irrigation costs are high, which impose the deficit irrigation to be practised to maximise the profits (Turner, 1990; and Hoffman and Martin, 1993). Hence, an efficient irrigation scheduling model should have a variable MAD value option available for the user to modify it through different growth stages of the crop (Buchlieter, 1995). Therefore, in line with these recent findings, a user-defined variable MAD option was built into the irrigation scheduling computer model developed in this study.

It should be noted that the *target moisture level approach* depends on AW and prevailing climatic conditions, which produce variable irrigation frequencies and amounts. Therefore, this approach can best perform only in those irrigation systems where irrigation supplies are quite flexible in terms of both time and amounts for applications. Another advantage inherent with this approach is that by selecting an

appropriate MAD value, the crop can be grown to give the maximum crop yield (Hearn and Constable, 1984).

This approach is practised in Tha Muang and Tha Makka irrigation areas in Thailand (Murty et al., 1991). This approach is also expected to be practised in the GMIA. This is because of the on-going improvements in the existing infrastructure as committed by the local water authorities (RWC, 1990). However, the candidate is not aware of any applications of this approach yet in the Goulburn-Murray Irrigation area.

### *(iii) Fixed Irrigation Amount Approach*

It is worthwhile to mention that in some irrigation systems, it is quite customary to schedule an irrigation when a predetermined net irrigation amount (e.g. 50mm) is required. Generally, this approach is adopted for shallow rooted moisture stress sensitive crops. This approach has been reported to be practised in some areas of the GMIA and some parts of New South Wales for pastures (Thompson et al., 1982; and Heslop, 1991). In these areas, the irrigation amount is computed from the difference of 'Class A' pan evaporation and rainfall (E-R) from the start of the previous irrigation, and when this E-R exceeds 50mm, an irrigation is required. The approach is of limited use in flood irrigation, if the irrigation amount to be applied is small. Nevertheless, this approach has a good promise in terms of its adoption with sprinkler systems which can be easily used to apply small irrigation amounts.

In order to employ this approach in computer-based irrigation scheduling programs, it is first desirable to convert the predetermined irrigation amount into an equivalent soil moisture depletion level, and then an irrigation could be scheduled when the corresponding depletion level is reached. For agricultural crops, as they grow, their daily water use also increases, and hence, the frequency of irrigation also significantly increases. Therefore, like the target moisture level approach, this approach also required a flexible water delivery system.

In order to be compatible with the most popular irrigation timing approaches, in this study only first two of the aforementioned three irrigation-timing approaches were adopted.

## 5.6 ALGORITHMS EMPLOYED IN IRRIGATION SCHEDULING MODEL OF THIS STUDY

This section briefly summarises the algorithms that were used in the irrigation scheduling model of this study. Five components of the water balance model given by Eq. 5.9 i.e. net irrigation, effective rainfall, capillary rise, deep percolation and evapotranspiration were used in this model. The surface runoff (DR) component was not considered in the irrigation scheduling model since the farms considered in this study and in general in the Goulburn Murray Irrigation Area, GMIA (Victoria, Australia) were flat for which the surface runoff was negligible.

The net irrigation ( $IR$ ) component was estimated by multiplying the gross irrigation ( $IR_{\text{gross}}$ ) value with an irrigation application efficiency factor, as discussed in Section 5.3.2. The effective rainfall (RF) term was estimated by adjusting the total measured rainfall through the use of a rainfall correction factor, as explained in Section 5.3.3. The capillary rise (CR) and deep percolation (DP) were combined in the irrigation scheduling model and were accounted for through the  $\theta_{DU}$  calibration process (as described in Section 5.3.5), which basically increases  $\theta_{DU}$  (or field capacity) by a maximum of 25% of available water (Section 5.2.1). The details of calibration procedure are discussed later in Section C.10.

The evapotranspiration or water uptake by plants was modelled as a diffuse volumetric “sink” controlled by a sink term as given in Eq. 5.11. This sink term,  $S(\theta, z)$  itself is a function of the soil matrix moisture content ( $\theta$ ), and the maximum extraction rate ( $S_{\text{max}}$ ) by plant ( $\text{cm d}^{-1}$ ). The soil matrix moisture related parameter,  $\alpha(\theta)$  can be computed using Figure 5.5, which introduces certain assumptions to adequately model the transient nature of the ET process, after an irrigation event.

In addition to water balance component algorithms, a choice for irrigation-timing approaches viz.: i) fixed irrigation interval, and ii) target moisture level were also included in the irrigation scheduling model of this study.

## 5.7 IRRIGATION SCHEDULING COMPUTATIONS

As discussed earlier, the irrigation scheduling process basically deals with two issues viz. (i) when to irrigate and (ii) how much to apply. This section describes how the developed Irrigation scheduling model can be used to address these two issues. In addition to these two issues, another case is considered which reflects the current irrigation practice of GMIA, that involves 3-day advance water ordering as discussed later in Section 5.7.3.

### 5.7.1 Module - I: When to Irrigate

This component of the irrigation scheduling process involves two stages. The first stage deals with the monitoring of the daily soil moisture status of the effective root zone as it diminishes following each irrigation and/or rainfall event. The second stage involves the comparison of this soil moisture status against a given irrigation timing approach, so that an irrigation can be decided (Curwen and Massie, 1985).

#### *Stage - I*

In the absence of measured SMC of the root zone, the water balance model as given by Eq. 5.9 can provide these SMC estimates on any day during the growing season of a crop. Equation 5.9 is reproduced below as Eq. 5.20.

$$SMC_j = \int_0^Z \theta_{j,z} dz = \int_0^Z \theta_{j-1,z} dz + IR_j + RF_j - ET_j - DP_j \quad (5.20)$$

where  $SMC_j$  = soil moisture content of the effective root zone depth ( $Z_e$ ) on  $j^{\text{th}}$  day  
(cm)

and all other terms are as defined earlier in depth units.

It is noteworthy that the use of Eq. 5.20 requires SMC information on day (j-1). If the measured SMC of (j-1)<sup>th</sup> day is not available, this can be estimated through Eq. 5.20,

which however, again requires an initial estimate of the SMC at the start of the irrigation. This initial estimate of SMC is normally assumed close to the field capacity. In order to avoid water wastage and leaching, this value could be set as a fraction of field capacity (i.e. just below field capacity) to simulate the actual field conditions (Plant et al., 1992).

On any  $j^{\text{th}}$  day, if the measured SMC at some discrete root zone depths are available, the  $SMC_j$  can be calculated as follows:

$$SMC_j = \int_0^Z \theta_{j,z} dz = \sum_{i=1}^n \theta_{j,i} z_i \quad (5.21)$$

- where  $\theta_{j,i}$  = volumetric soil moisture content of sub-layer  $i$  on  $j^{\text{th}}$  day ( $\text{cm}^3 \text{cm}^{-3}$ )  
 $z_i$  = thickness of the root zone sub-layer  $i$  (cm)  
 $n$  = number of sub-layers

Once the SMC of the effective root zone on a particular day is known, the next step (i.e. Stage- II) requires this SMC status to be translated into a meaningful characteristic variable. This variable is referred to as the root zone soil moisture depletion (SMD) level, and is defined as the difference between drained upper limit (or field capacity) and the current soil moisture content (SMC) on the  $j^{\text{th}}$  day. Thus, the SMD represents the amount of water depleted from a fully irrigated root zone profile. This SMD is used as a check against a pre-determined irrigation timing approach related parameter (hereafter referred to as the *irrigation timing parameter*) to decide on the irrigation.

As stated earlier (Section 5.5), the two most common irrigation timing approaches (i.e. fixed irrigation interval approach and target moisture level approach) were selected for this study. However, the choice of an irrigation timing approach among these two approaches is mainly dictated by the local irrigation water supply infrastructure constraints and/or by the farmer's behaviour. The translation procedure of the SMC status for each of these aforementioned two approaches is the same and is described as follows.

The total SMD of the effective root zone to the current day since the date of previous irrigation can be computed as follows:

$$SMD_j = \sum_{i=1}^n SMD_{j,i} \quad (5.22a)$$

and

$$SMD_{j,i} = DUL_{j,i} - SMC_{j,i} \quad (5.22b)$$

also

$$DUL_{j,i} = \theta_{DU(i)} z_i \quad (5.22c)$$

where  $SMD_j$  = soil moisture deficit of the effective root zone on  $j^{\text{th}}$  day (cm)

$SMD_{j,i}$  = SMD of sub-layer  $i$  on  $j^{\text{th}}$  day (cm)

$\theta_{DU(i)}$  = volumetric soil moisture content of sub-layer  $i$  at drained upper limit (or field capacity) level ( $\text{cm}^3 \text{cm}^{-3}$ )

and all other terms are as defined earlier.

After having translated the SMC of the effective root zone on a particular day to the SMD variable as per above procedure, this SMD can be utilised for an irrigation decision which is described below as Stage - II.

## Stage - II

Under Stage – II, SMD is compared against the corresponding *irrigation timing parameter* for an irrigation decision. This check procedure for each of the aforementioned two irrigation timing approaches is described as below.

### i) *Fixed interval approach*

In this case, the  $SMD_j$  is computed on a daily basis from the date of the previous irrigation until the pre-specified irrigation interval (in days) is reached. At the end of the

pre-specified fixed interval, an irrigation equivalent to the current  $SMD_j$  is scheduled. This implies

$$IR_{net} = SMD_j \quad (5.23)$$

where  $IR_{net}$  = net amount of irrigation water required to recharge the root zone (cm)  
 $SMD_j$  = SMD on the last day of the pre-defined fixed irrigation interval (cm)

Since  $SMD_j$  represents only the net irrigation amount required to replenish the root zone depletion, the gross irrigation amount ( $IR_{gross}$ ) accounting for the irrigation system efficiency and the leaching requirements can be determined as in Section 5.7.2.

ii) ***Target moisture level approach***

Similar to the fixed interval approach, the  $SMD_j$  is computed on a daily basis. This  $SMD_j$  is then compared against a pre-determined critical SMD ( $SMD_{crit}$ ) value, which is defined as the amount of moisture that can be extracted from the root zone before an irrigation is applied. This reflects the onset of moisture shortage, so that the decision of the timing of an irrigation could be made. According to this, it is stipulated that an irrigation must commence when  $SMD_j$  approaches this pre-specified  $SMD_{crit}$  value. Mathematically it can be expressed as:

$$SMD_j \approx SMD_{crit} \quad (5.24a)$$

where  $SMD_{crit}$  = critical SMD of the root zone at which an irrigation is invoked (cm)

The  $SMD_{crit}$  can be estimated using the Maximum Allowable Deficit (MAD) approach (Section 5.5) as:

$$SMD_{crit} = \sum_{i=1}^n (MAD_i \times AW_i) \quad (5.24b)$$

where  $MAD_i$  = user-specified maximum allowable deficit of plant available water (fraction) of sub-layer  $i$ ,  
 $AW_i$  = plant available water of sub-layer  $i$  (cm), and  
 and all other terms are as defined earlier

When the above criteria of an irrigation event as given by Eq. 5.24a is met, there is a need to irrigate on that day. Accordingly:

$$IR_{net} = SMD_{crit} \quad (5.24c)$$

where  $IR_{net}$  = net amount of irrigation water required to replenish the root zone (cm),  
 and all other terms are as defined earlier

It is worthwhile to mention that Eq. 5.24b can perform satisfactorily in homogeneous root zone soil profiles. However, it may not perform well in heterogeneous soils due to varying soil physical properties of the root zone sub-layers. This aspect can be explained by the fact that after an irrigation event when the entire root zone is uniformly wet, the moisture uptake by plants through ET is mainly derived from the upper sub-layer ( $z_1$ ) due to high rooting density in that zone (Belmans et al., 1979). With the depletion of moisture in the upper sub-layer, the “centre of gravity” of moisture uptake/extraction by roots is shifted towards the next lower wetter sub-layers (Huck and Hillel, 1983). However, there is a possibility that due to relatively higher moisture extraction rate from the upper sub-layer, the MAD limit of this upper sub-layer would reach earlier than the other adjacent lower sub-layers. This can render the plant to go under earlier moisture stress and ultimately affecting the yield.

It is interesting to note that in the above case, it is quite possible that the overall SMC of the entire root zone will still be at some reasonable level, but in reality the crop would

have already suffered and undergone to meet yield losses. This affect would be more pronounced during the high evaporative demand periods in heterogeneous root zone soil profiles where coarser top soils are underlain by fine textured clay soils. This situation becomes more critical at early growth stage when the parent roots in adjacent lower sub-layers have not yet fully developed their root hair system to extract moisture from those localised sub-layer zones. Therefore, some researchers (e.g. Hsiao, 1990; and Hoffman and Martin, 1993) emphasised that the SMC information alone was not enough, but the soil water potential information which gives an indication about the plant stress is also required for an efficient scheduling. However, the inclusion of soil water potential information would need some additional data which is difficult to expect from the farmers in most irrigation systems.

An alternative but simple approach to overcome the above problem partially can be to select an appropriate single MAD value to represent all sub-layers for use in irrigation scheduling (Triphati, 1992; and Theiveyanathan et al., 1998). Therefore, while choosing the operational values of MAD for heterogeneous soils, one should have a careful consideration about the selection of MAD values during various growth stages of the crop. This would avoid the undue moisture stress from the given soil-crop combination.

### **5.7.2 Module – II: How Much to Irrigate**

The estimation of the amount of irrigation water is the final step of the irrigation scheduling process. As indicated above, an irrigation is triggered on the day when a pre-defined irrigation timing approach related criterion is met. However, the actual amount of irrigation water to be applied would depend on crop, soil, weather, as well as other economic factors of local conditions. If water is easily available and inexpensive, full irrigation is practised. However, when cost factors come into play, deficit irrigation may be practised, even at the expense of maximum crop yield. Since in most irrigation systems in Victoria, it is usually customary to follow the full irrigation practice, this practice is considered in this study. The net amount of irrigation water ( $IR_{net}$ ) can be computed for the two irrigation timing approaches from Eqs. 5.23 and 5.24c.

The irrigation water amount is also constrained by the efficiency of the irrigation system. Thus, while considering the efficiency characteristic of the irrigation system, the gross amount of irrigation water ( $IR_{gross}$ ) to be applied during an irrigation event to recharge the root zone at full (i.e. DUL) level in depth units can be estimated as;

$$IR_{gross} = \frac{IR_{net}}{\eta_{app}} \quad (5.25)$$

where  $IR_{gross}$  = gross irrigation water depth required to bring the SMC of the root zone at full (or DUL) level (cm),

$\eta_{app}$  = irrigation application efficiency (fraction), and

all other terms are as defined earlier.

It is important to note that the amount of irrigation water computed by Eq. 5.25 represents the amount of water that is needed only to meet the water loss through the ET process, and does not include other inevitable water amounts that must be supplied by irrigation for various beneficial uses. Irrigation water requirements other than ET include extra water required for leaching of harmful salts from the root zone, for crop cooling or frost protection, and for soil temperature management (Burman et al., 1983). In many cases, most of these additional requirements are met during the normal irrigation. For example, if fertiliser is applied to fields by mixing with irrigation water during normal irrigation which is primarily applied to satisfy the ET requirements, then the extra water required for fertiliser application could be ignored. Similarly, other requirements can be identified, and the actual amount of irrigation water to be applied can be adjusted accordingly.

The leaching requirements, if necessary, can be added in the  $IR_{net}$  value in Eq. 5.25. The average leaching requirement and application efficiency values for use in Eq. 5.25 can be found in the literature (e.g. Doorenboss and Pruitt, 1977; Ayers and Westcot, 1985; RWC, 1988; and Wolters, 1992).

### ***Contribution from Expected Rainfall***

The final irrigation amount decision is also controlled by the probability of rain and the amount of rain forecasted during the next irrigation period. Therefore,  $IR_{gross}$  computed from Eq. 5.25 (after having been adjusted for the aforementioned extra water requirements) can be further modified to allow for the local rainfall forecasts. In case of a high probabilistic rainfall forecast, an irrigation can be delayed or completely withheld depending on prevailing local field conditions. For scheduling of irrigations during the irrigation season (i.e. for short-term operational planning), the rainfall forecasts can be obtained from the local meteorological offices. However, for use in the estimation of total irrigation water requirements before the start of irrigation season (i.e. for pre-season planning), the probabilistic rainfall predictions can be obtained from the analysis of historical rainfall records. Probabilistic rainfall predictions based on a statistical approach were discussed in Chapter 4.

### **5.7.3 Module – III: Forecasting the Next Irrigation**

Under Module-I, the issues of when to irrigate was addressed for two irrigation timing criteria. It basically gives the SMC status of the farm, which indirectly gives the farmer an indication of the irrigation need. However, water may not be available from the water supply authority to irrigate the farm on this day. Therefore, the normal practice adopted in Goulburn-Murray Irrigation Area (GMIA) is to put the water order three days in advance to the water supply authority. This requires forecasting of next irrigation.

Irrigation forecasts can be achieved by forecasting crop water use during the next few days. Forecasting crop water use not only allows for an improved short-term planning by the farm managers to optimise their timing for on-farm and/or other social activities, but also leads to the integration of on-farm system with the main delivery system. This in turn enhances the real-time operation of the main supply system leading towards more reliable water deliveries to individual farms. In addition, this also helps to maintain constant flow rates in the main channel system to avoid damage to the channel system,

which would result from frequently varying flow rates. Therefore, for aiding irrigation scheduling decisions, a good irrigation scheduling program should have a 3-14 days irrigation forecasting module built in it. The irrigation-forecasts beyond 3-day period can help the farmers to optimise their timing for other activities more efficiently. Therefore, in this sub-section, a methodology for forecasting of crop water use over the 3-14 days period is described.

### Algorithm for Irrigation Forecasts

The basic principle of forecasting crop water use is similar to that of real-time crop water use ( $ET_c$ ) estimates, except that it requires daily  $ET_o$  forecasts for the user-specified forecast period. The daily forecasted  $ET_o$  values can be obtained from the local agencies (if available). However, in this thesis, for simplicity the average of past 14-days  $ET_o$  values was used to give the forecasted  $ET_o$  value for use in irrigation forecasts.

Given the forecast  $ET_o$ , the crop water use ( $ET_c$ ) can be calculated on a daily basis as per the procedures outlined in Section 5.3. The daily forecasted  $ET_c$  value obtained from these procedures could then be employed in the water balance model (Section 5.7.1) to predict the soil moisture deficit (SMD) for each day of the forecast period. This daily SMD value could then be compared against a pre-defined  $SMD_{crit}$  parameter to invoke an irrigation, if the *target moisture level approach* (which uses MAD) had been used as the irrigation timing criteria. In the *fixed interval approach*, timing for next irrigation is already fixed. In both cases, the amount of irrigation can be computed from SMD.

It is important to mention that for calculations during the forecast period, both the rainfall and irrigation components need to be set equal to zero in Eq. 5.20 to represent the worst scenario. This implies that this is the earliest possible day that the irrigation is required. The farmers then can use this forecast irrigation day to decide when to lodge an order for their irrigation water with the water authority and/or to focus on their other on-farm activities. If rainfall occurs during the forecast period, it is understood that the farmer would delay the irrigation application. In order to meet the farmers' general scheduling

needs, an option for irrigation forecast for a period of 7-14 days was incorporated in the irrigation scheduling model of this study.

Pleban and Israeli (1989), while describing the desirable features of an irrigation scheduling program, suggested that a user-friendly irrigation scheduling program should be designed to adapt to different users and conditions, and this program should have an option available to update the soil moisture status of the root zone from field measurements during any time of the growing season of the crop. This option would help to give more reliable irrigation forecasts. Hence, this option was also incorporated into the irrigation scheduling model of this study.

## **5.8 MODEL VALIDATION**

In developing a computer simulation model, the validation of the model by comparing its output with the actual performance is a crucial part. The validation aspect of the irrigation scheduling model is described in this section. The validity of the irrigation scheduling model was tested against the field measured SMC data. For this purpose, the algorithms of the irrigation scheduling model discussed in Sections 5.3. to 5.7 were translated into a computer program using FORTRAN-77. This was important before the irrigation scheduling model could be transformed into a formal irrigation management computer software package for use at commercial farms. A portion (i.e. SMC simulation component) of this irrigation scheduling model which was used for testing against the field measured SMC data is schematically shown in Figure 5.6.

### **5.8.1 Study Site**

To investigate the validity of the model, the irrigation scheduling model was tested against the field measured SMC data at a farm in the Goulburn-Murray Irrigation Area (GMIA) in Victoria (Australia). The farm site selected for model evaluation was in Tongala, which is a small town located approximately 200 km north of Melbourne (Figure 4.1) . This site was selected because SMC measurements were available for this site from a study carried out by Wood et al. (1998). These data were used to calibrate and verify the developed irrigation

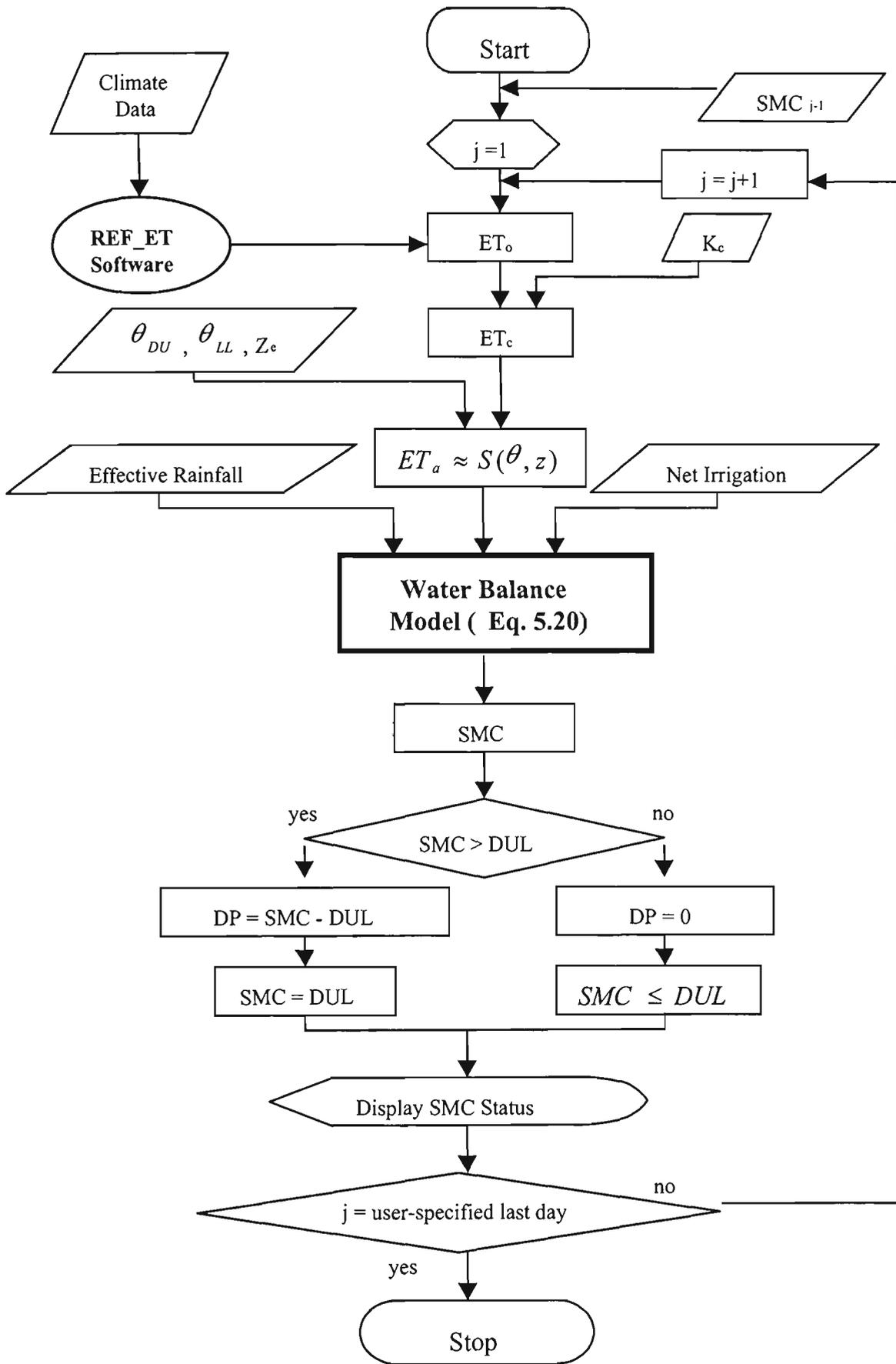


Figure 5.6 Schematic of Irrigation Scheduling Model for Soil Moisture Simulation

scheduling model. Volumetric SMC measurements had been made using Aquaflex probes on a daily basis. The daily SMC data were available for the 1997-98 irrigation season from 8<sup>th</sup> October 1997 to 27<sup>th</sup> March 1998.

The crop grown at the site was perennial pasture (which is a mixture of white clover, perennial ryegrass and paspalum). Irrigated perennial pastures in the GMIA are flood irrigated during August through May, and are grazed rotationally by dairy cattle for milk production. The soil at the site is East Shepparton Fine Sandy Loam with 40 cm top soil overlying a dense red clay of 25 cm thickness. This clay layer restricts downward water movement as well as rooting activity beyond the top profile.

As stated earlier (in Section 3.6.4), the required input climatic data (e.g. pan evaporation etc) for this analysis were obtained from the Kyabram research station, which is situated 15 km to the south west of Tongala. In-situ rainfall measurements were available from the Tongala office of Goulburn-Murray Water. The other required crop and soil related information were obtained from literature (RWC, 1988; Heslop, 1991,1995; Blackie, 1993; and Wood et al., 1998). As per these references, the physical properties of the soil adopted in this study were SAT, DU and LL with values of 46%, 41%, and 15% by volume respectively. The rooting depth soil profile used in the irrigation scheduling model was 40cm. A value of 3 for *ZeroET days* parameter was used, which was an approximate time required to reach from SAT level to the FACP level, after a heavy precipitation. event. The details of various input data items and the required format of input data files for irrigation scheduling model evaluation are described in Section C.10 of Appendix C.

### **5.8.2 Evaluation Strategy**

The evaluation of the irrigation scheduling model was based on testing of two types of SMC data series produced by the model. These data series were; i) SMC simulations, and ii) SMC forecasts. The first type of data series refers to the daily SMC values given by the model over the time period for which soil, crop and climate related input data items

(i.e.  $ET_o$  and rainfall) are available. This type of SMC series can be produced as a result of retrospective simulation of the water balance model given by Eq. 5.20. The second type of SMC series refers to the daily SMC forecasts given by the model over the time period for which the soil and crop related input data items are available, but the climate related input data (i.e.  $ET_o$  and rainfall) are not available. Hence, this type of SMC series can be produced by the model using forecast  $ET_o$  values in Eq. 5.20.

It is important to note that in real-life situation, for SMC forecasts, the daily  $ET_o$  data for the forecast period are not available. Since the model evaluation was done after the irrigation season had finished, for this analysis both  $ET_o$  and rainfall data were also available. However, to represent the real-life situation, for testing the SMC forecasting ability of the model, these  $ET_o$  and rainfall data were not used. Instead, forecast  $ET_o$  was used, and rainfall was assumed as zero. In this study, for simplicity, the average of past 14-day  $ET_o$  values was used as the forecast  $ET_o$  value (for the next day). The evaluation strategy for each of the above two types of SMC series (i.e. SMC simulation and forecast) is described below. Since known  $ET_o$  and rainfall data were used in SMC simulations, the simulation results should perform better than forecast results.

### 5.8.2.1 SMC Simulations

For evaluation of SMC simulations, fifteen irrigation application events during the 82-day period from 8<sup>th</sup> October to 28<sup>th</sup> December 1997 were selected, because of daily measured SMC and climatic data availability (as shown later in Figure 5.7). The irrigation interval between selected irrigation events ranged from 9 to 17 days. After having entered the required input data items, the model produced SMC values on a daily basis for each of the fifteen irrigation events.

The model evaluation strategy for SMC simulations was based on both qualitative and quantitative procedures. The qualitative procedures visually compared the measured and simulated SMC time series over the given period of analysis. The quantitative procedure used statistical analysis to calculate the coefficient of determination ( $R^2$ ), average error

(AE), absolute average error (AAE), root mean square error (RMSE), modelling efficiency (EF) and the coefficient of residual mass (CRM) between the measured and model-simulated SMC values.

The  $R^2$  parameter indicates the degree of general agreement between the measured and model-simulated SMC values. The AE statistical parameter represents the average difference (in %vol SMC) between the measured and model-simulated SMC values. It indicates whether the model has a tendency to over-estimate or under-estimate the observed SMC. A negative AE value indicates that the model generally under-estimates the measured SMC and vice versa. The AAE parameter represents the average absolute difference between the measured and simulated SMC values of the trialed irrigation period. RMSE describes the average percentage difference between the measured and simulated SMC values relative to the measured value, for the irrigation period under consideration. The EF parameter indicates the capability of the model to simulate actual field conditions. The CRM parameter is equivalent to that of AE, except that it indicates the over/under estimation characteristic of model in a non-dimensional form as adopted by some researchers (e.g. Antonopoulos, 1997) in their soil moisture simulation studies. These error parameters were computed as (Loague and Green, 1991; Liu et al., 1998):

$$AE = \frac{1}{n} \sum_{i=1}^n (\theta_p - \theta_m) \quad (5.30)$$

$$AAE = \frac{1}{n} \sum_{i=1}^n |\theta_p - \theta_m| \quad (5.31)$$

$$RMSE = 100 * \left\{ \frac{1}{n} \sum_{i=1}^n (\theta_p - \theta_m)^2 \right\}^{0.5} / \bar{\theta}_m \quad (5.32)$$

$$EF = 1 - \left( \frac{\sum_{i=1}^n (\theta_p - \theta_m)^2}{\sum_{i=1}^n (\theta_m - \bar{\theta}_m)^2} \right) \quad (5.33)$$

$$CRM = \left( \frac{\sum_{i=1}^n \theta_p - \sum_{i=1}^n \theta_m}{\sum_{i=1}^n \theta_m} \right) \quad (5.34)$$

where  $\theta_p$  = predicted/simulated volumetric SMC (%)

$\theta_m$  = measured volumetric SMC (%)

$\bar{\theta}_m$  = mean of measured SMC (%)

n = number of SMC data values

and all other symbols are as defined earlier

The optimum values of  $R^2$ , AE, AAE, RMSE, EF and CRM parameters are 1, 0, 0, 0, 1, and 0 respectively. The values of AAE less than 2% (in volumetric SMC units) are acceptable for irrigation scheduling purposes (Liu et al., 1998). The value of EF varies between  $-\infty$  for total lack of fit and 1 for exact fitting; a value less than 0 indicates that the model simulations are worse than simply using the observed mean. Positive values of CRM means that the model over-estimates the measurements and vice versa (Loague and Green, 1991). The results of the two (i.e. qualitative and quantitative) evaluation criteria are discussed in Section 5.8.3.

#### 5.8.2.2 SMC Forecasts

As in SMC simulations in Section 5.8.2.1, the same fifteen irrigation application events were selected to evaluate the SMC forecasting ability of the irrigation scheduling model. Only those irrigation application events were selected for which daily measured SMC and other required climatic data were available. In order to comply with the farmer's normal needs of at least 3-day advance water orders, SMC forecasts were tested for 3-day forecast periods. However, for further insight a 5-day forecast period was also considered. As mentioned earlier, in this study the daily SMC forecasts were calculated using the water balance model (Section 5.7.3) which used the average of past 14-day  $ET_o$  values. With regards to the selection of irrigation events, the following considerations were taken into account:

- As discussed earlier in Section 5.4.6, during the transient period (i.e. soon after the precipitation event), the SMC is highly variable in time and space. Therefore, to avoid the influence of transient conditions, only those days occurring after the transient period were used for SMC forecasts.

- To be able to compare between the forecast and observed SMC, rainfall and irrigation events must not affect the SMC data. Therefore, those days which were occurring at least three days before an irrigation or rainfall event were used for SMC forecasts.
- The comparisons of forecast and observed SMC were made only at the final day of respective (3-day or 5-day) forecast period, since the farmers are generally interested on the irrigation amount at the end of the forecast period.

In order to assess the forecast performance, only two statistical parameters namely AE and AAE were used. However, for forecast analysis, these statistics were calculated both in terms of SMC in %vol as well as in terms of days. The latter statistics (i.e. in days) were calculated the same way as SMC (in %vol) except that in this case the comparison was made in days rather than %vol SMC. The comparison figure in days between the final forecast and observed SMC values is obtained just by counting the difference of number of days (either in lag or forward shift) between the final observed SMC value and the forecast value similar to the observed SMC value. The test statistics of SMC forecasts are also discussed in Section 5.8.3.

### **5.8.3 Results and Discussion**

#### **(a) SMC Simulations**

The error statistics (discussed in Section 5.8.2.1) computed for the 1997-98 irrigation season of the Tongala site are given in Table 5.1. As shown in this table, the values of these parameters were computed for 15 data sets (ranging from 9 to 17 SMC observations per data set). A summary of these error statistics (i.e. minimum, maximum, and average values) is presented in Table 5.2. The precision achieved with the irrigation scheduling model developed in this study was also compared with that reported in the literature for other models. This is described as below.

Table 5.1 Error Statistics for Comparison Between Model-Simulated and Measured SMC (% volume) at Tongala Study Site

Data Set	R <sup>2</sup>	AE (%vol)	AAE (%vol)	RMSE (%vol)	EF	CRM
1	0.99	-0.66	0.66	2.81	0.85	-0.02
2	0.97	-0.45	1.01	2.80	0.71	-0.01
3	0.91	-1.73	1.83	5.32	0.43	-0.04
4	0.99	1.02	1.29	4.46	0.93	0.03
5	0.98	0.67	0.85	2.39	0.91	0.02
6	0.98	1.05	1.05	2.91	0.81	0.02
7	0.99	1.22	1.22	3.52	0.88	0.03
8	0.97	-0.87	1.15	3.30	0.84	-0.02
9	0.93	1.04	1.05	3.11	0.51	0.02
10	0.96	1.24	1.26	4.60	0.74	0.03
11	0.99	1.19	1.19	3.28	0.85	0.03
12	0.99	-0.27	0.42	1.47	0.98	-0.01
13	0.99	-0.71	0.89	2.71	0.80	-0.02
14	0.98	-0.77	0.83	2.49	0.70	-0.02
15	0.99	-0.86	0.88	2.42	0.90	-0.02

Table 5.2 Summary Statistics of 15-data Sets for SMC Comparison at Tongala Site

Statistical Parameter	Average	Range
Coefficient of determination, R <sup>2</sup>	0.97	0.91 - 0.99
AE (SMC %vol.)	0.07	-1.73 - 1.24
AAE (SMC %vol.)	1.04	0.42 - 1.84
RMSE (%)	3.17	1.47 - 5.32
EF	0.79	0.43 - 0.98
CRM	0.002	-0.04 - 0.03

The coefficient of determination (R<sup>2</sup>) has an expected value of 1. As can be seen from Table 5.2, their average values are indeed very close to 1. The range of variation, when considering individual data set, also indicates that R<sup>2</sup> is generally close to one. When comparing this average value of R<sup>2</sup> with other studies, it could be observed that these R<sup>2</sup> values are acceptable as per Liu et al. (1998) who suggested a value of R<sup>2</sup> > 0.80 for comparisons between model simulations and observations.

De Faria et al. (1992) using VB4 and SWACROP models for wheat crops, reported that AE ranged from 2.4% to 3.3% and 2.4% to 3.6% respectively for these models. Mahdian and Gallichand (1995) using the SUBTOR model in Canada, achieved AE and AAE values ranging from -3.3 to 0.7% and 3.3 to 4.2% respectively. Antonopoulos (1997) in Greece, while testing a soil moisture simulation model using three different  $S_{\max}$  functions obtained the maximum values of AE, RMSE and EF parameters as 1.4%, 12.52% and 0.67 respectively. The CRM values in his study ranged from -0.05 to 0.02.

For a loamy soil in China, Liu et al. (1998) used ISAREG model for maize and wheat crops, and achieved the average AAE values less than 2% for both crops. In their study, the maximum value of average relative error parameter (an equivalent term to that of RMSE parameter of the present study) obtained was equal to 10%.

As can be observed from Table 5.2, for the irrigation scheduling model developed in this study all error statistics compared well with the above reported literature values. Therefore, based on these error statistics, it can be concluded that the developed irrigation scheduling model is of acceptable accuracy for simulating SMC in the soil profile of pasture crops.

Figure 5.7 shows the simulated and measured SMC values during the 1997-98 irrigation season of the pasture at the Tongala study site. From this figure, it is also clear that the model simulates the effects of soil-plant-atmosphere interactions reasonably well. However, some over and under-estimation by the model can be noted. For example, from 2<sup>nd</sup> Nov onwards the model under-estimated the SMC measurements. This can be explained due to the simple fact that SMC of root zone was already at its SAT level (due to the previous irrigation event of 29<sup>th</sup> Oct) when the rainfall on 31<sup>st</sup> Oct occurred, and hence this rainfall was totally treated as deep percolation loss by the model due to the assumption incorporated in it for such events (Section 5.3.5 and 5.4.6). However, as it can be observed from Figure 5.7 that it settled down itself after a few days, while the SMC was still reasonably above the refill point.

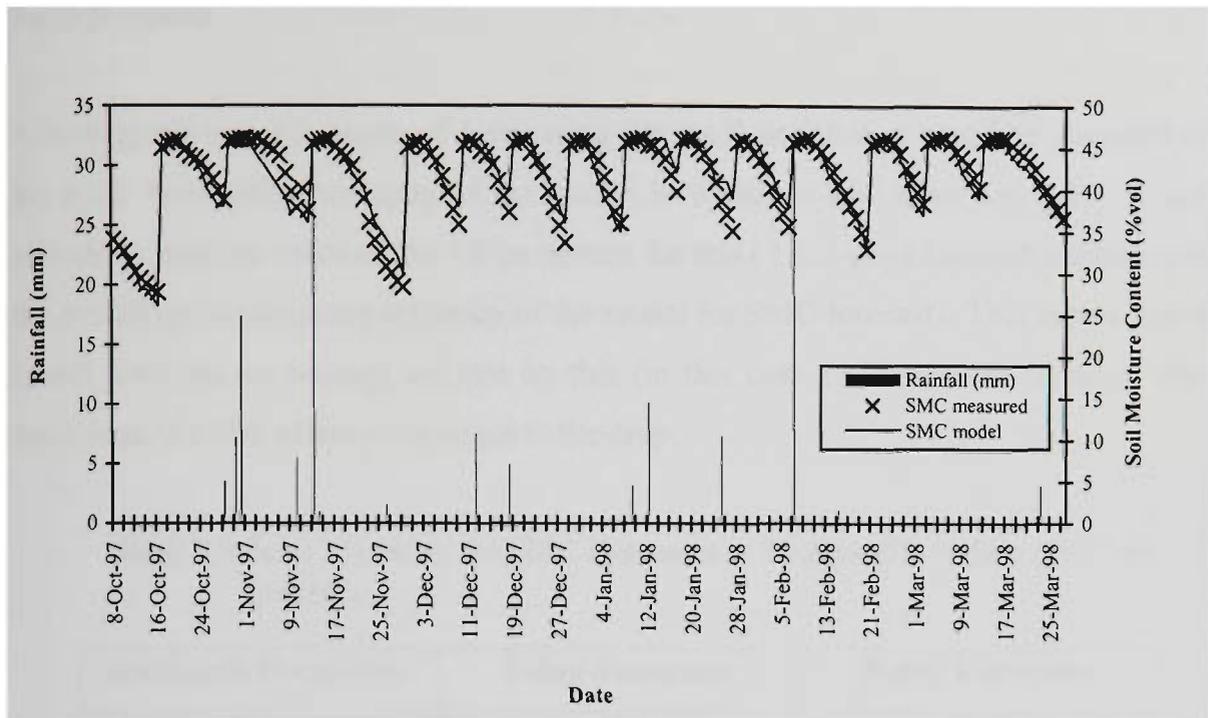


Figure 5.7 Measured and Model-simulated Soil Moisture Contents at Tongala Study Site

With regards to over-estimation, the three significant over-estimation events of 25<sup>th</sup> Nov, 12<sup>th</sup> Jan and 24<sup>th</sup> Jan can be attributed to the combined effect of model inaccuracy, rainfall recording as well as SMC measurement errors that are not unusual during field data measurements. Also, it is interesting to note that the average CRM value in this case is positive which indicates an overall tendency of the model to over-estimate the SMC measurements. Notwithstanding this, the error statistics described above indicate that the developed irrigation scheduling model easily satisfy the acceptance criterion for SMC simulations, and hence could be safely employed as an irrigation scheduling as well as a planning tool at farm level.

**(b) SMC Forecasts**

The error statistics of SMC forecasts for 3-day and 5-day forecast periods are given in Table 5.3. These error statistics are the mean values of the fifteen events.

### 3-day forecasts

Analysing the errors in terms of days, using the AAE statistics, it could be observed that the SMC forecasting accuracy of the model is within  $\pm 1.69$  days for 3-day forecast periods. A positive value of the AE parameter for this ( i.e. 3-day) forecast period reveals the overall over-estimating tendency of the model for SMC forecasts. This means that the model forecasts on average are late by this (in this case 1.69) number of days, which could lead to a risk of moisture stress to the crop.

Table 5.3 Error Statistics for SMC Forecasts at Tongala Study Site (1997-98 Season)

Statistical Parameter	3-day Forecasts	5-day Forecasts
AE (days)	0.94	0.89
AAE (days)	1.69	2.00
AE (SMC %vol.)	0.94	1.11
AAE (SMC %vol.)	1.69	1.78
ARE (%)	4.92	5.57

Wood et al. (1998), while evaluating different methods for forecasting SMC for 3-day period for use in irrigation scheduling of pasture crop, obtained a positive value of the AE parameter and the AAE value equal to 1.3 for their best SMC forecasting method. In their study, the forecasts were based on the analysis of measured SMC values of previous fifteen days, prior to the forecast starting day. The comparison of AAE value obtained in present study with that of reported value by Wood et al. (1998) reveals that the irrigation scheduling model SMC forecasts are quite comparable.

A two to three day's disagreement between the model forecasted and the actual irrigation date becomes risky in the case of those cash crops which are frequently irrigated at relatively small irrigation intervals (such as 7-10 days periods, especially during their sensitive growth stages, for example grain filling). However, for irrigation schedules of those crops which are irrigated at 10-30 days irrigation intervals, there may not be a

significant risk. Nevertheless, the use of improved daily  $ET_o$  forecast values (e.g. if available from local agencies) in the irrigation scheduling model can help to mitigate the risk of moisture stress, even for demand predictions of short irrigation-interval crops. Alternatively, an adjustment (e.g. an increase by 10%) to the daily  $ET_o$  forecast values (as computed by the model) could also serve this purpose. This adjustment factor can be obtained through the validation study such as described in this section.

Another crude way of avoiding the moisture stress could be that the user can invoke a 7-days forecast, and then irrigate at least two days prior to the model forecasted irrigation date. With regards to the use of this (7-day forecast) method, it is important to mention that in this case the current (or forecast starting) day should not be occurring more than three days prior to the end of normal irrigation interval (or in other words should be approximately seven days after the last irrigation event, if a 10-day interval is considered).

The above discussion on the capability of the irrigation scheduling model in terms of 3-day SMC forecasts revealed that for crops with short (i.e. 7-days) irrigation intervals, the performance of the model was not satisfactory. This was mainly due to the algorithms used in the model for estimation of forecast  $ET_o$  values, which were primarily based on the simple average of past 14-day  $ET_o$  values. However, the model evaluation in terms of its capability to simulate the daily SMC under field conditions (as discussed earlier under sub-section titled 'SMC Simulations') showed quite promising results. The simulation results revealed that the irrigation scheduling model was quite successful to consider the variability of evaporative demand of crops and also to account for exactly the rainfall received during the irrigation period. This leads to the conclusion that in comparison with the farmer's simple judgement (which does not generally consider variability of evaporative demand and rainfall contribution), the use of the developed irrigation scheduling model for operational planning (i.e. scheduling) of irrigated crops can facilitate saving of significant amounts of irrigation water. This aspect will be demonstrated later with a case study in Section C.9.5.

### *5-day forecasts*

It is important to note that in Table 5.3, the AE and AAE error statistics for 5-day forecast period also revealed a similar over-estimation trend of the irrigation scheduling model. Additionally, in this case it is also interesting to note that the AAE value (equal to 2.0) is even slightly higher than that of the 3-day forecast period. This is not surprising because in case of 5-day forecasts, the current (or forecast starting) day was more closer to the last irrigation application date by two days as compared with the 3-day forecast case. The closer is the current (or forecast starting) day to the last precipitation (i.e. irrigation and/or rainfall) event, the lower would be the SMC forecasting accuracy. This aspect is explained as below.

Figure 5.7 shows the typical existing irrigation practice adopted by the farmer in the study area. As can be observed from this figure, on average an irrigation interval of 10-days with each irrigation application up to SAT level was practised. Considering an average irrigation interval of 10-days with each irrigation up to SAT level, the *current day* of 5-day forecast period is expected to be highly influenced by the transient condition (from SAT to FCAP level) of the soil followed by an irrigation event as compared with the *current day* of the 3-day forecast period. This is due to the empirical assumptions (Section 5.4.6) incorporated in the model. It is important to note that in this study, the *current day* of the 5-day forecast period is assumed to occur five days before the next irrigation event or in other words five days after the last irrigation event, if a 10-day irrigation interval is considered. Similarly, the *current day* of the 3-day forecast period is assumed to occur three days before the next irrigation event or seven days after the last irrigation event. It implies that farther the *current day* (i.e. forecast starting day) from the last precipitation (i.e. irrigation and/or rainfall) event, the more reliable would be the irrigation forecasts. This can easily be achieved in case of those crops which are irrigated at relatively longer (such as 10-days or more ) irrigation intervals. Hence, this aspect highlights the limitation of such semi-empirical irrigation scheduling model, since it would prove more useful for operational planning of long irrigation-interval crops than for short (i.e. less than 10-days) irrigation-interval crops. However, as mentioned earlier,

even for short irrigation-interval crops the model's irrigation forecasting performance could be quite satisfactory given the above mentioned two (either using improved  $ET_0$  forecasts or  $ET_0$  adjustment) techniques are adopted.

It is worth noting that the forecast error statistics in terms of SMC (%vol) as given in Table 5.3 also mimic the same forecast situation, however, are not able to convey the message in quantitative measures as in the error statistics in terms of days. Therefore, the forecast error statistics in terms of days were only discussed here, while the error statistics in terms of SMC (%vol) were presented just for reader's information.

### **(c) Concluding Remarks**

The SMC simulation analysis indicated that the developed irrigation scheduling model easily satisfied the acceptance criterion for SMC simulations, and hence could be safely employed as an irrigation scheduling as well as a planning tool at farm level.

Based on the SMC forecast analysis, it was revealed that the irrigation scheduling model would prove more useful for operational planning of long irrigation-interval crops than for short (i.e. less than 10-days) irrigation-interval crops. However, as mentioned earlier, even for short irrigation-interval crops, the irrigation forecasting performance of the model can be improved with accurate  $ET_0$  forecasts or  $ET_0$  adjustment as discussed.

It is important to appreciate that at the Tongala study site, the SMC simulations of the developed irrigation scheduling model showed an excellent agreement with the daily measured SMC data without the need for any significant calibration. The only parameter required to be adjusted was *ZeroET days* (Section C.4.1 and C.10.1), which in this case was set to 3 days based on the visual observation of plotted graph of daily measured SMC data values. Although the performance of this model was found to be quite satisfactory at the Tongala site, in order to use the model under different soil and environmental conditions, the irrigation scheduling model developed in this study needs to be calibrated against measured SMC data under local conditions. The calibration aspect of this model is described in detail in Section C.10 of Appendix C.

## 5.9 SUMMARY

The estimation of irrigation water requirements is an important component of the on-farm water management programs undertaken to make the efficient use of the available water resources. This can be achieved by employing an efficient irrigation scheduling model. A semi-empirical model for the management and forecasting of irrigation water requirements at an on-farm level is developed in this study. The model employs a water budgeting approach, and includes mechanisms for simulating soil moisture movement, root growth and crop evapotranspiration.

The model requires only a few input parameters which are readily available. They include: daily rainfall, previous irrigation (i.e. time and amount), reference crop evapotranspiration, physical characteristics of the soil (e.g. saturation, field capacity, and permanent wilting points etc.), irrigation timing criteria (e.g. fixed interval or target moisture level approach using the MAD concept), and the crop coefficients relevant to the growth stages of a crop. Another optional input parameter to the model is the soil moisture extraction characteristics of the root system of the crop. The model calculates the components of the water balance on a daily basis including actual evapotranspiration, deep percolation and the soil moisture depletion at different depths of the soil profile, to decide on an irrigation, based on a pre-defined irrigation timing criterion.

The advantage of the developed irrigation scheduling model over the previous irrigation scheduling models is that the ET component of the model accounts for dynamic root water extraction process using simple functions for which only the rooting depth information is required. Furthermore, the other required parameters (e.g. for computation of  $ET_0$ ) can be easily estimated. The model also allows an option for considering the short-term (3-14 days) future evaporative demand of the crop for forecasting of irrigation, several days in advance. The model has the flexibility for its use under a wide range of soil, crop and climatic conditions, given the relevant soil, crop and climatic data are provided.

The qualitative and quantitative procedures adopted for model evaluation showed that there was good agreement between the model-simulated and the measured SMC values for pasture crop. The comparison of the model simulations with the other models reported in literature suggests that the model developed in this study is quite successful, and hence could safely be employed in irrigation scheduling at a farm level.

The irrigation scheduling model described in this chapter was loosely linked with the REF\_ET (Chapter 3 and Appendix A) and RAIN\_PRE (Chapter 4 and Appendix B) software to develop integrated software package – IRrigation Planning Scheduling And Evaluation (IRPSAEV). The outputs of REF\_ET and RAIN\_PRE are used in the IRPSAEV package. Since the IRPSAEV model is the most important component of this thesis, the computer program describing the IRPSAEV model is described separately in Appendix C, including the use of this computer software under different conditions and calibration of the model. This is in line with the other computer software developed in this thesis (i.e. those explained under Chapters 3 and 4), which are also given in Appendices.

# CHAPTER 6

## CONCLUSIONS AND RECOMMENDATIONS

### 6.1 CONCLUSIONS

The main aim of the research study in this thesis was to develop methods and tools to facilitate efficient use of available water at an on-farm level. For this purpose, an irrigation scheduling model called IRPSAEV (i.e. IRrigation Planning Scheduling And Evaluation) based on the simple water balance approach was developed. In the development of the IRPSAEV model, two major components of the water balance equation, namely crop evapotranspiration and expected rainfall were considered in detail. The conclusions related to these two aspects and in general related to the developed IRPSAEV model are given in Sections 6.1.1 - 6.1.3.

#### 6.1.1 Crop Evapotranspiration

A common procedure for estimating crop water use is to first determine the daily reference crop evapotranspiration ( $ET_o$ ), and then multiply it by a specific crop coefficient ( $K_c$ ). This procedure gives the potential crop water use ( $ET_c$ ). Finally, the actual crop water use (or actual crop evapotranspiration,  $ET_a$ ) is determined based on the soil moisture availability at the time.  $ET_o$  can be determined by direct measurements (e.g. lysimetry) or estimated by empirical methods using climatic data. For use with computer-based irrigation scheduling programs,  $ET_o$  estimation methods are preferred, since  $ET_o$  from direct measurements are limited. This method was used in IRPSAEV model.

There are numerous empirical methods available for estimating  $ET_o$  using meteorological data. However, the choice of the method for estimating  $ET_o$  is essentially based on the location, the climate, the intended estimation period, and the input data availability for the site in question. Various studies revealed that these methods need to be evaluated and calibrated under local conditions before using in irrigation scheduling studies. A critical review of the previous studies indicated that to

date no evaluation/calibration study was done for these methods under Australian conditions specifically for use with the irrigation scheduling models. Hence, ten methods ranging from simple temperature-based to data extensive combination methods were investigated for their suitability under Australian conditions. The study sites were Tatura and Aspendale in Victoria, and Griffith in New South Wales (NSW). The conclusion of this study are described as below.

The investigation study revealed that combination methods generally provided the most accurate  $ET_0$  estimates. This is understandable since they were based on physical laws and rational relationships. However, the analyses also revealed that no single daily  $ET_0$  estimation method using meteorological data was satisfactory for all sites.

It was observed that all  $ET_0$  methods required local calibration against measured lysimeter (or base method)  $ET_0$  data for better performance. When measured lysimeter data are not available, the  $ET_0$  estimates computed from an  $ET_0$  estimation method which is appropriate for the study site can be used as the base method for evaluation of other methods. Depending upon the climatic situation of a specific site, a locally calibrated less data requiring simple  $ET_0$  estimation method can produce even better results than the data extensive combination methods. The results also revealed that the availability of climatic data alone should not be the sole criterion in selecting an  $ET_0$  method since some of the needed data could be estimated from other variables with sufficient accuracy to permit using one of the better  $ET_0$  estimating methods. It was also observed that the simplified U.S. Class-A Pan evaporation (SEV) method can provide good results provided that the pan is properly maintained and accurate measurements are taken.

In some cases, the farm manager likes to know the approximate total irrigation requirement of a certain crop before the season starts, so that he/she can decide on the area to be cultivated. This is termed as pre-season planning in this thesis. For pre-season irrigation planning, the mean daily estimates of  $ET_0$  are required. In general, the mean daily  $ET_0$  estimates can be obtained from historical daily  $ET_0$  data. However, in the absence of historical daily  $ET_0$  data, mean monthly pan evaporation data can also be used to compute the mean daily  $ET_0$  estimates.

Based on the conclusion that no single daily  $ET_0$  estimation method using meteorological data was satisfactory for all sites, a user-friendly menu driven computer software (REF\_ET) was developed to compute daily  $ET_0$  estimates from ten different  $ET_0$  estimation methods. These ten methods were the same methods that were evaluated at the three sites in Victoria and NSW. Since the availability of the measured climatic data can force the user to use specific  $ET_0$  estimation methods, a user-specified “priority order” option to use the desired  $ET_0$  estimation methods was incorporated in this package. The package first attempts to compute  $ET_0$  estimates using the user-specified highest priority (i.e. highest ranked)  $ET_0$  estimation method. However, if the climatic data required for this method are not available, then the software uses the method having the second highest priority, and so on. In this way, all ten  $ET_0$  methods are considered. Hence, the user-specified “priority order” option assures that an  $ET_0$  estimate is computed for each day of the study period based on the user-specified  $ET_0$  method, provided the required input data are available. However, if data are not available for a particular day relevant to any of the  $ET_0$  estimation methods, then  $ET_0$  is not computed for that day.

It is important to note that in addition to this above stated “priority order” option, there is another option available in REF\_ET. Under this option, the REF\_ET package computes daily  $ET_0$  estimates using all ten  $ET_0$  methods at the same time, ignoring the user-specified priority order.

Since  $ET_0$  methods also require local calibration for best performance under site specific conditions, the package was also provided with an option to accept a “local calibration coefficient” for each of the ten  $ET_0$  estimation methods. Therefore, the package is comprehensive to estimate daily  $ET_0$  for any climatic region.

The  $ET_0$  estimates given by the REF\_ET software can be effectively used for irrigation scheduling to save significant amounts of irrigation water at a farm level. The package is also useful for extension agencies and other irrigation/research professionals.

## 6.1.2 Short-term Rainfall Prediction

As stated earlier, an estimation of actual crop evapotranspiration ( $ET_a$ ) is required for the irrigation interval under consideration for implementing irrigation scheduling programs for short-term planning and operation of irrigation systems.  $ET_a$  is determined based on the soil moisture availability of the farm, which in turn depends on the amount of expected rainfall during the irrigation interval. Since the irrigation interval (or period) varies between 7-14 days in Victoria (Australia), the expected rainfall deals with the total rainfall over this interval and in some cases may be zero (or very small).

The most common approach employed for predicting the expected amount of rainfall over a required period has been to fit an appropriate statistical distribution to the historical rainfall records after creating the required rainfall series of the required period. The expected rainfall is then predicted with a certain probability of exceedance. A review of literature related to this subject revealed that no such study was done previously under Australian conditions to study the expected rainfall over short periods such as 7-14 days for use in short-term planning and operation of irrigation systems.

A study of rainfall records at three locations (namely Tatura, Tongala and Pyramid Hill) in the Goulburn-Murray Irrigation Area, GMIA of Victoria (Australia) revealed that the short-term rainfall data series were positively skewed, and that there were considerable number of non-rainy periods giving zero values in the data series. In addition, high outliers were also found in most data series. The initial analysis revealed that the presence of zeros and outliers in the data series posed problems in fitting conventional statistical distributions (which do not explicitly account for zeros) to these data series. Hence, a method that accounts for zero values was required to model them.

The total probability theorem (TPT) and leaky-law (LL) methods that account for the zeros were tested for their ability to model the short-term rainfall data series at the three sites. In order to adopt the TPT method with normal distribution function, the non-zero part of the data series first needs to be normalised. For this purpose, three

transformations (namely power, log and square-root) were considered in the TPT method. The analysis revealed that the non-zero rainfall data series could successfully be normalised using at least one of the above three transformations, provided that the series were adjusted for less than 1mm rainfall values (i.e. setting these values to zeros), and the outliers were removed using the Walsh (1959) outliers test. It was observed that TPT using the power transformation (TPTP) was more effective to model the short-term data series in comparison with the log (TPTL) and square root (TPTS) methods.

Fitting of short-term rainfall data series by the LL method was significantly improved after <1mm adjustment and removal of outliers. However, the LL fitting analysis revealed that the LL method could not model all short-term rainfall data series.

An investigation on the implication of removal of outliers on short-term rainfall predictions indicated that the removal of outliers does not significantly affect the short-term rainfall predictions given by TPT and LL methods.

The analysis of short-term rainfall data series at the three sites revealed that although TPT and LL were satisfactory methods to model rainfall series with zeros, none of these two methods was individually able to fit all short-term rainfall data series at the three sites. Since there was no single distribution method available to fit all short-term rainfall data series, the joint use of TPT and LL methods was investigated to fit these data series. The joint use of TPT and LL methods revealed that various short-term rainfall data series were successfully fitted by at least either of these two methods. Hence, the joint use of TPT and LL methods was found to be the best choice for rainfall predictions in this study, since this method models all short-term rainfall data series.

Based on the concept of the joint use of TPT and LL methods, a user-friendly menu driven computer software (RAIN\_PRE) was developed to predict the expected rainfall. The package is comprehensive to predict rainfall for irrigation intervals between 5-30 days. The rainfall predictions given by the RAIN\_PRE software can be effectively used in irrigation scheduling studies in an attempt to save significant amounts of irrigation water at a farm level.

### 6.1.3 Irrigation Scheduling Model

A review of literature revealed that among several techniques for scheduling irrigation, the computer based irrigation scheduling programs had most promise to aid in efficient use of available water at a farm level. It was also noted that several computer programs are currently available for scheduling purposes with varying degree of sophistication. However, the use of these programs among farmers has been slow.

Keeping in view of the above points, a simple mathematical irrigation scheduling model was developed in this study. The model employed simple algorithms for simulating the soil-plant-atmosphere system. The model requires only a few input parameters which are readily available. They include: daily rainfall, irrigation records, reference crop evapotranspiration, physical characteristics of the soil (e.g. saturation, field capacity, and permanent wilting points etc.), and the crop coefficients relevant to different growth stages of the crop. Another optional input parameter to the model is the soil moisture extraction characteristics of the root system of the crop. The advantage of the developed irrigation scheduling mathematical model over the previous irrigation scheduling models is that the evapotranspiration component of the model accounts for dynamic root water extraction process by using simple functions for which only the rooting depth information is required.

The qualitative and quantitative procedures adopted for model evaluation showed that there was good agreement between the predicted and the measured soil moisture content (SMC) values for pasture crop. The comparison of precision achieved with this model with the other models reported in literature suggests that the model developed in this study is quite successful, and hence could be safely employed as an irrigation scheduling as well as planning tool at a farm level.

The model calculates the components of the water balance on a daily basis including actual evapotranspiration, deep percolation, and the soil moisture depletion at different depths of the soil profile, to decide on an irrigation based on a user-specified irrigation timing criterion. The model also allows an option for considering the short-

term (3-14 days) future evaporative demand of the crop for forecasting of irrigation several days in advance. The model has the flexibility for its use under a wide range of soil, crop, and climatic conditions, given the relevant soil, crop and climatic data are provided.

### *Irrigation Planning, Scheduling And Evaluation (IRPSAEV) Computer Software*

The above stated irrigation scheduling mathematical model algorithms were integrated with the REF\_ET and RAIN\_PRE software to develop an effective irrigation management tool for use by the farmers to facilitate efficient use of available water at an on-farm level. This integrated model is referred to as IRrigation Planning Scheduling And EVALuation (IRPSAEV) computer software package. The IRPSAEV package is user-friendly, and can be operated under four modes namely PLANning, SCHEduling, EVALuation and CALibration. Although IRPSAEV and its four operational modes are described in Appendix C, the important conclusions related to IRPSAEV are given below.

The PLANning mode of the IRPSAEV package facilitates to predict the expected (or future) irrigation schedules as well as estimates of total irrigation water demand over the entire season before the actual irrigation season starts, to serve as a pre-season planning tool. The pre-season planning would help the farmer to decide how much area to bring under cultivation for specific crops to maximise the net farm profits. The SCHEduling mode provides the schedule (i.e. time and amount) for the next irrigation during any time of the irrigation season. This information can be used by the farmer for real-time operation of an irrigation system.

The EVALuation mode facilitates to predict the required irrigation schedules for the crop under consideration for the previous irrigation season. This information can be used to evaluate the performance of the irrigation schedules adopted by the farmer during the past irrigation season, and to attract the farmer's attention to use the IRPSAEV package for potential water savings in future seasons.

The package has flexibility for its use under a wide range of soil, crop and climatic conditions. Like all other semi-empirical models, in order to use the package under

different soil and environmental conditions, the IRPSAEV model also needs to be calibrated against appropriate measured SMC data under local conditions. This can be done using the CALibration mode

The advantage of the developed IRPSAEV package over previous software developed under Australian conditions is that it defines the irrigation scheduling problem from the farmer's viewpoint and adapt the package interface to his/her concepts and needs. This is an important factor lacking in most previous models, and as such responsible for slow acceptance of irrigation scheduling programs among the farmers in the past.

The case studies carried out for planning and scheduling irrigations at a farm site in the GMIA demonstrated the usefulness of the IRPSAEV package. The results of the case study revealed that the developed IRPSAEV package could be effectively used as an operational as well as a planning tool at a farm level to harvest significant water savings in addition to other environmental related benefits. The potential for using the developed IRPSAEV package as an efficient irrigation management tool on the commercial farms is enormous.

## **6.2 RECOMMENDATIONS FOR FUTURE RESEARCH**

The research conducted in this study mainly concentrated on three aspects related to short-term planning and management of irrigation systems. They are: estimation of crop evapotranspiration, estimation of expected rainfall during the irrigation interval and development of an irrigation scheduling model. The former two aspects are input to the latter. Although the research was successfully carried out on the above three aspects, some recommendations are given below to improve the findings of the research of this study and to improve the computer software developed as part of this study.

### **6.2.1 Evapotranspiration**

- In this study, the evaluation/calibration of various  $ET_0$  estimation methods at Aspendale and Tatura sites was based on limited available input data. This can be

further improved by using more input climatic and lysimeter data if available in future.

- In the current study, only three sites were investigated. In future, more study sites can be investigated to cover various representative climatic conditions in the MDB area.

### **6.2.2 Short-term Rainfall Predictions**

- The short-term (e.g. 4-14 day) rainfall predictions using the TPT and LL methods were quite satisfactory at the three study sites. However, due to temporal and spatial variability, the performance of TPT and LL methods at other sites should also be evaluated.
- For operational purposes, the short-term rainfall predictions should be investigated using stochastic time series analysis, for improved results.

### **6.2.3 Irrigation Planning, Scheduling and Evaluation (IRPSAEV) Model**

It is important to appreciate that like all other computer models, the proposed IRPSAEV package has a number of limitations that can affect its application and accuracy. Since significant gaps remain in understanding the complexities of scheduling and distributing water in large irrigation systems, the IRPSAEV package developed in this study can be considered as one of the attempts to provide a better tool with which irrigation professionals (as well as farm managers) could address some of these gaps. Although the IRPSAEV software can be effectively used as a pre-season planning as well as real-time operational (or scheduling) tool at a farm level, it cannot address many socio-economic issues that are just as important in irrigation management. Some recommendations are listed below to improve the IRPSAEV model developed in this thesis.

- In the present study, with regards to the use of the IRPSAEV model, it was assumed that water is unlimited and was always available on request. Further

focus may include the considerations of the effects of deficit irrigation (i.e. limited water supply available).

- In the present format of the IRPSAEV model, no explicit consideration for groundwater contribution was made. Future research can be extended to include a component to factor the groundwater table contribution.
- Although the performance of the IRPSAEV package was found to be good for pasture, it needs to be further evaluated for other crops under different soil and climatic environments.
- At present, in SCHEDuling mode of the IRPSAEV package, the irrigation forecasting module uses daily  $ET_0$  values which are based on simple average of past 14-day  $ET_0$  data values. However, to represent the real-time prevailing climatic conditions, a time series approach can be incorporated in the model for  $ET_0$  estimates to make improved irrigation forecasts.
- Issues such as transferable water rights, water quality affects, economic returns and capacity constraints of the system can also be addressed either with modifications to the IRPSAEV model or by coupling some other packages/tools (e.g. unsteady canal-flow models, water-quality models) with the IRPSAEV package.
- By incorporating a mixed linear program, the developed IRPSAEV package can also be used for whole farm management to produce optimum irrigation schedules for different crops.

## REFERENCES

1. ABARE (1995). Farm Management and Technology in the Australian Dairy Industry 1993-4. Australian Dairy Industry Survey. Australian Bureau of Agriculture and Resource Economics.
2. ABARE (1997). Technology and Farm Management Practices in the Australian Dairy Industry 1995-96. Australian Dairy Industry Survey. Australian Bureau of Agriculture and Resource Economics, August 1997.
3. Adamowski, K. (1985). Nonparametric Kernel Estimation of Flood Frequencies. *Water Resour. Res.*, 21(11):1885-1890.
4. Adamowski, K. (1996). Nonparametric Estimation of Low-Flow Frequencies. *J. Hydr. Engrg., ASCE*, 122(1):46-49.
5. Adamowski, K. and Feluch, W. (1990). Nonparametric Flood Frequency Analysis with Historical Information. *J. Hydr. Engrg., ASCE*, 116(8):1035-1047.
6. ADC (1997). Dairy Compendium 1997. Australian Dairy Corporation, Victoria.
7. Adoum, D.D. (1993). Factors Affecting the Initial Adoption of Agricultural Expert Systems - A survey of Expert Users from California. PhD Thesis, Univ. of Maryland, College Park.
8. Akhand, M.N.A. (1992). A Canal Irrigation Water Allocation Model. PhD Dissertation, Dept. Agric. Bio. Engrg., Univ. of Arizona, U.S.A..
9. Allen, R.G. (1986). A Penman for All Seasons. *J. Irrig. and Drain. Engrg., ASCE*, 112(4):348-368.
10. Allen, R.G. (1992). Evaluation of a Temperature Difference Method for Computing Grass Reference Evapotranspiration. Report Submitted to UN-FAO Water Resources Development and Management Service, Land and Water Dev. Div., Rome, Italy, pp50.
11. Allen, R.G. and Pruitt, W.O. (1986). Rational Use of the FAO Blaney-Criddle Formula. *Irrig. and Drain. Engrg., ASCE*, 112(2):139-155.
12. Allen, R.G., Jensen, M.E., Wright, J.L. and Burman R.D. (1989). Operational Estimates of Reference Evapotranspiration. *J. Agron.*, (81):650-662.

13. Allen, R.G., Smith, M., Pereira, L.S. and Perrier, A. (1994b). An Update for the Calculation of Reference Evapotranspiration. Int. Commission on Irrig. and Drain. (ICID) Bulletin No. 2, Vol., 43, :35-92.
14. Allen, R.G., Smith, M., Perrier, A. and Pereira, L.S. (1994a). An Update for the Definition of Reference Evapotranspiration. Int. Commission on Irrig. and Drain. (ICID) Bulletin No. 2, Vol., 43, :1-34.
15. Allison, B.E., Fetcher, L., Leucht, A., and Sivakumar, M.V.K. (1993). Use of the CERES-Millet Model for Production Strategy - Analysis in the Sudano-Sahelian Zone. Int. Comm. on Irrig. and Drain., (ICID), 2<sup>nd</sup> Workshop on Crop-Water-Models, Hague, The Netherlands:175-188.
16. Amatya, D.M., Skaggs, R.W. and Gregory, J.D. (1995). Comparison of Methods for Estimating REF-ET. J. Irrig. and Drain. Engrg., ASCE, 121(6):427-435.
17. Amatya, D.M., Skaggs, R.W. and Gregory, J.D. (1996). Comparison of Methods Estimating REF-ET. Tech. Note, J. Irrig.& Drain. Engrg., ASCE, 122(6):362-364.
18. Angus, D.E. (1980). Estimating Solar Radiation in Australia. Proc. Agricultural Engineering Conference, IEAust., Geelong, :171-174.
19. Angus, D.E. (1983). Improved Technique for Estimating Daily Global Radiation. Proc. I.S.E.S., Solar World Congress, Perth, Pergamon Press, :12-15.
20. Antonopoulos, V.Z. (1997). Simulation of Soil Moisture Dynamics on Irrigated Cotton in Semi-Arid Climates. Agric. Water Management, 34:233-246.
21. Armstrong, A.C., Castle, D.A., and Tyson, K.C. (1993). SWARD: A Model of Grass Growth and the Economic Utilisation of Grassland. Int. Comm. on Irrig. and Drain. (ICID), 2<sup>nd</sup> Workshop on Crop-Water-Models, Hague, The Netherlands, :189-198.
22. Armstrong, D., Knee, J., Doyle, P., Pritchard, K., and Gyles, O. (1998). More Milk and Dollars from Irrigation Water: A Practical Guide for Improved Water-Use on Irrigated Dairy Farms. Dept. Natural Resour. and Environment, Tatura, Victoria.
23. Arora, V.K., Prihar, S.S., and Gajri, P.R. (1987). Synthesis of Simplified Water Use Simulation Model for Predicting Wheat Yields. Water Reso. Res., 23(5):903-910.
24. ASAE (1985). Advances in Evapotranspiration. Nat. Conf., ASAE, St. Joseph, MI.

25. ASCE (1996). Evaporation and Transpiration. Chapter 4, Hydrology Handbook, (2<sup>nd</sup> ed.), Task Committee on Hydrology Handbook of Management Group D of the Am. Soc. Civil Engrs., ASCE Manual No. 28, ASCE, New York, N.Y., :125-252.
26. ASCE Research and Education Admin. Committee (1989). Research Needs In Irrigation And Drainage-1989. J. Irrig. & Drain. Engrg., 115(4): 714-724.
27. Austin, C. (2000). Intelligent Irrigation Scheduling Software. Conf. Irrigation Association of Australia, 23-25 May, Melbourne, pp 327-331.
28. Austin, N. R. and Prendergast, J. B. (1997). Use of Kinematic Wave Theory to Model Irrigation on Cracking Soils. Irrig. Sci., (18):1-10.
29. Austin, N. R. (1998). Sustainable Use of Water and Fertiliser in the Irrigated Dairy Industry of Australia. PhD Thesis, Dept. Civil & Envi. Engrg., Uni. of Melbourne.
30. Austin, N. R., Prendergast, J. B. and Collins, M. D. (2000). Water and Nutrient Movemnt from Border Irrigated Dairy Pastures: A Field Study. Irrigation Association of Australia, 23-25 May, Melbourne, pp 41-51.
31. Austin, N. R., Prendergast, J. B. and Dick, R. M. (1995). Towards Environmentally Sound Fertiliser Management and Irrigated Pastures. Pp 55-61 in Nutrient Management in Irrigated Agriculture: research and Implementation Conference, Proceedings. (echuca, 19 Jun – 20 Jun). Melbourne: Agrilcture Victoria.
32. Ayers, R.S. and Westcot, D.W. (1985). Water Quality for Agriculture. Food and Agric. Org. of the United Nations, Irrig. and Drain. Paper No. 29, (Rev. 1), FAO, Rome, Italy.
33. Azhar, A.H., Murty, V.V.N. and Phien, H.N. (1992). Modeling Irrigation Schedules for Lowland Rice with Stochastic Rainfall. J. Irrig. and Drain. Engrg., ASCE, 118(1):36-55.
34. Babajimonopolous, C., Budina, A., and Kalfountzos, D. (1995). SWBACROS: A model for the Estimation of the Water Balance of a Cropped Soil. Environ. Soft., 10(3):211-220.
35. Babajimonopolous, C., Panoras, A., Mavroudis, I. And Bilas, G. (1996). The Computation of the Water Balance and the Modelling of the Irrigation Schedule of a Cotton Crop with the Model SWBACROS. Hydraulic Engineering Software IV, W.R. Blain, (ed.), Computational Mechanics Publications, Southampton:183-192.

36. Baier, W. & Robertson, G.W. (1966). A New Versatile Soil Moisture Budget. *Canadian J. Plant Sci.*, 46:299-315.
37. Baki, A.B.M. (1993). Predicting Daily Runoff Using Catchment Water Balance Models With Stochastic Data. PhD Thesis, Dept. of Civil and Mining Engineering, The Uvi. of Woollongong, Western Australia.
38. Barnett, V. and Lewis, T. (1980). *Outliers in Statistical Data*. John Willey and Sons, Chichester, New York, Brisbane, Toronto.
39. Batchelor, C.H. (1984). The Accuracy of Evapotranspiration Estimated with the Modified Penman Equation. *J. Irrig. Sci.*, 5:223-233.
40. Belmans, C., Feyen, J., and Hillel, D. (1979). An Attempt at Experimental Validation of Macroscopic-Scale Models of Soil Moisture Extraction by Roots. *Soil Sci.*, 127:174-186.
41. Belmans, C., Wesseling, G.W. and Feddes, R.A. (1983). Simulation Model for the Water Balance of a Cropped Soil, SWATRE. *J. of Hydrology, ASCE*, 63:271-286.
42. Benson, M. A. (19689). Uniform Flood-Frequency Estimating Methods for Federal Agencies. *Water Resources Research*, 4, pp 891-898.
43. Bernardo, D.J., Whittlesey, N.K., Saxton, K.E. and Bassett, D.L. (1988). Irrigation Optimization Under Limited Water Supply. *Trans. ASAE*, 31(3):712-719.
44. Blaikie, S.J. (1993). Root-Shoot Interactions in the Growth of Irrigated White Clover. Doctoral Dissertation, School of Agric. & Forestry, Univ. of Melbourne.
45. Blaikie, S.J. and Mason, W.K. (1993). Restrictions to Root Growth Limit the Yield of Shoots of Irrigated White Clover. *Aust. J. Agric. Res.*, 44:121-135.
46. Blaikie, S.J., Martin, F.M. , Mason, W.K., and Connor, D.J. (1988). A Basis for Improved Soil and Water Management for Irrigated Pastures in Northern Victoria. *Aust. J. Expt. Agric.*, 28:315-319.
47. Blaney, H.F. and Criddle, W.D. (1950). Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. *USDA Soil Conserv. Serv.*, SCS-TP 96, :44.
48. Boisvert, J.B., Dyer, J.A., and Brewin, D. (1992). *The Versatile Soil Moisture Budget Reference Manual – VB4*. CLBRR, Agriculture Canada, Ottawa, ON.

49. Bonython, C.W. (1950). Evaporation Studies Using Some South Australian Data. *Trans. Roy. Soc. Sth. Australia*, 73 Pt., (2):198-219.
50. Borg, H. and Grimes, D. W. (1986). "Depth Development of Roots with Time - An Empirical Description. *Trans. ASAE*, 29(1):194-197.
51. Bosen, J.F. (1960). A Formula for Approximation of Saturation Vapor Pressure Over Water. *Mon. Weather Rev.*; 88(8):275-276.
52. Bouchet, R.J. (1963). Evapotranspiration Relee et Potentielle Signification Climatique. *Int. Assoc. Sci. Hydrology Pub.* 62:134-142.
53. Boughton, W.C. (1966). A Mathematical Model for Relating Runoff to Rainfall with Daily Data. *Civ. Eng. Trans., IEAust., Vol., CE8(1):83-93.*
54. Boughton, W.C. (1968). A Mathematical Catchment Model for Estimating Runoff. *J. Hydrology (New-Zealand)*, 7(2):75-100.
55. Boughton, W.C. (1984). A Simple Model for Estimating the Water Yield of Ungauged Catchments. *Civil Engrg. Trans., IEAust., Vol., CE26(2):83-88.*
56. Bowman, K. O. (1973). Power of te Kurtosis Statistic, B2, in Tests of Departures from Normality, *Biometrika*, 60(3), pp 623-628.
57. Box, G. E. P. and Cox, D. R. (1964). An Analysis of Transformation. *Journal of Royal Statistical Society*, B 26, pp 211-252.
58. Boyd, M.J., Yau, Y.C. and Tedeschi, M.E. (1986). Application of SFB Rainfall-Runoff Model to a Perennial Catchment. *Hyd. and Water Reso. Sympo., Griffith University, Brisbane*, :382-383.
59. Bradford, S. and Letey, J. (1992). Simulated Effects of Water Table and Irrigation Scheduling as Factors in Cotton Production. *Irrig. Sci.*, 13:101-107.
60. Broner, I., Weinrich, A. and Lorenz, J. (1998). Cropflex Water and Fertilizer Management Program. "Water is Gold", *Conf. Proc. Irrig. Assoc. of Australia (IAA), Brisbane, Qld., Australia*, :141-147.
61. Brown, K.W. and Rosenberg. N.J. (1973). A Resistance Model to Predict Evapotranspiration and its Application to Sugar Beet Field. *Agronomy Journal*, 65:341-347.
62. Brunt, D. (1952). *Physical and Dynamical Meteorology*. 2nd ed., Uni. Press, Cambridge.

63. Brutsaert, W.H. (1975). Comments on Surface Roughness Parameters and the Height of Dense Vegetation. *J. Meteorol. Soc., Japan*, (53):96-97.
64. Brutsaert, W.H. (1979). Heat and Mass Transfer to and from Surfaces With Dense Vegetation or Similar Permeable Roughness. *Boundary-Layer Meteorol.*, 16:365-388.
65. Brutsaert, W.H. (1982). *Evaporation into the Atmosphere; Theory, History and Application*. D. Reidel Publ. Co., Boston, Mass.
66. Buchleiter, G. W., Heerman, D. F. and Wenstrom, R. J. (1996). Economic Analysis of On-Farm Irrigation Scheduling. *Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference, San Antonio Convention Centre, San Antonio, Texas, ASAE*, pp 986-991.
67. Buchleiter, G.W. (1995). Improved Irrigation Management Under Centre Pivots with SCHED. *Crop-Water-Simulation Models in Practice*, L.S. Pereira et. al., (eds.), Wageningen Pers., Wageningen, The Netherlands, :27-47.
68. Buishand, T. D. (1977). Stochastic Modelling of Daily Rainfall Sequences, H. Veenman and Zonen, B. V. Wageningen, The Netherlands,:54-56.
69. Burman, R. D., Pochop, M. A. and Yonts, C. D. (1982). Statistical and Numerical Representation of Irrigation Water requirements *Trans. ASCE*, 25 (1), pp 165-168.
70. Burman, R.D., Cuenca, R.H. and Weiss, A. (1983). Techniques for Estimating Irrigation Water Requirements. *Advances in Irrigation*, D. Hillel, (ed.), Vol. 2, Academic Press, New York, N.Y.,:335-394.
71. Burman, R.D., Jensen M.E. and Allen, R.G. (1987). Thermodynamic Factors in Evapotranspiration. James, L.G. and English, M.J., (eds), *Proc. Irrig. and Drain. Spec. Conf.*, ASCE, , Portland, Ore., :28-30.
72. Burman, R.D., Nixon, P.R., Wright, J.L. and Pruitt, W.O. (1980). Water Requirements. *Design and Operation of Farm Irrigation Systems*, M.E., Jensen, (ed.), ASAE Monograph No. 3, ASAE, St. Joseph, Missouri, :189-232.
73. Bush, B., Finger, L. and Bethune, M. (2000). Irrigation Scheduling Techniques for Border Irrigated Perennial Pastures. *Irrigation Association of Australia*, 23-25 May, Melbourne, pp 423-429.

74. Businger, J.A. (1956). Some Remarks on Penman's Equations for the Evapotranspiration. *Netherlands Journal of Agric. Sci.*, 4:77-80.
75. Camp, C.R., Christenbury, C.W. and Doty, C.W. (1988). Scheduling Irrigation for Corn and Soybean in the Southeastern Coastal Plain. *Trans. ASAE*, 31(2):513-518.
76. Camp, C.R., Karlen, D.L. and Lambert, J.R. (1985). Irrigation Scheduling and Row Configurations for Corn in the Southeastern Coastal Plain. *Trans. ASAE*, 28(4):1159-1165.
77. Campbell, R.B. and Phene, C.J. (1976). Estimating Potential Evapotranspiration from Screened Pan Evaporation. *Agric. Met.*; 16:343-352.
78. Chang, Y.Y. and Corapcioglu, M.Y. (1997). Effect of Roots on Water Flow in Unsaturated Soils. *J. Irrig. and Drain. Engrg.*, ASCE, 123(3):202-209.
79. Chiew, F.H.S. and Jayasuriya, L.N.N. (1990). Applicability of Morton's Complementary Relationship Method of Estimating Evapotranspiration in Rainfall-Runoff Modelling. *Conf. Agric. Engrg.*, 11-14 Nov, Toowoomba, Australia,:289-293.
80. Chiew, F.H.S. and McMahon, T.A. (1991). The Applicability of Morton's and Penman's Evapotranspiration Estimates in Rainfall-Runoff Modelling. *Water Resour. Bulletin, American Water Resour. Assoc.*,27(4):611-620.
81. Chiew, F.H.S., Kamaladasa, N.N., Malano, H.M. and McMahon, T.A. (1995). Penman-Monteith, FAO-24 Reference Crop Evapotranspiration and Class-A Pan Data in Australia. *Agric. Water Management*, 28:9-21.
82. Childs, S.W., Gilley, J.R. and Splinter, W.E (1977). A Simplified Model of Corn Growth Under Moisture Stress. *Trans. ASAE*, 20(4):858-865.
83. Childs, S.W., Gilley, J.R., and Splinter, W.E. (1977). A Simplified Model of Corn Growth Under Moisture Stress. *Trans. ASAE*, 20(4):858-865.
84. Christiansen, J.E. and Hargreaves, G.H. (1969). Irrigation Requirements from Evaporation. *Trans. Int. Comm. on Irrig. and Drain.*, Vol. III,:23.569-23.596.
85. Chudleigh, P. and Hayes, G. (1998). Productivity and Economical Sustainability of the Australian Dairy Industry. Case Study Report, Vol 1, January, Virtual Consulting Group Albury and Agrans Research Brisbane, Report to DRDC and LWRRDC.

86. Clark, R.T. (1984). *Mathematical Models in Hydrology*. Food and Agric. Org. of the United Nations, Irrig. and Drain. Paper No. 19, FAO, Rome, Italy.
87. Clarke, N.D., Tan, C.S., and Stone J.A. (1992). *Expert System for Scheduling Supplemental Irrigation for Fruit and Vegetable Crops in Ontario*. *Can. Agric. Engrg.*, 34(1):27-31.
88. Clothier, B.E., Kerr, J.P., Talbot, J.S. and Scotter, D.R. (1982). *Measured and Estimated Evapotranspiration from Well-Watered Crops*. *New Zealand J. Agric. Res.*, 25(3):301-307.
89. Corapcioglu, M.Y. (1992). *Modeling Plant Uptake and Biodegradation of Semi-volatile Hydrocarbon Compounds*. *Water Sci. and Tech.*, 26(7,8):1651-1658.
90. Coupland, R.T. (1974). *Procedures: IV, Under Ground Plant Parts*. Matador Tech. Report No. 41, Univ. of Saskatchewan, Saskatoon, Sask, p73.
91. Cuenca, R.H. (1988). *Hydrologic Balance Model Using Neutron Probe Data*. *J. Irrig. and Drain. Engrg.*, ASCE, 114(4):644-663.
92. Cuenca, R.H. (1991). *Hydrologic Balance Model Using Neutron Probe Data*. Technical note, *J. Irrig. and Drain. Engrg.*, ASCE, 117(3):454-456.
93. Curwen, D. and Massie, L.R. (1985). *WISP- The Wisconsin Irrigation Scheduling Program*. *Proc. Nat. Conf. on Adv. in Evapotranspiration*, ASAE, St. Joseph, Mich., :351-356.
94. Cushman, H.J. (1982). *Nutrient Transport Inside and Outside the Root Rhizospheres: Theory*. *Soil Sci. Am. J.*, 46:704-709.
95. Dale, M. and Thompson, C. (1992). *R.A.R.T, Schedule - An Irrigation Scheduling Program Suitable for Spray Irrigated Perennial Horticultural Crops in the Mallee Region*. *Irrigation Revised Ed.*, Sunraysia Horticultural Centre, Dept. Agric. Irymple, Vic.:pp23.
96. Danuso, F., Gani, M., and Glovanardi, R. (1993). *Field Water Balance - BIDriCo 2*. *Int. Comm. on Irrig. and Drain.*, (ICID), 2<sup>nd</sup> Workshop on Crop-Water-Models, Hague, The Netherlands: 49-74.
97. Dastane, N.G. (1974). *Effective Rainfall in Irrigated Agriculture*. Food and Agric. Org. of the United Nations, Irrig. and Drain. Paper No. 25, FAO, Rome, Italy.

98. De Faria, R.T., Madamootoo, J. Boisvert, J. and Prasher, S.O. (1992). A Comparison of the Versatile Soil Moisture Budget and SWACROP Models in Brazil, ASAE paper No. 92-2114, St. Joseph, MI., USA.
99. De Faria, R.T., Madramootoo, C.A., Boisvert, J., and Prasher, S.O. (1994). Comparison of the Versatile Soil Moisture Budget and SWACROP Models for a Wheat Crop in Brazil. *Can. Agric. Engrg.*, 36(2):57-68.
100. De Faria, R.T., Madamootoo, J. Boisvert, J. and Prasher, S.O. (1992). A Comparison of the Versatile Soil Moisture Budget and SWACROP Models in Brazil, ASAE paper No. 92-2114, St. Joseph, MI., USA.
101. De Jong, R. and Cameron, D.R. (1978). Computer Simulation Model for Predicting Soil Water Content Profiles. *Soil Sci.*, 128:41-48.
102. De Jong, R. and Hayhoe, H.N. (1984). Diffusion-based Soil Water Simulation for Native Grassland. *Agric. Water Management*, 9:47-60.
103. Denmead, O.T. and Shaw, R.H. (1962). Availability of Soil Water to Plants as Affected by Soil Moisture Content and Meteorological Conditions. *J. Agronomy*, 54(5):385-390.
104. De Souza, F. and Yoder, R.E. (1994). ET Estimation in the Northeast of Brazil: Hargreaves or Penman-Monteith Equation. Technical Paper, ASAE Int. Winter Meeting, St. Joseph, Mich.
105. Dilley, A.C. (1968). On the Computer Calculation of Vapour Pressure and Specific Humidity Gradients from Psychrometric Data. *J. of App. Meteo.*, 7(4):717-719.
106. Dilley, A.C. and Shepherd, W. (1972). Potential Evaporation from Pasture and Potatoes at Aspendale. *Agric. Meteo.* (10):283-300.
107. Diment, G.A. (1991). Wide Use of a Generalized Headworks and Resources Model, REALM. *Proc. Int. Hydrology and Water Resources Symp.*, Perth, :579-585.
108. Donnelly, J. (1992). MetAccess™ - Analysing Weather Conditions. CSIRO Div. Plant Industry, Canberra: Horizon Agric. Pty. Ltd. Roseville, NSW, Australia.
109. Doorenbos, J. and Kassam, A.J. (1979). Yield Response to Water. Food and Agricultural Organisation of the United Nations, *Irrig. and Drain. Paper No. 33*, FAO UN, Rome, Italy.

110. Doorenbos, J. and Pruitt, W.O. (1977). Guidelines for Predicting Crop Water Requirements. Food and Agricultural Organisation of the United Nations, Irrig. and Drain. Paper No. 24, (2<sup>nd</sup> ed.), FAO UN, Rome, Italy.
111. Douglass, W. and Poulton, D. (1998). Towards Efficient Water Use on Irrigated Dairy Pastures, Australian National Committee on Irrigation and Drainage, 1998-Conf., Living with Limited water, Princeton Conf. Centre, Sale, Victoria.
112. DRDC (1997). Strategic Plan for the Five Years 1997-2002. Dairy Research and Development Corporation, Glen Iris, Victoria.
113. Duffie, J.A. and Beckman, W.A. (1980). Solar Engineering of Thermal Processes. John Wiley & Sons Inc., New York, N.Y.
114. Elliott, R.L., Johns E.L. and Weghorst, P.A. (1992). ETBC: Interactive Software for Blaney-Criddle Estimates of Evapotranspiration. T., Engman, (ed.), Proc. Irrig. and Drain. Sessions at Water Forum'92, ASCE, Baltimore, Maryland, :134-139.
115. Ellis, T.M.R. (1990). FORTRAN-77 Programming. (2<sup>nd</sup> ed.), Addison-Wesley Pub. Co., New York.
116. Eratakulan, S. J. (1970). Probability Distribution of Annual Droughts. Proc. American Soci. Civil Engineers, J. Irri. & Drain Div., ASCE, 96 (IR4): 461-474.
117. Erlanger, P.D., Poulton, D.C. and Weinmann, P.E. (1992). Development and Application of an Irrigation Demand Model Based on Crop Factors. Conference on Engineering in Agriculture, Albury, NSW, Australia, :293-298.
118. Feddes, R.A. (1976). Simulation of Field Uptake by Plants Using a Soil-Water Dependent Root Extraction Function. J. of Hydrology, 31(1):13-26.
119. Feddes, R.A. and Rijtema, P.E. (1972). Water Withdrawal by Plant Roots. J. Hydro., Amsterdam, The Netherlands, 17:33-59.
120. Feddes, R.A., Kowalik, P.J., Kolinska, M.K. and Zaradny, H. (1978). Simulation of Field Water Use and Crop Yield – Simulation Nomogram. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands, pp189.
121. Federer, C.A. (1979). A Soil-Plant-Atmosphere Model for Transpiration and Availability of Soil Water. Water Resour. Res., 15:555-562.

122. Fereres, E. (1981). The Irrigation Management Program: A New Approach to Computer Assisted Irrigation Scheduling. Proceedings of the ASAE, Irrigation Scheduling Conference, St. Joseph, MI.
123. Fereres, E., Goldfien, R.E., Pruitt, W.O., Henderson, D.W, and Hagan, R.M.(1981). The Irrigation Management Program - A New Approach to Computer Assisted Irrigation Scheduling. Proc. Irrig. Scheduling for Water and Energy Conservation in 80's, ASAE, St. Ioseph, Mich., :202-207.
124. Field, J.G., James L.G., Bassett, D.L. and Saxton, K.E. (1988). An Analysis of Irrigation Scheduling Methods for Corn. Trans. ASAE, 31(2):508-512.
125. Finkel, H.J. (1982). CRC Handbook of Irrigation Technology. Vol-I, CRC Press, Inc., Boca Raton, Florida.
126. Frevert, D.K., Hill, R.W. and Braaten, B.C. (1983). Estimation of FAO Evapotranspiration Coefficients. J. Irrig. and Drain., ASCE, 109(2):265-270.
127. Gardner, W.R. (1964). Relation of Root-Distribution to Water Uptake and Availability. Agron. J., 56(1):41-45.
128. Gardner, W.R. (1991). Modelling Water Uptake by Roots. Irrig. Sci., 12:109-114.
129. Garratt, J.R. and Hicks, B.B. (1973). Momentum, Heat and Water Vapor Transfer to and from Natural and Artificial Surfaces. Q. J. Roy. Meteorol. Soc.; 99:680-687.
130. Giannerini, G. (1995). RENANA: A Model for Irrigation Scheduling, Employed on a Large Scale. Crop-Water-Simulation Models in Practice, Pereira et al. (eds.), Selected papers of the 2<sup>nd</sup> workshop on Crop-Water-Models, Int. Com. on Irrig. and Drain., (ICID), Wageningen Pers, The Netherlands:17-26.
131. Gibbons, F.R. and Gill, E.D. (1964). Terrains ans Soils of Basaltic Plains of far Western Victoria. Proc. Roy. Soc. Vic. 77(2), :387-395.
132. Goulburn Murray Water, (1995a). Murray Valley Area Irrigator Handbook. GMW, Tatura, Victoria :47.
133. Goulburn Murray Water, (1995b). Murray Valley Irrigation Area. Goulburn Murray Water Internal Handout; GMW Tatura, Victoria.
134. Goulburn Murray Water, (1995c). Central Goulburn Irrigation Area. Goulburn Murray Water Internal Handout; GMW Tatura, Victoria.

135. Goulburn Murray Water, (1996). A New Era in Rural Water Services. Goulburn Murray Water Internal Handout; GMW Tatura, Victoria.
136. Goulburn Murray Water, (1997a). Central Goulburn Area Profile- Annual Review 1996/97. Central Goulburn Irrigation Area Water Committee, GMW internal report; GMW Tatura, Victoria.
137. Goulburn Murray Water, (1997b). Goulburn-Murray Water Headworks Group. Goulburn Murray Water Internal Handout; GMW Tatura, Victoria.
138. Haise, H. R. and Hagan, R. M. (1967). Predicting Irrigation Needs. Irrigation of Agricultural Lands, R. M. Hagan et al. Eds, American Society of Agronomy, Madison, Wisc. Monograph No 11, pp 577-604.
139. Haise, H.R., and Hagan, R.M. (1967). Predicting Irrigation Needs. Irrigation of Agricultural Lands, R.M. Hagan et al., (eds.), Am. Soc. of Agronomy, Madison, Wisc., Monograph No. 11:577-604.
140. Hall, N., Poulter, D. and Curtotti, R. (1994). ABARE Model of Irrigation Farming in the Southern Murray-darling Basin. ABARE Res. Report. 94.4, :63; Australian Bureau of Agriculture and Resource Economics, Canberra.
141. Hanks, R.J. and Hill, R.W. (1980). Modelling Crop Responses to Irrigation in Relation to Soils Climate and Salinity. Irrig. Information Centre, IIIC, Pub. No. 6.
142. Hann, C.T. (1977). Statistical method in Hydrology. The Iowa State University press, Ames, Iowa.
143. Hargreaves, G.H. (1975). Moisture Availability and Crop Production. Trans. ASAE, 18(5):980-984.
144. Hargreaves, G.H. (1989). Accuracy of Estimated Reference Crop Evapotranspiration. J. Irrig. and Drain. Engrg., ASCE, 115(6):1000-1007.
145. Hargreaves, G.H. (1990). Crop ET Modelling. Int. Winter Meeting, Amer. Soc. Agric. Engrs., ASAE Paper No. 902517, Chicago, Illinois, :1-15.
146. Hargreaves, G.H. (1991). Accuracy of Estimated Reference Crop Evapotranspiration. Tech. note, J. Irrig. & Drain. Engrg., ASCE 117(4):977-979.
147. Hargreaves, G.H. and Samani, Z.A. (1985). Reference Crop Evapotranspiration from Temperature. Appl. Engrg. in Agric., 1(2):96-99.

148. Harrison, L.P. (1963). Fundamental Concepts and Definitions Relating to Humidity. In Wexler,A.(ed.); Humidity and Moisture, Vol. 3, Reinhold Pub., N.Y.
149. Hatfield, J.L. and Allen, R.G. (1996). Evapotranspiration Estimates Under Deficient Water Supplies. *J. Irrig. and Drain. Engng.*, ASCE 122(5):301-308.
150. Hayhoe, H.N. & De Jong, R. (1988). Comparison of Two Soil Water Models for Soybeans. *Can. Agric. Engrg.*, 30:5-11.
151. Hearn, A.B. and Constable, G.A. (1984). Irrigation for Crops in a Sub-humid Environment. *Irrig. Sci.*, 5:75-94.
152. Hedditch, M. (1985). Water Watch - An Irrigation Scheduling Service for Summer and Winter Crops in the M.I.A and C.I.A. *Farmer's Newsletter, Irrig. Res. and Extension Committee, New South Wales Dept. of Agric, NSW, Australia*, 127:4-7.
153. Heerman, D.F., Haise, H.R., and Mickelson, R.(1976). Scheduling Centre Pivot Sprinkler Irrigation Systems for Corn Production in Eastern Colorado. *Trans. ASAE*, 19(2):284-287 & 293.
154. Henry, J.L. (1978). Simulation of Moisture Behaviour of the Root Zone and Irrigation Demand. Computer Programs WV03 and WV07, Groundwater Branch, Queensland Water Resour. Council, QWRC, Australia.
155. Heslop, W.A. (1991). Irrigation Scheduling Using the Evaporation Graph. Loddon-Torrumbarry Region, Kerang; Rural Water Commission (RWC) of Victoria, Internal Report.
156. Heslop, W.A. (1995). A Guide to Water Requirements for Crops in the Kerang Region. Goulburn Murray Water (GMW) Working Document, Kerang, Victoria.
157. Heslop, W.A., Holland G.F. and Poulton, D.C. (1990). Development of an Irrigation Scheduling Service in the Boort and Cohuna Districts. Rural Water Commission of Victoria, RWC Internal Report, :45.
158. Hess, T. (1996). A Microcomputer Scheduling Program for Supplementary Irrigation. *Comput. & Electron. in Agric.*, 15:233-243.
159. Hill, R.W. and Allen, R.G. (1996). Simple Irrigation Scheduling Calendars. *J. Irrig. and Drain. Engrg.*, ASCE, 122(2):107-111.
160. Hoffman, G.J. and Martin, D.L. (1993). Engineering Systems to Enhance Irrigation Performance. *Irrig. Sci.*, 14:53-63.

161. Hoogenboon, G., Huck, M.G. and Hillel, D. (1987). Modification and Testing of a Model Simulating Root and Shoot Growth as Related to Soil Water Dynamics. *Advances in Irrigation*, D. Hillel, (ed.), 4<sup>th</sup> edition, :331-338.
162. Hoogland, J.C. Feddes, R.A. Belmans, C. (1981). Root Water Uptake Model Depending on Soil Water Pressure Head and Maximum Extraction Rate. *Acta Horti.*, 119:123-136.
163. Hounam, C.E. (1958). Evaporation Pan Coefficients in Australia. In *Climatology and Microclimatology*, UNESCO, :52-60.
164. Hounam, C.E. (1966). The Routine Measurement of Evaporation. In *Agric. Meteorol., Proc. W.M.O. Seminar*, Melbourne, :195-202.
165. Hounam, C.E. (1973). Comparison Between Pan and Lake Evaporation. *W.M.O. Tech. Note No. 126*, WMO-354, p52.
166. Howell T.A., Phene C.J., Meek, D.W. and Miller, R.J. (1983). Evaporation from Screened Class-A Pans in Semi Arid Climate. *Agric. Meteorol.*, (29):111-124.
167. Hsiao, T.C. (1990). Plant Atmosphere Interactions, Evapotranspiration and Irrigation Scheduling. *Acta Hort*, 278:55-65.
168. Huck, M.G., and Hillel, D. (1983). A Model of Root Growth and Water Uptake Accounting for Photosynthesis, Respiration, Transpiration and Soil Hydraulics. *Advances in Irrigation*, D. Hillel, (ed.), Vol. 2, Academic Press, N.Y., :273-333.
169. Hussein, A.S.A. (1999). Frass ET Estimates Using Penmn-Type Equations in Central Sudan. *J. Irrig. and Drain. Engrg.*, ASCE; 125(6):324-329.
170. Hussain, Q., Mushabbir, P.M. and Christoph, F. (1990). Relationship Between Observed and Estimated Crop Evapotranspiration and Climatic Variations. *Agric. Mechanisation in Asia, Pacific and Latin America*, 21(3):61-65.
171. ICID (1995). *Crop-Water-Simulation Models in Practice*. Pereira et al. (eds.), Selected papers of the 2<sup>nd</sup> workshop on Crop-Water-Models, Int. Com. on Irrig. and Drain., (ICID), Wageningen Pers, The Netherlands.
172. Jacovides, C.P and Kontoyiannis, H. (1995). Statistical Procedures for the Evaluation of Evapotranspiration Computing Models. *Agric. Water Management*, (27):365-371.

173. James, L.G. (1988). Principles of Farm Irrigation System Design. John Wiley & Sons, Inc., New York, N.Y.
174. Jamieson, P.D. (1992). Comparison of Methods of Estimating Maximum Evapotranspiration from a Barley Crop. *New Zealand J. Sci.*, 25(2):175-181.
175. Jensen, M.E. and Haise, H.R. (1963). Estimating Evapotranspiration from Solar Radiation. *J. Irrig. and Drain. Engrg.*, ASCE, 89:15-41.
176. Jensen, M.E., (1974). Consumptive Use of Water and Irrigation Water Requirements. Rep. Tech. Com. on Irrigation Water Requirements, ASCE, Irrig. & Drain. Div., 227p.
177. Jensen, M.E., Burman, R.D. and Allen, R.G. (1990). Evapotranspiration and Irrigation Water Requirements. Committee on Irrig. Water Requirements, Div. Irrig. and Drain., ASCE, Manual No. 70., ASCE, New York, N.Y.
178. Jensen, M.E., Robb, D.C.N. and Franzoy, C.E. (1970). Scheduling Irrigations Using Climate-Crop-Soil Data. *J. Irrig. Drain. Div.*, ASCE; 96(1):25-38.
179. Jensen, M.E., Wright, J.L., and Pratt, B.J.(1971). Estimating Soil Moisture Depletion from Climate, Crop and Soil Data. *Trans. ASAE*, 14(5):954-957.
180. Jury, W.A. and Tanner, C.B. (1975). Advection Modification of the Priestley and Taylor Evapotranspiration Formula. *Agron. J.*, 67(6):840-842.
181. Katul, G.G., Cuenca, R.H., Grebet, P., Wright, J.L. and Pruitt, W.O. (1992). Analysis of Evaporative Flux Data for Various Climates. *J. Irri.& D.*, ASCE; 118(4):601-618.
182. Khaliq, M.N. (1995). Stochastic Modelling of Rainfall Occurrences and its Use for Modelling Effects of Climatic Changes on Rainfall Extreme Events. PhD Thesis, Dept. of Engrg. Hydrology, Uni. College Galway, Republic of Ireland.
183. Kincaid, D.C. and Heerman, D.F. (1974). Scheduling Irrigations Using a Programmable Calculator. USDA Bulletin ARS-NC 12, Poineer Industrial, Park, 2000 West Poineer, Parkway, Peoria, IL.
184. Kite, G. W. (1977). Frequency and Risk Analysis in Hydrology. Water Resources Publ., USA, pp 224
185. Kohler, M.A., Nordenson, T.J. and Fox, W.E. (1955). Evaporation From Pan and Lakes. U.S. Dep. Com., Weather Bur. Res. Paper No. 38, :21.

186. Lattimore, M.E., Thompson, J.A., and O'Callaghan, K.L. (1994). Irrigation Frequency for White Clover and Lucerne on a Cracking Clay in the Murrumbidgee Valley, New South Wales. *Aust. J. Expt. Agric.*, 34:41-49.
187. Law, A. M. and Kelton, W. D (1991). *Simulation Modelling and Analysis. Selected Input Probability Distributions 2<sup>nd</sup> Ed.*, McGraw Hill Inc., NY, Sydney.
188. Linacre, E.T. (1977). A Simple Formula for Estimating Evaporation Rates in Various Climates, Using Temperature Data Alone. *Agric. Meteorol.*, 18:409-424.
189. Linke, G.K., Barling, R.D. and Amenta, V. (1995). Options for Nutrient Reduction for the Irrigation Areas of the Goulburn and Broken Catchments. *Proc. Conf. Nutrient Management in Irrigated Agriculture- Research and Implementation; Institute of Sustainable Irrigated Agric., ISIA Echuca, Victoria, Australia*, :91-98.
190. List, R.J. (1963). *Smithsonian Meteorological Tables*, 6th ed.; Smithsonian Institution, Washington.
191. List, R.J. (1984). *Smithsonian Meteorological Tables*, 6th rev. ed.; Smithsonian Institution, Washington.
192. Liu, Y. Teixeira, J.L. Zhang, H.J. and Pereira, L.S. (1998). Model Validation and Crop Coefficients for Irrigation Scheduling in the North China Plain. *Agric. Water Management*, 36:233-246.
193. Loague, K. & Green, R.E. (1991). Statistical and Graphical Methods for Evaluating Solute Transport Models- Overview and Application. *J. Contam. Hydrol.* 7:51-73.
194. Long, A.A. (1991). Northern Irrigation Areas: Water Losses in the Irrigation Delivery System. State Water Resources Plan, Water Resource Management Report Series No. 60; Department of Conservation and Environment, Victoria, Australia.
195. Loveday, J. (1974). *Methods for Analysis of Irrigated Soils*. Tech. Communication No.54, Commonwealth Bureau of Soils, Agriculture Bureaux, CSIRO, Australia.
196. Lowe, P.R. (1977). An Approximating Polynomial for the Computation of Saturation Vapour Pressure. *J. Appl. Met.* (16):100-103.
197. Mahadian, M.H. & Gallichand, J. (1995). Validation of the SUBTOR Model for Simulating Soil Water Content. *Trans. ASAE*, 38(2):513-520.

198. Mahdian, M.H. and Gallichand, J. (1996). Modeling Soil Water Content and Pressure Head with SWACROP in Potato Fields. *Can. Agric. Engrg.*, 38(1):1-10.
199. Maheshwari, B., Nelson, N. and Macadam, R. (1997). Issues in Transfer and Adoption of Irrig. Technology in Australia. *J. Agric. Engrg. Australia*; 26(1):15-23.
200. Mahey, R.K., Feyen, J., and Wyseure, G. (1984). Numerical Analysis of Irrigation Treatments of Barley with Respect to Drainage Losses and Response. *Trans. ASAE*, 27:1805-1810 & 1816.
201. Makkink, G.F. (1957). Testing the Penman Formula by Means of Lysimeters. *J. Inst. Water Engng.*; 11(3):277-288.
202. Marino, M.A. and Tracy, J.C. (1988). Flow of Water Through Root-Soil Environment. *J. Irrig. and Drain. Engrg.*, ASCE, 114:588-604.
203. Maskey, R. (1995). Attitude of Dairy Farmers About the Automation of Flood Irrigation. Cobram District Office Report, Dept. Nat. Resour. & Envir., Victoria.
204. Matalas, N. C. (1963). Probability Distribution of Low Flows. *Statistical Studies in Hydrology*, US Geol. Surv. Prof. Pap. 434-A, pp27.
205. McIlroy, I.C. (1966). Evaporation and its Measurement: Part-A. In *Agric. Met.*, Proc. W.M.O. Seminar, Melbourne, :243-263.
206. McIlroy, I.C. and Angus, D.E. (1964). Grass, Water and Soil Evaporation at Aspendale. *Agric. Meteorol.*; 1(3):201-224.
207. McIntyre, D.S. (1974 a). Water Retention and Moisture Characteristics. *Methods for Analysis of Irrigated Soils*, J. Loveday (ed.), Tech. Communication No. 54, Commonwealth Bureau of Soils, Commonwealth Agric. Bureaux, CSIRO, Australia, :43-62.
208. McIntyre, D.S. (1974 b). Volume Change. *Methods for Analysis of Irrigated Soils*, J. Loveday (ed.), Tech. Communication No. 54, Commonwealth Bureau of Soils, Commonwealth Agric. Bureaux, CSIRO, Australia, :63-66.
209. McMahan, T. A. and Mein, R. G. (1986). *River and Reservoir Yields*. Water Researches Publications.
210. McMohan, T. A. (1984). *Irrigation and Ground Water Accessions*. A report Prepared for the Salinity Committee of the Vic Parliament on the Proceedings of a Technological Seminar, June 1984.

211. McMohan, T. A. and Diaz Arenas, A. (1982). Methods of Computation of Low Streamflow. Studies and Reports in Hydrology No. 36(UNESCO, Paris), pp 95.
212. McNaughton, K.G. and Jarvis, P.G. (1984). Using the Penman-Monteith Equation Predictively. Agric. Water Management, 8:263-278.
213. MDBMC (1995). An Audit of Water Use in the Murray Darling Basin – A Component of Natural Reso. Mngmt. Strategy, Murray Darling Basin Comission.
214. MDBMC (1996). Setting the Cap Report of the Independent Audit Group, November 1996. Murray Darling Basin Ministerial Council.
215. Meek, D.W. and Phene, C.J. (1991). Accuracy of Estimated Reference Crop Evapotranspiration. Tech. note, J. Irrig. & Drain. Engrg., ASCE, 117(4):975-977.
216. Meyer, W.S. (1994). Standard Reference Evaporation Calculation for Inland South Eastern Australia. Tech. Memo. Div. of Water Reso., CSIRO, Griffith.
217. Meyer, W.S., Smith, D. and Shell, G. (1995). Estimating Reference Crop Evaporation and Crop Evapotranspiration from Weather Data and Crop Coefficients. Tech. Memo., Div. of Water Reso., CSIRO, Griffith.
218. Michalopoulou, H. and Papaioannou, G. (1991). Reference Crop Evapotranspiration Over Greece. Agric. Water Management, 20:209-221.
219. Mohan, S. (1991). Intercomparison of Evapotranspiration Estimates. Hydro. Sci., 36(5):447-460.
220. Mohan, S. and Arumugam, N. (1996). Comparison of Methods for Estimating REF-ET. Tech. Note, J. Irrig. and Drain. Engrg., ASCE, 122(6):361-362.
221. Molz, F.J. (1976). Water Transport in Soi-Root System: Transient Analysis. Water Resour. Res., 12:805-808.
222. Molz, F.J. (1981). Models of Water Transport in the Soil-Plant System: a Review. Water Resour. Res., (17):1245-1260.
223. Monteith, J.L. (1965). Evaporation and the Environment. In The State and Movement of Water in Living Organisms; XIXth Symp. Soc. for Exp. Biol., Swansea, Cambridge Uni. Press; (19):205-234.
224. Monteith, J.L. (1981). Evaporation and Surface Temperature. Quarterly J. Royal Meteo. Soc.; (107):1-27.

225. Moran, P. A. P. (1980). Calculation of Normal Distribution Function. *Biometrika*, UK, 67(3):675-676.
226. Morton, F.I. (1983). Operational Estimates of Actual Evapotranspiration and Their Significance to the Science and Practice of Hydrology. *J. Hydrol.* 66(1):1-76.
227. Morton, F.I. (1991). Hydrologic Balance Model Using Neutron Probe Data. Technical note, *J. Irrig. and Drain. Engrg.*, ASCE, 117(3):451-454.
228. Mukammal, E.I. and Neuman, H.H. (1977). Application of the Priestley-Taylor Evaporation Model to Assess the Influence of Soil Moisture on Evaporation from a Large Weighing Lysimeter and Class A-Pan. *Boundary-Layer Met.*; 12:243-256.
229. Mulcahy, S. and Schroen, J. (1993). *Irrigation and Drainage Reference Manual. Target-10 Water on Water off Working Group*, Victoria, Australia.
230. Murray Darling Basin Commission, (1990). *The River Murray: A Multi-Use Resource*. Murray Darling Basin Commission, MDBC Internal Handout; MDBC, Canberra, Australia.
231. Murray, F.W. (1967). On the Computation of Saturation Vapour Pressure. *J. Appl. Meteorol.*, 6:203-204.
232. Murty, V.V.N., Azhar, A.H. and Kemachandra, R.A.D. (1991). *Farm Irrigation System Design Constraints and Improvement in Major Irrigation Projects*. Asian Institute of Technology, Bangkok, AIT Research No. 249.
233. Murty, V.V.N., Azhar, A.H., Sarwar, A. and Sudsaisin, K. (1992). Simulation of Tertiary Unit Efficiencies in Large Irrigation Saytems. *Agric. Water Management*, 21:13-22.
234. Nathan, R. J.(1990). *Low Flow Hydrology: Application of a Systems Approach*. PhD Thesis, Dept. of Civil and Agric. Engrg., University of Melbourne, pp 383
235. Nexhip K. J., Mundy, G. N., Collins, M. D. and Austin, N. R (1997). *Development of Nutrient Water Quality Targets for Irrigated Pasture Sub-Catchments*. Final Report MDBC NRMS Project I5037, Hydrologic Res. Group, Agriculture Victoria.
236. Nkemdirim, L.C. (1976). Crop Development and Water Loss - A Case Study Over a Potato Crop. *Agric. Meteorol.*, 16:371-388.
237. Northcote, K.H. (1979). *A Factual Key for the Recognition of Australian Soils*. CSIRO-Australia, Melbourne: Rellim Tech. Pub., Glenside, South Australia, 4<sup>th</sup> ed.

238. O'Leary, G.J. (1985). Operational Details of a Simulation Model of the Wheat Crop. Tech. Report Series No. 107, Department of Agriculture, Victoria, Australia.
239. Parmele, L.H. and McGuinness, J.L. (1974). Comparison of Measured and Estimated Daily Potential Evapotranspiration in a Humid Region. *J. Hydro.*, 22:239-251.
240. Penman, H.L. (1948). Natural Evaporation from Open Water, Bare Soil and Grass. *Proc. Roy. Soc., London, England*; A193:120-145.
241. Penman, H.L. (1952). The Physical Bases of Irrigation Control. Report of the 13th Int. Horticultural Congress, London, 2:913-924.
242. Penman, H.L. (1961). Weather, Plant and Soil Factors in Hydrology. *Weather*, 16:207-219.
243. Penman, H.L. (1963). Vegetation and Hydrology. Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England, :125.
244. Penman, H.L. and Schofield, R.K. (1951). Some Physical Aspects of Assimilation and Transpiration. *Symp. of the Soc. for Experimental Biology*, 5:115-129.
245. Phene, C. J., Itier, B. and Reginato, R. J. (1990). Sensing Irrigation Needs. Visions of the Future, *Proc. 3<sup>rd</sup> Nat. Irrig. Symp.*, ASAE, St Joseph, Mich., pp 429-443.
246. Phien, H. N., Arbhabhirama, A. and Eggers, H. (1978). Water for the Northeast: Drought Analysis, Part 1: Rainfall Analysis. Report Prepared for the Water resources planning Sub-committee of Thailand, AIT, Bangkok.
247. Phien, H. N., Arbhabhirama, A. and Sunchindah, A. (1980). Rainfall Distribution in Northeastern Thailand. *Hydrological Sciences Bulletin*, 25(2), pp 167-182.
248. Phien, H. N., Sunchindah, A. and Patnaik, D. (1982). Normality of Hydrological Data. *Water Reso. Bulletin; Sci. Bulletin Amer. Water Reso. Assoc.*, 18(1): 13-30.
249. Pilgrim, D. H. and Doran, D. G. (1987). Australia Rainfall and Runoff- A guide to Flood Estimation – Pilgrim Edition. IE Aust., Australia.
250. Plant, R.E., Horrocks, R.D., and Zelinski, L.J. (1992). CALEX/Cotton: An Integrated Expert System Application for Irrigation Scheduling. *Trans. ASAE*, 35(6):1833-1838.

251. Plate, E.J. (1971). Aerodynamic Characteristics of Atmospheric Boundary Layers. AEC Critical Review Series; U.S. Atomic Energy Commission, Div. Tech. Info. U.S. Gov. Print. Office, Washington, DC.
252. Pleban, S. & Israelie, I. (1989). Improved Approach to Irrigation Scheduling Programs. *J. Irrig. & Drain. Engrg.*, ASCE, 115(4):577-587.
253. Poplawski, W.A. & Stewart, B.J. (1984). An Irrigation Demand Assessment Model. Proc. Conf. Agric. Engrg., Soc. Engrg in Agric., Bundaberg, Australia, :243-247.
254. Poulton, D. (1982). R.A.R.T, Schedule - An Irrigation Scheduling Program Suitable for Spray Irrigated Perennial Horticultural Crops in the Mallee Region. Irrigation Tech. Unit, RWC, Kerang, Victoria, Australia.
255. Prasad, R. (1988). A Linear Root Water Uptake Model. *J. Hydrol.*, 99:297-306.
256. Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T. (1988). *Numerical Recipes- The Art of Scientific Computing*. Cambridge Uni. Press, NY.
257. Priestley, C.H.B. and Taylor, R.J. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters. *Mon. Weath. Rev.*; 100:81-92.
258. Pruitt, W.O. (1960). Relation of Consumptive Use of Water to Climate. *Trns. Am. Soc. Agric. Engrs.*; 3(1):9-13, 17.
259. Pruitt, W.O. (1966). Empirical Method of Estimating Evapotranspiration Using Primarily Evaporation Pans. Proc. Conf. on Evapotranspiration and its Role in Water Resources Management, Chicago, ASAE, :57-61.
260. Pruitt, W.O. and Swann, B.D. (1986). Evapotranspiration Studies in NSW: Daily Vs. Hourly Meteorological Data. *Irrogation'86*, Darling Downs Institute of Advanced Education, Toowoomba, Queensland, Australia, pp29.
261. Raats, P.A.C. (1976). Analytical Solutions of a Simplified Flow Equation. *Trans. ASAE*, 19:683-689.
262. Ramdas, L.A. (1957). Evaporation and Potential Evapotranspiration Over the Indian Sub-Continent. *Indian J. Agric. Sci.*, 27(2):137-149.
263. Read Sturgess and Assoc. (1991). Derivation of Economic Demand Schedules for Irrigation Water in Victoria. Department of Conservation and Environment Victoria, Report No. 65.

264. Rendell, R. and Thomas, D. (1985). Water Requirements and Predicted Irrigation Frequencies in the Kerang Region. DFA Internal Report, Department of Agriculture, Victoria, Australia.
265. Richards, L.A. (1931). Capillary Conduction of Liquids Through Porous Mediums. *Physics* 1:318-333.
266. Rijtema, P.E. (1965). An Analysis of Actual Evapotranspiration. Agric. Res. Report No. 659; Institute for Land and Water Management Research., Wageningen.
267. Rijtema, P.E. (1968). Derived Meteorological data: Transpiration. Proc. of the Symposium on Agroclimatological Methods, Reading, 1966.
268. Rijtema, P.E. and Ryhiner, A.H. (1966). De Lysimeters in Nederland. Verslagen Mededelingen en Hydrologische Communicaties TNO, 14:86-149.
269. Ritchie J.T. (1972). Model for Predicting Evaporation from a Row Crop with Incomplete Cover. *Water Reso. Res.*, 8:1204-1213.
270. Ritchie, J.T. (1985). A User Oriented-model of the Soil Water Balance in Wheat. *Wheat Growth and Modeling*, W. Day, and R.K. Atkin (eds.), Plenum Publishing Co., New York, N.Y., :293-305.
271. Robertson, D., MacDonald, P., Austin, N., Bethune, M. and Wood, M (2000). Improved Irrigation Practices for Forage Production, Draft Report on the Development and Testing of Aim. Dept. Natural Reso. and Environment, Victoria.
272. Russell, G. (1980). Crop Evaporation, Surface Resistance and Soil Water Status. *Agric. Meteorol.*, 21:213-226.
273. RWC (1988). Irrigation and Drainage Practice. Rural Water Commission of Victoria, RWC, Armadale, Victoria, Australia.
274. RWC (1990). Customer Service Review Summary Report. Rural Water Commission and Murray Valley Irrigators Advisory Committee, Victoria, p25.
275. Saxton, K.E., Johnson, H.P. and Shaw, R.H. (1974). Modeling Evapotranspiration and Soil Moisture. *Trans. ASAE*, 17(4):673-677.
276. Saxton, K.E., Johnson, H.P., and Shaw, R.H. (1974). Modeling Evapotranspiration and Soil Moisture. *Trans. ASAE*, 17:673-677.

277. Scherer, T.F., Fox, F.J., Slack, D.C. and Clark, L. (1990). Near Real-Time Irrigation Scheduling using Heat-Unit Based Crop Coefficient. Proc. Nat. Conf. on Irrig. and Drain., ASCE, Durango, Col., :544-551.
278. Schouwenaars, J.M. (1988). Rainfall Irrigation and Sowing Strategies in Southern Mozambique. Agric. Water Management, 13(1):49-64.
279. Shannon, E. L., Holden, J. R. and Raine, S. R. (1996). Adoption of Improved Irrigation Practices by Burdekin Canegrowers, Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference, San Antonio Convention Centre, San Antonio, Texas,ASAE, pp 214-219.
280. Shuttleworth, W.J. (1992). Evaporation. Chapt. 4, Handbook of Hydrology, J. Maidment (ed.), McGraw-Hill Inc., New York, NY.
281. Siddeek, F. Z., Dillaha, T. A. and Loganathan, G. V. (1988). Water Management for Low Land Rice Irrigation. J. Irrig. and Drain. Engrg., 114(3):407-423.
282. Siddig, A.A. (1982). Computer Aided Irrigation Scheduling. PhD Dissertation, Silsoe, Bedford, UK.
283. Sigma Plot<sup>R</sup> (1997). User Manual SigmaPlot 4.0 for Windows 95 NT&3.1. SPSS Inc., 444N Michigan Avenue, Chicago, IL., USA.
284. Singh, B., Boivin, J., Kirkpatrick, G., and Hum, B. (1995). Automatic Irrigation Scheduling System (AISSUM): Principles and Applications. J. Irrig. And Drain. Engrg., ASCE, 121(1):43-56.
285. Singh, B., Boivin, J., Kirkpatrick, G., Houle, B. and Hum B. (1994). The Surface Energy and Water Balance System (SEWBS): A computer-Assisted Approach to Irrigation Scheduling. West Indian J. Engrg., 17(1):29-45.
286. Singh, R. and Singh, J. (1996). Irrigation Planning in Cotton Through Simulation Modelling. Irrig. Sci., 17:31-36.
287. Slatyer, R.O. and McIlroy, I.C. (1961). Practical Microclimatology, CSIRO, Melbourne, UNESCO, Australia.
288. Smith, C. (1993). Pasture Management for Dairy Farmers. Department of Agriculture, Victoria, Australia, pp:93.

289. Smith, M. (1992). Report on the Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements. Div. of Land and Water Dev., FAO, Rome, Italy.
290. Stanhill, G. (1962). The Control of Field Irrigation Practice from Measurements of Evaporation. *Israel J. Agric. Res.*; (12):51-62.
291. Stapper et al. (1986). Fortran Subroutine for Clear-day Global Radiation Estimates. In Meyer, W.S. (ed. 1994), Standard Reference Evaporation Calculation for Inland South Eastern Australia. Tech. Memo. Div. of Water Reso., CSIRO, Griffith.
292. Stapper, M. (1991). SIRAG-FIELD Version 1.3 - Irrigation Scheduling for Annual Field Crops. User Guide, CSIRO Div. of Water Reso., Griffith, NSW, Australia.
293. Stegman, E.C. and Coe, D.A. (1984). Irrigation Scheduling Software for Microcomputer. ASAE NCR Meeting, Morris, MN, ASAE, St. Joseph, MI., Paper No. 84 -301.
294. Steiner, J.L., Howell, T.A. and Schneider, A.D. (1991). Lysimetric Evaluation of Daily Potential Evapotranspi. Models for Grain Sorghum. *Agron. J.*, 83:240-247.
295. Stewart, J.B. (1983). A Discussion of the Relationships Between the Principal Forms of the Combination Equation for Estimating Crop Evaporation. *Agric. Meteo.* (30):111-127.
296. Stewart, J.I. and Hagan, R.M. (1973). Functions to Predict Effects of Crop Water Deficits. *J. Irrig. and Drain. Engrg.*, ASCE, 99(4):421-439.
297. Stockle, C. and Cambell G.S. (1985). A Simuation Model for Predicting Effect of Water Stress on Yield. *Advances in Irrigation*, D. Hille, Edition 3, :284-312.
298. Stricevic, R. and Caki, E. (1997). Relationships Between Available Soil Water and Indicators of Plant Water Status of Sweet Sorghum to be Applied in Irrigation Scheduling. *Irrig. Sci.*, 18:17-21.
299. Subbaiah, R. and Rao, K.A. (1993). Root Growth Simulation Model under Specified Environment. *J. Irrig. & Drain. Engrg.*, ASCE, 119(5):898-904.
300. Sudsaisin, K. (1990). Models for Irrigation Scheduling in a Canal Command Area. M.Engg. Thesis, Asian Institute of Technology, Bangkok, Thailand.
301. Szeicz, G. and Long, I.F. (1969). Surface Resistance of Canopies. *Water Reso. Res.*, 5:622-633.

302. Szeicz, G.E.G. and Tajchman, S. (1969). Aerodynamic and Surface Factors in Evaporation. *Water Reso. Res.*, 5:380-394.
303. Tanner, C.B. and Pelton, W.L. (1960). Potential Evapotranspiration Estimates by the Approximate Energy Balance Method of Penman. *J. Geophysical Res.*, 65:3391-3413.
304. Taylor, H.M. and Klepper, B. (1975). Water Uptake by Cotton Root Systems: An Examination of Assumptions in the Single Root Model. *Soil Sci.*, 120(1):57-67.
305. Taylor, H.M. and Klepper, B. (1978). The Role of Rooting Characteristics in the Supply of Water to Plants. *Adv. Agronomy*, 30:99-128.
306. Teixeira, J.L. and Pereira, L.S. (1992). ISAREG, An Irrigation Scheduling Simulation Model. *ICID Bulletin*, 41(2):29-48.
307. Teixeira, J.L., Fernando, R.M., and Pereira, L.S. (1995). RELREG: A Model for Real-Time Irrigation Scheduling. *Crop-Water-Simulation Models in Practice*, Pereira et al. (eds.), Selected papers of the 2<sup>nd</sup> workshop on Crop-Water-Models, Int. Com. on Irrig. and Drain., (ICID), Wageningen Pers, The Netherlands: 3-16.
308. Tetens, O. (1930). Uber Einige Meteorologische Begriffe. *Z. Geophys.*; (6):297-309.
309. Theiveyanathan, S., Myers, B.J., Benyon, R.G., and Polglase P.J. (1998). Irrigation Scheduling for Eucalypt Plantation in Australia. *Water is Gold, Proc. Conf. Irrig. Assoc. Australia (IAA)*, Brisbane, Qld, :423-433.
310. Thivianathan, S.T., Connor, D.J. and Angus, D.E. (1991). Water Demand of Wheat Crops- Evaluation and Estimation. *Int. Hyd. & Water Reso. Symp*, Perth, :694-698.
311. Thom, A.S., Thony, J.L. and Vauclin, M. (1983). On the Proper Employment of Evaporation Pans and Atmometers in Estimating Potential Transpiration. *Quart. J. Roy. Meteorol. Soc.* (107):711-736.
312. Thomas, W.O. (1985). A Uniform Technique for Flood Frequency Analysis. *Proc. Amer. Soc. Civ. Engrs, J. Water Resou. Planning and Mangmt.*, 111(3):321-337.
313. Thompson, J., Sykes, J., Hedditch, M., and Chase, D. (1982). Irrigation Scheduling of Wheat. *Farmer's Newsletter*, No. 121, Irrig. Res. and Extension Committee, NSW Dept. of Agric, New South Wales, Australia, 121:2-4.

314. Thornthwaite, C.W. (1948). An Approach Towards a Rational Classification of Climate. *Geograph. Rev.*, 38,55.
315. Thornthwaite, C.W. and Mather, J.R. (1955). The Water Balance. *Climatology*, 8(1), Lab. of Climat., Centeron, N.J.
316. Tracy, J.C. and Marino, M.A. (1989). Management Model for Control of On-Farm Irrigation. *J. Irrig. and Drain. Engrg.*, ASCE, 115(6):954-972.
317. Tripathi, R.P. (1992). Irrigation Timing for Wheat Based on Climate, Crop and Soil Data. *J. Irrig. and Drain. Engrg.*, ASCE, 118(3):370-381.
318. Turc, L. (1961). Evaluation Des Besoins en Eau D'irrigation, Evapotranspiration Potential, Formule Climatique Simplifrice et Mise a Jour (in French); English Title: Estimation of Irrigation Water Requirements, Potential Evapotranspiration - A Simple Climatic Formula Evolved up to Date. *Ann. Agron.*, 12:13-49.
319. Turner, N.C. (1990). Plant Water Relations and Irrigation Management. *Agric. Water Management*, 17:59-73.
320. Turrall, H. N. (1993). The Evaluation of Surge Flow in Border Irrigation (With Special Reference to Cracking Soils). PhD Thesis, Uni. of Melbourne, Australia.
321. Van Bavel, C.H.M. (1967). Changes in Canopy Resistance to Water Loss from Alfalfa Induced by Soil Water Depletion. *Agric. Meteorolo.*, 4:165-176.
322. Van Vleck, G.K., Deukmejian, G. and Kennedy, D.N. (1986). Crop Water Use in California. Bulletin 113-4; Department of Water Resources, California, USA, :116.
323. Van Zyl, W.H. and De Jager, J.M. (1987). Accuracy of the Penman-Monteith Equarion Adjusted for Atmospheric Stability. *Agric. & Forest Meteorol.*, 41:57-64.
324. Vanderkimpen, P.J. (1991). Estimation of Crop Evapotranspiration by Means of the Penman-Monteith Equation. PhD Thesis, Dept. of Biological and Irrigation Engineering, Utah State Uvi., Logan, Utah, USA.
325. VIDA (1994). Report of Victorian Dairy Farm Survey, 1993. Victorian Dairy Authority, September 1994. pp42, Melbourne, Victoria.
326. Viessman, W.Jr., Harbaugh, T.E. and Knapp J.W. (1972). Introduction to Hydrology. Intex Educational Publications, NY, USA.

327. Villalobos, F.J. and Fereres, E. (1987). Necesidades Hídricas de Los Cultivos y Programación de Los en Los Vegas Bajas Del Guadiana Dirección General de Investigación, Extensión y Capacitación Agraria, Apdo -217, Badajoz.
328. Villalobos, F.J. and Fereres, E. (1989). A Simplified Model for Irrigation Scheduling Under Variable Rainfall. *Trans. ASAE*, 32(1):181-188.
329. Walker, W.R. Prajamwong, S., Allen, R.G. and Merkle, G.P. (1993). USU Command Area Decision Support Model – CADSM. *Int. Comm. on Irrig. and Drain.*, (ICID), 2<sup>nd</sup> Workshop on Crop-Water-Models, Hague, The Netherlands:231-272.
330. Walsh (1959). Large Sample Non-Parametric Rejection of Outlying Observations. *Ann Inst. Statist. Math, Tokyo-Japan*, 10, 223-232 (44,283,285).
331. Watts P.J. and Hancock, N.H. (1984). Evaporation and Potential Evaporation - A Practical Approach for Agricultural Engineers. *Proc. Conf. on Agric. Engrg.*, Bunderberg, :290-297.
332. Watts, P.J. McKay, M.E. and Bourne, J.F. (1984). Estimating Crop Water Requirements. *Proc. Conf. on Agric. Engrg., Soc. for Engrg in Agric., (SeAg)*, Bundaberg, Australia, :378-380.
333. Weeks, W.D. (1983). The Calculation of Evaporation in Queensland. *I.E. Aust. Qld. Div. Tech. Papers*, 24(4):1-5.
334. Wesseling, J.G., and Van Den Broek, B.J. (1988). Prediction of Irrigation Scheduling with the Numerical Model SWATRE. *Agric. Water Management*, 14:299-306.
335. Wesseling, J.G., Elbers, J.A., Kabat, P., Van Den Broek, B.J., Huygen, J.C., Van Dam, J.C., and Feddes, R.A. (1994). SWAP 1993 – Input Instructions Manual. *RAPPORT 45*, Wageningen, The Netherlands: Vakgroep Waterhuishouding.
336. Wesseling, J.G., Kabat, P., Van De Broek, B.J., and Feddes, R.A. (1989). SWACROP – Instructions for Input. The Winand Starting Centre for Integrated Land, Soil and Water, Wageningen, The Netherlands.
337. Wold, S. (1974). Spline Functions in Data Analysis. *Technometrics*, 16(1):1-16.

338. Wolters, W. (1992). Influences on the Efficiency of Irrigation Water Use. Int. Institute for Land Reclamation and Improvement (ILRI), Pub. No. 51, Wageningen, The Netherlands.
339. Wood, M. and Malano, H. (1996). Real-Time Monitoring and Control of On-Farm Surface Irrigation Systems. Project-UME12 Milestone Report No 4, Dept. Civil & Envir. Engrg., Univ. of Melbourne.
340. Wood, M. and Martin, M. (2000). Improved Irrigation Practices for Forage Production—Module 2: Alternative Irrig. Tech. Desktop Analysis, Tatura, VIC, pp 74.
341. Wood, M. Malano, H. and Turrall, H. (1997). Real-Time Monitoring and Control of On-Farm Surface Irrigation Systems. Project-UME12 Milestone Report No 5, Dept. Civil & Envir. Engrg., Univ. of Melbourne.
342. Wood, M. Malano, H. and Turrall, H. (1998). Real-Time Monitoring and Control of On-Farm Surface Irrigation Systems. Project-UME12 Final Report, Dept. Civil & Envir. Engrg., Univ. of Melbourne.
343. Wright, J.L. and Jensen, M.E. (1972). Peak Water Requirements of Crops in Southern Idaho. *J. Irrig. and Drain. Engrg.*, ASCE, 96(1):93-201.
344. Wright, J.L. (1981). Crop Coefficients for Estimates of Daily Crop Evapotranspiration. *Irrig. Scheduling for Water and Energy Conservation in the 80's: Proc.*, ASAE Irrig. Scheduling Conf., St. Joseph MI., :18-26.
345. Wright, J.L. (1982). New Evapotranspiration Crop Coefficients. *J. Irrig. and Drain. Engrg.*, ASCE, 108(2):57-74.
346. Wyseure, G.C.L., Sanmuganathan, K., and O'Callaghan, J.R. (1994). Use of Simulation for Combining Rainfed and Irrigated Sugarcane Production in the Dry Zone of Sri Lanka. *Comput. & Electron. in Agric.*, 11:323-335.
347. Yamashita, S. Walker, W. R. (1994). Command Area Water demand. 1: Validation and Calibration of UCA Model. *J. Irrig. & Drain. Engrg.*, ASCE, 120(6):1025-1042.
348. Yau, Y.C. (1985). Computer Modelling of Rainfall-Runoff Using SFB Model. ME. Thesis, Dept. Civil and Mining Engrg., Uni. of Woollongong, Western-Australia.

## APPENDIX A

### REFERENCE CROP EVAPOTRANSPIRATION ESTIMATION COMPUTER SOFTWARE

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## APPENDIX A

### REFERENCE CROP EVAPOTRANSPIRATION ESTIMATION COMPUTER SOFTWARE

As stated in Section 3.6.5, no single  $ET_o$  estimation method that uses meteorological data was satisfactory for all climatic regimes. Depending upon the climatic situation of a specific site, a locally calibrated less data requiring simple  $ET_o$  estimation method may produce even better results than the data extensive combination methods. As concluded in Section 3.6.5, the  $ET_o$  estimation methods must be locally calibrated against measured lysimeter (or base-method)  $ET_o$  data before they are used in irrigation scheduling studies. Furthermore, the availability of the measured climatic data can also dictate the selection of an  $ET_o$  estimation method for the site under consideration. Thus, there is a need to develop a computer software to compute  $ET_o$  estimates with multiple choice of  $ET_o$  estimation methods to suit local conditions. Therefore, based on this concept, an  $ET_o$  estimation computer software (REF\_ET) was developed, as part of this thesis.

In this appendix, a brief description of REF\_ET package encompassing its salient features is described first, followed by the detailed description of various inputs of the software. The use of REF\_ET package is then explained through a simple example. This appendix is written as a stand-alone document and therefore, most of the description given in Section 3.7 is repeated here.

#### A.1 General Description of REF\_ET Computer Software

The REF\_ET package was developed to compute daily  $ET_o$  estimates with multiple choice from ten different  $ET_o$  estimation methods. These methods range from simple temperature-based methods to complicated data extensive combination methods, as described in Section 3.2. These methods were evaluated using data from three different sites in Victoria and NSW (Australia) as described in Sections 3.3 to 3.6. While

developing this package, a special consideration was given to its robustness, efficient computation, and user-friendliness. To achieve the above considerations, the ten  $ET_o$  estimation methods considered in the package were first coded in FORTRAN-77 to facilitate faster computations, and then menu-driven user interfaces developed to run under both DOS and Window environments.

The REF\_ET software is composed of a single computational component (ETO), which is supported by a number of subroutines. The source codes of ETO and its supporting subroutines can be requested from the candidate. The flow chart of ETO is shown in Figure A.1.

Since the availability of the measured climatic data can force the user to use specific  $ET_o$  estimation methods, a user-specified “priority order” option to use the desired  $ET_o$  estimation methods among the ten available was incorporated in this package. The package first attempts to compute  $ET_o$  estimates using the user-specified highest priority (i.e. highest ranked)  $ET_o$  estimation method. However, if the climatic data required for this method are not available, then the software uses the method having second highest priority, and so on. In this way, all ten  $ET_o$  methods are considered. Therefore, with this user-specified priority order option, there is a high likelihood that an  $ET_o$  estimate is computed for each day of the study period based on the user-specified  $ET_o$  estimation method subject to availability of data. However, if data are not available for a particular day for all preferred  $ET_o$  estimation methods, then  $ET_o$  estimation is not made for this day. It is important to note that in addition to this above stated “priority order” option, there is another option available in the package. Under this option, the REF\_ET package computes daily  $ET_o$  estimates for the study period using all ten  $ET_o$  methods at the same time, ignoring the user-specified priority order.

As stated earlier,  $ET_o$  methods also require local calibration for best performance under site specific conditions. Therefore, in order to make the package compatible under wide range of climatic conditions, the package was also provided with an option to accept a

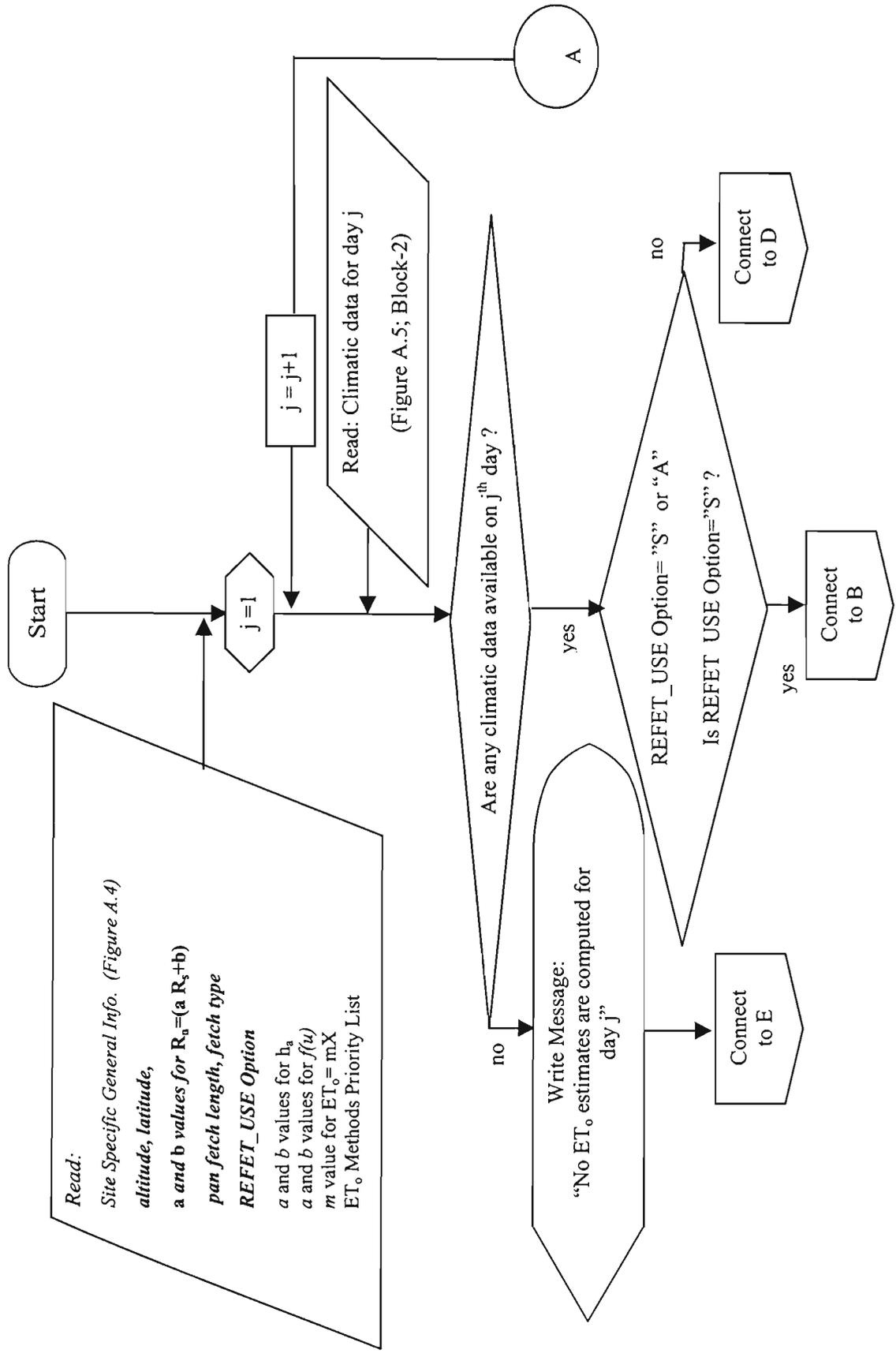


Figure A.1 Flow Chart of ETO

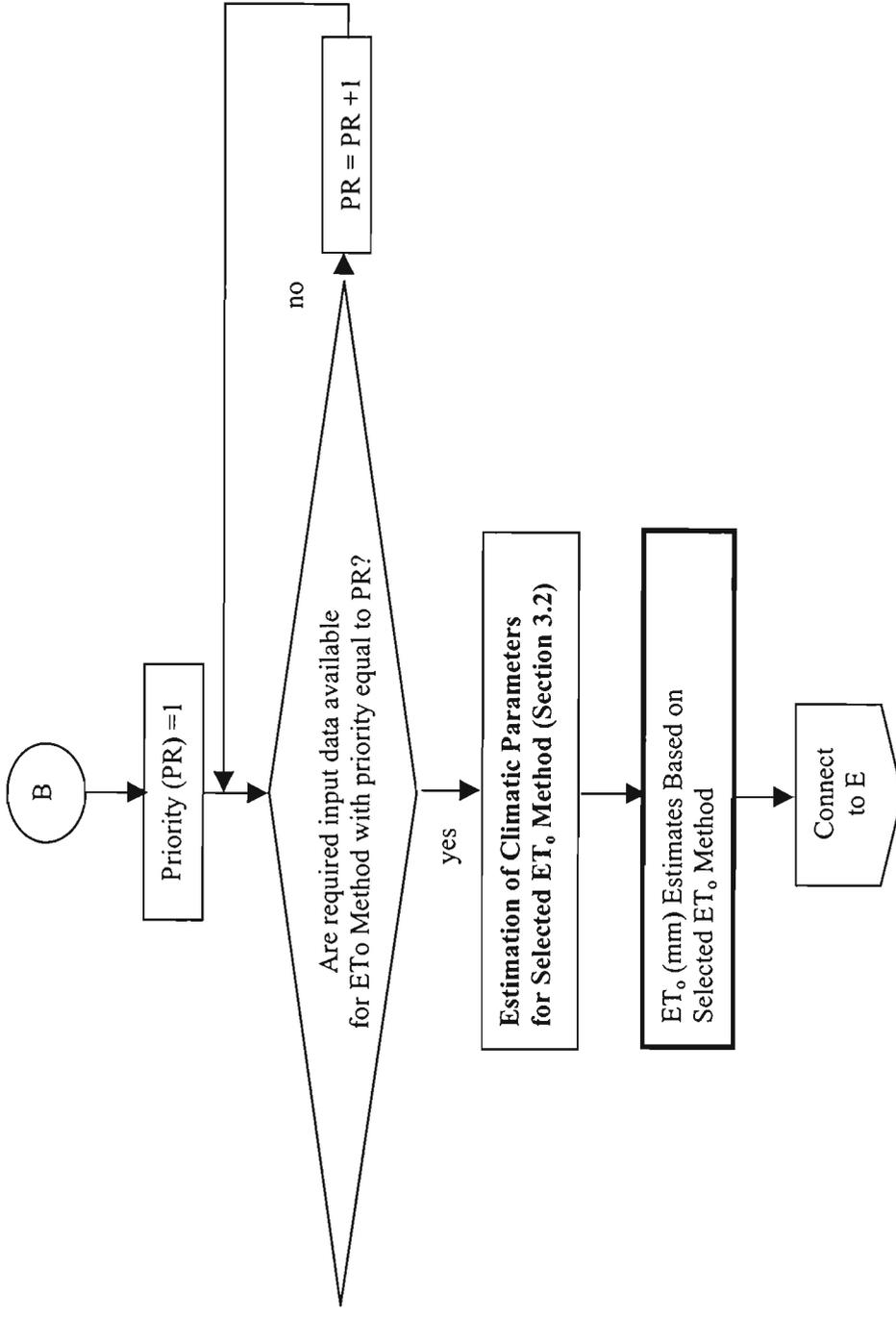


Figure A.1 Flow Chart of ETO (continued)

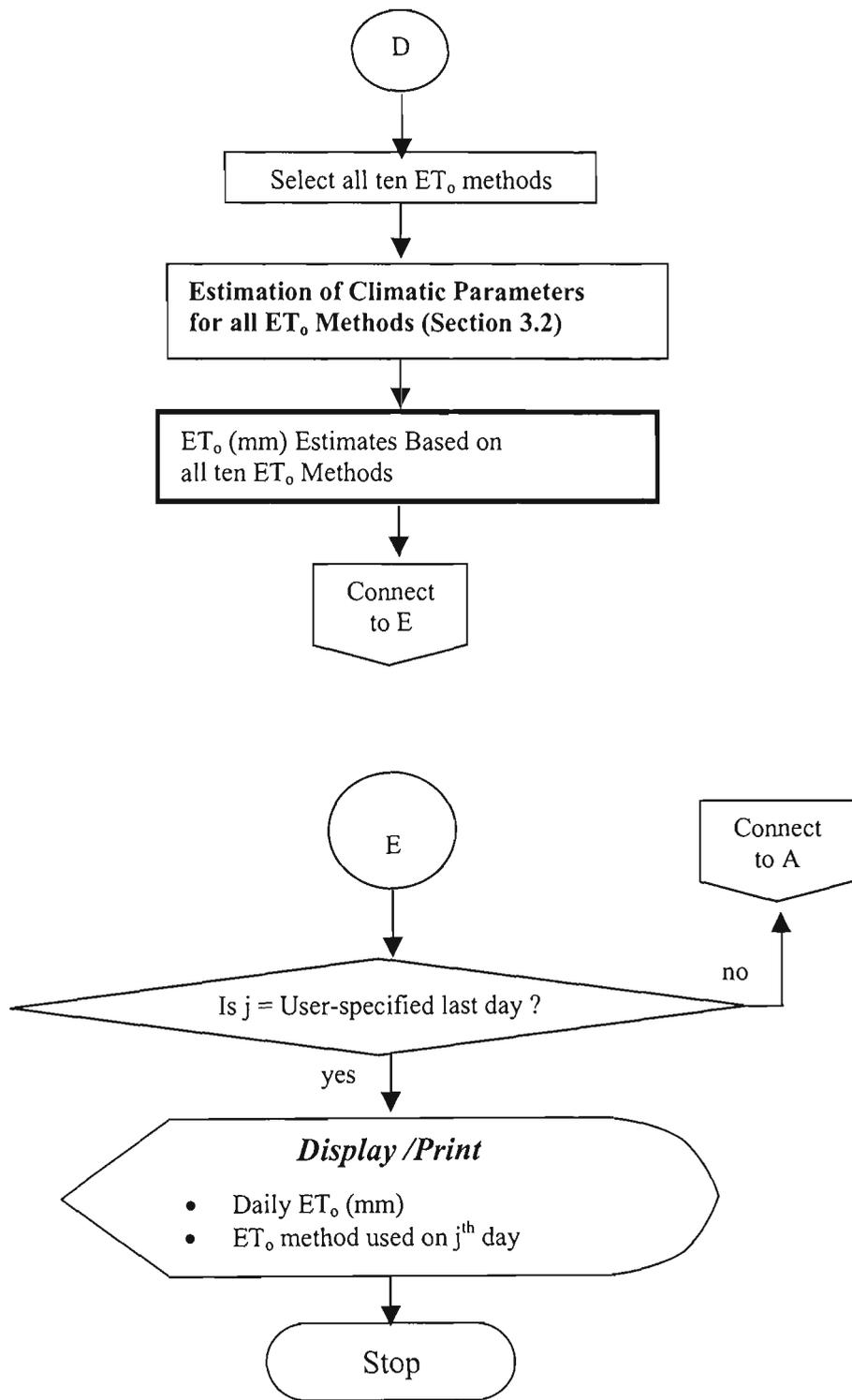


Figure A.1 Flow Chart of ETO (continued)

“local calibration coefficient” for each of these ten  $ET_0$  estimation methods. Therefore, the package is comprehensive to estimate daily  $ET_0$  for any climatic region.

The software requires measured climatic data on a daily basis as its major input. The other information such as priority order and calibration coefficient for each of the ten  $ET_0$  methods, site specific general information such as altitude and latitude etc., are entered through menus of the package. The details of these input data items are given in Section A.4. After entering the required input data, the package can be run to give  $ET_0$  estimates for each day of the available input data period. The structure of REF\_ET package is shown in Figure A.2.

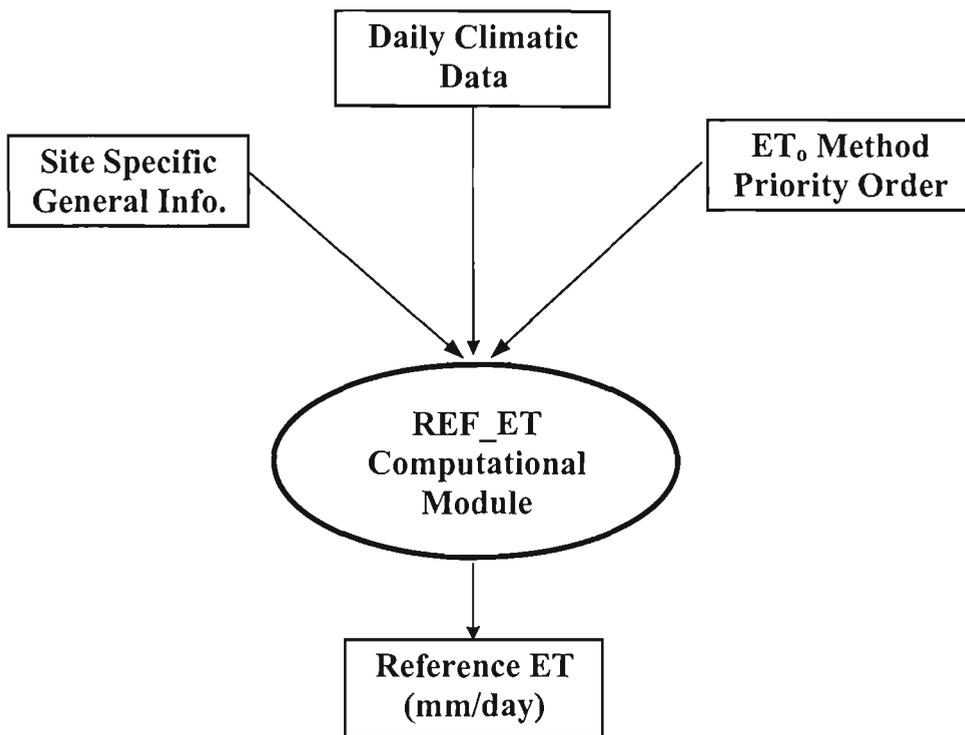


Figure A.2 General Execution Structure of REF\_ET Software.

## A.2 Installation and Starting of REF\_ET

REF\_ET can be run on a personal computer (PC) both in DOS and Windows environments. The installation of the REF\_ET package requires the following steps:

- Insert the REF\_ET package INSTALLATION DISK#1 in drive A: of the PC, and then type EINSTALL.
- Press F1 function key for installation of the DOS version, or F2 key for installation of the Windows version.
- Follow the instructions as prompted on the screen to complete the installation.

At the completion of the REF\_ET installation, a subdirectory called REF\_ET will be created in the main C: directory of the PC for the Windows version. Create a short-cut icon as for any other windows package. Double-click the icon and the Main Menu of the software is displayed as shown in Figure A.3. Sections A.4 to A.5 explain the Windows version of the software.

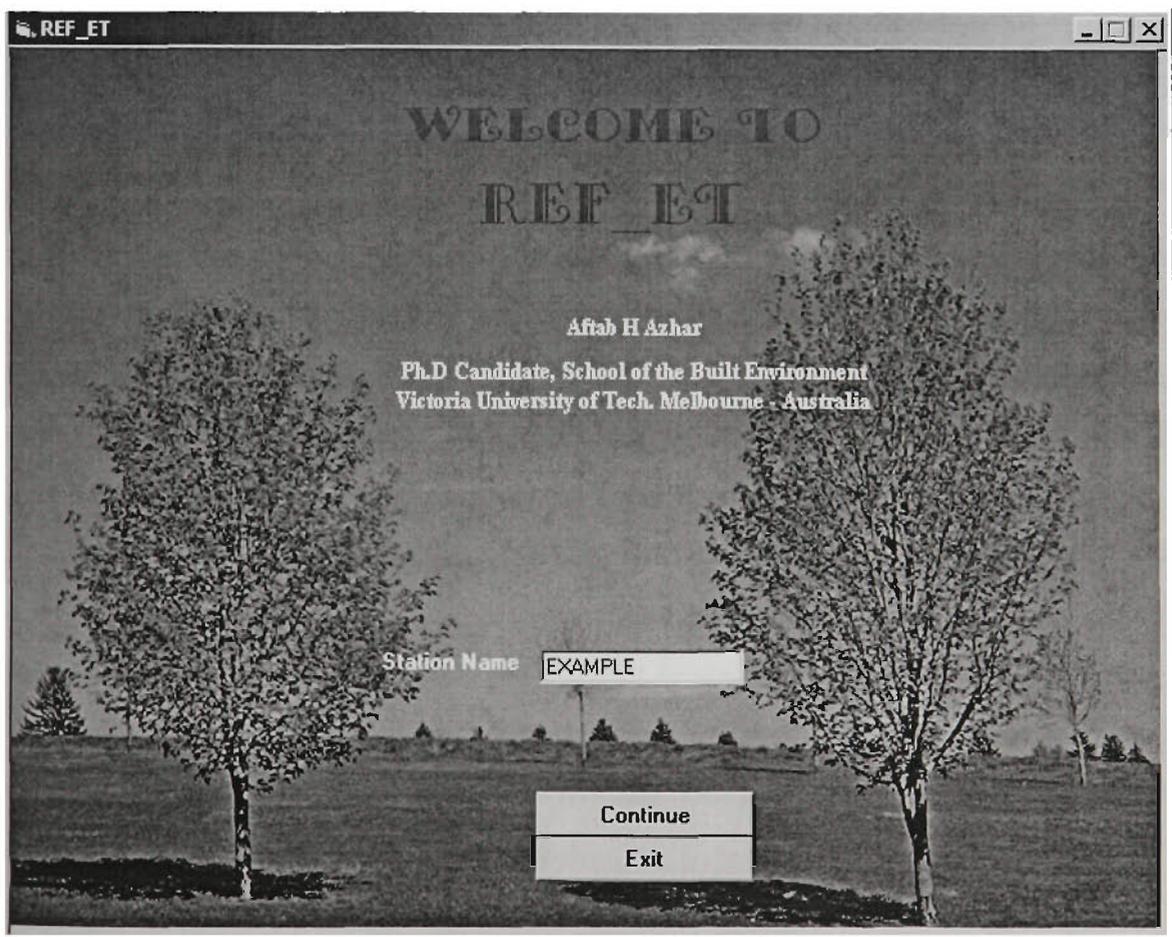


Figure A.3 Main Menu of REF\_ET Software

At the completion of the installation for running under DOS, a subdirectory called DREF\_ET will be created in C: directory. To start the DOS version, the user is required to go to the DREF\_ET subdirectory and type DREF\_ET. It is important to mention that in this Appendix, the Windows version of the REF\_ET package is described in detail. However, a brief description of the DOS version is also given in Section A.6. Two versions do not differ much in its operation.

### A.3 Main Menu

The Main Menu of REF\_ET package is shown in Figure A.3. As can be observed from this figure, there is only one input data box namely *Station Name* that requires the station name (for which  $ET_o$  estimates are required) to be specified by the user. The two command buttons shown in Figure A.3 facilitate the operation of the Main Menu.

#### *Station Name*

This input data box refers to the name of input data file (of maximum eight characters) for which the  $ET_o$  estimates are desired. This file name is usually the name of the climatic station at which the climatic data were recorded. If REF\_ET is used for the first time, the user may enter the station name as SAMPLE. This will open a sample input data file which later on (Section A.4), after updating the data can be renamed and saved under a different station name. If the *Station Name* has the file name the user wishes to edit, click the CONTINUE button to bring the user to the next sub-menu namely *Site Specific General Information*. This sub-menu lets the user to update the input data of this data file. If the user enters a file name which does not exist in the C:REF\_ET sub-directory, the REF\_ET will open a new input data file under this specified name and take the user to the *Site Specific General Information* sub-menu.

#### **CONTINUE Button**

The CONTINUE button starts the REF\_ET session by bringing the user to the next sub-menu namely *Site Specific General Information*. This is explained in Section A.4.

**EXIT Button:** This button quits the REF\_ET session.

#### A.4 Site Specific General Information Sub-Menu

This sub-menu is used to provide the general information about the site under consideration and is shown in Figure A.4. The information provided through this sub-menu is used by the REF\_ET software for estimation of parameters of various ET<sub>o</sub> methods. The information collated through this sub-menu are stored in the same input data file which contains the daily climatic data. This information is appended to the climatic data information. The input data file is described in Section A.4.1.

**Data Update Menu**
\_ | □ | X

## Site Specific General Information

Altitude(m)

Latitude(d)

Rn =(a\*R<sub>s</sub>+b)

Pan Fetch Length(m)

Fetch Type (Green/Dry)

REFET\_USE (S/A/\*)

### ET<sub>o</sub> Method Calibration Information

Priority	ET <sub>o</sub> Method	ET <sub>o</sub> =m*X		F(u)=a+bU		h=a+bU	
		mValue		aValue	bValue	aValue	bValue
<input style="width: 20px;" type="text" value="1"/>	Penman_Meyer (M_Y)	<input style="width: 60px;" type="text" value="1.00"/>		<input style="width: 60px;" type="text" value="17.86"/>	<input style="width: 60px;" type="text" value="3.80"/>		
<input style="width: 20px;" type="text" value="4"/>	Modified_Penman (W_H)	<input style="width: 60px;" type="text" value="1.21"/>					
<input style="width: 20px;" type="text" value="3"/>	Mclloy (Mcl)	<input style="width: 60px;" type="text" value="1.13"/>				<input style="width: 60px;" type="text" value="0.44"/>	<input style="width: 60px;" type="text" value="0.32"/>
<input style="width: 20px;" type="text" value="7"/>	Penman_Monteith (P_M)	<input style="width: 60px;" type="text" value="1.40"/>					
<input style="width: 20px;" type="text" value="2"/>	FAO_Radiation (RAD)	<input style="width: 60px;" type="text" value="0.97"/>					
<input style="width: 20px;" type="text" value="6"/>	Ritchie (RIT)	<input style="width: 60px;" type="text" value="1.22"/>					
<input style="width: 20px;" type="text" value="8"/>	FAO_Pan (PAN)	<input style="width: 60px;" type="text" value="1.40"/>					
<input style="width: 20px;" type="text" value="5"/>	Simple_Evaporation (SEV)	<input style="width: 60px;" type="text" value="1.10"/>					
<input style="width: 20px;" type="text" value="9"/>	Improv_Hargreav (IHA)	<input style="width: 60px;" type="text" value="1.36"/>					
<input style="width: 20px;" type="text" value="10"/>	Hargreaves (HAR)	<input style="width: 60px;" type="text" value="1.63"/>					

<b>Update General Info.</b>	
<< Back	ET <sub>o</sub> >> Computation
Edit *.CLI File	

Figure A.4 Site Specific General Information Sub-Menu

As can be observed from Figure A.4, there are 31 input data boxes that require data values to be specified by the user. It is important to mention that each input box requires the respective data item to be entered in specific data format as shown in default values. The four command buttons shown in Figure A.4 facilitate the operation of this sub-menu. The 31 input data boxes as well as the command buttons of this sub-menu are explained below.

*(i) Altitude*

This input data item refers to the altitude (m) of the station under consideration.

*(ii) Pan Fetch Length*

This data item refers to the length of the fetch (m) surrounding the US Class-A pan at the climatic station.

*(iii) Latitude*

This input data item refers to the latitude (degrees) in southern hemisphere of the station under consideration.

*(iv) Fetch Type*

This data item refers to the type the fetch surrounding the US Class-A pan at the climatic station. There could be two types of fetch either Green or Dry surrounding the U.S. Class-A pan at the site (Doorenbos and Pruitt, 1977).

*(v)  $R_n=(a*R_s+b)$*

This input data item refers to the locally calibrated empirical constants ( $a$  and  $b$ ) related to the functional relationship between the net radiation ( $R_n$ ) and the solar radiation ( $R_s$ ) at the climatic station. First input field is reserved for  $a$ , while the second is for  $b$ . The linear

relationship between  $R_n$  and  $R_s$  of the form  $R_n = a R_s + b$  is explained in Sections 3.2.7. The estimation procedure and values of  $a$  and  $b$  constants for different study sites are given in Section 3.6.2.

If  $R_n$  measurements are not available at the station, then  $a$  and  $b$  parameters can be used to compute the  $R_n$  estimates using the  $R_s$  values measured at the station.  $R_s$  is measured at most climatic stations. Alternatively,  $R_n$  can also be estimated from  $R_s$  values using the Meyer (1994) method described in Section 3.2.7. However, the Meyer method requires some additional climatic data items including the dew point temperature measurements. It is important to mention that latter method gives more reliable estimates of  $R_n$  compared to the first method, and hence is preferred to the first method if dew point temperature is available. The REF\_ET automatically chooses this priority if dew point temperature is available in the climatic data (Section A.4.1).

(vi) *REFET\_USE Option*

This data item refers to the option for output  $ET_o$  estimates. If *REFET\_USE Option* is specified as S (an abbreviation for Scheduling), then the daily  $ET_o$  (mm) estimates given by REF\_ET software are based on the user-specified highest priority  $ET_o$  estimation method, provided that the required input climatic data for that method is available. The priority/rank aspect of various  $ET_o$  estimation methods is described in sub-section (vii) below. It is important to note that for option S the  $ET_o$  estimates given by REF\_ET package are the calibrated values. These calibrated values (hereafter referred to as the calibrated  $ET_o$  estimates) are obtained using the calibration coefficient of respective  $ET_o$  estimation method as described in Section 3.5.3. The previously estimated calibration coefficients ( $m$ ) for various  $ET_o$  estimation methods then need to be entered by the user for local conditions which are described in sub-section (ix). If *REFET\_USE Option* is specified as 1, the  $ET_o$  estimates would be the same as for S except that in this case the  $ET_o$  estimates are produced without calibration (i.e. calibration coefficient “ $m$ ” value is assumed as 1.0).

If *REFET\_USE Option* is specified as **A**, the daily  $ET_o$  estimates are produced using all ten  $ET_o$  estimation methods with calibration, provided that the required input climatic data are available for these methods. If on any day, the required data for a certain method are not available, no  $ET_o$  estimate is produced for that method on that day. In order to show this missing data a dummy value for  $ET_o$  equal to 99.9 is written in the output file for that method. It is important to mention that under this option, the priority order is ignored because all methods are used. This option is usually selected when comparison of various  $ET_o$  methods is required for research purposes. If *REFET\_USE Option* is specified as **\***, the  $ET_o$  estimates are the same as for **A** except that in this case the  $ET_o$  estimates are produced without calibration. For irrigation scheduling purposes, the *REFET\_USE Option* can be specified as **S** to produce the calibrated  $ET_o$  estimates on a daily basis for the site under consideration.

As can be observed from Figure A.4, the remaining input data items are related to the ten  $ET_o$  estimation methods included in the software. The relevant input data items are appearing in seven columns. These are explained as below:

*(vii) Priority/Rank*

This data item refers to the priority number of the  $ET_o$  method specified in next column under *ETo Method* heading. This input data item is entered as an integer number. The priority number 1 indicates the user's top priority for respective  $ET_o$  method among the ten methods. Similarly, the priority number 2 indicates the user's second top priority for the  $ET_o$  method, and so on. The REFET\_ET software first attempts to compute  $ET_o$  estimates using the  $ET_o$  method with priority number 1. However, if the climatic data required for this method are not available, then the REF\_ET uses the method having priority number 2, and so on. In this way, all ten  $ET_o$  methods are considered, provided the priority number is assigned a value which is between 1 and 10 (both inclusive). If the priority number is entered as 0 (i.e. zero) for a method, then this method is not considered by the REF\_ET software for  $ET_o$  estimates. The priority numbers for various  $ET_o$

estimation methods based on their performance at different study sites are listed in Tables 3.5, 3.7 and 3.9.

*(viii) ETo Method*

This column contains the names of the  $ET_o$  estimation methods included in the software. An abbreviated name of the respective  $ET_o$  method is also given in parenthesis. This abbreviated name is indicated in the output file to indicate the method used for  $ET_o$  estimates.

*(ix) mValue for  $ET_o=mX$*

The user-specified calibration coefficients “m” are specified in this column for each of the ten  $ET_o$  estimation methods with non-zero priority numbers to suit local conditions, as described in Section 3.5.3. The values of “m” for various  $ET_o$  estimation methods for different study sites are listed in Tables 3.5, 3.7 and 3.9.

*(x) aValue and bValue for  $F(u)=a+b(u)$*

Two input parameters of the wind function,  $f(u)$  (i.e. a and b, Section 3.2.7) are specified in these two columns. It is important to note that among the ten  $ET_o$  estimation methods, the  $f(u)$  component is required only for the M\_Y combination method.

*(xi) aValue and bValue for  $h_a=a+b(u)$*

Two input parameters of atmospheric conductance,  $h_a$  (i.e. a and b, Section 3.2.9) are specified in these two columns. Since  $h_a$  exists only in the McIlroy (McI) method, these parameters are required only for this method.

The various command buttons in this sub-menu (i.e. Figure A.4) are explained below:

### ***Update Button***

This button updates the information entered through the aforementioned 31 input boxes for the specified station. By double-clicking this button, a YES/NO option is prompted for the user to indicate whether or not to update the input data (entered through these 31 input boxes) for this station. The YES choice replaces the old information with the newly entered input values for the station in the \*.CLI input data file, where \* denotes the station name. The NO choice does not update the above information. The format of the \*.CLI input data file is explained in Section A.4.1

### ***Back Button***

This button facilitates to go to the previous sub-menu.

### ***Edit \*.CLI File Button***

This button facilitates the editing of the climatic and/or other input data items contained in the \*.CLI input data file. This button is particularly useful to update/enter the daily climatic data items in the \*.CLI data file. The user may update the daily climatic data at this stage before the  $ET_0$  estimates are made.

### ***$ET_0$ >> Computation Button***

By clicking this button, the following three functions are sequentially performed:

- the information in the \*.CLI file is copied to another temporary file called REF\_ET.CLI for use by the software.
- $ET_0$  estimates (mm) are computed for the station on a daily basis using the aforementioned inputs (i.e. stored in REF\_ET.CLI file).
- brings the user to the next sub-menu designated as the *ET<sub>0</sub> Display/Print Sub-Menu* (Section A.5).

### A.4.1 Input Data

As stated earlier, the daily climatic data is the only major input required by REF\_ET. This data is provided through an ASCII input data file called \*.CLI that is created by the user using any standard editor (e.g. DOS editor). The \* symbol represents the name of the file with a maximum of eight characters, and CLI represents the extension of the file. As stated earlier, for convenience the name of the local climatic station can be used as the data file name. A typical format of \*.CLI input data file is shown in Figure A.5. It is important to mention that in Figure A.5 every line starts with a '#' symbol followed by a numeric value up to 2 digits. The “#” and the numeric value are present in Figure A.5 to refer the line number in the data file for explanation purposes. In the actual input data file of REF\_ET software, these 3 columns do not exist.

### A.4.2 Data Format

As can be seen from Figure A.5, the data file is divided into two blocks. The first block contains general information as well as the locally calibrated parameters for ET<sub>o</sub> methods for the site under consideration as described in Section A.4. The second block contains the climatic data measured at the site. As can be seen, all numeric data are entered in normal FORTRAN fixed format which is given in any FORTRAN language manual (e.g. Ellis, 1990). It is important to note that almost all numeric data are entered with two digits after the decimal point. The exception is the *Col. 1 (PRIORITY)* of line#13-22 and the data in line#26-27 which are entered as an integer (i.e. without decimal point) format of length two. In addition, the daily climatic data in the second block (i.e. line#34 onwards) are entered with only one digit after the decimal point. As can be seen from Figure A.5, the data are entered in a fixed format. Therefore, the best way to prepare the input data file is to edit an existing file, enter new information at the appropriate places with the correct format and save it under the desired name.

```

# 1 EXAMPLE .CLI Tatura example Station Climate data used by "REF_ET" for ETo
# 2 ****Block(1) starts***** Site specific general data
# 3 ALTITUDE (m) e.g. 3.0 ---->: 114.00
# 4 LATITUDE(Degree) e.g. 38.0-->: 36.44
# 5 Fetch length for PAN (m) --->: 100.00
# 6 Fetch_Type (Green or Dry)--->:Green
# 7 Rn =(a*RS+b) a&b---F6.2----->:000.00 000.00
# 8 ***REFET_USE Option (S/A/1) :S
# 9 Priority 1 2 3...---->1st 2nd & 3rd .. respectively: 0-->UNWANTED ETo_method
#10 Below data MUST F5.2 Format: ETo=m*X F(u)=a+bU : h=a+bU :
#11 Col.1 Col.2 Col.3 Col.4 Col.5 Col.6 Col.7 Col.8
#12 PRIORITY ETo_method CODE mValu aValu bValu aValu bValu
#13 1 Penman_Meyer M_Y--> 1.00 17.86 3.80
#14 4 Penman_Watt&Hanc W_H--> 1.21
#15 3 McIlroy MCI--> 1.13 0.44 0.32
#16 7 Penman_Monteith P_M--> 1.40
#17 2 FAO_Radiation RAD--> 0.97
#18 6 Ritchie RIT--> 1.22
#19 8 FAO_Pan PEV--> 1.40
#20 5 Pan_Evaporation SEV--> 1.10
#21 9 Improv_Hargreav IHA--> 1.36
#22 10 Hargreaves HAR--> 1.63
#23 END_CODE*****Block(2) Starts*****
#24 For FAO-radiation Hist. mean monthly RHm(%) and DAY-time Wind(km/hr) are:
#25 JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
#26 HIST_RH(%)----> 49 51 54 62 74 80 79 73 66 58 53 49
#27 HIST_U(km/hr)-> 14 12 12 12 11 10 12 14 15 15 15 15
#28 Following Daily Climatic Data are: T->oC; Radiation->MJ/M^2/d; WIND->Km/day
#29 Rain & Pan-->mm; Rel.Humdity-->% : EToG-->NO data but EmerGency ETo (mm)
#30 !--Date--! TmaxC TminC TdryC TwetC TdewC Rs** Rn** RH%% Wind* Rain Epan EToG
#31 15/08/1965 000.0 000.0 000.0 000.0 000.0 00.0 00.0 00.0 000.0 00.0 00.0 99.9
#32 ***** ***** ***** ***** ***** ***** ***** ***** ***** ***** ***** *****
#33 01/12/1990 8.4
#34 02/12/1990 33.8 15.7 27.4 19.5 15.3 22.1 12.9 59.0 72.0 0.0 5.2
#35 03/12/1990 28.0 17.1 23.8 19.4 17.1 22.2 84.0 79.2 0.0 3.4
#36 04/12/1990 33.6 15.7 28.0 20.0 16.0 29.9 17.8 62.0 0.0 8.6
#37 05/12/1990 22.2 30.0 20.8 16.1 30.2 17.7 52.0 136.8 0.0 8.6
#38 06/12/1990 9.1
#39 07/12/1990 35.3 24.4 31.4 21.2 16.1 17.0 39.0 0.0
#40 08/12/1990 25.5 14.4
#41 09/12/1990 23.2 13.0 20.1 14.4 10.1 27.6 15.8 64.0 165.6 0.0 5.7

: : : : : : : : : : :
: : : : : : : : : : :
: : : : : : : : : : :

```

Figure A.5 Typical Format of REF\_ET Input Data (\*.CLI) File

The various input data items in Figure A.5 are explained as follows:

### A.4.3 Input Data Items

As shown in Figure A.5, the first two lines are general title lines that show the file name and other information. These two lines are not used in REF\_ET calculations, but used for the output. Most of the lines (except few commentary lines) use standard FORTRAN fixed format (Ellis, 1990).

- Line#3-5: the input data items in line#3-5 are already explained in Section A.4. The format is A30, F6.2. The A30 format is reserved for explanatory note of respective data item, while F6.2 is reserved for numerical value of data item. However, it is important to note that the data items in line#3-5 are entered in fixed format after the 30 spaces of explanatory note of respective data item.
- Line#6: the input data item in this line has also been explained in Section A.4. The format is A30, A5. The A30 format is reserved for explanatory, while A5 is reserved for specification of the data item.
- Line#7: the input data items in line#7 have also been explained in Section A.4. The required format is A30, F6.2,1X,F6.2. The A30 format is for explanatory note, while F6.2 is reserved for numerical values of two data items.
- Line#8: the input data item in line#8 is also already explained in Section A.4. The format is A30, A1. Like previous data items the A30 format is reserved for explanatory note, whereas A1 is reserved for specification of the data item.
- Line#9-12: contain the explanatory notes for the specification of data related to the ten  $ET_o$  estimation methods incorporated in the REF\_ET software and are explained in Section A.4.

Line#13-22: They are also explained in Section A.4. As can be seen data items in Line#13-22 under Col. 4-8 are entered using the standard FORTRAN format of F5.2, whereas Col. 1 values are entered using I2 format.

Line#23: Specifies the completion of Block(1) of input data items in the data file by an END\_CODE. After this line the second Block(2) starts which is explained below.

Line#24-25: These lines give the explanatory notes about the historical mean monthly relative humidity(%) and day-time wind speed (km/hr) climatic data items required for the FAO-24 Radiation (RAD) method at the site under consideration. As shown in line#25, these data items are required for each month.

Line#26: contains the mean monthly relatively humidity (%) data for each month.

Line#27: contains the mean monthly day-time wind speed(km/hr) data for each month.

It is worth mentioning that if the above stated historical data are not available, then line#26-27 can be left blank. In this case, the REF\_ET will automatically understand that RAD method is not to be used for this site. Alternatively, a zero priority order for RAD in line#17 under Col. 1 would also skip the RAD method.

Line#28-32: contain the explanatory notes about the various daily climatic variables and their units which are accepted by the REF\_ET software. As can be seen line#28-29 indicate the desired units of various climatic data items. Line#30-32 are the example guide lines for entering various climatic data items in the file.

Line#33: This is the starting point of the daily climatic data items.

As shown in Figure A.5, the daily climatic data items are entered in a columnar pattern. In the first column, the date is entered occupying the first ten places, and is left and right aligned. Following the date entry, the climatic data items are entered under respective data item's heading. For missing data items, the respective place is left blank. It is important to mention that on any day if the climatic data are not measured at the station, then an  $ET_o$  value from a nearby station or an average of last seven day's  $ET_o$  value can be entered in the last (i.e. EToG) column of respective date. This is important because irrigation scheduling needs daily  $ET_o$  values. Following the aforementioned pattern, all climatic data items are entered in the file on a daily basis. The abbreviated codes for various climatic data items (line#30) used in the input file are explained as below.

HIST_RH(%)	= mean monthly relative humidity (%)
HIST_U(km/hr)	= mean monthly day-time wind speed (km/hr)
TmaxC	= maximum temperature ( $^{\circ}C$ ).
TminC	= minimum temperature ( $^{\circ}C$ ).
TdryC	= dry-bulb temperature ( $^{\circ}C$ ).
TwetC	= wet-bulb temperature ( $^{\circ}C$ ).
TdewC	= dew point temperature ( $^{\circ}C$ ).
Rs	= solar radiation ( $MJm^{-2} d^{-1}$ ).
Rn	= net radiation ( $MJm^{-2} d^{-1}$ ).
RH%	= relative humidity (%).
Wind	= wind speed measured at 2m height (Km/24hr).
Rain	= rainfall (mm).
Epan	= US Class-A pan evaporation (mm).
EToG	= an emergency $ET_o$ value from a nearby station or average of last seven days $ET_o$ values

## A.5 ET<sub>o</sub> Display/Print Sub-Menu

This sub-menu is shown in Figure A.6. This sub-menu is used to display and/or print the ET<sub>o</sub> estimates. As can be observed from Figure A.6, there are three command buttons and a message display box available to operate this sub-menu. These are explained below.

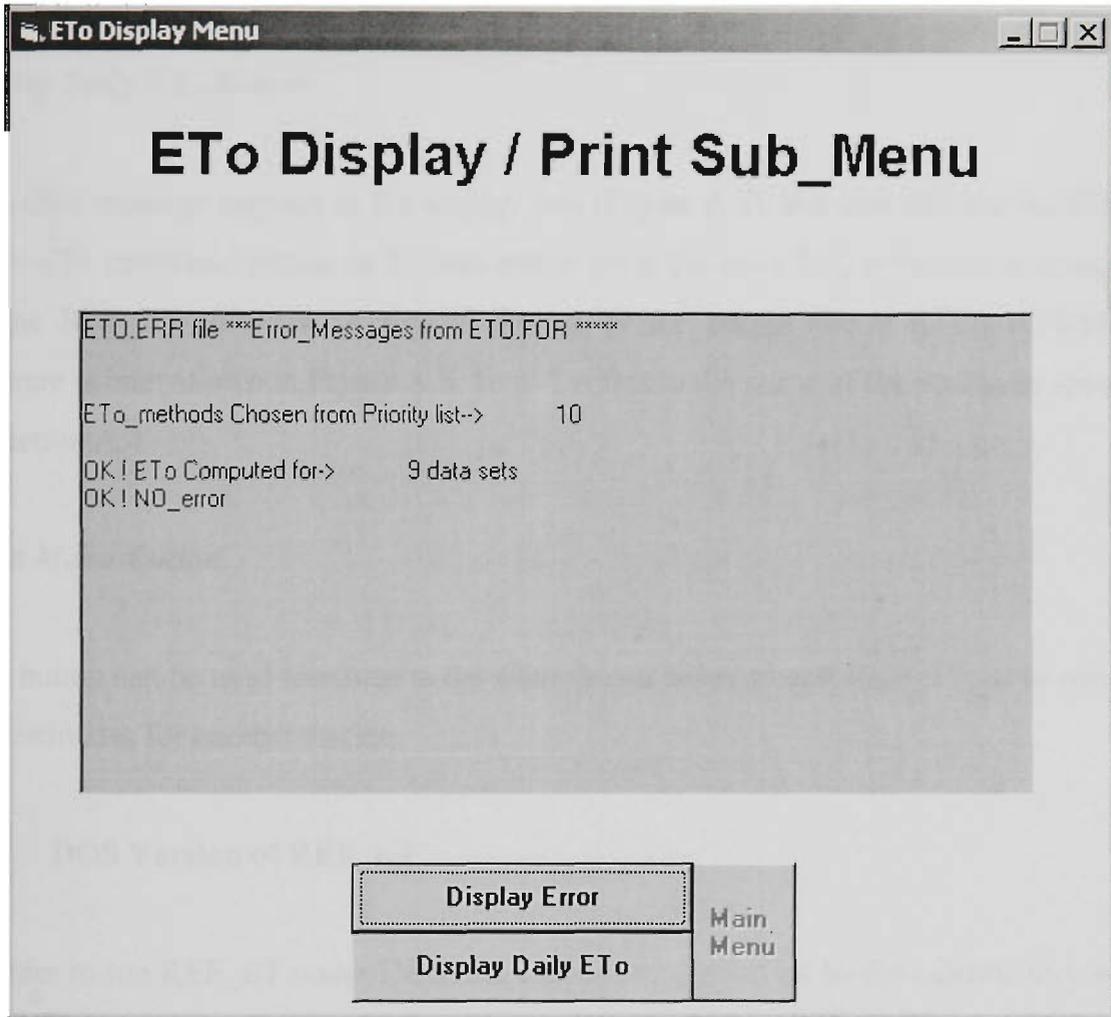


Figure A.6 Eto Display/Print Sub-Menu

### *Display Error Button*

In order to know whether or not the ET<sub>o</sub> estimates have been computed successfully, the *Display Error* button can be used to see the message. If the ET<sub>o</sub> estimates are computed successfully by the REF\_ET software, then an OK! message can be seen in the display

box. Otherwise, an error message is displayed. In case of an error, the error message in the display box prompts the user to refer to the main error message file named ETO.ERR (generated by the REF\_ET software). This file contains the cause of the error and suggestions to rectify the error. Then the user should exit the REF\_ET software by clicking on the *Main Menu* button. The ETO.ERR file can then be viewed by using a standard editor such as the DOS editor or Notepad in Windows.

### ***Display Daily ET<sub>o</sub> Button***

If an OK! message appears in the display box (Figure A.6), the user can use the *Display Daily ET<sub>o</sub>* command button to display and/or print the daily ET<sub>o</sub> estimates as computed by the REF\_ET software. A typical format of the output file (\*.ETO) of REF\_ET software is later shown in Figure A.8. Here \* refers to the name of the station as specified in Section A.4

### ***Main Menu Button***

This button can be used to return to the *Main Menu* either to quit REF\_ET, or to compute ET<sub>o</sub> estimates for another station.

## **A.6 DOS Version of REF\_ET**

In order to run REF\_ET under DOS, the user is required to go to the subdirectory where the REF\_ET software is (e.g. C:\DREF\_ET), and type DREF\_ET. The Main Menu of the software is then displayed as shown in Figure A.7. As can be observed from this figure, there are seven function keys to facilitate the operation of this menu. The function keys of this main menu are explained below.

### ***F1 Function Key***

This function key helps to see the list of existing \*.CLI input data files in C:\DREF\_ET subdirectory.

```
*** REF_ET MODEL ***
A H Azhar PhD Candidate VUT-Australia
*****
** (Use SAMPLE.* file for NEW Station)**
-----
F1 -List of existing Stations
F2 -EDIT *.CLI Climatic Data
F3 -ETo Computation
F4 -Display ERROR Messages
-----
F5 - Display/Print Output File *.ETO
F9 - HELP
F10 - EXIT
*****
PRESS A FUNCTION KEY TO SELECT
```

Figure A.7 Main Menu of REF\_ET DOS-Version

***F2 Function Key***

This key facilitates to edit the climatic and/or other input data items contained in the \*.CLI input data file selected by the user. The user may update the daily climatic data at this stage before the  $ET_o$  estimates are computed. By pressing this key, the user is requested to type the name of the desired station with a maximum of eight characters.

If REF\_ET is used for the first time, the user may enter the station name as SAMPLE. This will open a sample input data file. The data in this file can be changed to suit the application, and can then be renamed and saved as the desired file name. As explained in Section A.4.2, this is perhaps the best way of preparing a new data file, because of the FORTRAN fixed format.

### ***F3 Function Key***

By pressing this key, the daily  $ET_o$  estimates (mm) using the user-specified input data file are computed.

### ***F4 Function Key***

This key facilitates to view the error message after running REF\_ET. By pressing this key, the error message file (i.e. ETO.ERR) is displayed. If the  $ET_o$  estimates are computed successfully, then an OK! message is seen in this file. Otherwise a message is displayed indicating the cause of error and suggestions to rectify the error.

### ***F5 Function Key***

This key facilitates to display/print the  $ET_o$  estimates computed by the REF\_ET software. By pressing this key, the user is asked to enter the name of the station. Here \* refers to the name of the station.

### ***F9 Function Key***

This key provides some help regarding the use of the REF\_ET Software.

### ***F10 Function Key***

This key can be used to quit the current REF\_ET session or to restart  $ET_o$  calculations for another station.

## **A.7 Example**

In order to demonstrate the capability of the REF\_ET software for daily  $ET_o$  estimates, the software was used for the Tatura site in the Goulburn irrigation area of Victoria, Australia (Section 3.4). This is explained as below.

### ***(i) ET<sub>o</sub> Estimates for Scheduling Purposes***

The irrigation season at Tatura was spread from mid-August of a year through to mid-May of the following year. In this example, just for explanation purpose it was considered to estimate ET<sub>o</sub> for few a days in December, 1990. Thus, the input data file was prepared for this period according to the format of Section A.4.1, as shown in Figure A.5. The Tatura site was at 114.0 m height above the mean sea level with southern latitude equal to 36.43°. The U.S Class-A Pan was sited in a green fetch of 100.0 m. Hence, for input boxes namely *altitude(m)*, *Pan\_Fetch Length(m)*, *Latitude* and *Fetch Type (Green/Dry)*, the data values used were 114.0, 100.0, 36.43 and Green respectively. There was no reliable functional relationship available for R<sub>n</sub> and R<sub>s</sub> climatic variables for this site. Hence, both *a* and *b* for R<sub>n</sub> functional relationship (i.e.  $R_n = (a * R_s + b)$  input data box) were set to 0.0. For this station, it was desired to compute daily ET<sub>o</sub> for irrigation scheduling purpose. Hence, for input box namely *REFET\_USE Option*, the data item used was set as **S**. It was desired to use ten ET<sub>o</sub> methods following the priority order (or rank) given in Table 3.7. The locally developed calibration factors (Section 3.5.3) for ET<sub>o</sub> methods at Tatura given in Table 3.7 were used to obtain the best ET<sub>o</sub> estimates. All input data items for this example are shown in Figure A.5.

It is important to mention that after entering the data items in relevant input boxes of Figure A.5, the **Update** command button with YES option was used to save these information under TATURA.CLI file name (Figure A.5). The **EDIT \*.CLI File** button was then used to edit the input data in the file. The HIST\_RH(%) and HIST\_U(km/hr) climatic variables obtained from Bureau of Meteorology, Australia (BOM) were entered in this input data file. The daily climatic data for the period shown in Figure A.5 was also entered. After saving this input data file, the **ET<sub>o</sub> Computation** button was used to compute the ET<sub>o</sub> estimates for use in irrigation scheduling purposes. The **Display Error** button of Figure A.6 (when clicked), showed that all ET<sub>o</sub> estimates were successfully completed. Based on these details, the daily ET<sub>o</sub> estimates for this example station are shown in Figure A.8.

```

EXAMPLE.ETO      Tatura example                      :Text-->5_Lines:
** Rain & ETo PRODUCED by "REF_ET"--> an INPUT for IS_model **
Data format-->[DATE Rain(mm) & ETo(mm)]-->(A10,2X,F5.1,1X,F5.1)
15/08/1997--  0.0   3.6<---For example ONLY:
!<-Date->!  Rain! RefET  ET_MethdxxxxxxxxxxxxDAY
01/12/1990--  0.0   8.4    ???
02/12/1990--  0.0   7.0    M_Y
03/12/1990--  0.0   5.9    M_Y
04/12/1990--  0.0   8.9    RAD
05/12/1990--  0.0   9.5    SEV
06/12/1990--  0.0  10.0    SEV
07/12/1990--  0.0   8.8    IHA
08/12/1990--  0.0   6.5    HAR
09/12/1990--  0.0   7.2    M_Y

:           :           :           :           :
:           :           :           :           :
:           :           :           :           :

```

Figure A.8 REF\_ET Output (\*.ETO) File for Example Problem

As can be seen from Figure A.8, after first five lines the output is given in four columns. The first column specifies the date for which  $ET_o$  estimates were made. The second column gives the rainfall on respective date, which is the same as entered in the input data file. The third column gives the  $ET_o$  estimates on respective date and the fourth column shows the method used for  $ET_o$  estimates on this date. The codes for various  $ET_o$  methods given in the output file are the same as described in Section 4.2 of Chapter 4. The following paragraph illustrates how successfully the REF\_ET software computes  $ET_o$  estimates from any available climatic data items.

As shown in Figure A.8, on 01/12/1990 the  $ET_o$  estimate was 8.4 which was an arbitrary  $ET_o$  value specified for this date in the input data file (Figure A.5, Line#33). Hence, the method used in this case was unknown which is indicated as “???”. For 02/12/1990, the M\_Y method was used. This method was used because the required data for this method was completely available on this date. It is interesting to note that on this date the available climatic data was also enough to satisfy the data requirement of other three

combination (i.e. W\_H, McI and P\_M) methods, yet the M\_Y method was used by the software, since it was assigned the top priority among these four methods.

As stated earlier,  $R_n$  is one of the essential input data item for combination methods. As can be observed on 03/12/1990 although the  $R_n$  data were missing, yet the M\_Y method was used. The reason was that REF\_ET software while recognising the top priority for M\_Y method computed the  $R_n$  value using  $R_s$  and TdewC data items as per method described in Section 3.2.7.

As can be observed, on 04/12/1990 the method used was RAD (with priority 2). The reason for this was that on this date the wind speed which was an essential input data item for top-ranked M\_Y method was not available. Hence, the REF\_ET skipped this method and used the second top RAD method (with priority 2) for which the required data were completely available. Similarly on 05/12/1990, the SEV method was used because on this date all input data items with the exception of TmaxC were available. However, the absence of TmaxC disqualified the use of all methods except SEV method for which TmaxC was not required.

On 06/12/1990, only Epan data was available, hence the SEV method was used. On 07/12/1990, three climatic data items namely  $R_s$ , wind speed and Epan were not available. The absence of wind speed data disqualified all combination methods, the absence of  $R_s$  disqualified the RAD and RIT methods and the absence of Epan data disqualified the PEV and SEV methods. Hence, on this date, IHA method was used for which complete data were available. On 08/12/1990, only maximum and minimum temperature data were available, hence the HAR method was used. On 09/12/1990, again the M\_Y method was used because all data were available on that day.

The aforementioned discussion illustrated that how the REF\_ET software can successfully compute the daily  $ET_o$  estimates from any available climatic data obeying the user-specified priority list.

It is important to mention that under certain circumstances it is desired to compute  $ET_o$  estimates without any calibration. In this case, REF\_ET can be used in the same way as described above except that (in this case) the value of *REFET\_Use Option* data item in the input data file (Figure A.5, line#8) is replaced with 1. Then, the output file will give  $ET_o$  estimates without local calibration.

As described earlier (Section 3.5.4), in some irrigation systems, to compute the irrigation requirement only daily pan evaporation data is used instead of  $ET_o$ . Hence, in this case the \*.ETO output file is desired to have only pan evaporation estimates without any calibration. In order to achieve this goal, the REF\_ET software can be used in the same way as described earlier except that (in this case) in line#20 of input data file (Figure A.5) the SEV method is assigned the top priority (i.e. 1) and *REFET\_Use Option* data item in the data file (Figure A.5, line#8) is replaced with 1.

#### *(ii) $ET_o$ Estimates for Research Purposes*

As stated earlier (Section A.4), REF\_ET can also be used to produce  $ET_o$  estimates by all ten methods at the same time for research purposes. This is explained by the following example.

In order to compute the daily  $ET_o$  using all ten methods, the same input data file (Figure A.5) was used. The only difference in this case was that the value of *REFET\_USE Option* (Figure A.5, line#8) data item was specified as **A**. As stated earlier in Section A.4, the use of this option automatically ignores the priority order because all methods are used. In addition, if climatic data for certain method is not available, a dummy  $ET_o$  value of 99.9 is given for that method. The output file for this case is shown in Figure A.9. As can be seen from this figure, a value of 99.9 is shown for the methods for which climatic data were not available.

```

EXAMPLE .ETO      Tatura example      :Text-->5_Lines:
Calibrated Daily ETO (mm) estimates by ALL ETO_methods
99.9-->means climatic data NOT available for this method

---DATE---      M_Y* W_H* McI* P_M* RAD* RIT* PEV* SEV* IHA* HAR*
01/12/1990      99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9
02/12/1990           7.0  6.8  6.6  6.6  6.5  6.4  5.9  5.7  9.2  9.3
03/12/1990           5.9  6.0  5.7  6.0  6.3  6.1  4.0  3.7  6.6  6.9
04/12/1990      99.9 99.9 99.9 99.9  8.9  8.6 99.9  9.5  9.1  9.3
05/12/1990      99.9 99.9 99.9 99.9 99.9 99.9  9.3  9.5 99.9 99.9
06/12/1990      99.9 99.9 99.9 99.9 99.9 99.9 99.9 10.0 99.9 99.9
07/12/1990      99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9  8.8  8.2
08/12/1990      99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9 99.9  6.5
09/12/1990           7.2  7.5  7.2  7.1  7.3  6.9  6.3  6.3  6.0  5.9

:               :               :               :               :               :               :               :
:               :               :               :               :               :               :               :
:               :               :               :               :               :               :               :

```

Figure A.9 Typical Format of REF\_ET Output File using All ET<sub>o</sub> Methods

## APPENDIX B

### RAINFALL PREDICTION COMPUTER SOFTWARE

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## APPENDIX B

### RAINFALL PREDICTION COMPUTER SOFTWARE

As stated earlier (Section 4.6.6), the joint use of TPT and LL methods provides the best solution for reliable short-term rainfall predictions for data series with both zero and non-zero values. Therefore, a computer software package (RAIN\_PRE) was developed to predict short duration (7-14 days) rainfalls at specified probabilities of exceedance. In this section, a brief description of RAIN\_PRE package encompassing its salient features is described first, followed by the detailed description of various inputs of the software. Then, the use of the RAIN\_PRE package is explained through an example. A description is then presented to illustrate the applicability of this package for irrigation water savings at an on-farm level.

#### B.1 General Description of RAIN\_PRE Computer Software

The RAIN\_PRE package was developed aiming at saving irrigation water by making the best use of expected rainfall during the next irrigation period. While developing this package, a special consideration was given to its robustness, efficient computation, and user-friendliness. To achieve the above considerations, both the TPT with three transformations (i.e. power, log and square-root - Section 4.2.1) and LL methods were considered in the package, coded them with FORTRAN-77 to facilitate faster computations, and then menu-driven user interfaces developed to run under both DOS and Window environments.

The RAIN\_PRE software is composed of two computational components. The first component (PROG1) computes the necessary parameters for the TPT and LL methods, and the second component (PROG2) calculates the rainfall predictions. Both components are written in FORTRAN-77 code, each of which is supported by a number of subroutines. The source codes of PROG1 and PROG2, and their supporting subroutines

can be requested from the candidate. The flow chart of PROG1 and PROG2 are shown in Figure B.1 and B.2 respectively.

The package predicts the expected rainfall with a certain probability of exceedance over a pre-specified prediction period. In order to make the rainfall predictions compatible with various irrigation intervals of wide range of crops, a user-specified 5-30 day prediction period (which is also the irrigation interval) was incorporated in this package.

The software requires the historical rainfall record on a daily basis as its major input, and prediction period in days and exceedance probability (%). The other required information is entered through menus of the package. The details of these input data items are given in Section B.3.1. After entering the required input data, the package can be run to predict the expected rainfall at the specified exceedance probability levels over the given prediction period. The structure of RAIN\_PRE package is shown in Figure B.3.

## **B.2 Installation and Starting of RAIN\_PRE Software**

RAIN\_PRE can be run on a personal computer (PC) both in DOS and Windows environments. The installation of the RAIN\_PRE package requires the following steps:

- Insert the RAIN\_PRE package INSTALLATION DISK#1 in drive A: of the PC, and type INSTALL.
- Press F1 function key for DOS version installation, or F2 key for Windows version installation.
- Follow the instructions as prompted on the screen to complete the installation.

At the completion of the RAIN\_PRE installation, a subdirectory called RAIN\_PRE will be created in C: directory of the PC for the Windows (or DRAN\_PRE for DOS) version.

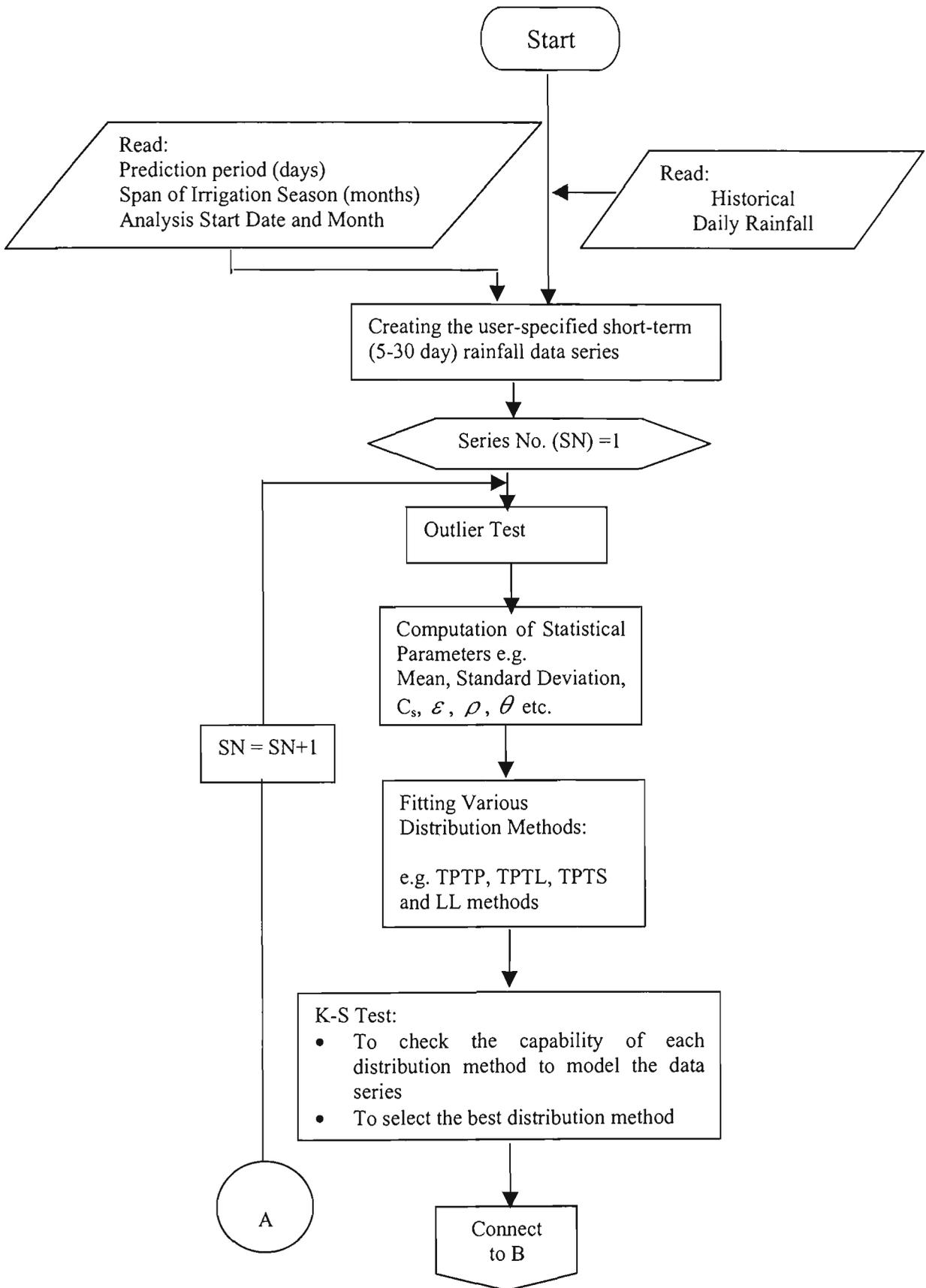


Figure B.1 Flow Chart of PROG1

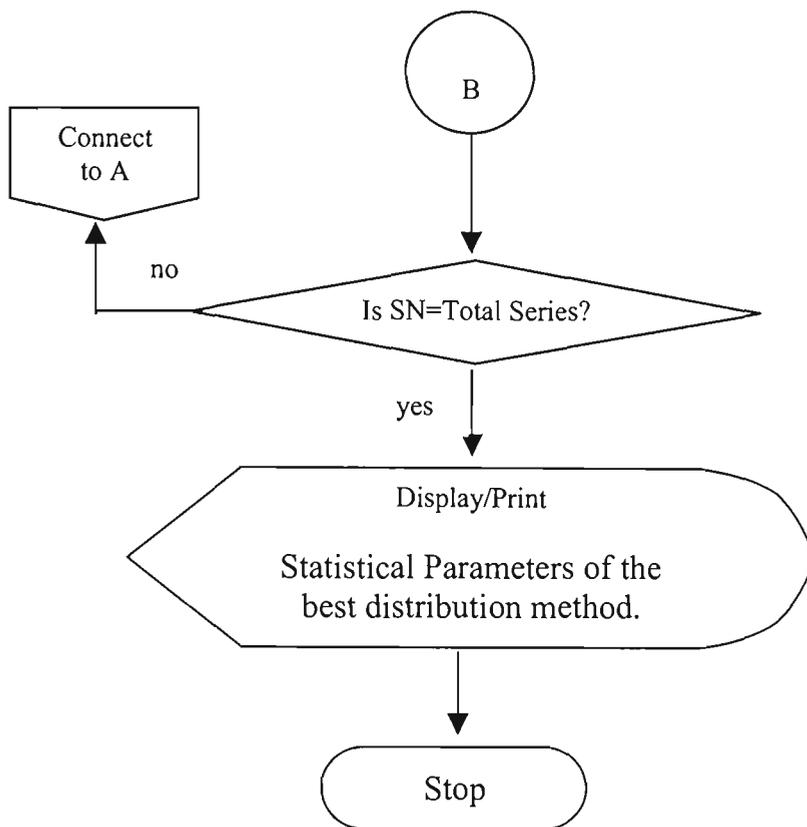


Figure B.1 Flow Chart of PROG1 (Continued)

Create a short-cut icon as for any other Windows package. Double-click the icon, and the Main Menu of the software is displayed as shown in Figure B.4. The CONTINUE button starts the RAIN\_PRE session by bringing the user to the next sub-menu namely *Historical Rain\_Data File General Information*. The EXIT button quits the RAIN\_PRE session. Sections B.3 to B.5 explain the Windows version of the Software.

At the completion of the installation for running under DOS, a sub-directory called DRAN\_PRE will be created in C: directory. To start the DOS version, the user is required to go to the DRAN\_PRE sub-directory and type DRAN\_PRE. It is important to mention that in this Appendix, the Windows version of the RAIN\_PRE package is described in detail. However, a brief description of the DOS version is also given in Section B.6. Two versions do not differ much in their operation.

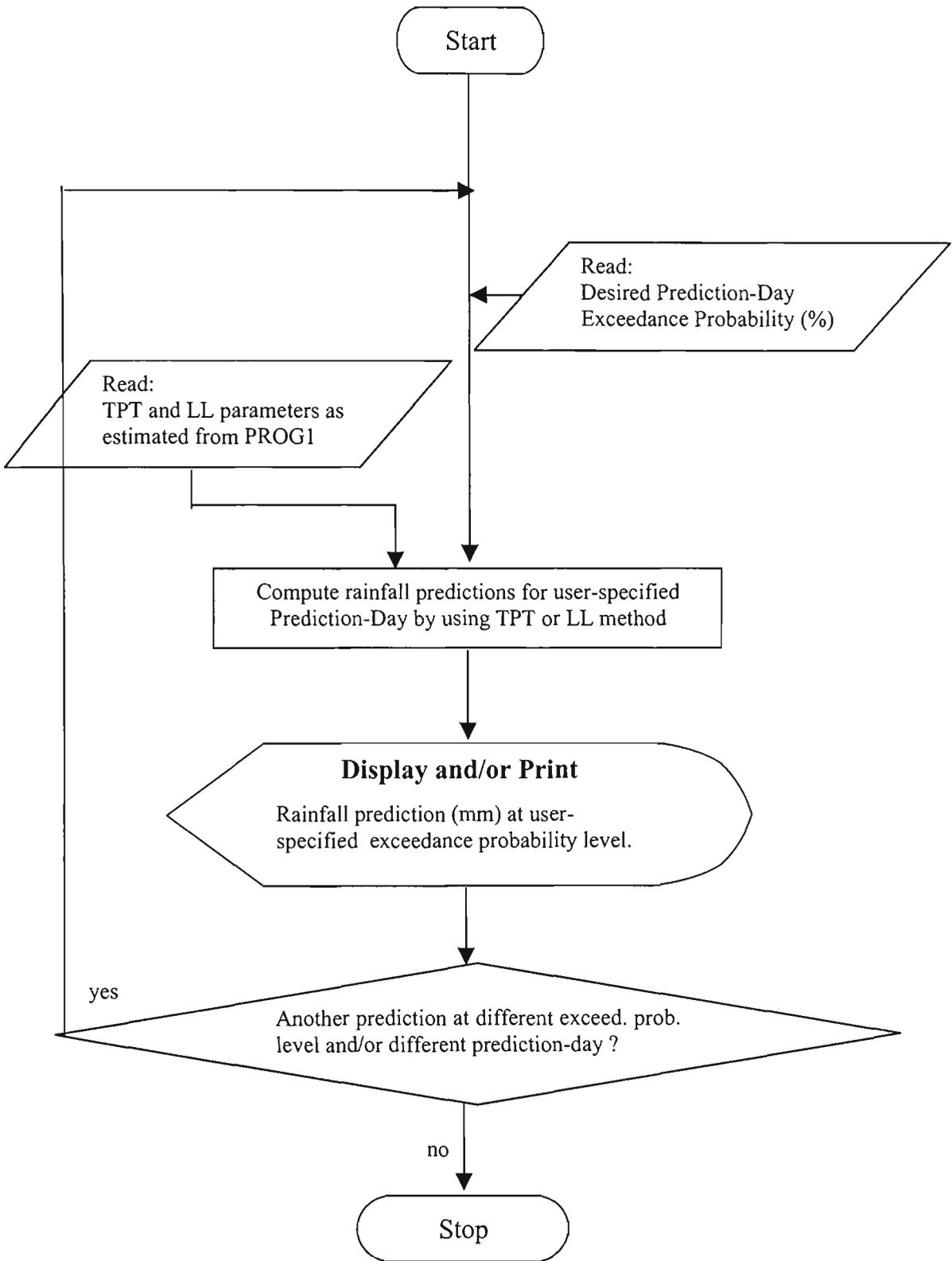


Figure B.2 Flow Chart of PROG2

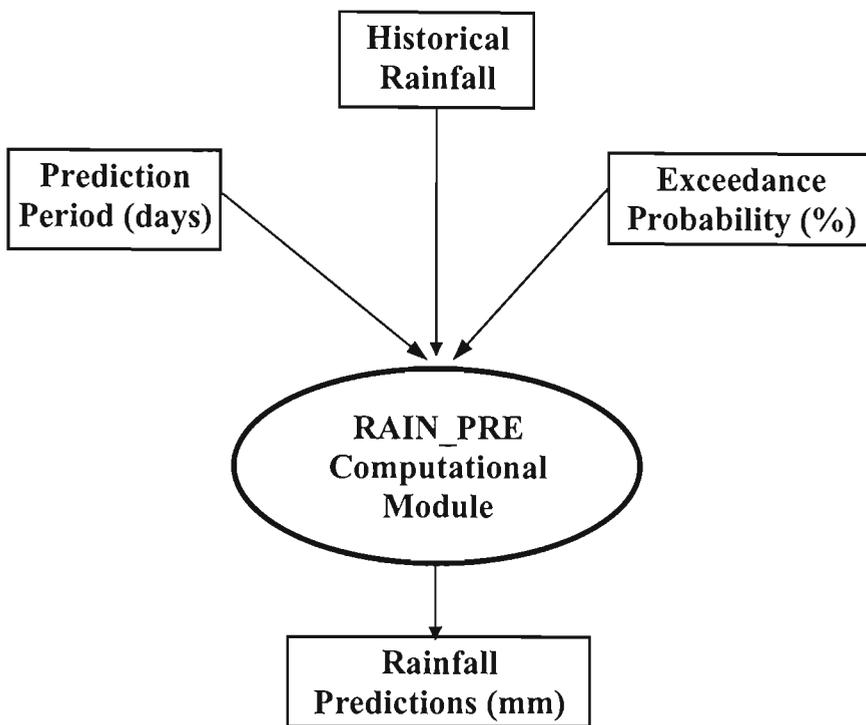


Figure B.3 General Execution Structure of RAIN\_PRE Software



Figure B.4 Main Menu of RAIN\_PRE

### B.3 Historical Rain\_ Data File General Information Sub-Menu

This sub-menu is used to input the general information about the input data file (i.e. historical daily rainfall file) which contains information about the rainfall data series. The format of the rainfall file is described in Section B.3.1. The information provided through this sub-menu is used by the RAIN\_PRE software for estimation of parameters of the TPT and LL methods. This sub-menu is shown in Figure B.5 with default values with the required format. It is important to mention that each input box (except the Station Name) requires the respective data value to be entered as a two-digit integer number. For example, a value of 1 is entered as 01. The various input data boxes of this sub-menu are explained as below.

**Hist. Rain\_Data** [X]

## Rain\_Data File General Information

Station Name

Total\_Span in Months (e.g. 12)  Ist\_Column Month's Calendar No. (e.g. 08)

Prediction\_Period in Days (e.g. 15)

Analysis\_Start Month's Calendar No. (e.g. 08)  Analysis\_Start Date (e.g. 15)

Update	Run	Next
Main Menu		

Hist. rain available (in IRR\_Yeras)--> 59  
 OK! 100% parameters computed  
 NO error encountered

Figure B.5 Rain\_Data File General Information Sub-Menu

(i) *Station Name*

This input data box refers to the name of historical rainfall input data file (of maximum eight characters) at a site, for which the rainfall prediction is desired. This filename is usually the name of the rainfall station at which the rainfall was recorded.

(ii) *Total\_Span in Months*

This input data item refers to the span of the irrigation season in months. For example, if irrigation season in the area starts on August 15 and continues through to May 15 of the next year, then the value of this box is 10, indicating ten months between the start and the end of the irrigation season. It is important to mention that the historical rainfall record in the rainfall data file must be provided for this entire span. Obviously, the *Total\_Span in Months* is limited to a maximum value of 12 months (i.e. one year).

(iii) *1<sup>st</sup>\_Column Month's Calendar No.*

This data item refers to the calendar number of the month, which appears in the first column of the rainfall data file (Section B.3.1). If August represents the first month given in the rainfall file, then the data input in this box is 08.

(iv) *Prediction\_Period in Days*

This refers to the number of days over which the rainfall prediction is desired. This usually corresponds to the irrigation interval of the crop under consideration. In order to cover a wide range of agricultural crops, a prediction period between 5-30 days can be considered.

(v) *Analysis\_Start Month's Calendar No.*

This data item refers to the calendar number of the month from which the statistical analysis is to be performed. If the user wishes the analysis to start from August, then the value of the calendar number is 08. However, when the season reaches January, the user may wish to do the analysis from January. Then, the value of the calendar number will be 01.

It is important to mention that depending on the timing of the irrigation season, the use of a dynamic value of this data item would facilitate faster run time avoiding unnecessary computations.

(vi) *Analysis\_Start Date*

This refers to the date from which the user desires the analysis to start. This input data item is a complementary component of *Analysis\_Start Month's Calendar No.* data item. For example, if the user wishes the analysis to start from 15<sup>th</sup> August, then the value of this data item is 15. Similarly, if the user wishes the analysis to start from 1<sup>st</sup> January, then this value is 01. It is worth mentioning that both *Analysis\_Start Date* and *Analysis\_Start Month's Calendar No.* would refer to values during the irrigation season.

***Update Button***

This button updates the information entered through the above six input boxes for the specified station. By double-clicking this button, a YES/NO option is prompted for the user to indicate whether or not to update the input data (entered through these six input boxes). The YES choice replaces the old information with the newly entered input values for the station in the \*.RGE file, where \* denotes the station name, provided this file already exists in the sub-directory (e.g. c:\RAIN\_PRE). If not, a new file is created by that name.

The NO choice does not update the above information. It is important to mention that if the RAIN\_PRE software is run for the first time and if NO option is chosen, then an error message indicating the non-existence of \*.RGE file appears. Hence, in this case, it is required that the \*.RGE file be created by using the YES option. The information in the \*.RGE is then copied to another temporary file called RAIN\_PRE.RGE for use by the software.

### ***RUN Button***

This button computes the TPT and LL parameters using the aforementioned inputs (i.e. stored in RAIN\_PRE.RGE file) for the station under consideration. These parameters are later utilised for rainfall predictions as explained in Section B.4.

If the input data are not correct or inconsistent, then the computations of RAIN\_PRE are terminated, giving an error message, which is stored in RAIN\_PRE.ERR file. The **Display Error** button can then be used to view the cause of error, which also indicates the remedy to correct the error. If the computations are completed successfully, an OK! message appears on the screen, which means the software is now ready for rainfall prediction estimates. In this case, the **Next** button can be used to proceed for rainfall predictions.

### ***Next Button***

The **Next** button takes the user to the next sub-menu designated as the Prediction Sub-menu. This sub-menu is described in Section B.4.

#### **B.3.1 Input Data**

As stated earlier (in Section B.1), the historical rainfall record is the major input required by RAIN\_PRE. This data is provided through an input data file called \*.RAN that is created by the user using a standard editor such as a DOS editor. The \* symbol represents the name of the file with maximum of eight characters, and RAN represents the extension of the file. For convenience, the name of the local rainfall station can be used as the data file name. A typical format of \*.RAN input data file is shown in Figure B.6.

As shown in Figure B.6, the first line is a general title line that shows the file name and the length of record available for this station. This line is not used in RAIN\_PRE calculations, but used for the output. The second line shows the starting calendar year for

```

File:TONGALB.RAN (Stn name: TONGALA :59 Years His. Rainfall record)
1929   AUG  SEP  OCT  NOV  DEC  JAN  FEB  MAR  APR  MAY  JUN  JUL
  1     0.0 17.3  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  2     0.0  3.8  6.6  0.0 19.3  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  3     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 13.5
  4     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  5     2.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  6     2.8  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  7     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  3.8
  8     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  9     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 10     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 18.8  0.0
 11    15.5  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  5.3  0.0
 12     0.8  0.0  0.0  0.0  0.0  0.0  0.0  0.0 20.3  0.0 26.4  0.0
 13     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.0  0.0  6.9  0.0
 14     2.0  0.0  7.6  0.0  0.0  0.0  0.0  0.0  0.5  0.0  0.0  0.0
 15     0.8  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 16     9.9  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 17     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.5
 18     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 19     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  2.8
 20     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.3
 21     3.0  0.0  0.0  0.0  0.0  0.0  0.0  0.5  0.0  0.0  0.0  0.0
 22     0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.3  0.0  0.0  0.0  0.0
 23     2.8  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 24     3.6  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  7.1  0.0  0.0
 25     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
 26     0.0  0.0  3.6  4.6  0.0  0.0  0.0  0.0  0.0  0.0  0.0  5.1
 27     0.0  0.0  0.0  0.0  8.9  0.0  0.0  0.0  0.0  0.0  0.0  5.3
 28     0.0  8.1  2.3  0.0  8.4  0.0  0.0  0.0  0.0  0.0  0.0  7.6
 29     0.0  0.0  0.8  0.0  0.0  0.0999.9  0.0  0.0  0.0  0.0  0.0
 30     0.0  0.0  0.0  0.0  0.0  0.0999.9  0.0  0.0  0.0  0.0  0.0
 31     0.0999.9  0.0999.9  0.0  0.0999.9  0.0999.9  0.0999.9  4.3
1930   AUG  SEP  OCT  NOV  DEC  JAN  FEB  MAR  APR  MAY  JUN  JUL
  1     0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  5.1  6.9  0.0  2.0
  2     6.1  0.0  0.0  0.0  0.0  0.0  0.0  3.0  0.0  0.0  0.0  0.0
  3     5.3  3.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  4     0.3  0.0  0.0  2.5  0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.0
  5     0.0  0.0  0.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0

  :     :     :     :     :     :     :     :     :     :     :     :
  :     :     :     :     :     :     :     :     :     :     :     :

```

Figure B.6 Typical Format of Historical Rainfall Input Data File

the data set, and the Julian calendar month's name in a three-character abbreviated form. This line is the real starting point of the historical rainfall record and used in RAIN\_PRE calculations. The calendar year in this line should have FORTRAN format I4, however,

the calendar months do not have a specific format, but written to align with daily rainfall data values in subsequent data lines. This line is followed by 31 lines which describe the day of each month and its daily rainfall.

As can be seen, data is in a typical tabular form. Data are entered in normal FORTRAN fixed format which is given in any FORTRAN language manual (e.g. Ellis, 1990). The fixed format for each of these 31 lines is (I4, 5x, 12F5.1). The missing data are entered as -99.9, and the non-existing (e.g. February 30<sup>th</sup>, April 31<sup>st</sup>, June 31<sup>st</sup> etc) rainfall data values are given by 999.99. As can be seen from Figure B.6, the lines 2 – 32 are repeated with appropriate rainfall data for the other years.

#### **B.4 Prediction Sub-Menu**

The Prediction Sub-menu is shown in Figure B.7. As can be observed from this figure, there are three input data boxes that require data to be specified by the user. These data are used for rainfall predictions. The four command buttons shown in Figure B.7 facilitate the operations of this sub-menu.

(i) *Desired Prediction\_Day*

This input data item refers to the starting day of the specified prediction period over which the rainfall prediction is made. This day is specified in a standard *dd/mm* format. Here, *dd* represents the date in a two-digit integer number, whereas *mm* represents the calendar number of the month as a two-digit integer. For example, *04/11* represents the prediction period that starts on 4<sup>th</sup> November.

(ii) *Exceedance Probability (%)*

This data item represents the exceedance probability level (%) corresponding to the rainfall prediction. This value is entered in FORTRAN format of F4.1.

Forecast Menu

## Prediction Sub\_Menu

Desired Prediction\_Day (dd/mm)

Exceed. Probability (%)

Leap Year (Y/N)

OK! Forecast done  
NO error encountered

Figure B.7 Prediction Sub-Menu

(iii) *Leap Year*

This data item indicates whether the current irrigation season falls in the leap year (i.e. includes Feb 29<sup>th</sup>) or not. If Y option is specified, the prediction calculations are made for a leap year. If N option is chosen, then the rainfall predictions are made for a non-leap year.

### ***Rainfall\_Prediction Button***

This button computes the rainfall predictions in mm for the desired prediction period (Figure B.5) corresponding to the given exceedance probability level (Figure B.7). The run status (i.e. whether or not the predictions are computed successfully) can be seen by clicking on the ***Display Error*** button. If the predictions are made successfully, then an OK! message appears in the display box. Otherwise, an error message is displayed in the display box.

### ***Next Button***

This button facilitates the viewing/printing of the rainfall predictions. This will display the *Prediction Display/Print Sub-Menu* as shown in Figure B.8. This is described in Section B.5.

### ***Main Menu Button***

This command button can be used to return to the Main Menu (Figure B.4) to quit the RAIN\_PRE session or to restart the rainfall predictions for another station.

## **B.5 Prediction Display/Print Sub-Menu**

This sub-menu is used to display and/or print the rainfall predictions. As can be observed from Figure B.8, there are five command buttons available to operate this sub-menu. These are explained below.

### ***Brief\_Prediction Display Button***

This button displays the rainfall prediction only for the single user-specified prediction period.

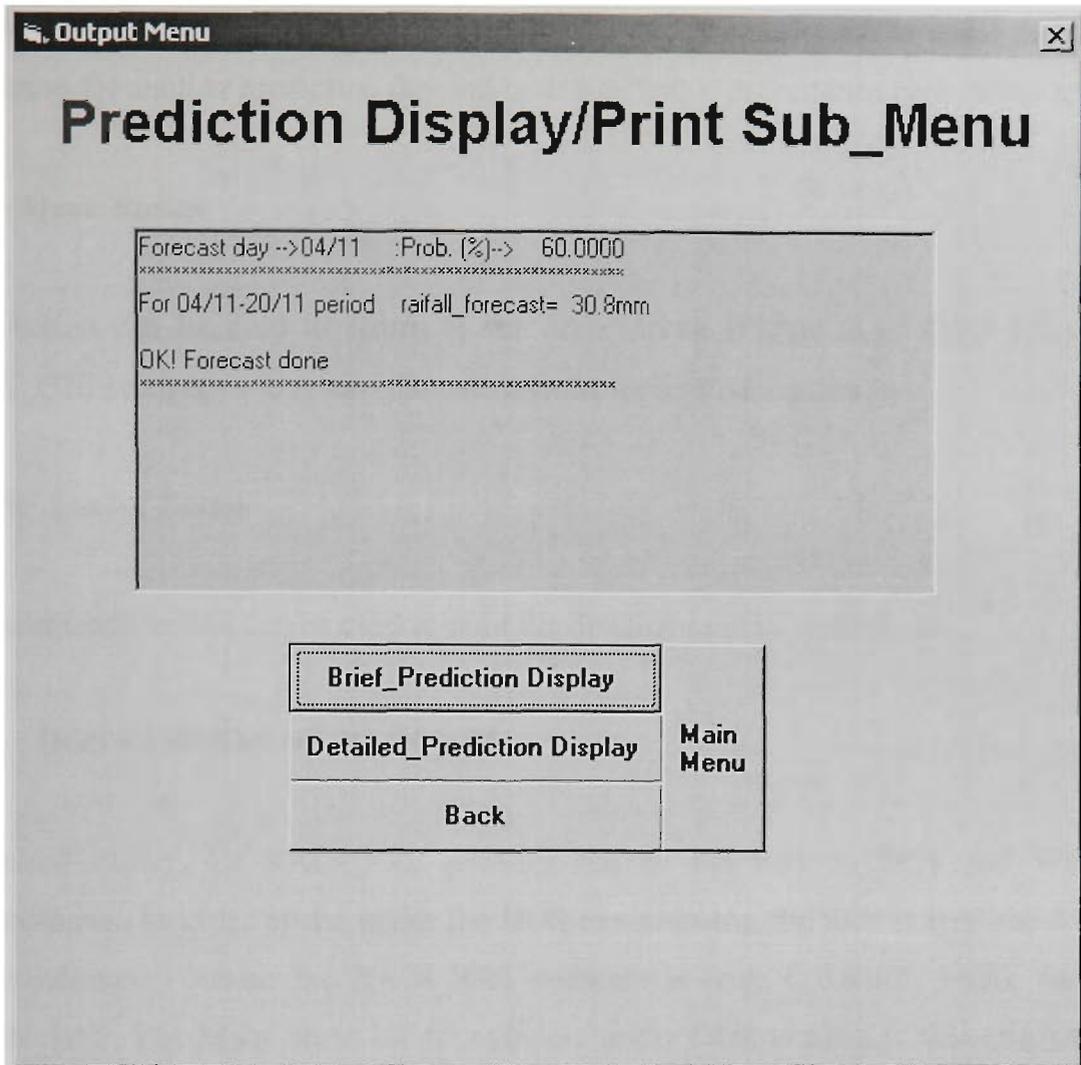


Figure B.8 Prediction Display/Print Sub-Menu

### ***Detailed\_Prediction Display Button***

This button displays the rainfall predictions for all irrigation periods starting from the *Analysis\_Start Date* (Figure B.5) to the user-specified *Desired Prediction\_Day* (Figure B.7).

### ***Back Button***

This button facilitates the RAIN\_PRE software to be run again to make predictions with different input data values without quitting the session. The user is taken back to the

*Prediction Sub-Menu* (Figure B.7). For example, the user may wish to make the rainfall prediction for another prediction day and/or at a different exceedance probability level.

### ***Main Menu Button***

This button can be used to return to the *Main Menu* (Figure B.4) either to quit the RAIN\_PRE session, or to restart the calculations for another station.

### ***Printer Symbol Button***

This command button can be used to print the detailed rainfall predictions.

## **B.6 DOS VERSION OF RAIN\_PRE**

As stated earlier, the RAIN\_PRE package can be run both in DOS and Windows environments. In order to run under the DOS environment, the user is required to go to the sub-directory where the RAIN\_PRE software is (e.g. C:\DRAN\_PRE), and type DRAN\_PRE. The Main Menu of the software under DOS version is then displayed as shown in Figure B.9. As can be observed from this figure, there are eight function keys to facilitate the operation of this menu. The function keys of this Main Menu are explained below.

### ***F1 Function Key***

This function key helps to see the list of existing \*.RAN input data files in the C:\DRAN\_PRE subdirectory.

```
*** WELCOME TO RAIN_PRE ***
Rainfall Prediction Computer Software
A H Azhar PhD Candidate VUT-Australia
*****
F9 -Run for TPT & LL Parameters Estimates
-----
*** (Use SAMPLE.* file for NEW Station)***
F1 -List of existing Stations
F2 -EDIT *.RAN   Historical Rainfall Data
F3 -EDIT *.RGE   General Information
-----
F6 -Display ERROR Messages
F7 -NEXT: Prediction Sub-Menu
F8 -HELP
F10 -EXIT
*****
PRESS A FUNCTION KEY TO SELECT
```

Figure B.9 Main Menu of RAIN\_PRE DOS-Version

***F2 Function Key***

By pressing this key, the user is requested to type the name of the desired station with a maximum of eight characters to select the input file This key also facilitates the editing of the historical daily rainfall data contained in the selected input data file. The user may update the daily rainfall data at this stage before the rainfall prediction parameters are computed.

If RAIN\_PRE is used for the first time, the user may enter the station name as SAMPLE. This will open a sample input data file. The data in this file can be changed to suit the local conditions, and can then be renamed and saved under a desired file name. This is the best way of preparing a new data file, because of the FORTRAN fixed format.

### ***F3 Function Key***

This function key is used to edit the general information (Section B.3) about the \*.RAN input data file that are stored in the \*.RGE data file. The contents of \*.RGE file are described in detail in Section B.3.

### ***F6 Function Key***

This key displays the error message after running RAIN\_PRE to compute the TPT and LL parameter estimates (using F9 function key which is described later). By pressing this key, the error message file (i.e. RAIN\_PRE.ERR) is displayed. If the parameters are computed successfully, then an OK! message is seen in this file. Otherwise, a message is displayed indicating the cause of error and suggestions to rectify the error.

If the computations of TPT and LL parameters are computed successfully, an OK! message appears in the error message file, which means the software is ready for rainfall prediction. In this case, the **NEXT** (i.e. F7) function key can be used to proceed for rainfall predictions.

### ***F7 Function Key***

This key takes the user to the next sub-menu namely **Prediction Sub-Menu** which is described in Section B.6.1.

### ***F8 Function Key***

This key provides some help regarding the use of the RAIN\_PRE Software.

### ***F9 Function Key***

This key computes the TPT and LL parameters using the aforementioned inputs (i.e. stored in RAIN\_PRE.RGE file) for the station under consideration. These parameters are later utilised for rainfall predictions, as explained in Section B.4.

### ***F10 Function Key***

This key can be used to quit the current RAIN\_PRE session.

## **B.6.1 Prediction Sub-Menu of DOS Version**

The Prediction Sub-menu of the DOS version is shown in Figure B.10. As can be observed from this figure, there are six function keys to facilitate the operation of this sub-menu. The function keys of this sub-menu are explained below.

### ***F1 Function Key***

This key is used to display/print the rainfall prediction for a single user-specified prediction period.

### ***F2 Function Key***

This key can be used to display/print the rainfall predictions for all irrigation periods starting from the *Analysis\_Start Date* (Figure B.5) up to the user-specified *Desired Prediction\_Day* (Figure B.7).

```
*** PREDICTION Sub-Menu ***
*****
F9 -Run for Rainfall Predictions
-----
F1 -Display/Print  Brief Prediction
F2 -EDIT *.RGE   Detailed Prediction
-----
F6 -Display ERROR Messages
F7 -BACK
F8 -HELP
F10 -EXIT
*****
PRESS A FUNCTION KEY TO SELECT
```

Figure B.10 Prediction Sub-Menu of RAIN\_PRE DOS-Version

***F6 Function Key***

This key displays the error message after running RAIN\_PRE for rainfall prediction estimates (i.e. using F9 function key which is described later). By pressing this key, the error message file (i.e. RAIN\_PRE.ERR) is displayed. If the predictions are computed successfully, then an OK! message is seen in this file. Otherwise, a message is displayed indicating the cause of error and suggestions to rectify the error. If the rainfall predictions are completed successfully, then F1 and/or F2 function keys can be used to display/print these predictions.

### ***F7 Function Key***

This key facilitates the RAIN\_PRE software to be run to make predictions for another station without quitting the session. The user is taken back to the Main Menu (Figure B.9).

### ***F8 Function Key***

This key provides some help regarding the use of the RAIN\_PRE Software.

### ***F9 Function Key***

This key computes the rainfall predictions in mm for the desired prediction period corresponding to the user-specified exceedance probability level.

### ***F10 Function Key***

This key can be used to quit the current RAIN\_PRE session, and to restart the session for another station.

## **B.7 Example**

In order to demonstrate the capability of the RAIN\_PRE software for short-term rainfall prediction, the software was used for the Tongala site in the Goulburn Irrigation Area (GIA) of Victoria, Australia. The historical rainfall records for this station were available for 59 years. The historical rainfall input data file was prepared according to the instructions in Section B.3.1, and is shown in Figure B.6.

The irrigation season at Tongala was from mid-August of a year through to mid-May of the following year. Hence, the *Total\_Span in Months* for the irrigation season was 10. As can be observed from Figure B.6, the first rainfall data column is August. Hence, for this

data file, the *1<sup>st</sup> Column Month's Calendar No.* was 08. For this station, it was desired to start the rainfall analysis from 15-August. Hence, the *Analysis\_Start Month's Calendar No.* and *Analysis\_Start Date* were input as 08 and 15. It was desired to predict the rainfall for a 17-day period commencing on 4<sup>th</sup> November at 60% exceedance probability level for use in irrigation schedules. Hence, for input boxes namely *Prediction\_Period in Days*, *Desired Prediction\_Day* and *Exceedance\_Probability(%)*, the data values used were 17, 04/11 and 60.0 respectively. All input data items for this example are shown in Figures B.5 and B.7.

After entering the data items in relevant input boxes of Figure B.5, the **Update** command button with YES option was used to save these information under the file name of TONGALB.RGE. The **Run** button was then used to compute the parameters for TPT and LL methods. After this, the **Display Error** button when clicked, indicated that all parameters were successfully computed and the software was ready for rainfall prediction calculations. Hence, the Prediction Sub-Menu (Figure B.7) was used to compute the rainfall predictions for the desired 17-day period as per details given in Section B.4. The **Display Error** button of Figure B.7 when clicked, showed that the rainfall predictions were successfully computed. Based on these details, the brief rainfall prediction for this example station is already shown in Figure B.8, while the detailed prediction is shown in Figure B.11. As can be seen in Figure B.8, only one rainfall prediction of **30.8mm** for a 17-day period starting from 04/11 to 20/11 is given. However, Figure B.11 shows the rainfall predictions from August-15 for a period of 17-days for each day of the irrigation season.

### **B.7.1 Use of RAIN\_PRE Predictions**

The rainfall predictions given by RAIN\_PRE can be used for *scheduling* and/or *pre-season planning* of irrigated crops, described as below.

```

TONGALB. (Stn name: TONGALA)
*****
File: RAIN_PRE.OUT
17_days Rainfall Predictions at various days
Predictions are at 60.0 % Exceedance level
*****

Rain_Prediction for ---> 15/08 - 31/08 = 34.5 mm
Rain_Prediction for ---> 16/08 - 01/09 = 35.4 mm
Rain_Prediction for ---> 17/08 - 02/09 = 34.7 mm
Rain_Prediction for ---> 18/08 - 03/09 = 38.6 mm
Rain_Prediction for ---> 19/08 - 04/09 = 38.2 mm
Rain_Prediction for ---> 20/08 - 05/09 = 37.2 mm

:      :      :      :      :      :
:      :      :      :      :      :
:      :      :      :      :      :

Rain_Prediction for ---> 30/10 - 15/11 = 26.6 mm
Rain_Prediction for ---> 31/10 - 16/11 = 28.9 mm
Rain_Prediction for ---> 01/11 - 17/11 = 29.0 mm
Rain_Prediction for ---> 02/11 - 18/11 = 28.7 mm
Rain_Prediction for ---> 03/11 - 19/11 = 28.6 mm
Rain_Prediction for ---> 04/11 - 20/11 = 30.8 mm
-99.9mm means NO Prediction_Method available

```

Figure B.11 Typical Format of Detailed Rainfall Prediction

## Scheduling

Scheduling provides the time and amount of water required for the next irrigation during the irrigation season. It is important to mention that in this thesis, the terms *scheduling*, *real-time scheduling* and *operational planning* are interchangeably used to refer the same thing. If the irrigation requirement without considering the expected rainfall for the next irrigation is known, then the amount of expected rainfall during the period followed by this irrigation can be subtracted from this irrigation requirement to save the irrigation water. This is explained as below.

For illustration purposes, assume a fixed interval (e.g. 17-days) based irrigation schedule which is due on 4<sup>th</sup> November with an irrigation requirement of 5.70cm. It should be

noted that this irrigation requirement does not consider the expected rainfall, which is the standard procedure in the GMIA of Victoria (Australia). It was assumed in this case that this schedule was known from an irrigation scheduling computer software such as the one described in Appendix C (i.e. IRPSAEV computer package). For this irrigation schedule, if the expected rainfall can be estimated at a certain exceedance probability level, then the irrigation requirement computed by the IRPSAEV-software can be made less by an amount equivalent to this rainfall prediction to save the irrigation water. Thus, the brief rainfall prediction of 30.8mm given by RAIN\_PRE (Figure B.8) if subtracted from the IRPSAEV-software irrigation requirement, would give an *effective irrigation requirement* of 2.62cm (i.e. 5.70-3.08). This *effective irrigation requirement* can then be used by the farmer when ordering irrigation water deliveries for the next irrigation. Depending upon the rainfall prediction value, the farmer can reduce the water order for the next irrigation. This will help to save an appreciable amount of irrigation water by making the best use of future rainfall, which would otherwise be lost. However, it should be noted that the rainfall prediction is a probabilistic estimate and hence, the farmer takes some risk in adopting these predictions. Nevertheless, the predictions are based on scientific analysis, which will reduce the cost of water to the farmer.

The rainfall prediction made by RAIN\_PRE does not indicate when it falls. Therefore, in case of upland irrigated crops (i.e. those crops which are irrigated up to the field capacity level, e.g. wheat, pastures etc.), it is possible that the rain might fall when the soil moisture content has already reached at its critical level that can reduce the yield. Hence, in order to avoid the moisture stress problem in upland crops, it is suggested that depending upon critical growth stages of the crop (e.g. flowering and grain filling which are critical stages) a relatively higher value of exceedance probability level should be adopted. However, in case of lowland irrigated crops (i.e. those crops which are grown in ponding water, e.g. paddy crop), this matter is not so critical. In these crops, the already ponding water can provide a temporary buffer to compensate the crop water use, if the predicted rainfall is received late.

## Pre-season Planning

Pre-season planning refers to the estimation of approximate total irrigation water requirement at a farm before the start of an irrigation season. More details of pre-season planning are given in Sections C.2, C.6 and C.9.3. Pre-season planning can help the farm manager to decide how much area to bring under cultivation for a certain crop to maximise the net return. Generally, in pre-season planning the irrigation schedules (i.e. time and amount of irrigation water) are estimated for the entire season without due consideration to the future rainfall. If for each irrigation schedule, the expected rainfall can be estimated at certain exceedance probability level, the irrigation water requirement computed can be made less by an amount equivalent to the predicted rainfall for respective schedule. This technique would facilitate to save significant amount of irrigation water by making the best use of future rainfall, which would otherwise be lost. This aspect is explained below in detail.

For example (as will be shown later in Sections C.6 and C.9.3), the pre-season planning for pasture crop at Tongala prompted 10 irrigation schedules for 1997-98 irrigation season without considering the future rainfall. These irrigation schedules are given in Figure C.12. Among these ten schedules, one was for 4/11/1997 to 20/11/1997 (i.e. 17-days) period with an expected irrigation requirement of 5.70 cm. If an exceedance probability of 60% is considered, then the rainfall prediction of 30.8mm given in Figure B.8 can be subtracted from 5.70 cm value to give an effective irrigation water requirement of 2.62cm for this period. Similarly, for all other irrigation periods as given in Figure C.12 (e.g. 21/11/97 to 6/12/97, 7/12/97 to 21/12/97 etc.) the rainfall predictions can be made using the RAIN\_PRE software. As per aforementioned procedure, if the rainfall predictions are subtracted from the irrigation requirement of respective period, it will lead to significant water savings.

## APPENDIX C

### IRRIGATION PLANNING SCHEDULING AND EVALUATION (IRPSAEV) COMPUTER SOFTWARE

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## APPENDIX C

# IRRIGATION PLANNING SCHEDULING AND EVALUATION (IRPSAEV) COMPUTER SOFTWARE

### C.1 INTRODUCTION

In this chapter, the Irrigation Planning Scheduling and Evaluation (IRPSAEV) computer software is described. The IRPSAEV package was developed using the fundamental concepts of water balance simulation and irrigation timing criteria described in Chapter 5, loosely integrating them with the REF\_ET and RAIN\_PRE software. First (as in Section 5.8), various components of the water balance model and irrigation timing criteria described in Chapter 5 were coded in FORTRAN-77 to facilitate faster computations, and then menu-driven user interfaces developed to run under both DOS and Window environments. The outputs of REF\_ET and RAIN\_PRE are used in the IRPSAEV package as inputs. Thus the IRPSAEV package was developed as a robust, computationally efficient and user-friendly package so that it can be used on commercial farms with least difficulty of operation. The IRPSAEV software is composed of one computational component (PCROP), which is supported by a number of subroutines. The flow chart of PCROP is shown in Figure C.1. It is important to note that Figures C.1(a) and (b) represent the planning and scheduling modes respectively, which will be explained later in Sections C.2, C.6 and C.7. The main purpose of the package is to make efficient use of available water at an on-farm level.

A daily time step was considered in the IRPSAEV software to support the farmer's decision on when to irrigate and how much to irrigate based on daily field observations of parameters related to the crop water use. The package requires only a few readily available input parameters related to the soil and crop characteristics, daily reference crop evapotranspiration ( $ET_0$ ) data and the irrigation scheduling records up to the current day

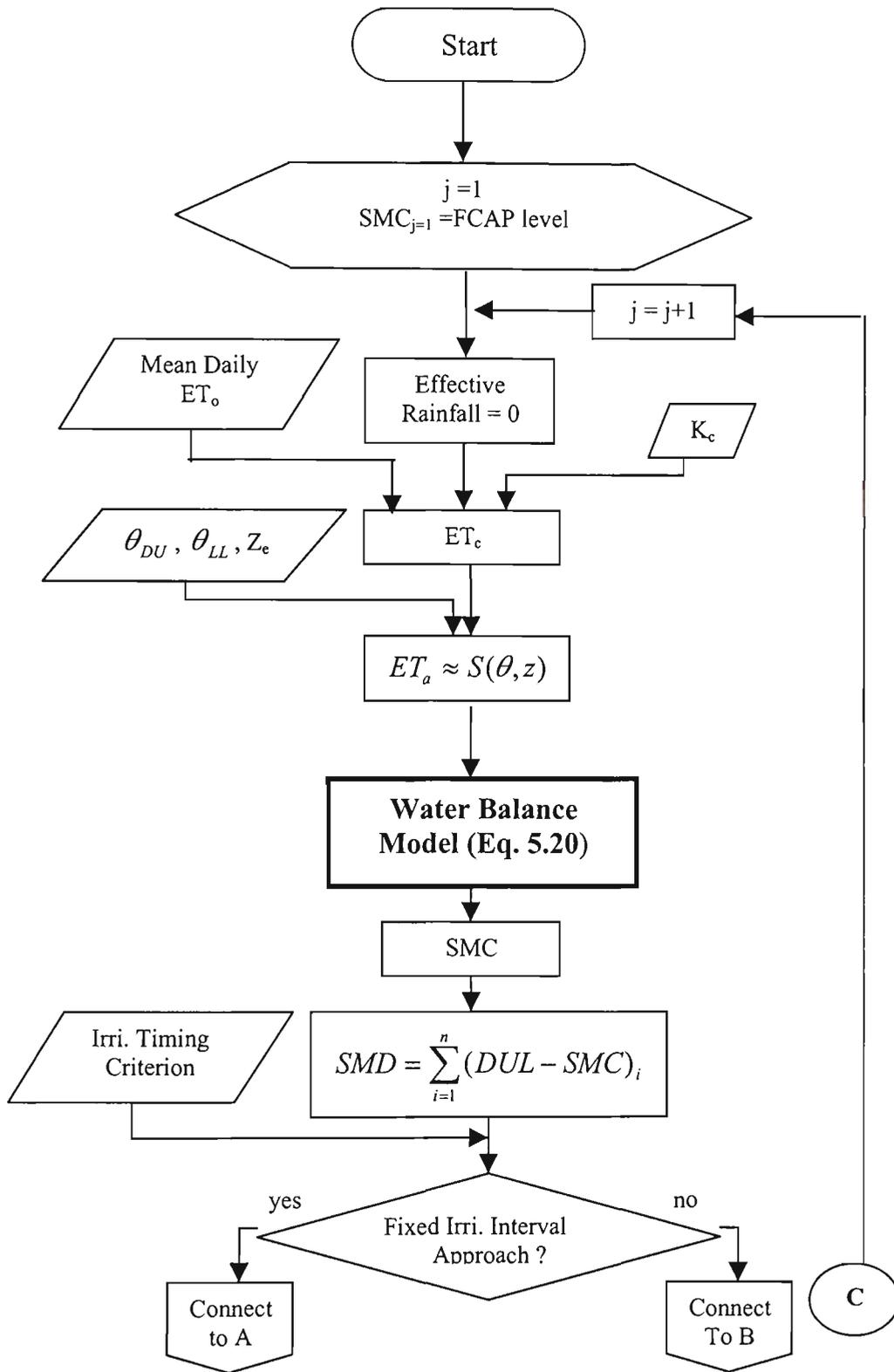


Figure C.1(a) Flow Chart of PCROP for PLANning Mode

(PLAN Mode flow-chart cont.)

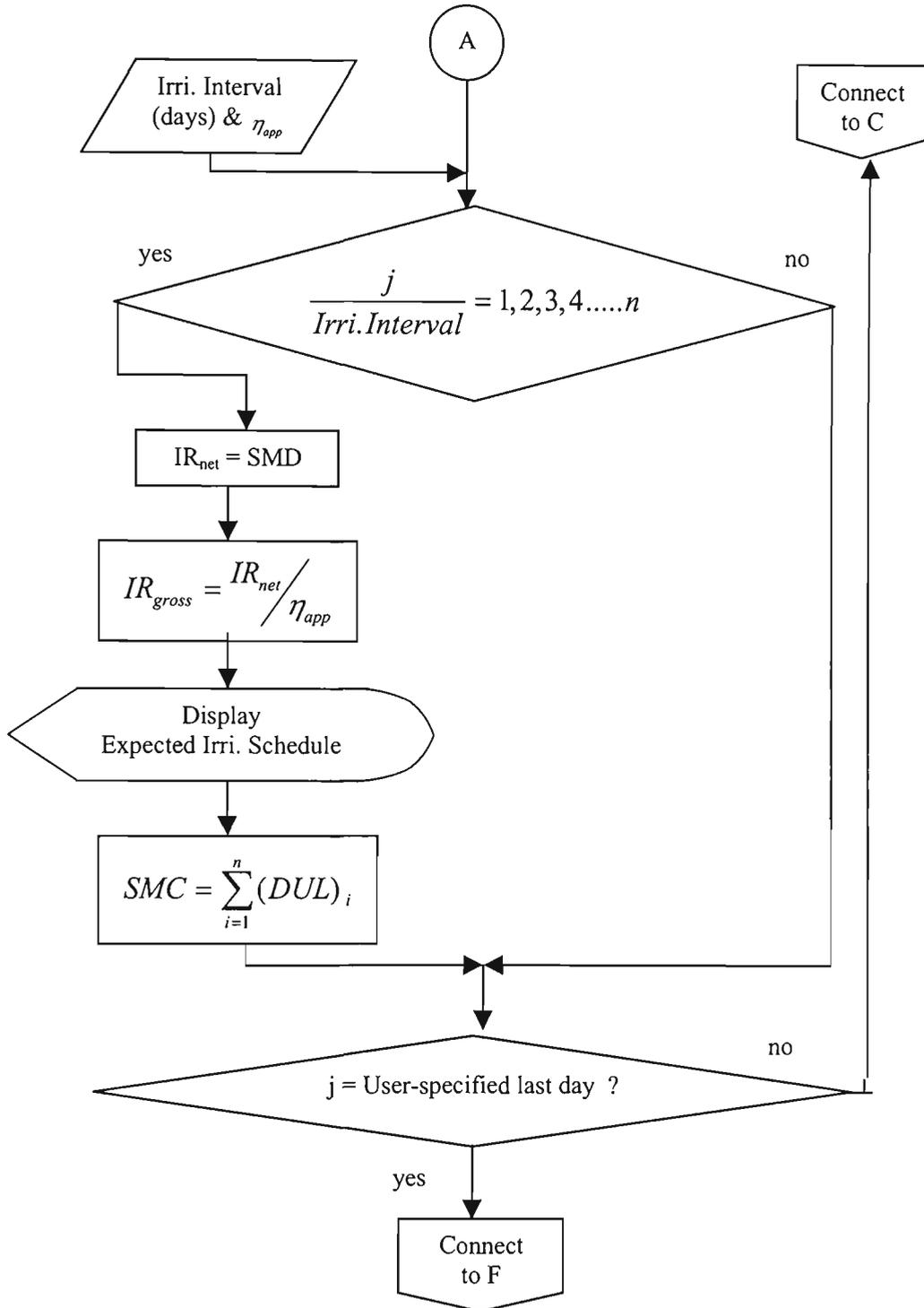
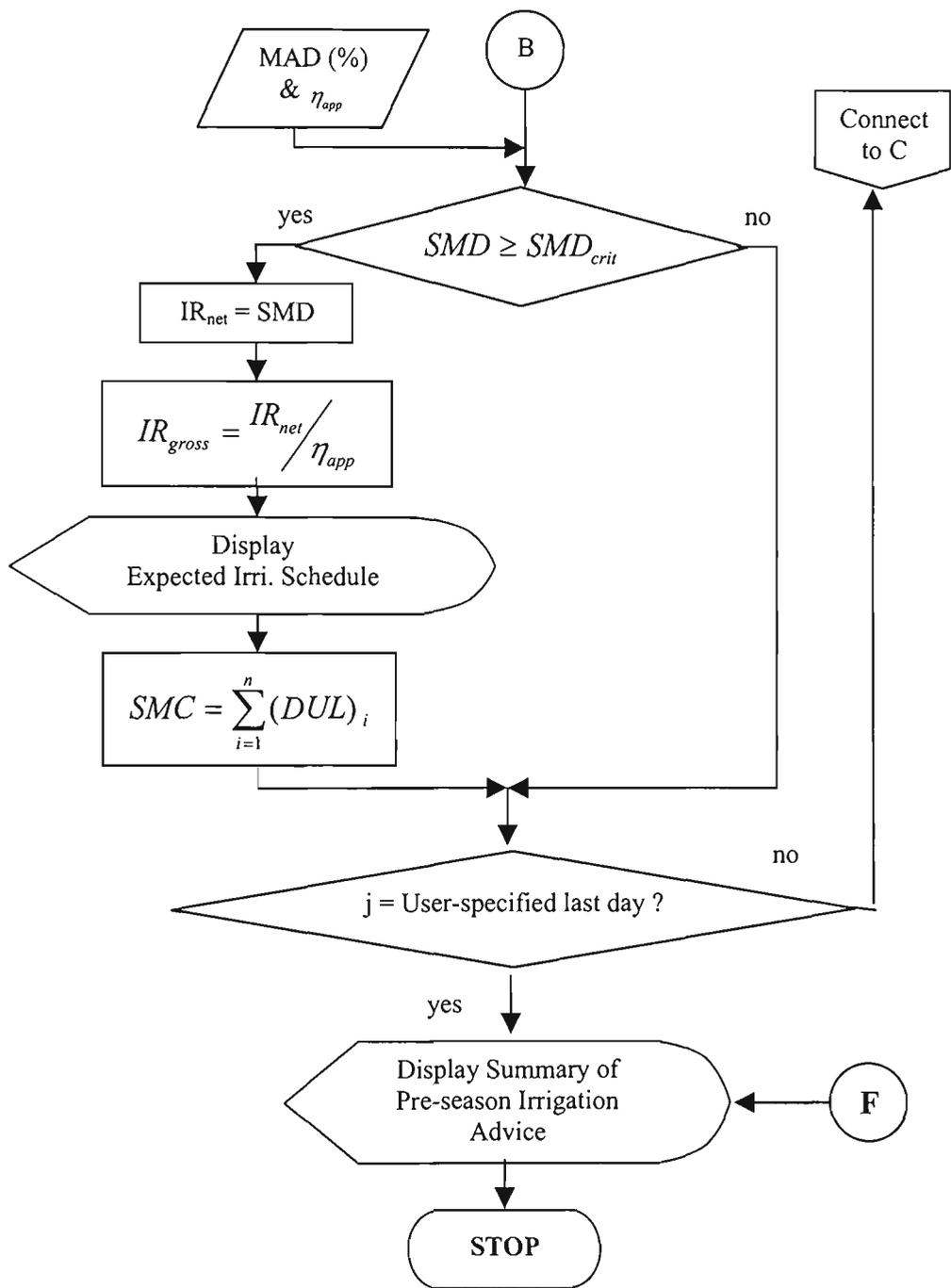


Figure C.1(a) Flow Chart of PCROP for PLANning Mode (continued)



(Legend is given in Figure C.1b)  
 Figure C.1(a) Flow Chart of PCROP for PLANning Mode (continued)

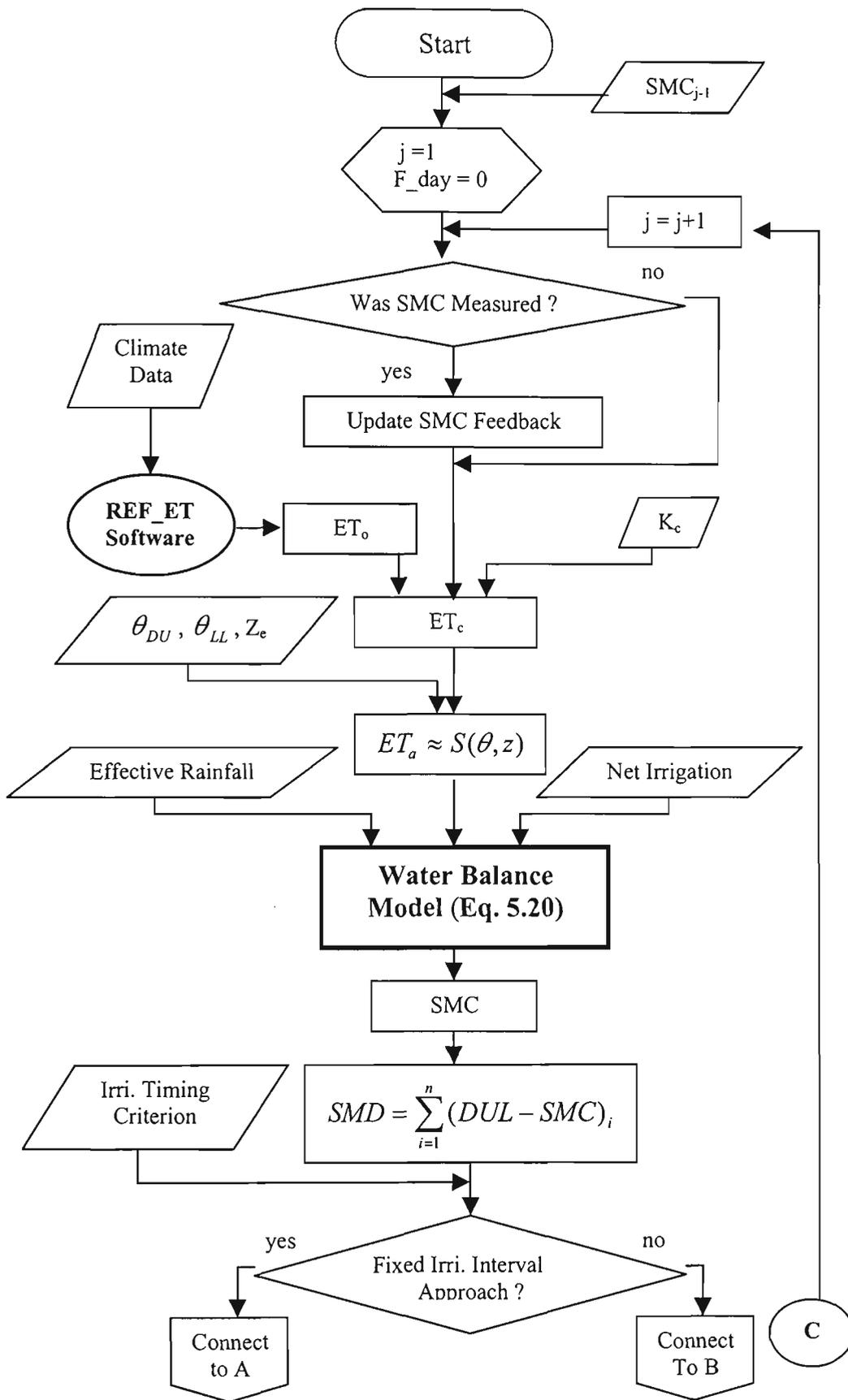


Figure C.1(b) Flow Chart of PCROP for SCHEDuling Mode

(SCHE Mode flow-chart cont.)

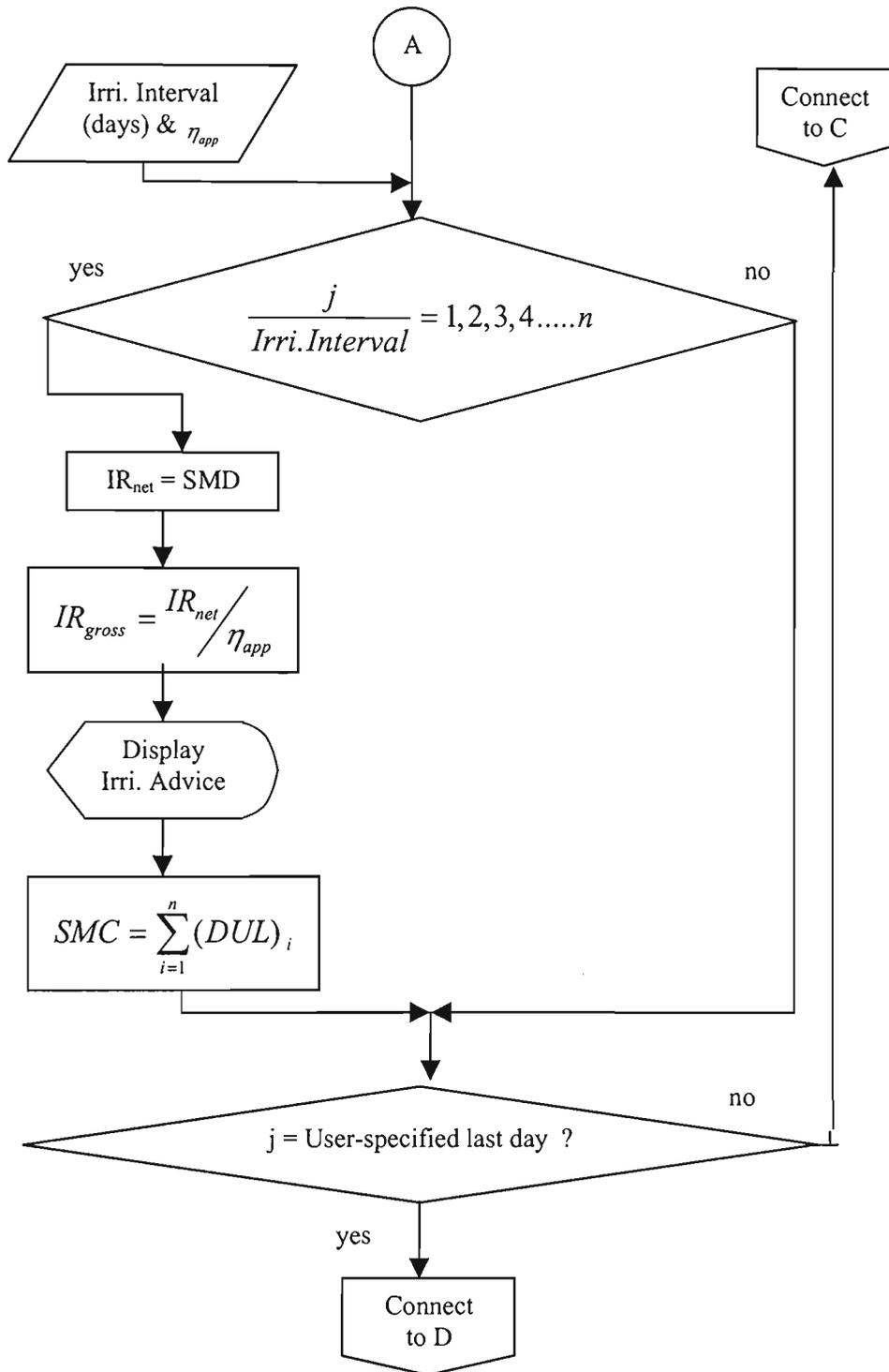


Figure C.1(b) Flow Chart of PCROP for SCHEDuling Mode (continued)

(A continued)

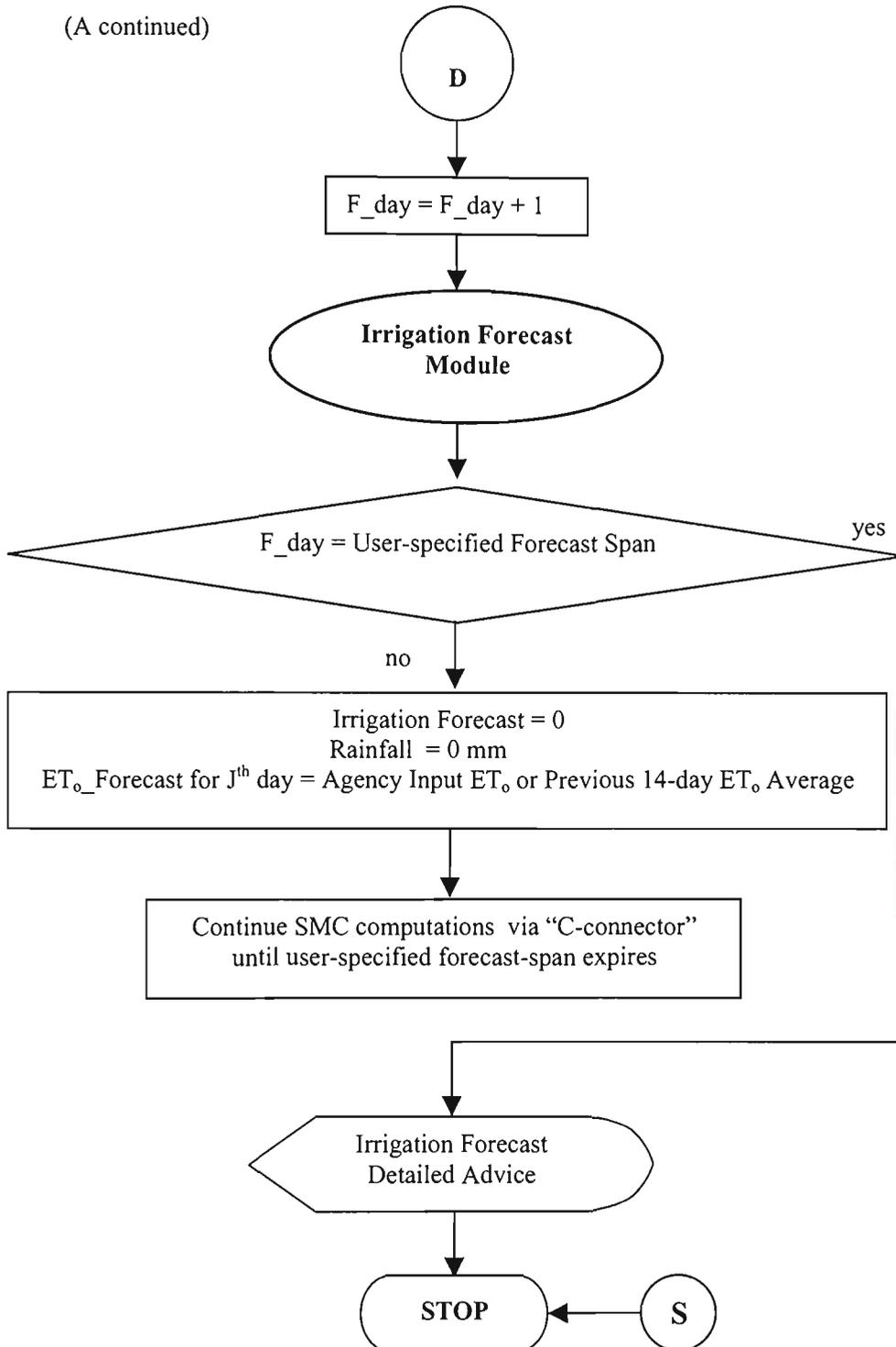


Figure C.1(b) Flow Chart of PCROP for SCHEDuling Mode (continued)

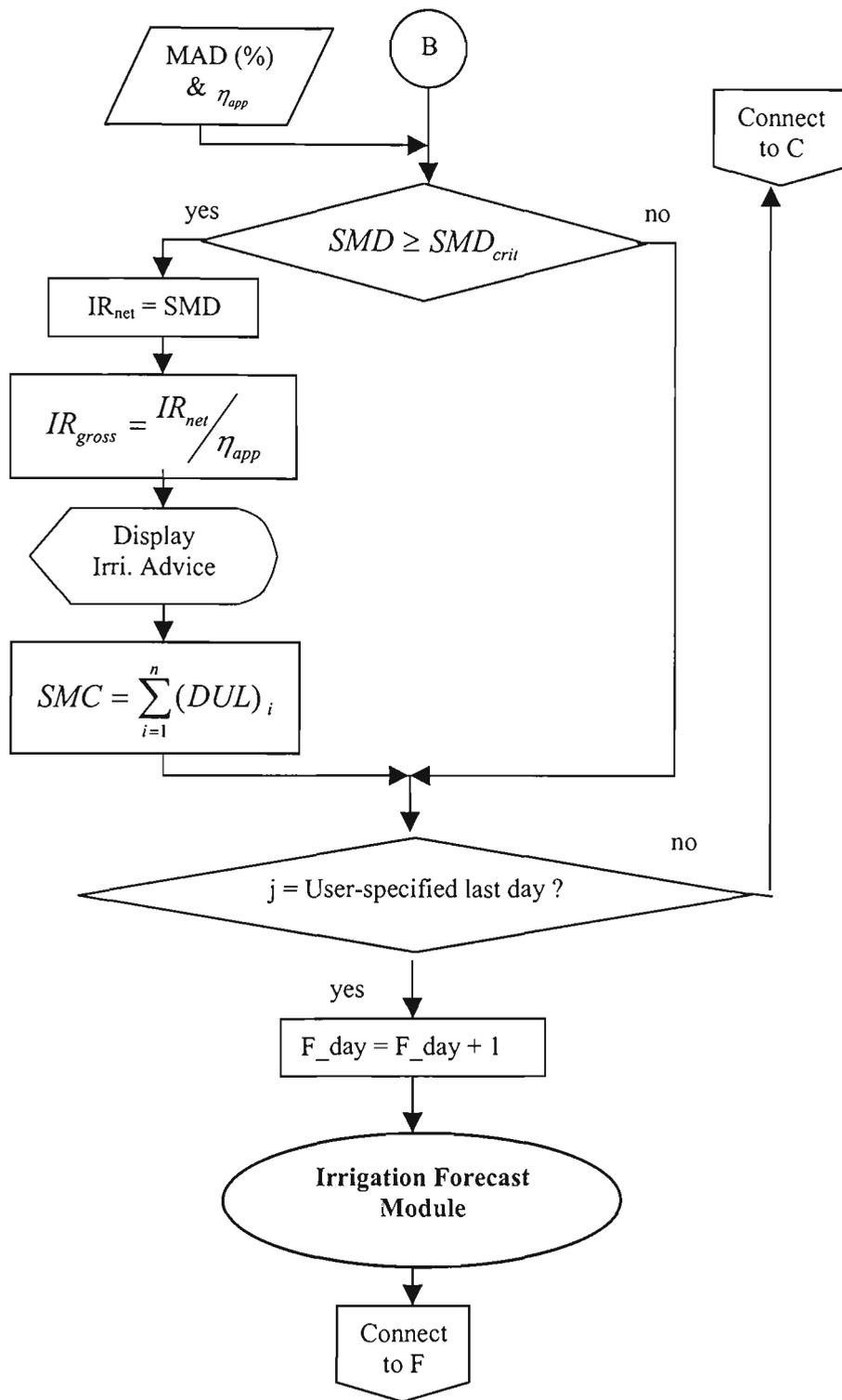


Figure C.1(b) Flow Chart of PCROP for SCHEDuling Mode (continued)

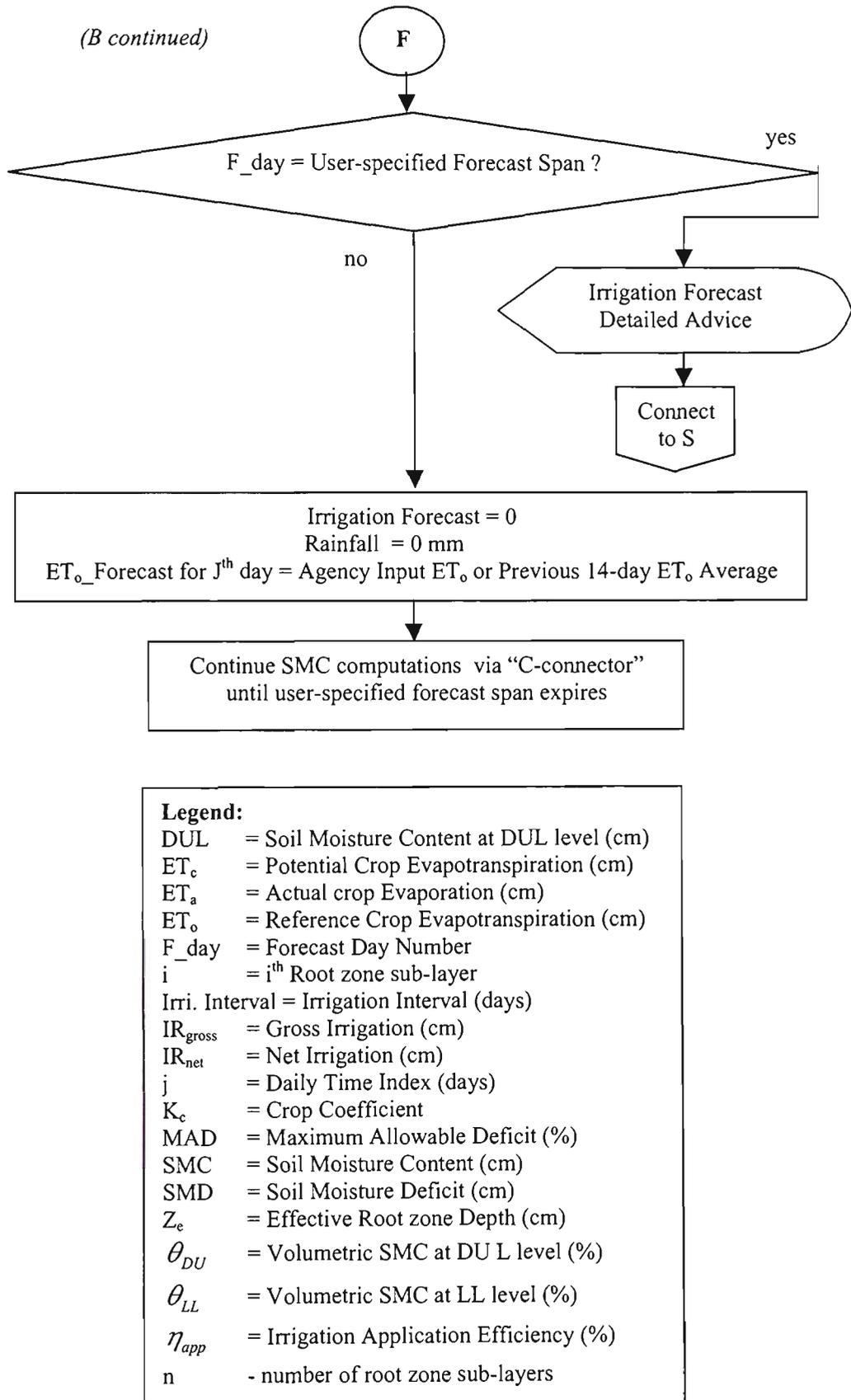


Figure C.1(b) Flow Chart of PCROP for SCHEDULING Mode (continued)

The input parameters are entered through a set of input data files that can be edited for any changes to include and/or to update the data by the user at any time while using the IRPSAEV package. The details of these input data files are given Section C.4. After having entered the input data, the package can be run to give the irrigation schedules (i.e. time and amount of irrigation) under three major operational modes viz.: I) *Planning mode*, II) *Scheduling mode*, and III) *Evaluation mode*. The general execution structure of the IRPSAEV package is shown in Figure C.2. The input data required for execution of these modes are presented in Table C.1.

As stated in Section 5.9, the IRPSAEV software is presented as a separate appendix since it is the major component of the thesis that links all previous chapters. A brief description of the IRPSAEV package encompassing its salient features is described first, followed by a detailed description of various inputs of the software. The modes of operations of the IRPSAEV package are described then. A case study is presented to illustrate the applicability of the IRPSAEV package as an effective irrigation management tool at farm level. The calibration technique is described then in order to use under distinct climatic and environmental conditions. Finally, the limitations of the IRPSAEV computer software are outlined at the end of the appendix.

It is worth noting that in this appendix the terms IRPSAEV package, IRPSAEV computer model and IRPSAEV model are interchangeably used to refer to the irrigation planning scheduling and evaluation computer software developed in this thesis.

## **C.2 Installation of IRPSAEV Software and Starting**

The IRPSAEV software can be run on a personal computer (PC) both in DOS and Windows environments. The installation of the IRPSAEV package requires the following steps:

- Insert the IRPSAEV package INSTALLATION DISK#1 in drive A: of the PC, and then type INSTALL.

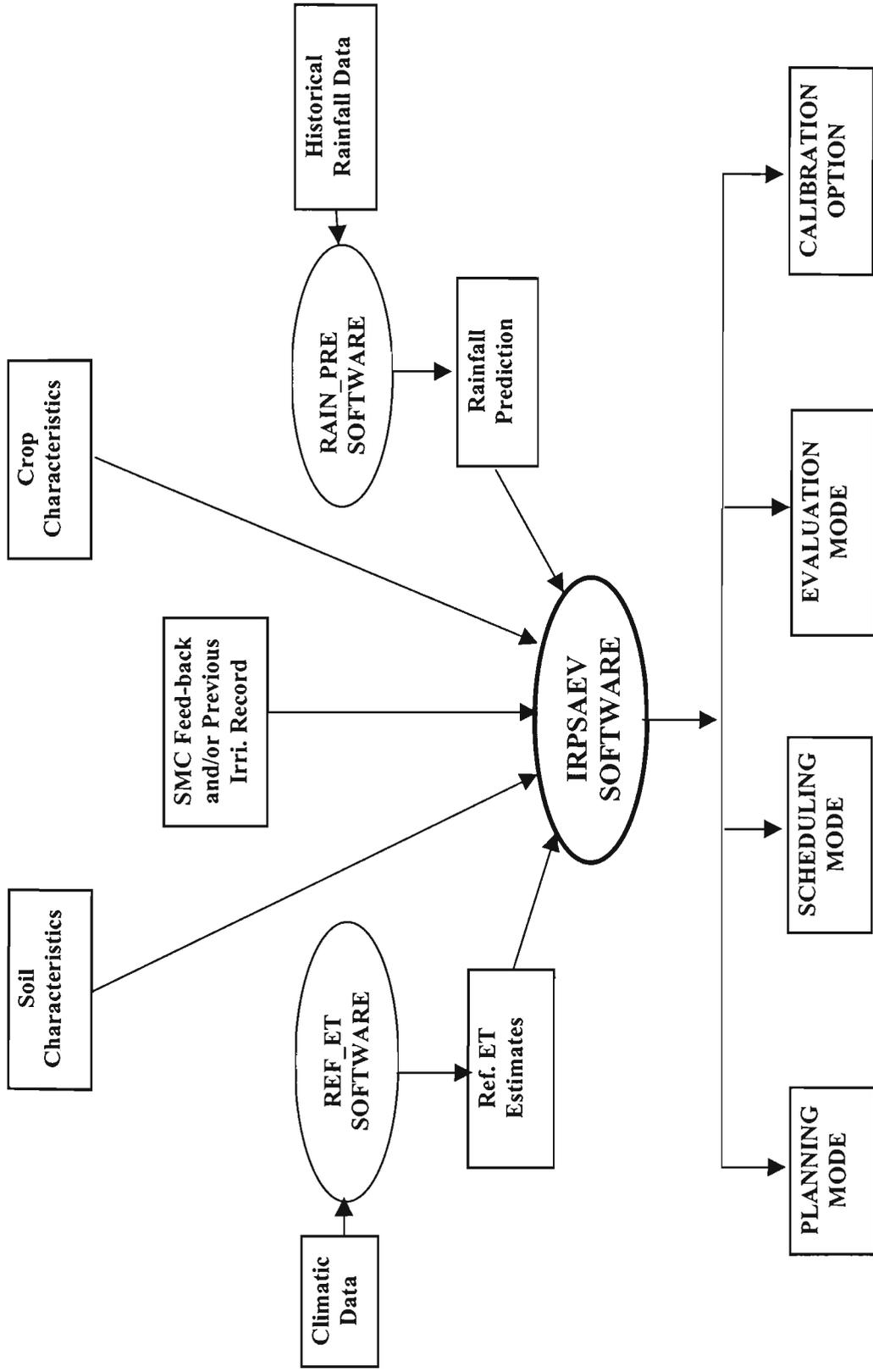


Figure C.2 General Execution Structure of IRPSAEV Package

Table C.1 Input Data Required for IRPSAEV Package

Data Type	PLAN Mode	SCHE Mode	EVAL Mode	CALI Option
Soil Characteristics	X	X	X	X
Ref. ET	X	X	X	X
Crop Characteristics	X	X	X	X
SMC Feed-back and/or Previous Irri. Record		X	X	X
Rainfall Prediction	X	X		

- Press F1 function key for installation of the DOS version, or F2 key for installation of the Windows version.
- Follow the instructions as prompted on the screen to complete the installation.

At the completion of the installation, a subdirectory called IS is created in the main C: directory for the Windows version (or DIS for the DOS version) with six sub-directories under IS (or DIS) viz. i) STOR, ii) DATA, iii) PLAN, iv) SCHE, v) EVAL, and vi) CALI. Create a short-cut icon as for any other Windows package to run on Windows version. For use of the DOS version, the user is required to go to the DIS subdirectory and type DIS. It is important to mention that in this chapter, the Windows version of the IRPSAEV package is described in detail. However, a brief description of the DOS version is also given in Section C.11. Both versions do not differ much in their operation.

Under Windows run mode, the Main Menu of the software is displayed as shown in Figure C.3. As can be observed from this figure, there are eight command buttons available to facilitate the operation of the Main Menu. The function of these command buttons is given below.

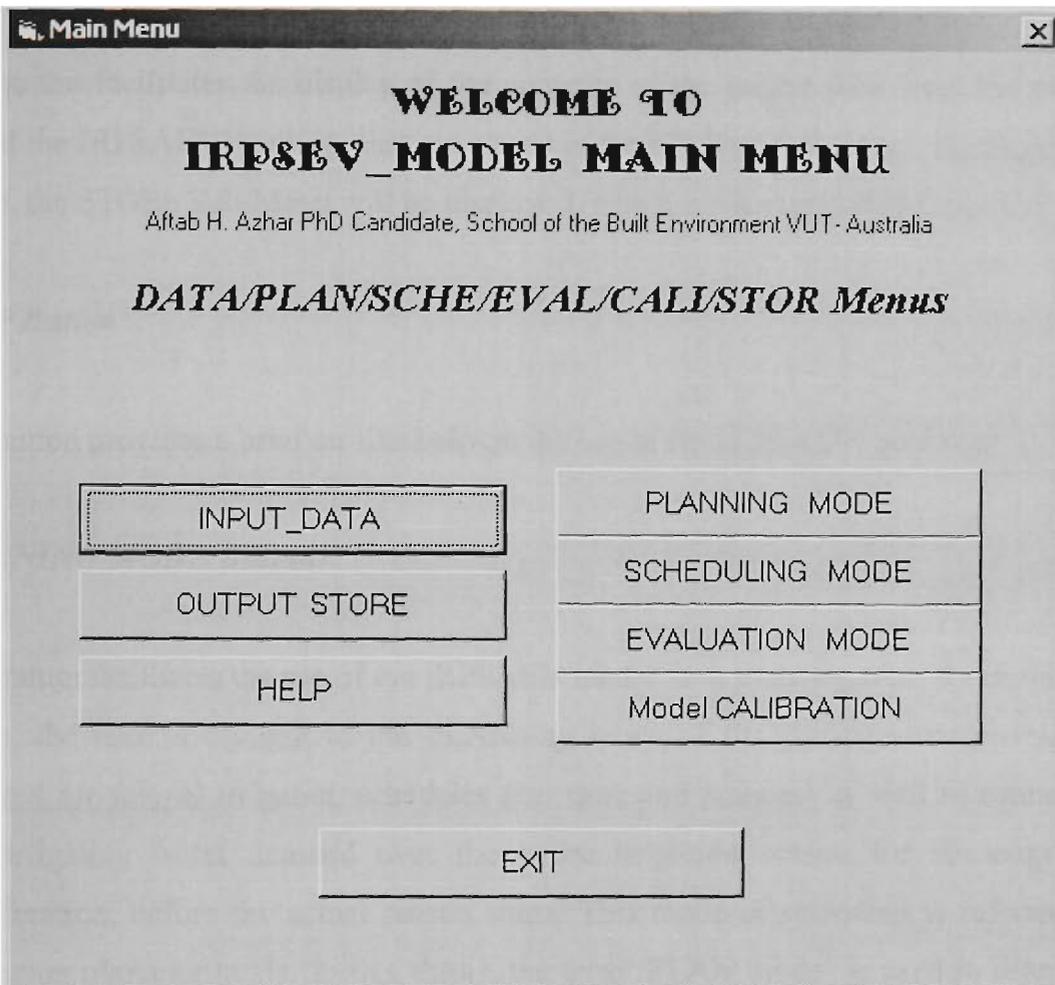


Figure C.3 Main Menu of IRPSAEV Computer Software

### ***INPUT\_DATA Button***

This button facilitates creating new input data files, and editing and updating the data in existing data files for use in various operational modes of the IRPSAEV package. By clicking this button, the INPUT\_DATA Sub-Menu will be displayed, which is discussed in Section C.3.

### ***OUTPUT STORE Button***

This button facilitates the display of the contents of the output files from the previous runs of the IRPSAEV package that are stored in the STOR subdirectory. By clicking this button, the STORE Sub-Menu will be displayed, which is discussed in Section C.5.

### ***HELP Button***

This button provides a brief on-line help on the use of the IRPSAEV package.

### ***PLANNING MODE Button***

This button facilitates the use of the IRPSAEV model as a planning tool. By clicking this button, the user is brought to the PLANning mode of the package that provides the expected (or future) irrigation schedules (i.e. time and amount) as well as estimates of total irrigation water demand over the entire irrigation season for the crop under consideration, before the actual season starts. This mode of operation is referred to as pre-season planning mode. In this thesis, the term 'PLAN mode' is used to refer to the pre-season planning mode of the IRPSAEV package. This mode requires the mean daily reference evapotranspiration (Section 3.5.4 and 3.6.4) data to render itself as a planning tool. The output of the PLAN mode can be used by the user for planning purposes. The details of PLAN mode is given in Section C.6.

### ***SCHEDULING MODE Button***

This button facilitates the use of the IRPSAEV model as a real-time operational (or scheduling) tool. By clicking this button, the user is brought to the SCHEduling mode of the IRPSAEV package that provides the schedules (i.e. time and amount) for the next irrigation during any time of the irrigation season. The scheduling mode of the IRPSAEV model is described in detail in Section C.7.

In a normal *scheduling mode* (hereafter referred to as the SCHE mode), the model gives the updated soil moisture contents (SMC) information of the root zone including the user-specified next 0-14 days SMC forecasts, both in tabular as well as graphical forms. This information can be used to see whether an irrigation is required during that forecast period. If an irrigation is forecasted, the expected date along with the amount of irrigation is also given. The farmer then can use this information (i.e. date and amount for next irrigation) to decide when to request water for irrigation from the local water authority and/or to plan other farm/social activities. Forecasting SMC also allows for improved short-term planning by the farmers leading to an integration of on-farm systems with the main water supply system.

#### ***EVALUATION MODE Button***

This button facilitates the use of the IRPSAEV model as an evaluation tool. By clicking this button, the user is brought to the evaluation mode of the package. This helps the farmer to compute scientific-based irrigation schedules which can be used to compare (or evaluate) the simple judgement-based irrigation schedules adopted by the farmer during the past irrigation season. In this thesis, the evaluation mode is referred to as *EVALuation (or EVAL) mode*. The EVALuation mode of the IRPSAEV model is described in detail in Section C.8.

#### ***IRPSAEV\_Model CALIBRATION Button***

This button facilitates the calibration of the IRPSAEV model to suite local conditions. By clicking this button, the user is brought to the CALibration option of the package that provides the model predicted SMC values on a daily basis. These SMC values can be used for calibration of IRPSAEV model under local conditions. The calibration aspect of the IRPSAEV model is described in detail in Section C.10.

***EXIT Button:*** This button quits the IRPSAEV session.

### C.3 INPUT\_DATA Sub-Menu

This sub-menu is used to prepare the input data files for the IRPSAEV model, and is shown in Figure C.4. The information provided through the input data files is used by the IRPSAEV software to produce irrigation schedules for the desired mode (i.e. planning, scheduling and evaluation - Section C.2). As can be seen from Figure C.4, there is only one input data box namely *Farm Name* that requires a farm name to be specified by the user. The eight command buttons shown in Figure C.4 facilitate the operation of this sub-menu.

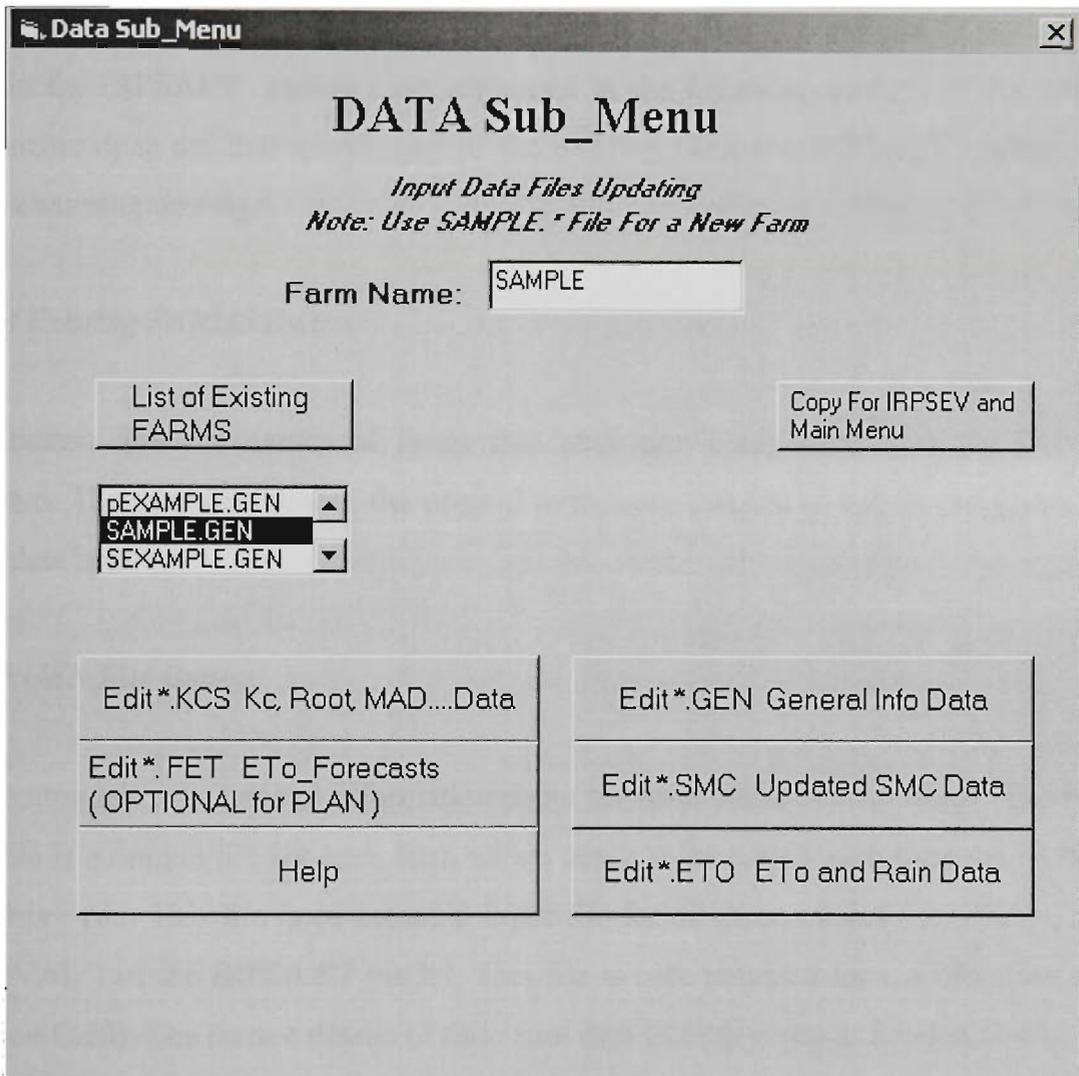


Figure C.4 DATA Sub\_Menu of IRPSAEV Software

### *Farm Name*

This input data box refers to the name of farm (of maximum eight characters) for which the irrigation schedules are desired. This name is usually assigned to the set of input data files for use by the IRPSAEV package. If IRPSAEV is used for the first time, the user may enter the station name as SAMPLE. This will open a sample input data file which after updating the data can be renamed and saved as the desired farm name. If the user is required to edit a previous file, click the corresponding EDIT \*.??? button. It is important to mention that \* refers to the file name whereas ??? represents the DOS extension of the file that is unique to the type of data contained in the file. The various DOS extensions used in the IRPSAEV package are explained in the following section. If the specified farm name does not match with any of the existing files, the IRPSAEV software will issue a warning message.

### *List of Existing FARMS Button*

This button lists the names of farms that were previously used with the IRPSAEV software. The user can choose the desired farm from this list to use in the *Farm Name* input data box.

### *Edit \*.GEN File Button*

This button edits the general information about the farm under consideration. The \*.GEN data file is a unique file for each farm which needs to be edited each time the IRPSAEV model is run. This file is an essential input file for all three modes (i.e. PLAN, SCHE and EVAL ) of the IRPSAEV model. This file is also required for CALibration option (Section C.10). The format details of this input data file are given in Section C.4.1.

#### *Edit \*.SMC File Button*

This button edits the soil moisture contents, SMC (%volume or %mass) data item stored in the \*.SMC file. This file is an essential input data file for SCHE mode and CALibration option, and not required for any other modes. The format detail of this input data file is given in Section C.4.5.

#### *Edit \*.ETO File Button*

This button edits the daily  $ET_o$  input data item contained in the \*.ETO data file. This file can be the output file from the REF\_ET software (Appendix A). Alternatively, the  $ET_o$  values can be directly input into this file. This file is an essential input data file for all modes of the IRPSAEV package except for PLAN mode. This file is also required for CALibration option. The format detail of this input data file is given in Section A.7.

#### *Edit \*.KCS File Button*

This button edits the input data items of the crop coefficient, root depth, rainfall correction factor and maximum allowable depletion contained in the \*.KCS input data file. This file is an essential input data file for all operational modes of the IRPSAEV package including CALibration option. The format details of \*.KCS input data file are given in Section C.4.2.

#### *Edit \*.FET File Button*

This button edits the daily forecast  $ET_o$  input data item contained in the \*.FET input data file. This file is required for pre-season PLAN and SCHE modes of the IRPSAEV software and not for other modes. The format details of this input data file are given in Section C.4.6.

*HELP Button:* This button provides a brief on-line help on the use of the IRPSAEV package.

### ***Copy for ISMODEL and Main\_Menu Button***

After having updated the respective input data files for the desired IRPSAEV model operational mode through edit buttons in Figure C.4, clicking this button copies these input data files (of selected farm) as ISMODEL.\* files. The \* refers to the 3-letter DOS extension of the input data file to distinguish the type of data contained in the file. Copying preserves the original input data files from being corrupted if some error occurs during the IS run. In addition to copying, clicking this button brings the user to the Main Menu (Figure C.3) to allow the user to choose the desired mode for IRPSAEV model run.

## **C.4 INPUT DATA FILES**

There are three major categories of input data items used in the IRPSAEV model. These include soil characteristics, plant characteristics and climatic data. These input parameters are stored in a set of six input data files which are subsequently used by the IRPSAEV model to suite the specific operational mode. As discussed earlier, the IRPSAEV model can be run under three operational modes. The essential input data files required for these operational modes with their 3-letters DOS extensions are summarised below:

- For PLANning mode, three input data files namely \*.GEN, \*.KCS and \*.FET are required.
- For SCHEduling mode, four input data files with extension of GEN, KCS, ETO and SMC respectively are required.
- For EVALuation mode, three input data files with extension of GEN, KCS and ETO respectively are required.

These input data files can be created using the *DATA Sub-Menu* (Figure C.4 of Section C.3). When these files are prepared for the first time, they can be created using *SAMPLE.\** files, where \* represents the 3-letter DOS extension of the data file that distinguishes the type of data contained in the file. These *SAMPLE.\** files (hereafter referred to as *SAMPLE* data files) can be edited by the user to suite the specific site conditions, and then saved under a user-specified farm name of maximum 8 characters. This is the best way to prepare these files. Some input data files once created, can be used throughout the irrigation season without further changes and even during the following future irrigation seasons with little editing of dates. However, the remaining files do need to be updated from field observations by the user during the course of the irrigation season.

#### **C.4.1 *SAMPLE.GEN* Data File**

The *SAMPLE.GEN* input data file contains general (or miscellaneous) information about various aspects of input data relevant to the farm under consideration. This data file is a unique file for a farm which needs to be edited each time the *IRPSAEV* model is run under selected operational mode (i.e. *PLAN*, *SCHE* or *EVAL*). Thus, this file is an essential file for all three modes. A typical format of the *SAMPLE.GEN* input data file is shown in Figure C.5.

It is important to mention that in Figure C.5 every line starts with a '#' symbol followed by a numeric value up to 2 digits. The '#' and the numeric value are present in Figure C.5 just to refer the line number in the data file for explanation purposes. In the actual input data file, these 3 columns do not exist. Also, it should be noted that the input parameters of this file are ordered in such a way that once these parameters are entered, they do not need to be changed during the whole irrigation season except the line#5 and line#8 data items which need to be edited each time the *IRPSAEV* package is run during the irrigation season. However, as will be shown later (Section C.9.4), depending upon the local conditions the input data items in line#10 and 11 may also need to be edited during the irrigation season.

```

# 1 File:SAMPLE.GEN      General Data File for IS_model  [22/09/99 time-->22:17]
# 2 Crop --->: Perennial Pasture
# 3 General Information: [1997-98 Irrigation Season]
*****Column No.-->*****#####$$$$$$$45!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# 5 Model EXECUTION Mode (PLAN: SCHE: EVAL)      :PLAN
# 6 Irrigation Season START Date ----->       :15/08/1997
# 7 Calculation Start (or True) Date----->    :25/10/1997
# 8 Irrigation Season END Date ----->         :09/04/1998
*****
#10 FOUR IRR_Delays DATES & adds (Ist & 2nd) -->:31/03/1998 1  00/00/0000 0
#11 (A10,I2,5X,A10,I2) (3rd & 4th) -->:00/00/0000 0  00/00/0000 0
*****
#13 CROP_Code & FORECAST_Period(days)...(I2&I2) : 1 7 Warn_MAD(%)-->20.00
#14 Max. NO.of ROOT_sublayers & EACH THICK.(cm) :01 40.00
#15 MAD_OPT?; SICK_OPT?; & Irri_INTERVAL(days)  :Y Y 07
#16 Waterlogged or ZERO_ET DAYS after Irri(I2)-->:03
#17 SMC_UPDATE (Y/N); & Unit (%VOL or MASS)-->:Y VOL
#18 Non_Efect_Rain Subtract or Multiply (S or M):S
#19 SATU_SMC of EACH Sub_layer (%)...(F6.2) -->: 46.00 46.00 46.00 46.00
#20 EXTRAirri_SMC of EACH Sub_layer (%) = -->: 5.00 0.00 0.00 0.00
#21 FCAP_SMC of EACH Sub_layer (%)... = -->: 41.00 41.00 41.00 41.00
#22 WILT_SMC of EACH Sub_layer (%)... = -->: 15.00 16.74 20.99 20.91
#23 BULK DENSITY of EACH Sub_layer(gm/cc)= -->: 1.54 1.51 1.47 1.51
#24 Cropped AREA (Hect) ==-->: 50.00
#25 Root EXTRACTION Pattern(%) for 4-Sublayers->:000. 000. 000.00
#26 Optional & need NO Change(F6.2)3-Sublayers->:000. 000. 000.
#27 2-Sublayers->:000. 000.
*****
#29 FORECAST_ETo for Scheduling (GIV or ???)---->:???.00.
#30 Calibrated_IS use Option..? (Y/N) ----->:N
#31 Calibration_Target Theta (%)...(F6.2) ---->:000.00
#32 Theta_Adjustment FACTOR (%)...(F6.2) ---->:000.00
*****For Planning ONLY *****
#34 FORECAST_ETo: Are below 5_Parameter OK?(Y/N):Y
#35 Ist Gaussian Parameter...(F6.2) YO---->: 6.92
#36 2nd Gaussian Parameter...(F6.2) A---->: -6.58
#37 3rd Gaussian Parameter...(F6.2) XO---->:188.26
#38 4th Gaussian Parameter...(F6.2) D---->: 01.00

```

Figure C.5 SAMPLE.GEN Input Data File

As shown in Figure C.5, the first four lines are general title lines that show the file name and other related information. These four lines are not used in IRPSAEV calculations, but used for the output to describe the run. As can be observed from Figure C.5, from line#5 (inclusive) onwards each of the data value is entered starting from column number 46 (which is preceded by a brief description of the respective data item up to column number 45, which are not used in IRPSAEV calculations). It is important to note that in this figure (and all other input data files described later in this section), all input data items use standard FORTRAN (e.g. Ellis, 1990) fixed format. As will be shown later, the required units as well as the corresponding FORTRAN format of each of the input data

items of the IRPSAEV package are specified in the input data files, as descriptive comments before the data item. Thus, the user is required only to type/enter the value of respective data item at its place as indicated in the data file. If the required unit and/or format of an input data item is not explicitly specified in the pertinent data file, then it is described in the main text of this thesis where ever this data item is explained for the first time. The various input data items contained in SAMPLE.GEN data file are explained as below.

**Line#1:** It shows the full name of this input data file under which it is saved. This file name is a user-specified farm name that could be changed as desired by the user.

**Line#2:** Shows the name of crop for which these data are stored. This crop name is same as specified in the \*.KCS (Section C.5.2) input data file where it is allotted a unique crop-code by the user.

**Line#3:** is a self explanatory title line.

**Line#4:** indicates the column number to serve as a formatting guide for inputting the data values in this file using FORTRAN format.

**Line#5:** The data item in this line indicates one of the three user-specified *operational modes* of the IRPSAEV package. This is a four character variable. The three operational modes available in the IRPSAEV package are: *PLAN* for Planning mode (Section C.6), *SCHE* for Scheduling mode (Section C.7) and *EVAL* for Evaluation mode (Section C.8). The standard FORTRAN format for this data item is A4.

**Line#6:** This line specifies the Irrigation Season Start Date. This is the date when the local water authority officially starts its water deliveries available to its users (i.e. the farmers), and is a datum line for all dated input data items of the IRPSAEV package. The format for this data item is A10.

**Line#7:** This line specifies the calculation start date from which the user wishes to start the water balance calculations of the IRPSAEV package. The format for this data item is A10.

In PLAN mode, this date refers to the expected date of first irrigation to the farm. In SCHE mode, this date is the date on which the previous irrigation was applied, so as to calculate the updated SMC status of the farm for the next irrigation timing decision. In EVAL mode, this date corresponds to the date on which the first irrigation was applied to the farm.

**Line#8:** This line represents the irrigation season end date. This is date on which the irrigation season is expected to end for PLAN mode. For SCHE mode, this corresponds to the today's date on which the user wants to see the SMC status of the farm, and wishes to know the expected (i.e. forecast) date of the next irrigation. In EVAL mode, this date represents the date on which the last irrigation season was terminated. The format for this data item is also A10.

**Line#9:** is a non-data line.

**Line#10 & 11:** These are the dates on which the farmer due to his/her personal (such as sickness) and/or other administrative constraints is unable to irrigate the farm. These data items skip the farmer irrigating the farm on these days. For a given run of the model, the IRPSAEV package can model only four such emergency events. Each of these events can be of maximum 14-day length. As can be seen from Figure C.5, these four irrigation-skipping events are entered individually with two events in line#10 and the other two in line#11. Each event is specified with its starting date followed by the additional days for which the farmer is unable to irrigate. For example, if the farmer is not be able to irrigate the farm on two days viz. 31/03/1998 and 1/04/1998, then for this event the corresponding data can be entered as shown in Figure C.5 (line# 10). As can be seen from this figure, the required format for each event is A10,I2. If no such event exists, then the zeros in line#10 and 11 do not need to be changed.

**Line#12:** is a non-data line.

**Line#13:** There are three input data items contained in this line. The first data item represents a user-defined `crop_code` (maximum of two digits integer) for the crop nominated in this data file entered in FORTRAN I2 format. This is the same `crop_code` as specified in the \*.KCS input data file (Section C.4.2) for this crop. This is an arbitrary number which is assigned by the user uniquely for a crop. This `crop_code` is utilised by the model to find out the additional information relevant to this crop, stored in the \*.KCS data file under this code. As shown later in Section C.4.2, the \*.KCS file can have data for several crops each of them assigned with a different crop code. However, the irrigation scheduling is done only for the crop for which the crop code has been specified in this data line.

The second data item in this line is the forecast period in days expressed in standard FORTRAN I2 format. This is an important input data item of the SCHE mode. This data item represents the number of days for which an irrigation forecast in advance is required for the SCHE mode. The third input data item of *Line#13* is the Warning MAD (%) value entered as standard FORTRAN FC.2. This parameter is required only for the SCHE mode where the *fixed irrigation interval* approach (Section 5.5.2) is adopted. This parameter value is used to give a warning message to the user, whenever the SMC of the root zone falls below this user-specified maximum allowable depletion (MAD) value. For other modes, the value of this parameter is automatically ignored by the IRPSAEV package.

**Line#14:** This line contains two data items. The first item represents the maximum depth of root zone of the crop expressed in terms of number of root zone sub-layers. The second data item represents the thickness of each sub-layer (cm), which is constant for all sub-layers (Section 5.4.3). For example, in Figure C.5 the maximum number of root sub-layers is one and the thickness of this sub-layer is 40cm. The required format for these two data items is I2,F6.2.

**Line#15:** This line contains three input data items that are described below.

The first data item (i.e. MAD\_Option) represents the user-specified irrigation timing approach (Sections 5.5.2 and 5.6.1) adopted for the crop under consideration. It is specified by YES or NO option using the abbreviated format of “Y” or “N”. “Y” implies that the target moisture level approach (using given MAD value for irrigation timing) is selected. “N” indicates that the *fixed irrigation interval approach* (which uses MAD) is adopted for this crop. The fixed irrigation interval approach in turn requires the specification of the fixed interval (in days) between each irrigation application, which is third data item of this line. This aspect is detailed later in this section.

The second data item (i.e. SICK\_Option) represents the presence of irrigation-skipping events (line#10 & 11) that occur during the irrigation season. “Y” means the irrigation-skip events exist, while “N” indicates no such events. In case of “N”, the calculations of the IRPSAEV model ignore irrigation-skipping events specified in Line# 10 & 11.

The third data item (i.e. *Irri\_Interval*) represents the frequency of irrigation applications for the crop under consideration. This parameter is specified in standard FORTRAN format I2. In Figure C.5, a value of 07 is entered to represent a 7-day irrigation interval. As stated earlier, this parameter is required only for the fixed irrigation interval approach. Hence, this parameter is used by the IRPSAEV package only if “N” is entered for the first data item of line#15. The required standard FORTRAN format for above three data items is A1,1X,A1,1X,I2.

**Line#16:** This line indicates the number of days followed by an irrigation and/or a heavy rain event during which the root zone remains at anaerobic conditions (i.e. saturation level). This occurs due to the slowly-draining gravitational water which causes the ET rate to be reduced to almost zero due to anaerobic conditions. In other words, this is the period followed by an irrigation and/or a heavy rain event during which water is ponded on the surface of the soil to cause the temporary anaerobic conditions. This parameter is a

characteristic of the soil, and the value of this parameter is based on farmer's experience under local conditions.

**Line#17:** This data line consists of two input data items. The first data item (i.e. SMC\_UPDATE) represents the user-specified SMC feed back option based on field observations. This option if selected as "Y", allows the user to enter field-measured SMC data into the calculation process. Hence, this option corrects the SMC values estimated by the IRPSAEV package to give accurate and more reliable irrigation predictions for the field. The measured SMC data are stored in a separate "\*.SMC" input data file in %volume or %mass units that is described in Section C.4.5

The second data item (i.e. UNIT) represents the system of units of the field-measured SMC data used in the model. In this regard, two most popular user-specified SMC units namely %volume or %mass (Section 5.2.1) are supported by the IRPSAEV package. This choice can be specified by the user by a 3-letter character symbol of VOL or MAS for %volume or %mass units respectively. This information is used by the IRPSAEV package, only if "Y" is entered for the first data item of line#17. The required standard FORTRAN format for these two data items is A1,1X,A3.

**Line#18:** The data item in this line indicates how the effective component of incoming rainfall is to be computed. In general, there are two ways to compute the effective rainfall. In the first case, the non-effective component is described as a specific percentage of the actual rainfall amount received, and thus needs to be multiplied to get the effective rainfall value usable by the crop (Singh et al., 1994). In the second case, the non-effective component is described by a specified amount (e.g. mm) which needs to be subtracted from the actual amount of rainfall received at the site (Heslop, 1991). The IRPSAEV package supports both these options. This can be specified by the user by entering M or S for the first and second choice respectively. The non-effective rainfall data (i.e. rainfall correction factors) for both cases are stored in the \*.KCS file, which is described in Section C.4.2. The required format for this data item is A1.

**Line#19:** This line represents the soil physical characteristic parameter related to the SMC at the saturation (SAT) level. This parameter needs to be specified for each of the sub-layers separately in % ( either Volume or Mass) based units. If the %mass unit is used in line#17, then additional information on the bulk density of respective sub-layer is also required (**Line#23**) The number of sub-layers are specified under line#14. The required format for each sub-layer for this data item is F6.2.

**Line#20:** This line represents the actual irrigation level applied during an irrigation event to the crop. Generally, it is aimed to bring the SMC of the root zone to the field capacity (FCAP) level through an irrigation application. However, in some cases due to management constraints it is inevitable to irrigate the field slightly above the FCAP level (in worse cases even upto the SAT level). In these circumstances, this parameter needs to be specified in terms of extra SMC% above the FCAP level. For example, if the irrigation practice adopted under local conditions is to fill the root zone upto the SAT level, then this (i.e. EXTRAirri\_SMC, line#20) parameter value can be entered as the difference between the SMC at SAT and FCAP levels of the respective sub-layer. Hence, if the irrigation practice is to irrigate to the level of FCAP, then the value of this parameter is zero. In Figure C.5, the value of this parameter for sub-layer one is 5%. It means that each irrigation event refills the first sub-layer upto 5% extra level above the FCAP level. Hence, it brings SMC of the first sub-layer at the SAT level after each irrigation, since the FCAP for this sub-layer is 41% (line#21). The required format for each sub-layer for this data item is F6.2.

**Line#21 & 22:** These parameters are SMC values at FCAP and wilting point (WILT) respectively. These data items have the same format as the SAT values described under *Line#19*.

**Line#23:** This line represents the bulk density (gm/cc) parameter of the soil. As stated under line#19, this information is required only if the SMC data in *Line#17 and Line#19-22* are specified in %mass units. Otherwise, this information is ignored by the IRPSAEV package. The format adopted for this parameter is the same as for the *Line#19* data item.

**Line#24:** This line represents the size of the farm under consideration in hectares. This is used to calculate the desired irrigation amounts in volumetric units (Mega litres, ML) - a popular unit adopted by Australian farmers for lodging water orders to local water authorities. As shown in Figure C.5, the size of the sample farm is 50 hectares.

**Line#25-27:** These lines represent the variable moisture extraction pattern by the crop roots under local conditions (Section 5.4.5). This parameter is an optional parameter. In case if the local values of this parameter are available, these values can be entered just by replacing the zero values shown in the data file of Figure C.5. It is important to mention that this information is required only if the maximum number of root zone sub-layers (line#14) are greater than 1. If this information is required, it needs to be specified for each sub-layer. To enter this information in the data file, only one data line from line#25-27 can be used based on the number of sub-layers specified in line#14. The required FORTRAN format for each sub-layer for this data item is F6.2.

When local information on variable moisture extraction pattern is not available, the zero values of this parameter as shown in line#25-27 of Figure C.5 do not need to be changed. In this case, the IRPSAEV package automatically computes this parameter using Eqs. 5.15 and 5.16 for use in Eq. 5.17b based on the information given in line#14.

**Line#28:** is a non-data line.

**Line#29:** This data line invokes for the availability of daily  $ET_0$  forecast data (Section 5.7.3) for use in the SCHE mode in order to make the irrigation forecasts several days in advance. When the daily  $ET_0$  forecasts are available from some local agency, these data can be entered through the \*.FET data file (Section C.4.5) for use by the IRPSAEV model. In this case, the availability can be indicated by specifying GIV.

However, if the forecast  $ET_0$  data are not available, it is indicated by ??? in this line or even leaving it blank. This instructs the IRPSAEV package to automatically select the

default option for forecasting these daily  $ET_o$  values based on the average of past 14-days  $ET_o$  data values (Section 5.8.2). In order to improve the default irrigation forecasts, these forecast  $ET_o$  values (based on the past 14-days  $ET_o$  values) can further be adjusted by a user-specified percentage. For this purpose, the forecast adjustment factor (in %) can be entered following ??? in this data line using the FORTRAN F3.0 format as shown in Figure C.5. This adjustment factor (in percentage) is used only when the default  $ET_o$  forecast method is used.

**Line#30-32:** The data items in these lines represent the calibration requirements of the IRPSAEV model for the site under consideration (Section C.10). When no calibration is required, the line#30 can be set to “N”, and then ignore the line#31 and line#32. However, if the calibration is required, the line#30 should be set to “Y”. In this case, the *calibration\_target theta (%)* and the *theta adjustment factor (%)* values need to be entered by replacing the zero values of data line # 31&32 of Figure C.5. The definition of these parameters are given later in Section C.10.

**Line#33:** is a non-data line

**Line#34-39:** The data items in these lines refer to the availability of the mean daily  $ET_o$  values (Sections 3.5.4 and 3.6.4) for use in the PLAN mode. These mean daily  $ET_o$  values are used to make the irrigation estimates for the coming irrigation season in advance before the actual season starts, for pre-season planning purposes.

When mean daily  $ET_o$  values are available for the required planning period (usually the entire irrigation season), these data can be directly entered through the \*.FET data file (Section C.4.6) for use by the IRPSAEV package. This availability can then be indicated by specifying the “N” option in line#34 and ignoring the data items in line# 35-39. However, if these mean daily  $ET_o$  data are not available, then they can be estimated using the 5-parameters Gaussian equation option available in the IRPSAEV package. This is the only option supported by the package for mean daily  $ET_o$  calculations. This can be indicated by choosing the Y option in line#34, and then substituting the values of 5-parameters in lines#35-39 of Figure C.5. The details of the 5-parameter Gaussian equation are given in Section 3.6.4.

## C.4.2 SAMPLE.KCS Data File

The SAMPLE.KCS input data file contains a commentary block of four lines (which is not used in the IRPSAEV package calculations), and four major input parameter blocks viz. i) crop coefficients, ii) root zone depth in terms of sub-layers, iii) non-effective rainfall and iv) maximum allowable Deficit (MAD) information, as shown in Figure C.6.

In order to use the information of this data file by the IRPSAEV package, this file needs to be supplied with data records for the entire irrigation season. This data file serves as a common data file for several crops provided the crop-specific information are included in this file with a unique crop\_code (an integer number) assigned to each crop. In case of several crops, the input parameter blocks are repeated for each crop in the data file. In order to use for different farms, this data file needs to be saved using the corresponding farm name. Similar to the SAMPLE.GEN data file, this file is also an essential file for all three operational modes of the IRPSAEV package. It is also required for the CALibration option.

### *CROP\_CODE*

This is a two-digit integer number assigned by the user uniquely to each of the crops contained in this data file to distinguish the data sets relevant to this crop from other crops. This code is employed by the IRPSAEV package for matching with the crop-code specified in line#13 of \*.GEN data file (Section C.4.1) before extracting the required information from \*.GEN file for the crop under consideration. In this \*.KCS data file, for sake of user convenience, the name of the corresponding crop is also written after the code. However, this name is not used in IRPSAEV calculations.

### *Crop Coefficient ( $K_c$ ) Data*

This is the first of the four input parameters contained in this file for a given crop. The utility of  $K_c$  parameter is detailed in Section 5.3.6.

```

File: SAMPLE.KCS Input Data File for IRPSAEV software
Crop coeficnt(Kc):Root_sublayers(number):Non_efct rain(mm or %) & MAD(%) data
Data are on a DAILY basis; but could be input in FROM-->TO format as below
Data entries of each parameter should be for full season & NOT exceed 52 lines
CROP CODE> 1 Perennial Pasture
Daily_Kc data values (F5.2); Minimum Data =Irri Season
      FROM          TO          VALUE
07 15/08/1997-->30/09/1997      1.00
    01/10/1997-->31/10/1997      0.86
    01/11/1997-->30/11/1997      0.75
    01/12/1997-->28/02/1998      0.72
    01/03/1998-->31/03/1998      0.75
    01/04/1998-->30/04/1998      0.86
    01/05/1998-->31/05/1998      1.00
*Daily Root depth sub-layers (I5); Minimum Data =Irri Season
      FROM          TO          VALUE
02 15/08/1997-->31/08/1997          1
    01/09/1997-->31/05/1998          1
*Daily Non_Effect Rain (mm or %) data(F5.2): Minimum Data=Irri Season
      FROM          TO          VALUE
06 15/08/1997-->31/08/1997      2.00
    01/09/1997-->30/09/1997      3.00
    01/10/1997-->31/10/1997      4.00
    01/11/1997-->30/03/1998      5.00
    01/04/1998-->30/04/1998      4.00
    01/05/1998-->31/05/1998      2.00
*Daily Maximum Allowable Deficit MAD(%) data(F5.2):Minimum Data=IrriSeason
      FROM          TO          VALUE
02 15/08/1997-->31/12/1997     35.00
    01/01/1998-->31/05/1998     35.00
END_CODE->99

```

Figure C.6 SAMPLE.KCS Input Data File

For adaptability of the IRPSAEV package under a wide range of scenarios, the  $K_c$  data in \*.KCS file are formatted to meet the three generally desirable compliance criteria of most irrigation systems. These criteria are:

- i) to use the  $K_c$  data that is known at specific dates so as to relate to various vegetative stages of the crop, as given in FAO-24 methodology (Doorenbos and Pruitt, 1977).
- ii) to comply with  $K_c$  values that are varying with forage cuts. For example, the alfalfa crop is cut at different occasions or the pasture is grazed by dairy cattle at various intervals (Allen et al., 1989).
- iii) to utilise the  $K_c$  data which is averaged over the specified time periods such as month or a week (Heslop, 1995).

Keeping in view of the above stated compliance criteria, the  $K_c$  data in this data file can be entered in the form of independent "FROM - TO" data groups by specifying the respective FROM and TO dates, with an upper limit of 52 data groups. Thus, if a crop has its irrigation season spanning over a period of one year, its  $K_c$  data can be entered on a weekly basis (i.e. 52 data groups). This can easily cover the general variability range of  $K_c$  observed during the growth period of a typical agricultural crop.

As shown in Figure C.6, the  $K_c$  values are entered following the FROM-TO date specification for the respective  $K_c$  data group. In order to be recognised by the IRPSAEV package, the total number of FROM - TO data groups can simply be indicated using an integer number in the first two columns of the line in which the first  $K_c$  data group is entered. For example, in the data file shown in Figure C.6, there are seven  $K_c$  data groups for the Perennial Pasture crop. The first data group has the  $K_c$  value of 1.00 for the period from 15/08/1997 to 30/09/1997 (i.e. 47-days). In the data file, the integer 07 is entered in the first two columns (FORTRAN I2 format) followed by a single blank space, and then the FROM date (i.e. 15/08/1997) is entered using standard FORTRAN format of A10. After the FROM date three column spaces are left blank, and then TO date (i.e. 30/09/1997) is entered using the same format as for FROM date. Finally, the  $K_c$

parameter is entered using standard FORTRAN format of F5.2 starting from column 28. Similarly, other  $K_c$  data groups are entered.

### *Root Depth Data*

This is the 2<sup>nd</sup> parameter stored in this data file which refers to the rooting characteristic of the crop. This parameter varies throughout the growth period of the crop until it attains its maximum value. As mentioned in Section 5.4.3, this parameter is entered in terms of the number of root sub-layers, which are of equal thickness. The input format of this parameter is exactly the same as for  $K_c$  given above, except that the value of this parameter is an integer number (with FORTRAN format I5) starting from column 28. For example, in the data file shown in Figure C.6, there are two data groups for root depth parameter. The first data group has the root depth sub-layer value of 1 for the period from 15/08/1997 to 31/08/1997 (i.e. 17-days).

### *Non\_effective Rainfall Data*

This is the 3<sup>rd</sup> of the four input parameters stored in this file. This refers to that proportion of actual incoming rainfall that is not available for plant use. A brief description of this parameter is given in Section 5.3.3 and C.5.1.

As described in Section C.4.1, for compatibility with the IRPSAEV package, the input units of this parameter must be either in depth (i.e. mm) or in % units depending on the data availability for non-effective rainfall for the crop under consideration. The IRPSAEV package recognises the depth (i.e. mm) or % units based on the second parameter of line#17 in the \*.GEN input file (Section C.4.1). The required format of *Non\_effective Rainfall* parameter is also the same as that of  $K_c$  as described above. For example, as shown in Figure C.6, there are six data groups for this parameter. The first data group has the *Non\_effective Rainfall* value of 2.00 mm for the period from 15/08/1997 to 31/08/1997 (i.e. 17-days).

### *Maximum Allowable Deficit (MAD) Data*

This is the last input parameter contained in this file. This refers to the extent to which the plant available water (AW) is allowed to deplete before an irrigation is applied. The details of this parameter are already discussed in Section 5.5.2 and C.5.1. This parameter must be entered in % units, and the format is also same as that of  $K_c$  as described above.

It is worth mentioning that this parameter is valid only if the *target moisture level approach* is used as the irrigation timing criteria (that uses MAD), which can be indicated by selecting the “MAD\_OPTION” in line#15 of \*.GEN file (Section C.3.1). If the fixed interval is chosen as the irrigation timing criteria for the next irrigation, then this data item is not required. Even if these data exist in the \*.KCS file, they are ignored by the IRPSAEV package for the fixed interval approach.

*END\_CODE->99*

As mentioned earlier, the MAD data set is the last data item in \*.KCS file for specific crop. For another crop to be included in this file, the same format of above described four data items should be repeated. The maximum number of crops each with a unique crop\_code that can be included in this data file is 98. However, this data file must have an end code with END\_CODE->99, to indicate the end of the file, after entering data for all required crops. This is shown in Figure C.6. If this END\_CODE is not given, the IRPSAEV software would terminate by showing an error message indicating missing end code information.

### **C.4.3 SAMPLE.ETO Data File**

Basically, this data file is an output file of REF\_ET software (Appendix A). This data file contains the  $ET_o$  estimates calculated by the REF\_ET software, and the rainfall data on a daily basis for use by the IRPSAEV package. As stated earlier in Section C.3, this file is an essential input data file for all modes of the IRPSAEV package except for PLAN

mode. This file is also required for CALibration option. The details of this file are described in Section A.7. A typical format of this data file is shown in Figure A.8. It is important to note that if the daily  $ET_0$  estimates are available from local agencies, then this SAMPLE.ETO data file should contain these  $ET_0$  instead of  $ET_0$  estimates from the REF\_ET software. In this case, the daily rainfall data need to be included in this file by the user. As mentioned in the text of this data file, the units for both the  $ET_0$  and rainfall data items should be in mm units.

#### C.4.4 SAMPLE.SMC data file

This is the data file in which the SMC (%volume or % Mass) status based on the actual field observations is stored. As stated earlier in Section C.3, this file is an essential input data file for SCHE mode and CALibration option, and not required for any other modes. This is an important file for SCHE mode to produce reliable irrigation predictions. A typical format of this input data file is shown in Figure C.7 and the details of each data item contained in this file are described as below.

```

File: SAMPLE.SMC ** Optional Input File for IRPSAEV** :Text-->5Lines
Measured SMC(%) MUST be GIVEN for ALL sub-layers i.e. for NLYR
1st day of season NOT accepted: F --> All Sub_Layers SMC(%) at SATURATION
16/08/1997i99.99 99.99 99.00 99.00 i->All Sub_Layers SMC(%) AFTER IRRI.
!<-Date->!iSMC1% SMC2% SMC3% SMC4% :Data format(F5.2,1X)@ 4-values/line
15/08/1997 46.00 46.00 46.00 46.00
25/08/1997i
29/08/1997F

:      :      :      :
:      :      :      :
:      :      :      :

```

Figure C.7 SAMPLE.SMC Input Data File

As shown in Figure C.7, the first five lines are explanatory lines, which are not used in IRPSAEV calculations. The measured SMC data information (whenever available) are

entered in this file starting from the sixth line by specifying the date and SMC values for each sub-layer. The SMC values can be entered for individual sub-layer under respective *SMC#%* (# denotes values 1 to 4) heading of the 5<sup>th</sup> explanatory line using FORTRAN format F5.2, as shown in Figure C.7. The normal irrigation application events can be entered simply by specifying the letter “*I*” following the date (in FORTRAN format A10) of that irrigation event. The IRPSAEV package treats this date as having the SMC of entire root zone at the FCAP level (or else at the user specified post-irrigation SMC level as indicated by line#20 of the data file *SAMPLE.GEN*). However, due to certain emergency circumstances (such as a flood or a heavy storm) if the field is flooded so that the SMC reaches the saturation level, then this event can be indicated in this file by the same way as an irrigation event except that “*I*” is replaced with “*F*” to indicate the flooded conditions. These SMC values are used in all future runs of the IRPSAEV model for this farm to produce irrigation predictions.

#### **C.4.5 *SAMPLE.FET* Data File**

The daily forecast  $ET_0$  data required by the IRPSAEV package for use in the pre-season PLAN and SCHE modes are stored in this data file. A typical format of this data file is shown in Figure C.8.

When the IRPSAEV package is run in the PLAN mode, if the mean daily  $ET_0$  values are available as forecast  $ET_0$  (as indicated in line#34 of the data file *SAMPLE.GEN*, Section C.4.1), then these  $ET_0$  data need to be entered in this file for a complete leap calendar year of 366-days (in case of non-leap year, the IRPSAEV package ignores the value for 29<sup>th</sup> February). For this purpose, the input format requires the daily forecast  $ET_0$  data values to be entered following the specification of respective date with the starting order just as a normal calendar year (i.e. 1<sup>st</sup> Jan. and 31<sup>st</sup> Dec. being the 1<sup>st</sup> and the last data sets respectively) as shown in Figure C.8.

```

SAMPLE.FET      Input file for IRPSAEV Model
CURVE_FIT Daily FORECAST_ET0(mm):5-Parameters Gaussian
Parameters MUST be Updated according to the site
Date  CURvET0(mm)
0101   7.88
0201   7.88
0301   7.87
0401   7.87
0501   7.87

:  :  :  :
:  :  :  :
:  :  :  :

2912   7.82
3012   7.82
3112   7.83

```

Figure C.8 SAMPLE.FET Input Data File

If mean daily  $ET_0$  values are not available as forecast  $ET_0$  (as indicated in line#34 of the data file SAMPLE.GEN in Section C.4.1), then the daily forecast  $ET_0$  data values are automatically calculated by the IRPSAEV package based on the given Gaussian 5-parameters as specified in SAMPLE.GEN file (Section C.4.1). The calculation procedure for forecast  $ET_0$  data values using the Gaussian 5-parameters is detailed in Section 3.5.4 and 3.6.4.

For SCHE mode if the daily forecast  $ET_0$  values are available from the local agency (as indicated by line#29 through GIV in SAMPLE.GEN file of Section C.4.1), then these data values need to be entered in this file by the user in the same format as adopted for PLAN mode. On the other hand, if the daily forecast  $ET_0$  values are not available (as indicated in line#29 of SAMPLE.GEN file through ???), then the IRPSAEV package automatically estimates these values for use in irrigation forecasts based on the average of past 14-days  $ET_0$  values, as explained in Section 5.8.2. The required FORTRAN format for date and  $ET_0$  data values for this file is A2,2X,F5.2.

## C.5 STORE Sub\_Menu

As stated earlier in Section C.2, this sub-menu is used to display the contents of the output files of the IRPSAEV package that are stored in the storage bank (i.e. in STOR sub-directory) from previous runs. This sub-menu is shown in Figure C.9.

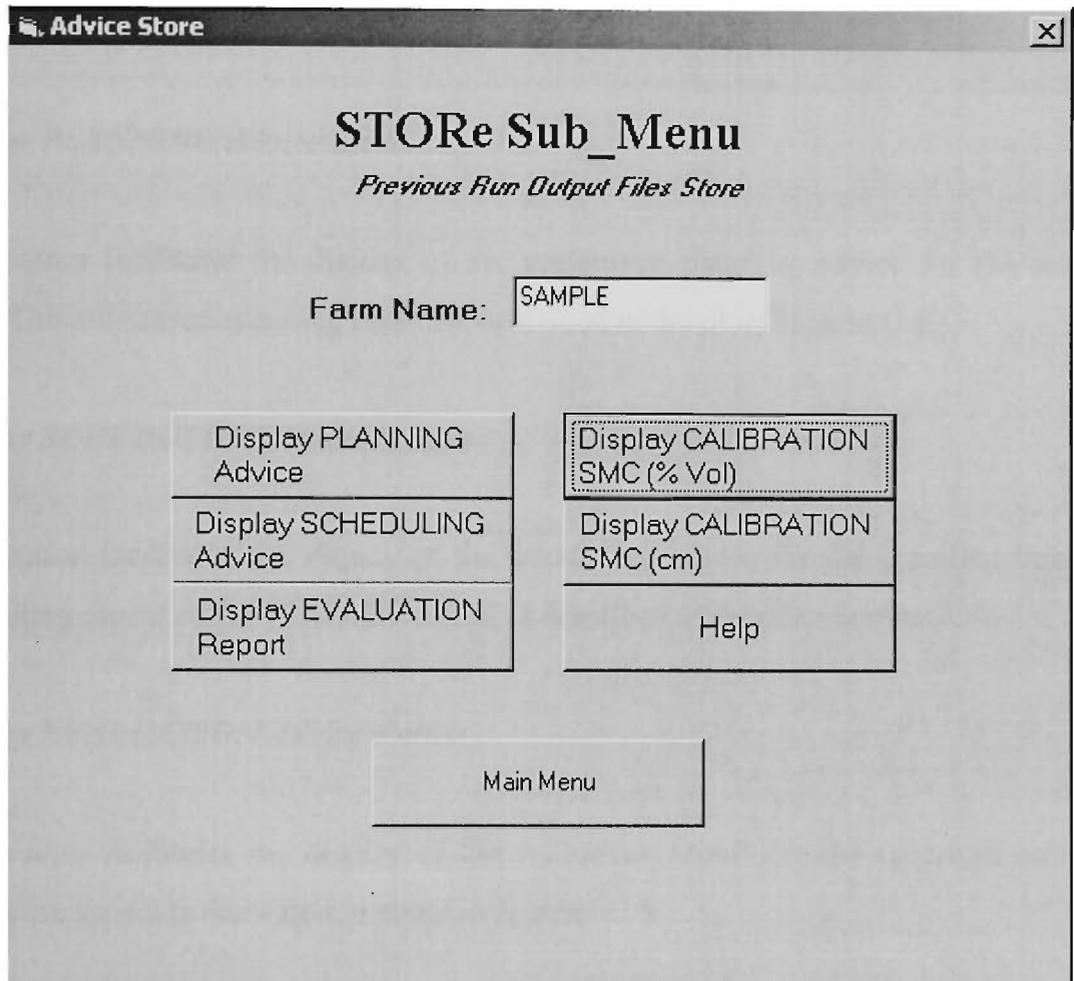


Figure C.9 STORE Sub\_Menu of IRPSAEV software

As can be seen from Figure C.9, there is only one input data box namely *Farm Name* that requires a farm name to be specified by the user. The seven command buttons shown in Figure C.9 facilitate the operation of this sub-menu. The *Farm Name* input data box and the command buttons of this sub-menu are explained below.

### ***Farm Name***

This input data box refers to the name of the farm (of maximum eight characters) for which the previously stored output file is desired to be displayed. After specifying the farm name, the other command buttons can then be used to display the required output file for this farm. It is important to note that the user-specified farm name should be the same as the output file name.

### ***Display PLANNING Advice Button***

This button facilitates the display of the pre-season planning advice for the specified farm. The pre-season planning aspect is described in detail in Section C.6.

### ***Display SCHEDULING Advice Button***

This button facilitates the display of the scheduling advice for the specified farm. The scheduling aspect of the IRPSAEV model is described in detail in Section C.7.

### ***Display EVALUATION Advice Button***

This button facilitates the display of the evaluation report for the specified farm. The evaluation aspect is described in detail in Section C.8.

### ***Display CALIBRATION SMC (%Vol) Button***

This button facilitates the display of the soil moisture content data in % volume units predicted by the IRPSAEV package for calibration purposes. This aspect is described in detail in Section C.10.

### ***Display CALIBRATION SMC (cm) Button***

This button facilitates the display of the soil moisture content data in depth (cm) units predicted by the IRPSAEV package for calibration purposes. This aspect is also described in detail in Section C.10.

***HELP Button:*** This button provides a brief on-line help on the use of IRPSAEV package.

### ***Main Menu Button***

This button returns the user to the Main Menu either to quit the IRPSAEV session, or to re-start an IRPSAEV session for the same or different specified farm.

## **C.6 PLANning MODE**

As outlined in Section C.2, the IRPSAEV package can be run under the PLAN mode before the start of an irrigation season to serve as a pre-season planning tool. The execution structure of the IRPSAEV package for planning mode is shown in Figure C.10. As shown in Figure C.10, the PLAN mode requires three input data files namely \*.GEN, \*.KCS and \*.FET. The details of these input data files are given in Section C.4. The planning mode is executed through PLAN Sub-Menu of the package.

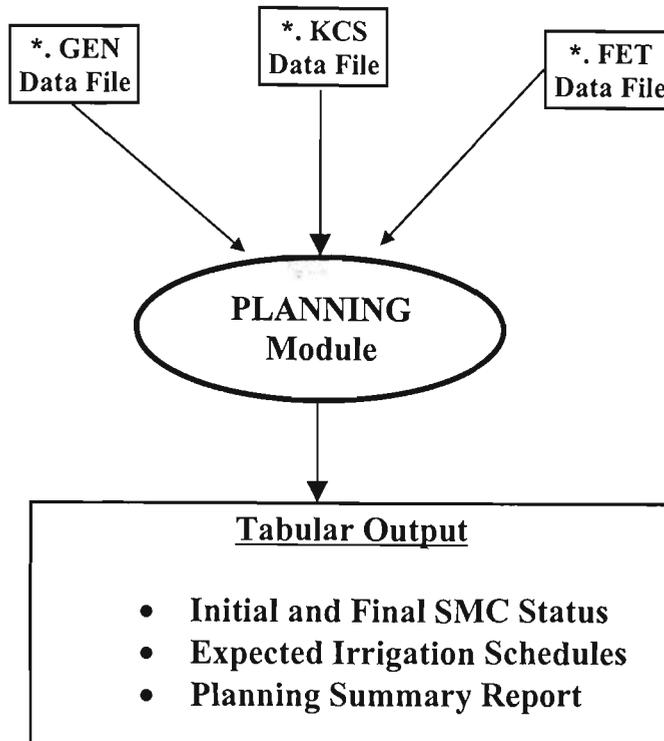


Figure C.10 Execution Structure of IRPSAEV Package in Planning Mode

### C.6.1 PLAN Sub-Menu

After updating the input data files as per Section C.3, and then choosing the PLAN mode from the Main Menu (Figure C.3), the user is brought to the PLAN Sub-Menu as shown in Figure C.11, with the updated input data files as ISMODEL.\* files (Section C.3).

As can be seen from Figure C.11, there are seven command buttons to facilitate the operations of the PLAN Sub- Menu. These are explained as below.

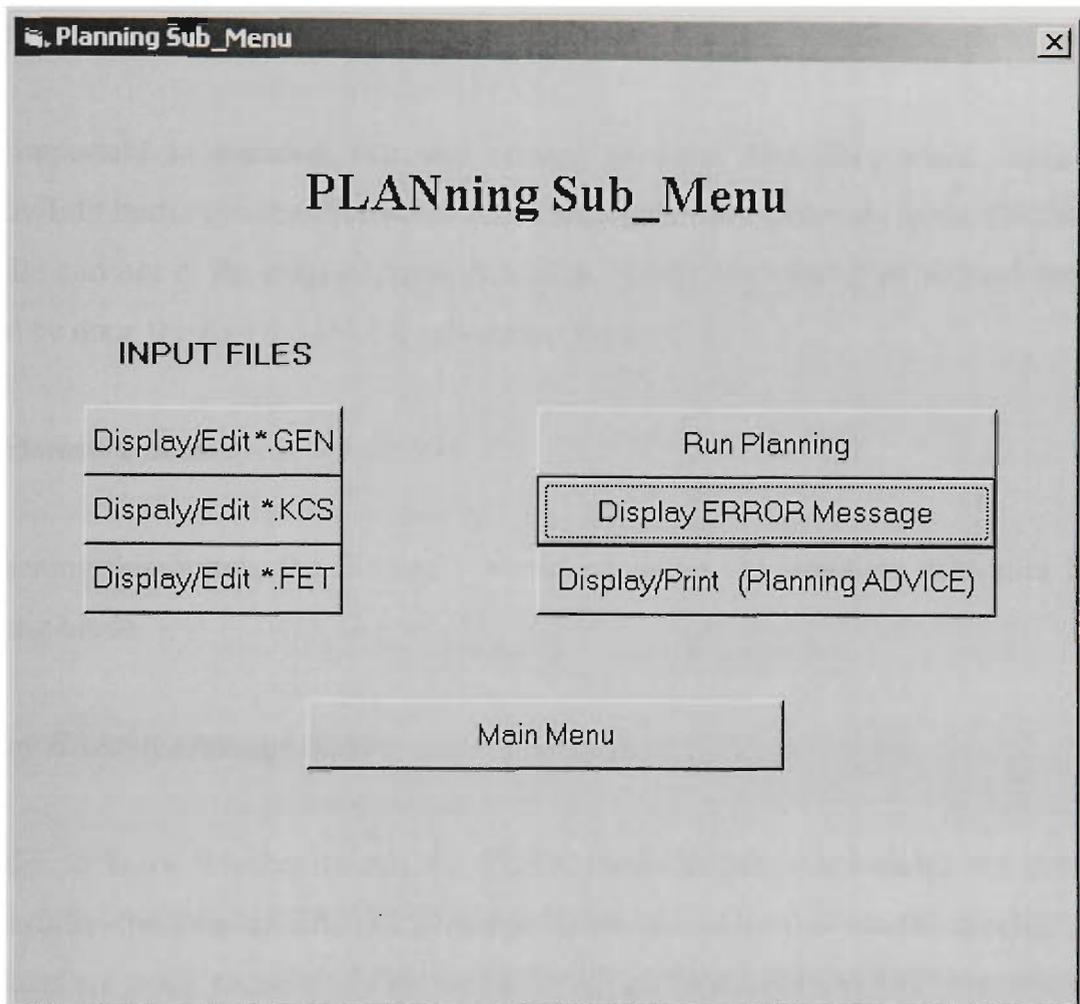


Figure C.11 PLANning Sub\_Menu of IRPSAEV Software.

***Display/Edit \*.GEN Button***

This button is used to edit the ISMODEL.GEN input data file.

***Display/Edit \*.KCS Button***

This button is used to edit the ISMODEL.KCS input data file.

### ***Display/Edit \*.FET Button***

This button is used to edit the ISMODEL.FET input data file.

It is important to mention that any editing of input data files while using these Display/Edit buttons in the *PLAN Sub-Menu* will update the data only in the ISMODEL.\* data file and not in the original input data files. Hence, the editing of original data files should be done through the DATA sub-menu (Figure C.4).

### ***Run Planning Button***

By clicking this button, the IRPSAEV model computes the irrigation schedules for the planning mode.

### ***Display ERROR Message Button***

In order to know whether or not the PLAN mode irrigation schedules are computed successfully, the ***Display ERROR Message*** button can be used to see the message. If the schedules are made successfully by the IRPSAEV software, then an OK! message can be seen. Otherwise, an error message is displayed with a brief guide to rectify the error.

### ***Display/Print (Planning ADVICE) Button***

If an OK! message appears when the *Display ERROR Message* button is clicked, the user can use the ***Display/Print (Planning ADVICE) Button*** to display and/or print the irrigation schedules, which are computed by the IRPSAEV software. This is the output of the PLAN mode, which is discussed in Section C.6.2.

### ***Main Menu Button***

This button can be used to return to the Main Menu either to quit the IRPSAEV session, or to restart the session for another station (or farm) or the same farm with different input files. However, before returning to the Main Menu, a message is prompted to store the current output files of this mode in the output storage bank for future reference. If YES option is selected by the user, the output files of this run are stored in the STOR sub-directory, which can later be displayed using STORE Sub\_Menu as described in Section C.5.

The computational details of various modes of IRPSAEV package including PLAN mode are outlined in the flowchart of Figure C.1a.

### **C.6.2 Output Files**

Under the PLAN mode, the IRPSAEV software predicts the expected irrigation schedules as well as estimates of total irrigation water demand over the entire season in advance for the farm under consideration. In addition, the expected SMC status of the root zone at the start and at the end of the season are also displayed. At the end of the output file, a summary for the entire season is also presented.

A typical output file of the PLAN mode is shown in Figure C.12. The results of this file can be used for planning purposes by the farmer. The crop code in the output file indicates the crop chosen by the user as entered in line#13 of the \*.GEN data file (Section C.4.1). The *Analysis Period* (in days) represents the user-specified planning period (as entered in \*.GEN data file: line#7 and 8) for which the pre-season planning was invoked.

The irrigation schedules (date and amount) given in Figure C.12 represent the expected irrigation application events based on the user-specified irrigation timing criteria as entered in line# 15 of \*.GEN file. These schedules assume zero future rainfall.

```

EXAMPLE: [1997-98 Irrigation Season]
*****
NOTE-->This file is NOT VALID for Scheduling_Mode
Current EXECUTION_MODE--> Future PLANNING
CROP_code--> 1: Analysis Period--> 73 to 238 th day
*****

Initial ENTIRE ROOT-zone(FCAP) SMC = 16.4000 cm
*****
Actual caculation STARTS NOW FROM--> 26/10/1997
At the end of --> 26/10/1997 SMC= 16.0 cm
  Irri. required on 04/11/1997 ==> 5.70 cm
  Irri. required on 21/11/1997 ==> 5.91 cm
  Irri. required on 07/12/1997 ==> 5.99 cm
  Irri. required on 22/12/1997 ==> 5.80 cm
  Irri. required on 06/01/1998 ==> 5.91 cm
  Irri. required on 21/01/1998 ==> 5.88 cm
  Irri. required on 05/02/1998 ==> 5.73 cm
  Irri. required on 21/02/1998 ==> 5.77 cm
  Irri. required on 11/03/1998 ==> 5.91 cm
  Irri. required on 01/04/1998 ==> 5.66 cm
At the end of --> 09/04/1998 SMC= 16.8 cm

***** Summary of Entire Period *****
Current EXECUTION_MODE--> Future PLANNING
!*****!
!* SEASON TERMINATED ON-->09/04/1998
!* NO Future Rainfall Considered in Planning *:
!* Total Potential Crop ETC ----->= 80.99 cm *:
!* Total Actual Crop ETA ----->= 57.84 cm *:
!* SMC at END of Season in ENTIRE Root = 16.82 cm *:
!* Total Amount of Irri EXPECTED ----->= 58.26 cm *:
!* Total NUMBER of Irri EXPECTED ----> = 10 *:
!* Note: Add ONE More Full_Irri to Above Estimates *:
!* Good Luck! *:
!*****!

```

Figure C.12 A Typical Output File of the PLANning Mode

At the end of the output file, a summary of irrigation advises encompassing the entire planning period is self-explanatory. The output file can be printed and/or saved on disc for future reference by the user.

It is important to note that at the end of the summary, one additional irrigation is also included. This is due to the fact that the IRPSAEV model starts its calculations with the assumption that at the beginning of irrigation season, the SMC is at FCAP level. This pre-season irrigation is not included in the predicted estimates. Therefore, at the end of the summary, this is shown separately as an additional irrigation.

## **C.7 SCHEduling MODE**

For real-time operation of irrigation systems, the IRPSAEV package can be run during the irrigation season under the SCHE mode to render itself as a real-time operational tool. The execution structure of the IRPSAEV package in SCHEduling mode is shown in Figure C.13. As shown in Figure C.13, the SCHE mode requires five input data files namely \*.ETO, \*.KCS, \*.GEN, \*.SMC and \*.FET. The details of these input data files are already given in Section C.4.

In a normal SCHE mode, the IRPSAEV software gives the root zone SMC for the *present* (or *current*) day on which the model is run including SMC forecasts for a user-specified forecast period of 0-14 days. These SMC forecasts are used to see whether an irrigation is required during that forecast period. This information is presented both in tabular and graphical forms in the output files. If an irrigation is predicted, the expected date along with the amount of irrigation is also given in the output file.

At the end of the output file, a summary of irrigation advice is also presented. The irrigation advice is based on the user-specified irrigation timing criteria (as entered in line#15 of \*.GEN data file), which is explained in Section 5.6.1 and C.5.1. The irrigation advice can be used by the farm manager to decide when to request water for irrigation from the local water authorities and/or to plan for other activities accordingly.

The SCHEduling mode can be executed through the SCHE sub-menu of the IRPSAEV package which is explained in Section C.7.1. The computational details of various modes of IRPSAEV package including SCHE mode are outlined in the flowchart of Figure C.1.

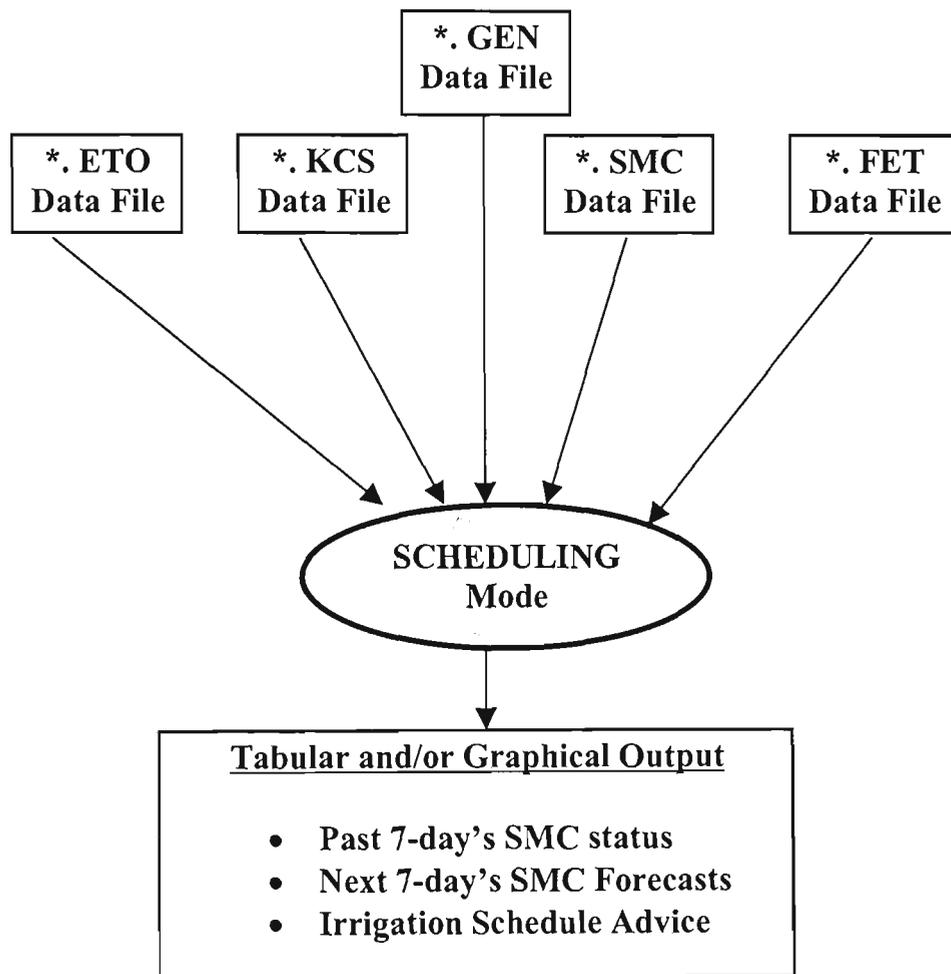


Figure C.13 Execution Structure of IRPSAEV Package in Scheduling Mode

### C.7.1 SCHE Sub-Menu

After updating the input data files as per Section C.3, choosing the SCHE mode from the Main Menu (Figure C.3) brings the user to the SCHE sub-menu as shown in Figure C.14, with the updated input data files as ISMODEL.\* files (Section C.3).

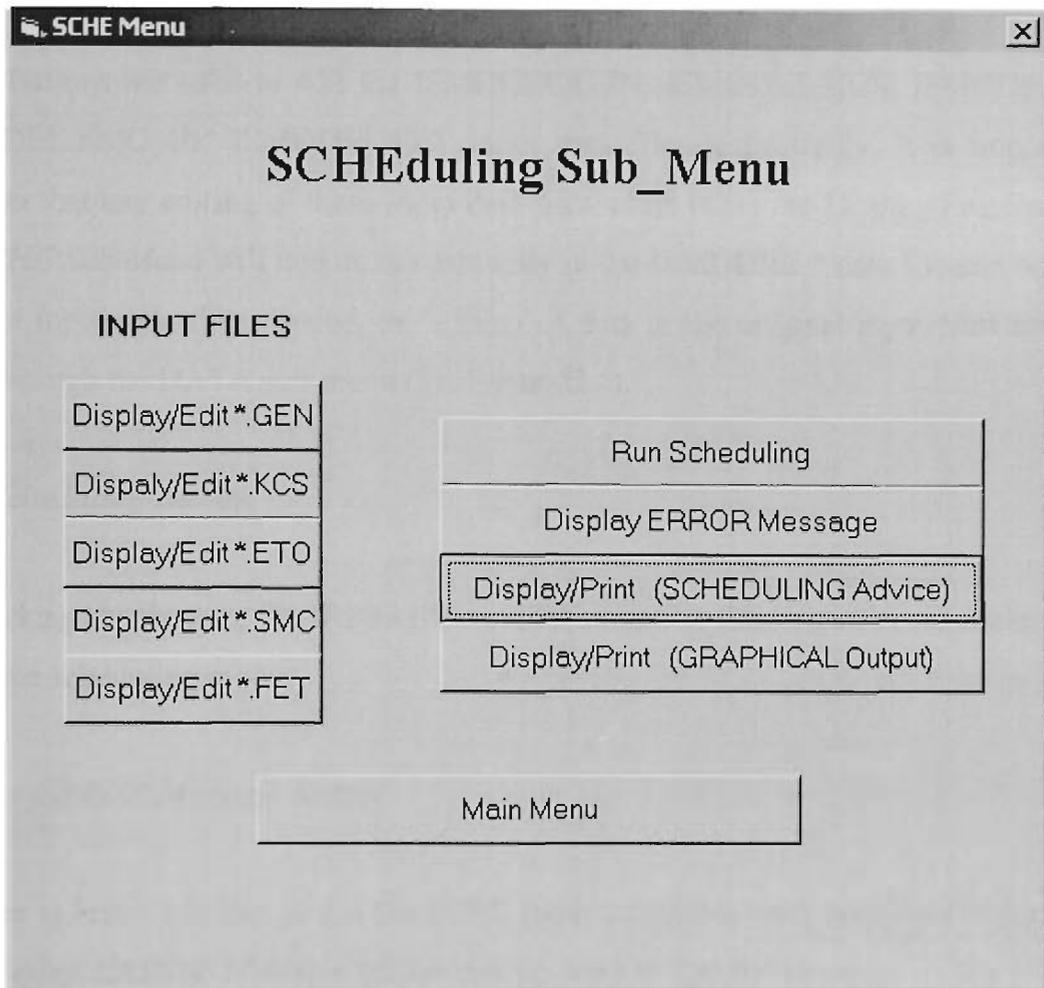


Figure C.14 SCHEduling Sub\_Menu of IRPSAEV Computer Software

As stated earlier, the SCHE mode requires five input data files namely \*.ETO, \* KCS, \*.GEN, \*.SMC and \*.FET. The \*.FET file is required only if the forecast  $ET_0$  is available from the local agency, which needs to be entered in this data file. As can be seen from Figure C.14, there are nine command buttons to facilitate the operations of the SCHE Sub- Menu. These are explained as below.

### ***Display/Edit \*.GEN, \*.KCS, \*.ETO, \*.SMC and \*.FET Buttons***

These buttons are used to edit the ISMODEL.GEN, ISMODEL.KCS, ISMODEL.ETO, ISMODEL.SMC and ISMODEL.FET input data files respectively. It is important to mention that any editing of these input data files while using the Display/Edit buttons in the *SCHE Sub-Menu* will update the data only in the ISMODEL.\* data file and not in the original input data files. Hence, the editing of data in the original input files should be done through the DATA sub-menu (i.e. Figure C.4).

### ***Run Scheduling Button***

By clicking this button, the IRPSAEV model computes the irrigation schedules for the real-time scheduling mode.

### ***Display ERROR Message Button***

In order to know whether or not the SCHE mode schedules were computed successfully, the ***Display ERROR Message*** button can be used to see the message. If the schedules were made successfully by the IRPSAEV software, then an OK! message can be seen. Otherwise, an error message is displayed with a brief guide to rectify the error.

### ***Display/Print (SCHEDULING Advice) Button***

If an OK! message appears when the ***Display ERROR Message*** button is clicked, the user can use the ***Display/Print (SCHEDULING Advice)*** button to display and/or print the irrigation schedules, which are computed by the IRPSAEV software. These irrigation schedules are contained in an Irrigation Advice report. This report is an output of SCHE mode, which is discussed in Section C.7.2.

### ***Display/Print (GRAPHICAL Output) Button***

This button facilitates to view and/or print the output in a graphical form. This is also discussed in Section C.7.2.

### ***Main Menu Button***

This button can be used to return to the Main Menu either to quit the IRPSAEV session, or to restart the session for another station (or farm) or the same farm with different input files. However, before returning to the Main Menu, a message is prompted to store the current output files of this mode in the output storage bank for future reference. If YES option is selected by the user, the output files of this run are stored in the STOR sub-directory, which can later be displayed using STORE Sub\_Menu, as described in Section C.5.

## **C.7.2 Output Files**

As stated earlier in Section 5.7.1, the irrigation advice of the IRPSAEV model is based on the computed SMC for the *present (i.e. current) day* and the user-specified irrigation timing criteria. An irrigation is advised if the user-specified MAD is exceeded, or if the specified fixed irrigation interval is exceeded, depending on the irrigation timing criteria specified as input in line#15 of \*.GEN file (Figure C.5). This advice assumes zero rainfall for the forecast period, thus the forecast date of an irrigation is the worst case. If rain falls before the next irrigation, it is assumed that the farmer would delay the irrigation application.

When the IRPSAEV package is run under the SCHE mode with target moisture level (which uses MAD, line#15 of Figure C.5) as the irrigation timing criteria, then there can be four possibilities for the *present day* SMC viz:

- i) the computed SMC of the *present day* is still fairly above the given MAD level so that no irrigation is required during the forecast period.
- ii) the computed SMC of the *present day* is not significantly above the given MAD level, and therefore an irrigation is essentially required during the forecast period.
- iii) the *present-day* computed SMC has already exceeded the given MAD level forcing the crop to undergo moisture stress, and therefore an irrigation is already overdue. However, this situation occurs occasionally.
- iv) the SMC status is the same as in (ii), but the farmer is unable to irrigate the farm on certain day (or days) due to special reasons (as outlined in Section C.4.1), and this day(s) falls within the user-specified irrigation forecast period.

For each of the above mentioned four scenarios (or cases), the IRPSAEV software produces different irrigation advises which are described under separate headings below. It is important to note that these irrigation advises given in the output files of the SCHE mode are based on the results of a case study, which was carried out at a farm in the Goulburn-Murray Irrigation Area (GMIA) of Victoria, Australia. The detail of this case study is presented in Section C.9. The elaborating example used in this sub-section has also been extracted from this case study. As stated earlier, in each of the following case the rainfall during the forecast period is assumed as zero to represent the worst condition for forecasted irrigation.

#### Case (i)

A typical output file of the SCHE mode for case (i) is shown in Figure C.15. In this example, the IRPSAEV model was run on 23/03/1998 for perennial pasture to compute the irrigation requirements during the next seven-day period.

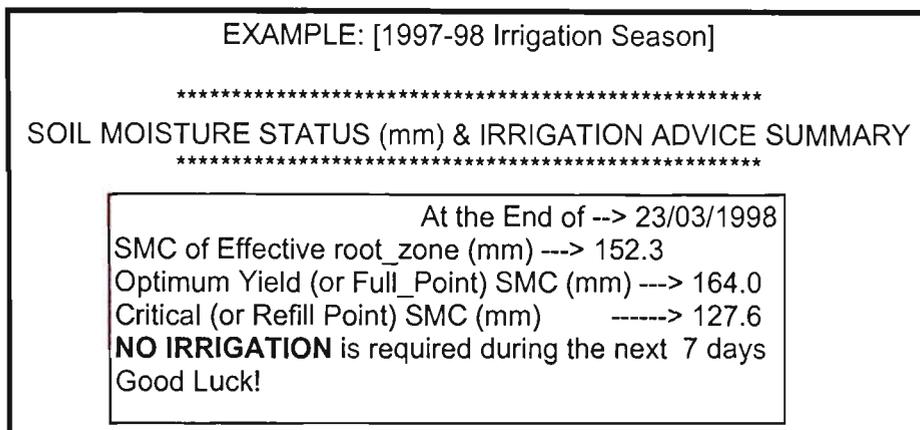
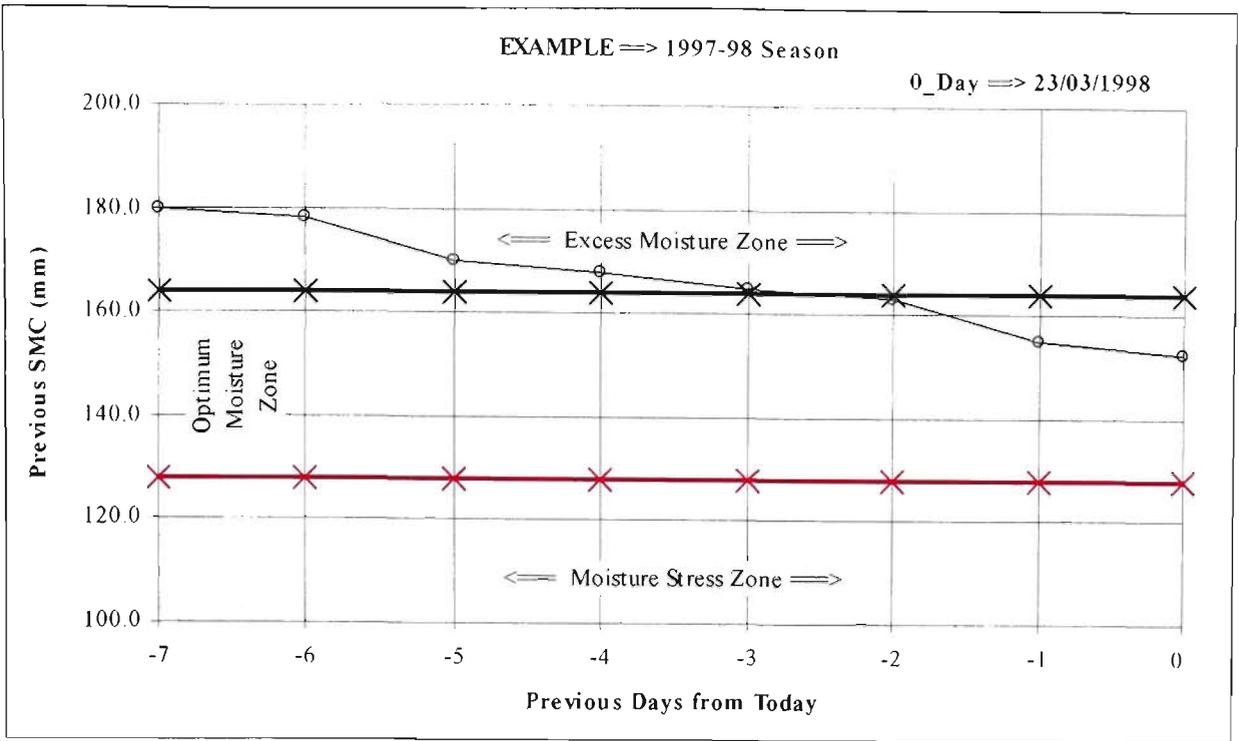


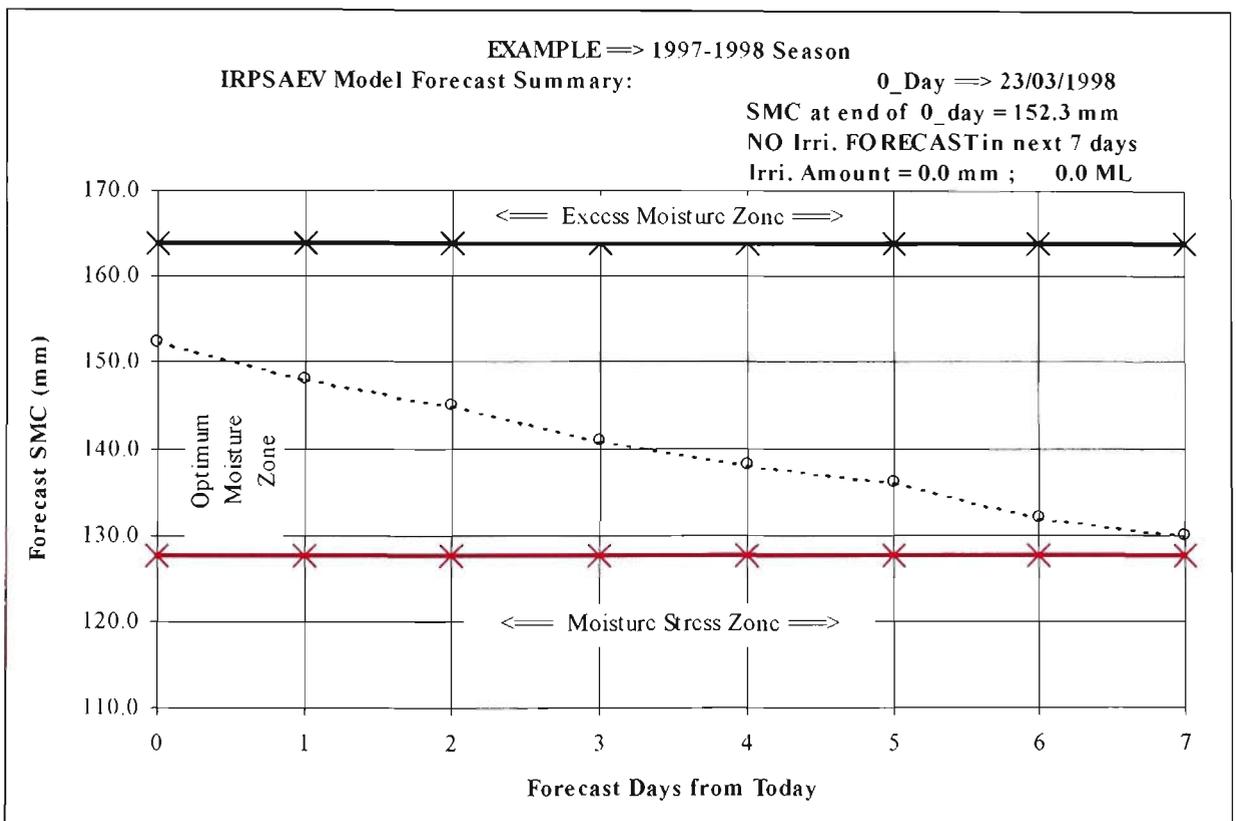
Figure C.15 Output of SCHEduling Mode with No Irrigation Forecast (Case-i)

As shown in Figure C.15, the model indicates that the root-zone SMC at the end of 23/03/1998 was 152.3 mm that was below the optimum yield or full point (i.e. FCAP) SMC (~164mm) level. However, this SMC was fairly above the refill SMC level, and did not fall below the user-specified MAD (35% ~ 126.6mm) level during the next 7-day period. Therefore, in the advice, no irrigation was forecasted within the next 7-day period.

The graphical presentation of this advice is shown in Figure C.16. In Figure C.16(a), three distinct graphical lines are shown. The graphical line with “0” symbols depicts the daily root-zone SMC evolution during the past seven days. This will give the farmer an overall picture of the SMC status for the past seven days. In this figure, the *0<sub>day</sub>* on x-axis refers to the present-day (i.e. 23/03/1998), whereas -1,-2,-3 ... etc. represent the previous days from present-day (i.e. 22/03, 21/03, 20/03 ...etc).



(a) SMC Status of Past Seven Days



(b) SMC Forecasts for Next Seven Days

Figure \*16 Graphical Output of SCHEDuling Mode with No Irrigation Forecast – Case (i)

The other two curves (i.e. upper and lower horizontal graphical lines with “\*” symbols), represent the SMC at optimum and critical levels respectively. Hence, the zone below the critical line represents the *moisture stress zone*, and the zone above the optimum line represents the *excess moisture zone*. Therefore, the zone between these two horizontal lines is regarded as the MAD or the optimum moisture zone for the crop under consideration. It is important to note that whenever the daily root zone SMC evolution line crosses the critical (i.e. lower horizontal) line, an irrigation is required. This will be shown later in case(ii).

In Figure C.16(b), the three graphical lines similar to those explained above are shown. However, in this figure the graphical line with symbols “0” is replaced with a dashed (---) line. This dashed graphical line represents the forecast SMC evolution during the next 7-day period. As in Figure C.16(a), in this figure the *0\_day* on x-axis refers to the present-day (i.e. 23/03/1998), whereas 1, 2, 3, ... etc. represent the next (forecast) days from the present-day (i.e. 24/03, 25/03, 26/03/...etc.). Whenever the dashed (i.e. forecast SMC) line crosses the critical (lower horizontal) SMC line, an irrigation is advised. As shown in this figure, the forecast SMC (dashed) line still remains in the MAD zone during the next 7-day period. Therefore, no irrigation was forecasted during the next 7-day period. This advise is also briefly shown at the top right hand corner of Figure C.16(b).

### Case (ii)

In this case, the IRPSAEV package was run a few days later on 27/03/1998 (Figure C.17) compared to case (i). This run revealed that that the SMC on 27/03/1998 was not enough, and was expected to exceed the given MAD (35% ~ 126.6mm) level during the user-specified next 7-days forecast period. As can be seen in Figure C.17, an irrigation is required on 1<sup>st</sup> April, 1998.

```

EXAMPLE: [1997-98 Irrigation Season]
*****
Irri. required on 01/04/1998 ==> 57.8mm or 28.9ML
Irri. required on 02/04/1998 ==> 60.6mm or 30.3ML
Irri. required on 03/04/1998 ==> 63.4mm or 31.7ML

*****
SOIL MOISTURE STATUS (mm) & IRRIGATION ADVISE SUMMARY
*****

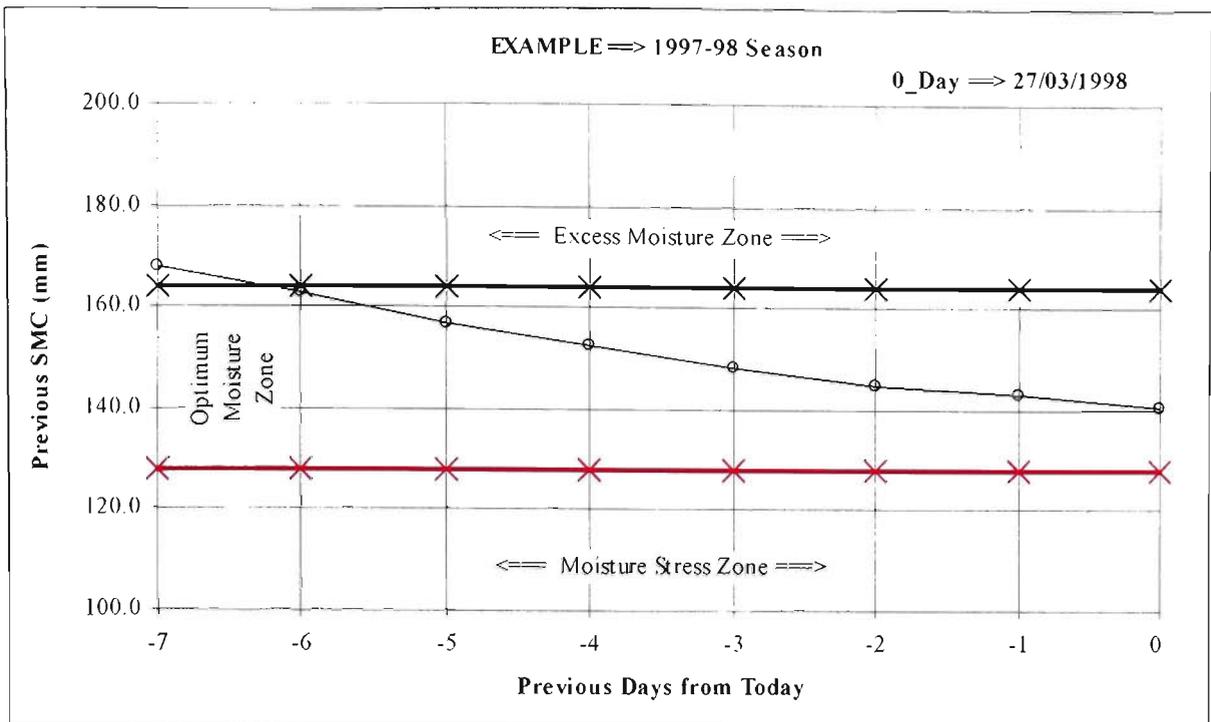
At the End of --> 27/03/1998
SMC of Effective root_zone (mm) ---> 140.2
Optimum Yield (or Full_Point) SMC (mm) ---> 164.0
Critical (or Refill Point) SMC (mm) -----> 127.6
IRRIGATION is FORECASTED on 01/04/1998:
Irri. amount to refill FCAP level ==>      37.8mm or 18.9ML
Irri. to refill upto EXTRA_level ==>      57.8mm or 28.9ML
Good Luck!

```

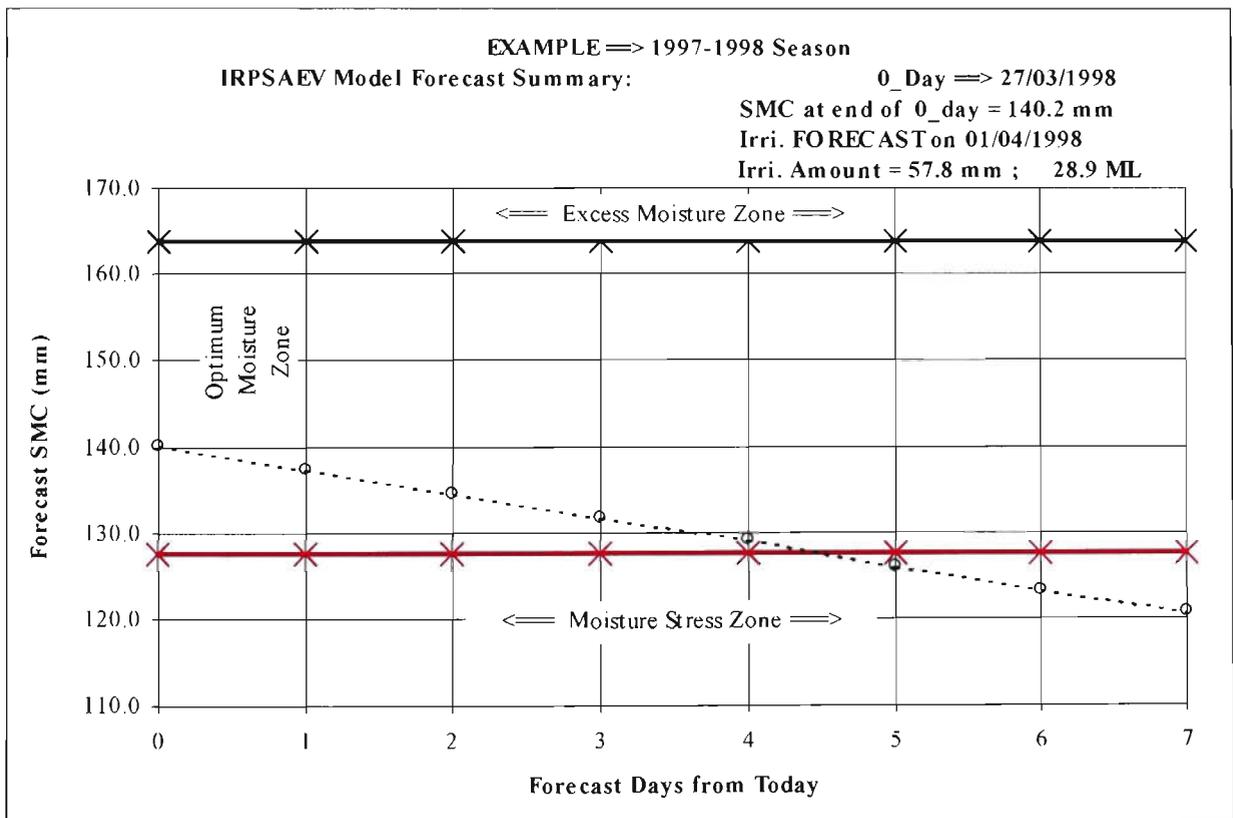
Figure C.17 Output of SCHEDuling Mode with Irrigation Forecast (Case-ii)

It is notable that in Figure C.17 before the overall summary, different irrigation schedules (dates and amounts) starting from the first day on which an irrigation was forecasted and onwards are presented. These would facilitate the farmer to choose the right amount of irrigation water for ordering in case the supply is not available to him/her on preferred (i.e. in this case 1<sup>st</sup> April, 1998) day for irrigation. It is important to note that in this case the farmer has indicated to irrigate the field beyond the FCAP level (as shown in line#20 of Figure C.5). Therefore, the various irrigation schedules shown in Figure C.17 before the overall summary, are based on the *beyond FCAP* level. In the summary it is indicated as EXTRA\_level irrigation.

The graphical aspect of case (ii) is elaborated in Figures C.18. The interpretation of these figures is similar to case (i).



(a) SMC Status of Past Seven Days



(b) SMC Forecasts for Next Seven Days

Figure 18 Graphical Output of SCHEDuling Mode with Irrigation Forecast – Case(ii)

Case (iii)

In exceptional circumstances, the farmer might come across a situation when he/she is not able to irrigate the farm at its right time. This causes the crop to suffer moisture stress due to late (or overdue) irrigation. When the IRPSAEV model is used for this case under the SCHE mode, it would give a warning message indicating an overdue irrigation.

Continuing with case (ii), it was assumed that the farmer could not abide by the advice of the IRPSAEV model under case (ii) of forecasted irrigation on 1<sup>st</sup> April, 1998, and ignored this irrigation application event. Thus, when the model was run on 02/04/1998, it revealed that the SMC on 02/04/1998 had already exceeded the user-specified MAD (35% ~ 126.6mm) level. The irrigation advice in this case is shown in Figure C.19.

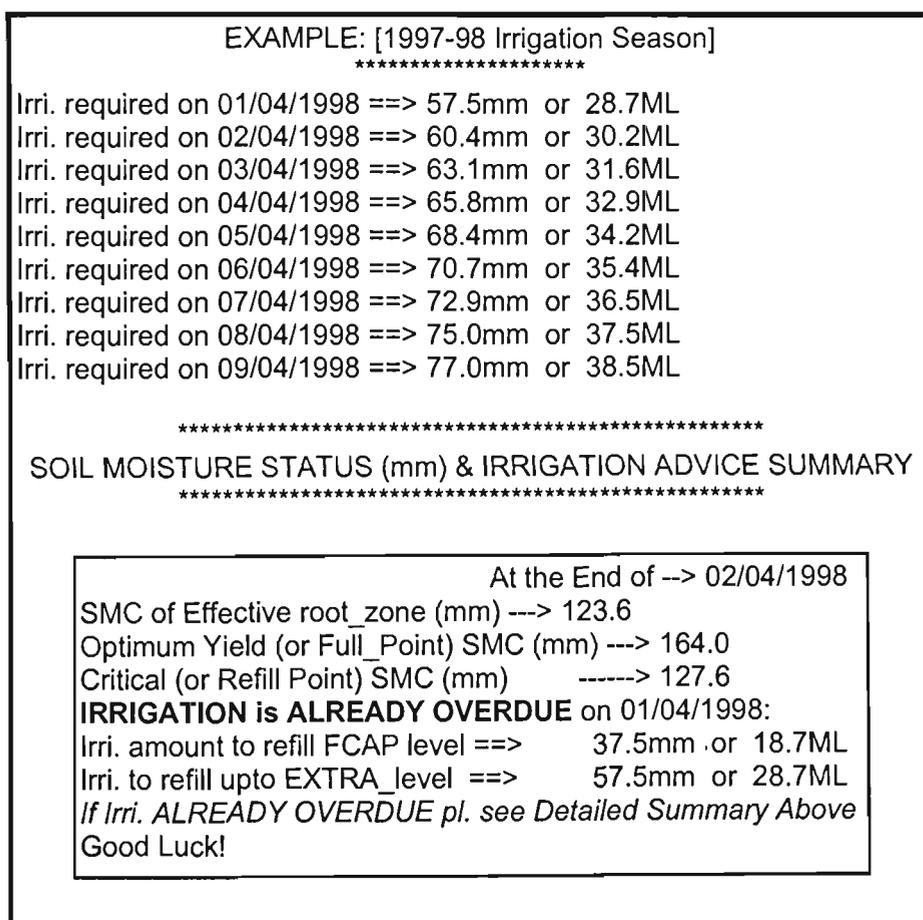


Figure C.19 Output of SCHEDuling Mode With an Overdue Irrigation (Case-iii)

As shown in Figure C.19, in addition to an overdue warning message, there are some additional 7-day forecast schedules presented. These schedules are useful to the farmer so that he/she could choose the right amount of water for ordering for a certain forecast day.

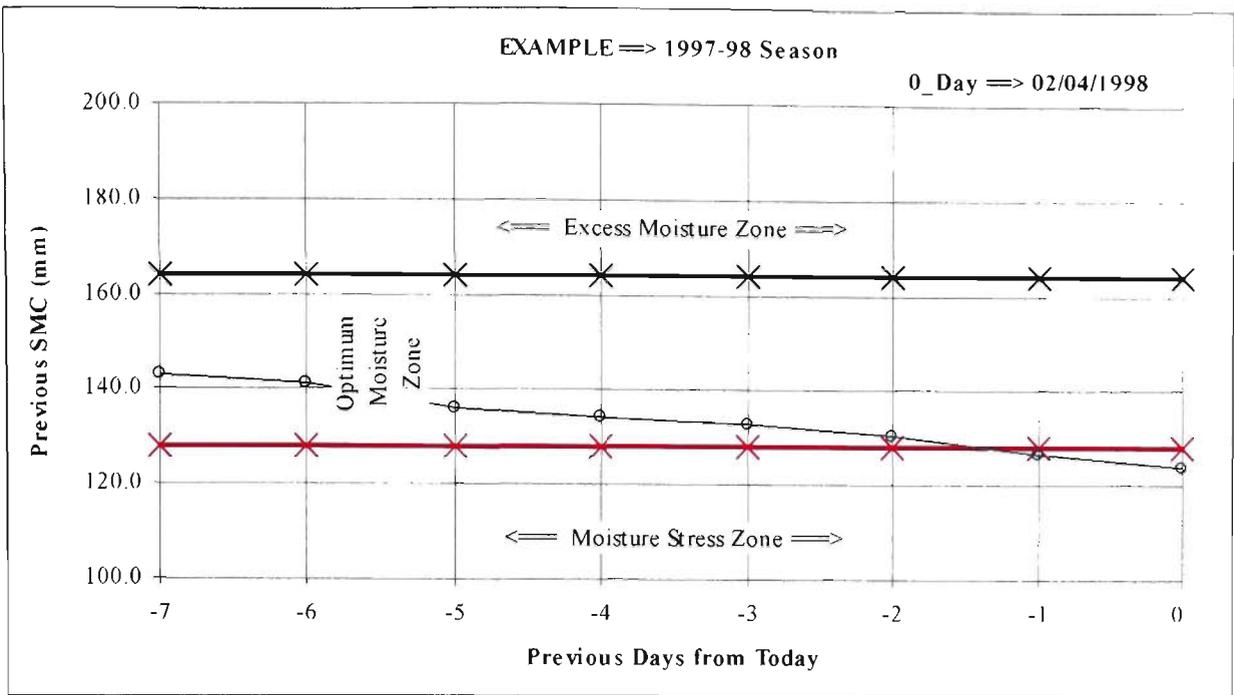
The graphical representation of this case is shown in Figure C.20. These figures show how far the SMC had exceeded the user-specified MAD level resulting in the moisture stress to the crop.

#### Case (iv)

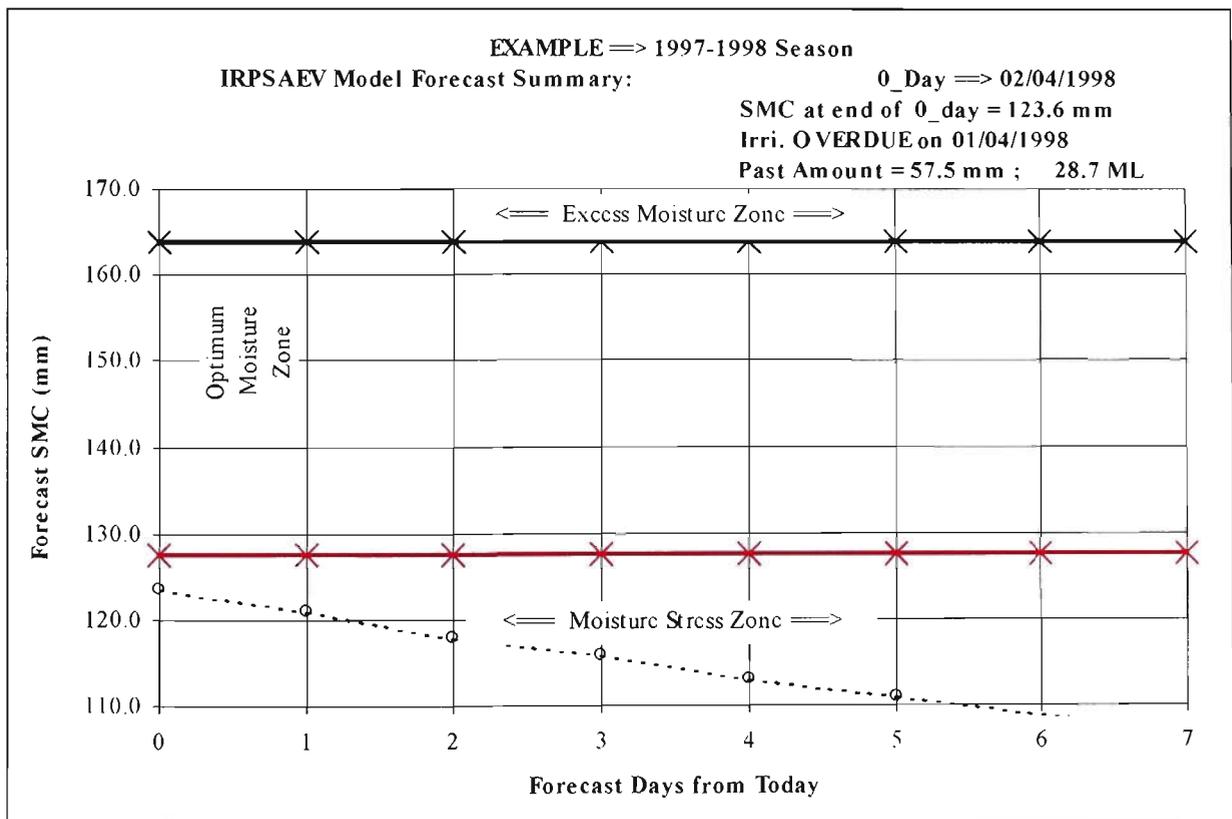
As stated earlier, this case is a slight variation of case (ii). Hence, the IRPSAEV package would issue a slightly different irrigation advice to Figure C.17 (that had an irrigation forecasted on 1<sup>st</sup> April, 1998). For this case (i.e. case-iv), using the same model run as described for case (ii), it was assumed that the farmer was unable to irrigate on 31/03/98 and 01/04/98 for his/her personal reasons (as shown in line#10 of \*.GEN data file, Figure C.5). For this case, the irrigation advice given by the IRPSAEV model is shown in Figure C.21. As can be observed from this figure, the irrigation advice includes an *intentionally deferred irrigation* message on 1<sup>st</sup> April, 1998, to indicate that the actual irrigation was forecasted on this day that had to be excused due to farmer's personal reasons. Hence, an alternate irrigation forecast on 02/04/1998 (i.e. the immediate next day) has also been indicated in this figure, together with some additional schedules, as in case (ii). These schedules are useful for the farmer to choose the right amount for water orders for a certain forecast day from the local water authorities.

It is important to note that if the forecasted irrigation does not fall on these *excused* day(s), then this intentionally deferred irrigation message is not issued, and therefore, the advice would be exactly the same as that of case (ii) i.e. Figure C.17.

The graphical representation of case-iv would be same as that of case (ii) except that the forecasted date would be different (i.e. in this case 2<sup>nd</sup> April).



(a) SMC Status of Past Seven Days



(b) SMC Forecasts for Next Seven Days

Figure 20 Graphical Output of SCHE Mode with an Overdue Irrigation – Case(iii)

```

EXAMPLE: [1997-98 Irrigation Season]
*****
ON→ 01/04/1998 Irri is DEFERRED Intentionally

Irri. required on 02/04/1998 ==> 60.6mm or 30.3ML
Irri. required on 03/04/1998 ==> 63.4mm or 31.7ML

*****
SOIL MOISTURE STATUS (mm) & IRRIGATION ADVICE SUMMARY
*****

At the End of --> 27/03/1998
SMC of Effective root_zone (mm) ---> 140.2
Optimum Yield (or Full_Point) SMC (mm) ---> 164.0
Critical (or Refill Point) SMC (mm) -----> 127.6
IRRIGATION is FORECASTED on 02/04/1998:
Irri. amount to refill FCAP level ==>      40.6mm or 20.3ML
Irri. to refill upto EXTRA_level ==>      60.6mm or 30.3ML
Good Luck!

```

Figure C.21 Output of SCHEDuling Mode with Deferred Irrigation (Case-iv)

## C.8 EVALuation Mode

At the end of an irrigation season, the IRPSAEV model can be run under the EVAL mode to serve as an evaluation tool. If run under EVAL mode, the model shows how successful were the irrigation schedules adopted by the farmer based on his/her judgement at the site where the IRPSAEV package was not used. This information can be useful to encourage the farmer to use computer-based irrigation scheduling program to achieve water savings.

The execution structure of the IRPSAEV package for EVALuation mode is shown in Figure C.22. As shown in Figure C.22, this mode requires three input data files namely \*.GEN, \*.KCS and \*.ETO. The details of these input data files are given in Section C.4.

The Evaluation mode is executed through the EVAL sub-menu of the IRPSAEV package, which is described in Section C.8.1.

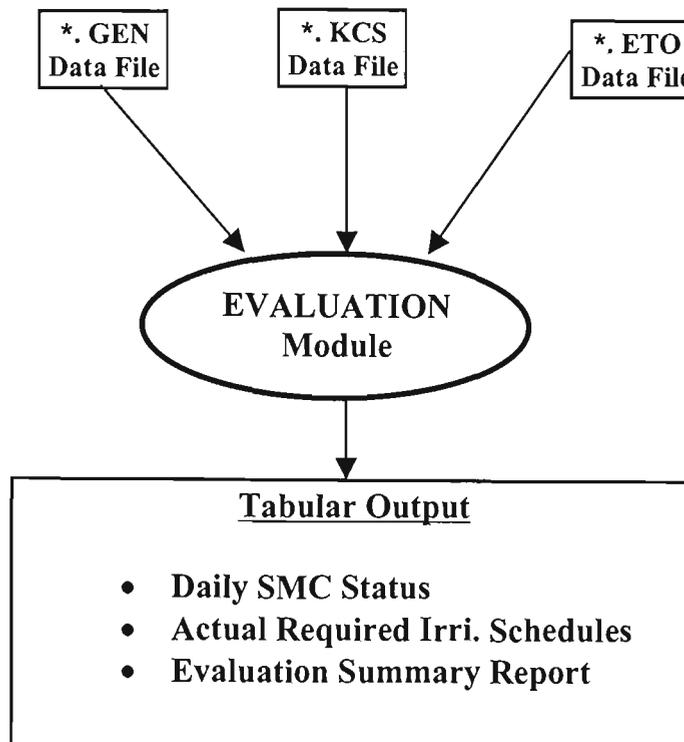


Figure C.22 Schematic of IRPSAEV Package in EVALuation Mode

### C.8.1 EVAL Sub-Menu

After updating the input data files as per Section C.3, choosing the EVAL mode from the Main Menu (Figure C.3) brings the user to the EVAL sub-menu as shown in Figure C.23, with the updated input data files as ISMODEL.\* files (Section C.3). As can be seen from Figure C.23, there are seven command buttons to facilitate the operations of the *EVAL Sub-Menu*. They are explained as below.

#### *Display/Edit \*.GEN, \*.KCS and \*.ETO Buttons*

These buttons are used to edit the ISMODEL.GEN, ISMODEL.KCS and ISMODEL.ETO input data files respectively. It is important to note that editing of input

data files while using these Display/Edit buttons in the *EVAl Sub-Menu* updates the data only in the ISMODEL.\* data file, and not in the original input data files. Hence, the editing of data in the original data files should be done through the DATA Sub-Menu (i.e. Figure C.4).

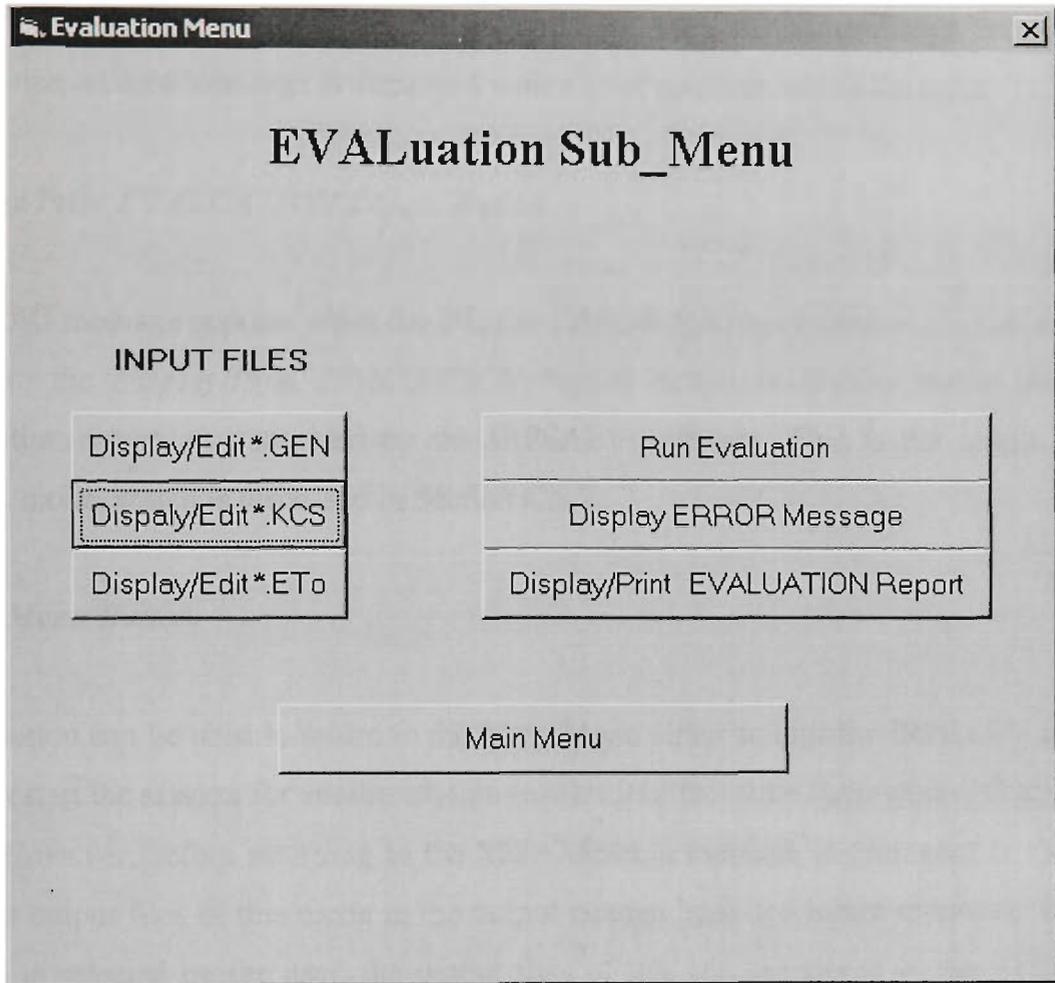


Figure C.23 EVALuation Sub\_Menu of IRPSAEV Software

### ***Run Evaluation Button***

By clicking this button, the IRPSAEV model computes the irrigation schedules for the evaluation mode.

### ***Display ERROR Message Button***

In order to know whether or not the EVAL mode schedules were computed successfully, the *Display ERROR Message* button can be used to see the message. If the schedules were made successfully by the IRPSAEV software, then an OK! message can be seen. Otherwise, an error message is displayed with a brief guide to rectify the error.

### ***Display/Print EVALUATION Report Button***

If an OK! message appears when the *Display ERROR Message* button is clicked, the user can use the *Display/Print EVALUATION Report* button to display and/or print the evaluation report, as computed by the IRPSAEV software. This is the output of the EVAL mode, which is discussed in Section C.8.2.

### ***Main Menu Button***

This button can be used to return to the Main Menu either to quit the IRPSAEV session, or to restart the session for another station (or farm) or the same farm with different input files. However, before returning to the Main Menu, a message is prompted to store the current output files of this mode in the output storage bank for future reference. If YES option is selected by the user, the output files of this run are stored in the STOR sub-directory, which can later be displayed using STORE Sub\_Menu as described in Section C.5.

## **C.8.2 Output Files**

If run under the EVAL mode, the IRPSAEV model predicts the actual irrigation schedules as well as estimates of total water demand for the previous irrigation season at the farm under consideration. In addition, the daily SMC status of the root zone over the

entire irrigation season is also given. At the end of the output file, a summary for the entire season is also presented.

A typical output file of the EVAL mode is given in Figure C.24. However, the figure shows only a small portion of the EVAL output file. The crop-code and the *analysis period* shown in Figure C.24 have the same interpretation as given under PLAN mode (Section C.6.2). However, the analysis period in this figure represents the period for which the evaluation was invoked by the user.

The irrigation schedules (date and amount) presented in Figure C.24 represent the actual model-predicted irrigation events based on the user-specified irrigation timing criteria, as indicated in line#15 of the \*.GEN file (Section C.4.1). Since these schedules are based on the previous season climatic data, they do consider the rainfall events which have already occurred during the past season.

At the end of the output file, a self-explanatory summary of irrigation schedules over the entire evaluation period is also given. It is important to note that at the end of this summary, like in PLAN mode, one extra full-irrigation has also been included in this given irrigation estimates. The reason for this is the same as explained under PLAN mode in Section C.6.2.

EXAMPLE: [1997-98 Irrigation Season]

\*\*\*\*\*

NOTE-->This file is NOT VALID for Scheduling\_Mode  
Current EXECUTION\_MODE--> Past EVALUATION  
CROP\_code--> 1: Analysis Period--> 73 to 238 th day  
\*\*\*\*\*

Initial ENTIRE ROOT-zone(FCAP) SMC = 16.4000 cm  
\*\*\*\*\*

Actual caculation STARTS NOW FROM--> 26/10/1997

At the end of --> 26/10/1997 SMC= 15.9 cm

At the end of --> 27/10/1997 SMC= 15.6 cm

At the end of --> 28/10/1997 SMC= 15.2 cm

: : :  
: : :

At the end of --> 07/11/1997 SMC= 13.2 cm

At the end of --> 08/11/1997 SMC= 12.7 cm

Irri. required on 08/11/1997 ==> 5.69 cm

At the end of --> 09/11/1997 SMC= 18.4 cm

At the end of --> 10/11/1997 SMC= 18.4 cm

At the end of --> 11/11/1997 SMC= 18.4 cm

At the end of --> 12/11/1997 SMC= 18.0 cm

At the end of --> 13/11/1997 SMC= 18.4 cm

At the end of --> 14/11/1997 SMC= 18.4 cm

At the end of --> 15/11/1997 SMC= 18.4 cm

At the end of --> 16/11/1997 SMC= 18.2 cm

At the end of --> 17/11/1997 SMC= 17.7 cm

: : :  
: : :

At the end of --> 06/04/1998 SMC= 12.7 cm

Irri. required on 06/04/1998 ==> 5.71 cm

At the end of --> 07/04/1998 SMC= 18.4 cm

At the end of --> 08/04/1998 SMC= 18.4 cm

At the end of --> 09/04/1998 SMC= 18.4 cm

\*\*\*\*\* Summary of Entire Period \*\*\*\*\*

Current EXECUTION\_MODE--> Past EVALUATION

!\*\*\*\*\*!

!\* SEASON TERMINATED ON-->09/04/1998

!\* All GIVEN Rainfall Adjusted & USED in Evaluation\*:

!\* Total Potential Crop ETC ----->= 85.64 cm \*:

!\* Total Actual Crop ETa ----->= 60.80 cm \*:

!\* Total Rainfall ----->= 13.90 cm \*:

!\* Deep Percolation Losses----->= 3.05 cm \*:

!\* Total EFFECTIVE Rainfall ----->= 4.95 cm \*:

!\* SMC at END of Season in ENTIRE Root = 18.40 cm \*:

!\* Total Amount of Irri REQUIRED ----->= 57.85 cm \*:

!\* Total NUMBER of Irri REQUIRED -----> = 10 \*:

!\* Note: Add ONE More Full\_Irri to Above Estimates \*:

!\* Good Luck! \*:

!\*\*\*\*\*!

Figure C.24 A Typical Output File of EVAL Mode

## **C.9 USE OF IRPSAEV SOFTWARE UNDER FIELD CONDITIONS**

In order to assess the potential benefits from the use of the IRPSAEV package under field conditions, the package was applied to a farm in the Goulburn-Murray Irrigation Area (GMIA) in Victoria, Australia. This was carried out by performing a case study relevant to each of the three operational (i.e. PLAN, SCHE and EVAL) modes of the package. In all modes, the *target moisture level approach* (which uses MAD, and hence also referred to as “MAD Option”) was adopted as the irrigation timing criteria (Section 5.5). In this section, these case studies are presented.

### **C.9.1 Study Site**

For this application, the study site selected was the same (i.e. Tongala) site as described in Section 5.8.1. This site was selected because the required input data for this site were available. Additionally, the farm was managed by the farmer who was well aware of the benefits of efficient irrigation scheduling. The size of the farm at the study site was 50 hectares. For the purpose of this case study, the 1997-98 irrigation season was used. The name of the farm used in the present case study is hereafter referred to as *EXAMPLE*. The input data files used for this example farm were the same as described in Section C.4 under SAMPLE name.

### **C.9.2 Existing Irrigation Practice**

The normal irrigation scheduling practice adopted by the farmer at the site was to irrigate the field approximately every ten days to its SAT level (as can be seen from SMC data of Figure 5.7). According to Wood et al. (1998), the recommended refill point for the soil-crop system at that farm was 32% SMC by volumetric basis (~MAD=35%). Note that the site had used approximately 10 ML/ha per annum for irrigating its perennial pastures (Wood et al., 1998). According to Armstrong et al. (1998), this falls in the medium range of water use in Victoria (the range varied between 6 ML/ha and 17 ML/ha). Therefore,

the expected benefits in terms of water savings, from this farm would be lower than those of the other over-irrigated farms in the area

### **C.9.3 Case Study I - PLAN Mode**

In order to investigate the ability of the IRPSAEV package to serve as a pre-season planning tool, the package was run under the PLAN mode. The period used for this purpose was from 25th October 1997 to 9th April 1998 (167 days). The contents of two of the three input data files namely EXAMPLE.GEN and EXAMPLE.KCS used for this mode are given in Figures C.5 and C.6.

The locally calibrated crop factors were available for this site instead of crop coefficients for the pasture crop. Hence, these crop factors were used to compute the potential crop evapotranspiration ( $ET_c$ ) values from US class-A pan evaporation data without the need for  $ET_o$  estimates (Section 3.5.4) for use by the IRPSAEV package. As stated in Section 3.5.4, for pre-season planning purposes, mean daily  $ET_o$  data are required. These mean daily  $ET_o$  data are utilised to compute the mean daily  $ET_c$  values for use by the IRPSAEV package for pre-season planning. In this study, for planning purposes the required mean daily  $ET_c$  values were calculated by the IRPSAEV software using the given Gaussian 5-parameters values (Figure C.5), which were obtained from the curve-fit (Section 3.6.4) of historical daily US class-A pan data of the nearby Kyabram station referred in Section 5.8.1. Since the Gaussian 5-parameters curve-fit values were available, the third customary input data file (\*.FET) for the PLAN mode for this site was not required.

For the PLAN mode, the IRPSAEV model was run on a daily basis by initialising the SMC at FCAP level (a default choice of the IRPSAEV model for PLAN mode). The MAD option was selected as the irrigation timing criteria, with a value of 35% as given in Wood et al. (1998) for the soil-crop system of the site. The equivalent SMC refill point to this MAD value was 32% on a volumetric basis. The recharge or full point SMC level adopted for each irrigation event was at SAT level - the usual practice followed by the farmer at the site.

The output file of the PLAN mode for this case study is shown in Figure C.12. As shown in this figure, the anticipated number of irrigations and the total irrigation water demand predicted by the model are 10 and 58.26 cm respectively. Since this planning does not account for the future rainfall, these irrigation figures (i.e. the irrigation number and amount) represent the worst scenario. Therefore, the actual number of irrigations during the season can be less than this figure depending on the amount of rainfall received during the actual season. As can be seen from Figure C.12, at the end of the summary of PLAN mode, one additional irrigation is also included in the predicted irrigation estimates. The reason for this is already explained in Section C.6.2.

The above information obtained from the PLAN mode were useful for the farmer to decide on the area for cultivation of this crop depending upon the water availability and capacity constraints of the supply system. This will help the farmer to foresee his/her farm returns from this crop before the actual season starts. If this type of information is available for other crops also (which can be obtained using the PLAN mode for those crops), this will help farmer to maximise his/her overall farm returns.

#### **C.9.4 Case Study II - SCHE Mode**

A case study example illustrating the SCHE mode of the IRPSAEV package to serve as a *real-time* scheduling tool has already been explained under Section C.7. The associated benefits achieved through the use of the IRPSAEV package as a real-time scheduling (or operational) tool over the whole irrigation season are detailed in Section C.9.5.

#### **C.9.5 Case Study III - EVAL Mode**

The two major aims of this part of the case study were: i) to evaluate the performance of the irrigation schedules used by the farmer and ii) to quantify the benefits which can be harvested through the adoption of the IRPSAEV package. These evaluations can help to build up the confidence of farmers to use the IRPSAEV package as a scheduling tool at the farm.

It should be noted that the major difference between the PLAN mode and the EVAL mode is that the latter is executed after the end of the irrigation season. Hence, the actual daily climatic data (i.e. pan evaporation data and rainfall) were available for the EVAL mode to evaluate what has really happened during the last irrigation season. Therefore, the EVAL mode was basically a retrospective run of the IRPSAEV package for the user-specified previous irrigation season.

In order to achieve the aforementioned aims of this part of the case study, the IRPSAEV package was run under the EVAL mode on a daily basis by initialising the SMC at FCAP level. The same MAD option was selected for this mode as for PLAN mode (Section C.9.3), with a value of 35% (~ refill point SMC as 32% on volumetric basis).

The period used for this analysis was also the same as used for the PLAN mode (i.e. from 25th October 1997 to 9th April 1998). The two of the three input data files required for this mode namely EXAMPLE.GEN and EXAMPLE.KCS are given in Figures C.5 and C.6 respectively. The third input data file EXAMPLE.ETO (produced by REF\_ET software) for use by the IRPSAEV model being a long data file is not included in this thesis. However, this data file can be requested from the candidate. The format details of the \*.ETO file are given in Appendix-A.

#### *Aim (i): Existing farmer's practice vs. IRPSAEV-model schedules*

A Part of the output file of the EVAL mode for this case study is shown in Figure C.24. As shown in this figure, the IRPSAEV-predicted number of irrigations and the total irrigation water required for the specified irrigation period was 10 and 57.85 cm respectively, excluding the initial irrigation (Section C.8.2). Since this evaluation also accounts for the rainfall which fell during the specified irrigation period, the EVAL mode irrigation figures (i.e. the number and amount) are expected to be less than those of the PLAN figures (Section C.9.3). However, it is interesting to note that the number of irrigations (and the total irrigation water demand) given by the EVAL mode for the

irrigation period is almost the same as that was predicted by the PLAN mode before the start of irrigation season. This was mainly due to the reason that the 1997-98 irrigation season was a dry year and did not receive much rainfall during this period.

Comparing the SMC predictions (obtained from the EVAL mode) with field-measured SMC data (where farmer's judgement-based irrigation practice was adopted), can give some idea of what level of water savings can be expected at the farm just by improving application timing through the use of IRPSAEV package. Figure C.25 shows the daily SMC status for 1997-98 irrigation season from the EVAL mode of the IRPSAEV package. By looking at this figure, it is immediately evident that the timing of irrigation, in terms of SMC at the time of application, was reasonably uniform. This is what the IRPSAEV software intended to do (i.e. the irrigation applications are applied at a constant soil moisture deficit). Applying irrigations at constant soil moisture deficit is achieved only by recognising the dynamic of evaporative demand during the irrigation season, while appreciating the contribution of incoming rainfall (not common during the 1997-98 being a dry year), which also affects the evaporative demand.

Thus, at the start of the season, when the evaporative demand is low, the irrigation interval should be relatively long. As the irrigation season progresses, the temperature increases, causing the evaporative demand to increase, which reduces the irrigation interval. The opposite occurs towards the end of the season. This factor is recognised and effectively modelled by the IRPSAEV model. As can be observed from Figure C.25, it shows a variable irrigation interval and the uniform soil moisture deficits before each irrigation throughout the season. In general, this factor is lacking in the farmer's judgement during the irrigation scheduling (which was observed at this farm too). This is discussed below.

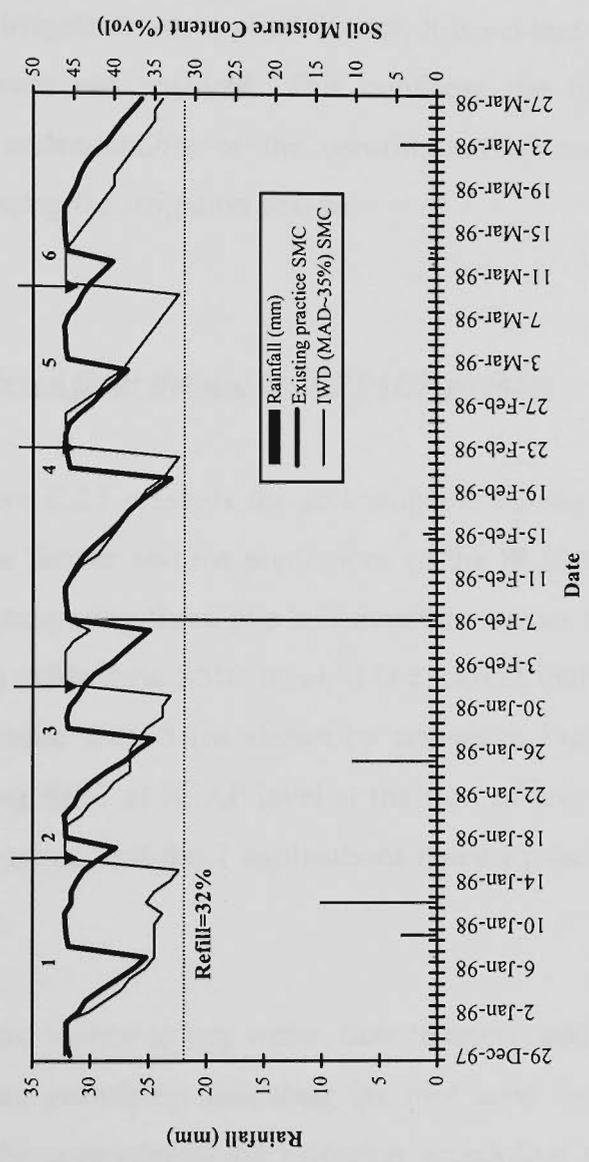


Figure C.25 Existing Irrigation Practice viz. IRPSAEV Model Predictions at Tongala

Figure C.25 also shows the measured SMC data from the field that was irrigated based on farmer's judgement. As can be observed from this figure, the soil water deficit prior to irrigations was not constant because the period between irrigations early in the season was too short. Thus, only a little of the available water (Section 5.2.1) was used by the pasture when the next irrigation was applied. Hence, it is evident that the irrigations were applied when they were not required. This confirms the belief that the farmer's judgement lacks the understanding of the contribution of rainfall and dynamics of evaporative demand during the irrigation season.

**Aim (ii) Benefits achieved from the use of IRPSAEV package**

As stated earlier, Figure C.25 presents the soil moisture curves based on the irrigation practice adopted by the farmer and the predictions of the IRPSAEV package during the irrigation season. By comparing these two soil moisture curves and recognising that the refill point lies at 32% volumetric SMC level, it is apparent that the irrigations required by the IRPSAEV software were 5 (as shown by arrows in Figure C.25) including the initial irrigation to bring SMC at FCAP level at the start of the irrigation season. These irrigation applications are against the 7 applications made by the farmer including initial irrigation.

The extra irrigations cost money to buy water, time to apply, add accessions to the water table, and affect pasture growth by saturating the root zone for up to three days. This means that by using the computer-based irrigation scheduling via IRPSAEV, not only two (~ 28% of total number of irrigations) irrigations would have been saved leading to significant financial savings, but also would have additional benefits of mitigation of environmental problems due to over-irrigation.

## C.10 MODEL CALIBRATION

Like all other mathematical models, the IRPSAEV model developed in this study also needs to be calibrated against appropriate measured SMC data to use the model under different soil and environmental conditions. Generally, the expected discrepancies between the observed and predicted moisture use curves (e.g. daily SMC graph as in Figure 5.7) can be of three types namely: i) vertical discrepancy, ii) horizontal discrepancy and iii) slope discrepancy (Yamashita and Walker, 1994), as shown in Figure C.26. Therefore, the aim of any effort of the IRPSAEV model calibration is to achieve a good agreement (of acceptable accuracy) between the observed and predicted moisture use curves by minimising the discrepancies between them. In this section, the calibration aspect of the IRPSAEV model is described.

### C.10.1 Calibration Parameters

The calibration of the IRPSAEV model can be carried out by adjusting four key parameters namely i) FCAP\_SMC,  $\theta_{DU}$  (i.e. line#21 of data file \*.GEN; Figure C.5), ii) *ZERO\_ET DAYS* (i.e. line#16 of data file \*.GEN; Figure C.5), iii) *Calibration\_Target Theta* (i.e. line#31 of data file \*.GEN; Figure C.5) and iv) *Root EXTRACTION Pattern* (i.e. line#25 of data file \*.GEN; Figure C.5). A common uniqueness of these parameters is that, being time and space variant, their values cannot be measured precisely, and therefore, require calibration. The use of these four parameters for calibration of the IRPSAEV model is described below. It is important to note that to simplify the description of the calibration procedure, the following discussion deals with only a time period between two irrigation events (i.e. an irrigation interval) in days such as 14-days. However, the adjustment of these parameters will have effect on SMC predictions over the entire irrigation season.

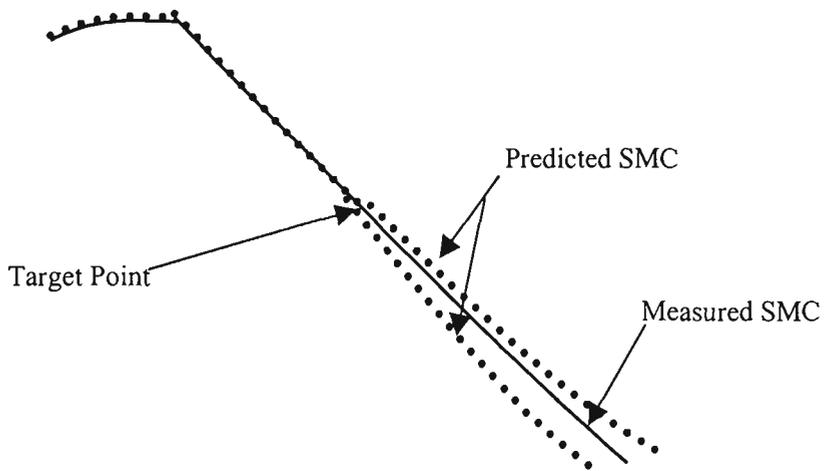
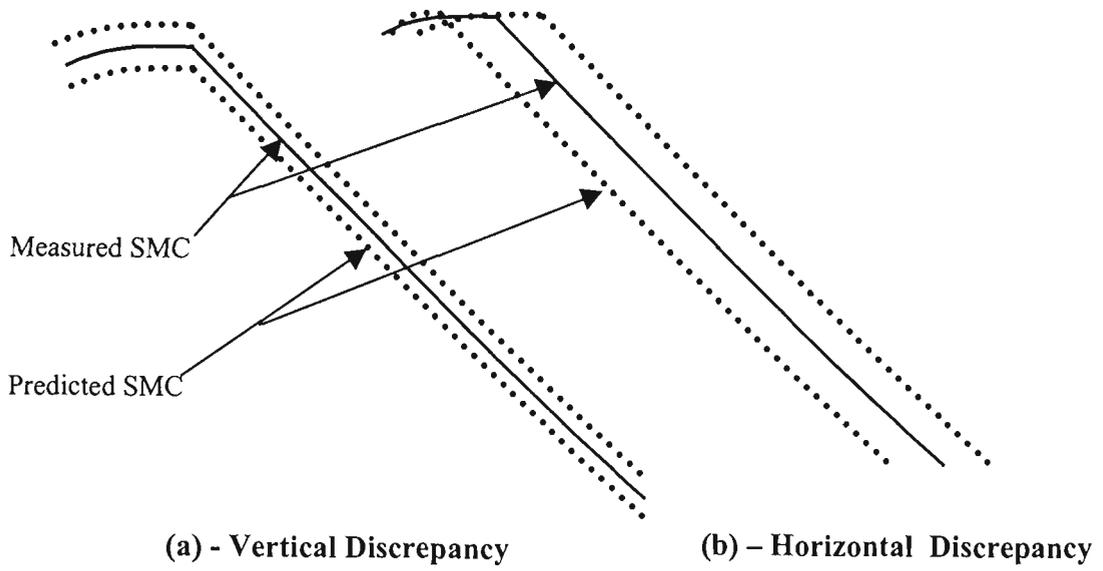


Figure C.26 Typical Discrepancies Between Measured and Model Predicted Soil Moisture Use Curves

(i) ***FCAP\_SMC*** ( $\theta_{DU}$ )

The effect of this parameter on moisture use curve is to shift the curve in vertical direction as shown in Figure C.26a. If the value of this variable is increased, the curve is shifted upwards, and vice versa if the value is decreased. Usually, a higher value of  $\theta_{DU}$  requires more water for each irrigation event, as less frequent irrigations or increased time intervals between two consecutive irrigations are invoked. However, where usual practice for irrigating the field is up to SAT level, a higher value of  $\theta_{DU}$  will require less water for each irrigation, and vice versa. The reason for this is that in this case some of the *excess water* (which drains from the saturated soil under the influence of gravity; Section 5.2.1 and 5.3.5) is also considered to be readily available to satisfy the crop ET requirements, which other wise would be considered as loss. Hence, the  $\theta_{DU}$  parameter which represents the initial moisture conditions followed by a heavy precipitation (i.e. rainfall and/or irrigation) event can be used to adjust the vertical lag between measured and predicted moisture use curves in model calibration. Since the adjustment of  $\theta_{DU}$  parameter changes the extra water available for plant ET, it can help to save significant amount of irrigation water by controlling the deep percolation losses as described in Sections 5.3.5 and 5.6.

(ii) ***ZERO\_ET DAYS***

The effect of ZERO\_ET DAYS on moisture use curve is to shift the curve in horizontal direction, as shown in Figure C.26b. If the value of this variable is increased, the curve is shifted to the right, and vice versa if the value is decreased. Usually, a higher value of ZERO\_ET DAYS requires less water for each irrigation event, as less frequent irrigations or increased time intervals between two consecutive irrigations are invoked. Hence, the ZERO\_ET DAYS parameter can be used to adjust a systematic horizontal lag between the two moisture use curves in model calibration.

### (iii) *Calibration\_Target Theta ( $\theta_{ct}$ )*

The effect of *calibration\_target theta* parameter is to change the slope of the moisture use curve. The break point on the moisture use curves (i.e. the point at which the predicted moisture use curve begins to diverge from the measured moisture use curve) is recognised as the target point, as shown in Figure C.26c. The SMC status (in % volumetric units) corresponding to this target point (as predicted by the IRPSAEV model during its water balance calculations) is known as the *calibration\_target theta*, and is denoted by  $\theta_{ct}$ . The value of this variable can be adjusted by the user, to change the slope of the model-predicted moisture use curve.

If the  $\theta_{ct}$  value is decreased by a certain percentage, the slope of moisture use curve is increased, and vice versa when the  $\theta_{ct}$  value is increased. Thus, this parameter can be used to minimise the systematic slope discrepancy between the two moisture use curves, as shown in Figure C.26c.

### (iv) *Root EXTRACTION Pattern*

The effect of *root EXTRACTION pattern* on moisture use curve is the same as that of  $\theta_{ct}$ . However, as this parameter changes with the crop growth, it can be used to fine-tune the slope discrepancies of the moisture use curves over the entire irrigation season. If the locally calibrated values of this parameter are available which represent different growth stages, the use of those data can reduce the calibration effort.

### *Moisture use curves for shallow and deep rooted crops*

It is important to note that the moisture use curves used for calibration purposes can be of two types, depending on the type of crop at the farm. These two curves are related to shallow-rooted crop with single root sub-layer, and deep-rooted actively growing

agricultural crop with multiple sub-layers. Basically, these curves are expressed in different units for different types.

For a shallow rooted crop with single root sub-layer, the moisture use curve can be constructed using the SMC data expressed in % volumetric units. For a deep rooted actively growing agricultural crop with multiple sub-layers, the moisture use curve needs to be constructed using SMC data expressed in depth (cm) units. The reason for this is that in case of multiple sub-layers, there exists a unique  $\theta_{cr}$  value for each sub-layer. Calibrating the model for each sub-layer individually complicates the calibration process. Furthermore, there is no way to represent these multiple  $\theta_{cr}$  values by a single entire root-zone representative value especially for heterogeneous soils. Alternatively, the model-predicted SMC of the entire root zone expressed in depth (cm) units can be conveniently used for calibration purposes. However, in this case the observed SMC data of each sub-layer would also need to be expressed in depth units and then summed up over the entire root zone. This can be easily done using Eq. 5.21 as described in Section 5.7.1. The calibration process for each of the aforementioned two types of crops (or cases) is described in Section C.10.2.

### **C.10.2 Calibration Process**

To facilitate the calibration process, the IRPSAEV model produces the two types of SMC output files: one in volumetric (%) units, and other in depth (cm) units. These SMC predictions given by the IRPSAEV model can be used to compare with the measured SMC values. The qualitative and quantitative tests (Section 5.8.2) can then be applied to test the agreement between these SMC predictions and measured data sets. A best fit of acceptable accuracy can be achieved by adjusting the aforementioned four calibration parameters through trial and error procedure. For calibration purposes, SMC predictions of the IRPSAEV model can be obtained by executing the IRPSAEV package under CALibration mode. The CALI mode can be executed through the CALI Sub-Menu of the IRPSAEV package, which is described in the following section.

### C.10.3 CALI Sub-Menu

After updating the input data files as in Section C.4, choosing the CALI mode from the main menu (Figure C.3) brings the user to the CALI Sub-Menu. A schematic of the calibration process of the IRPSAEV model is shown in Figure C.27, and the sub-menu of this mode is shown in Figure C.28. As shown in Figure C.27, the CALI mode requires four input data files: \*.GEN, \*.KCS, \*.SMC and \*.ETO data files. The preparation of these input data files is the same as that of the EVAL mode, which is already explained in Section C.4. It is important to mention that for CALI mode, the \*.SMC input data file needs to be prepared to include all irrigation events during the previous irrigation season.

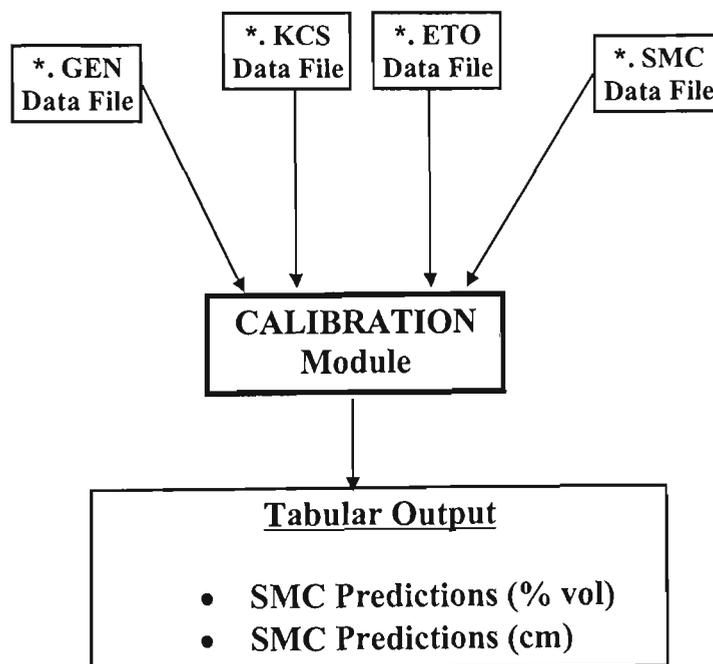


Figure C.27 Execution Structure of IRPSAEV Package for Calibration Option

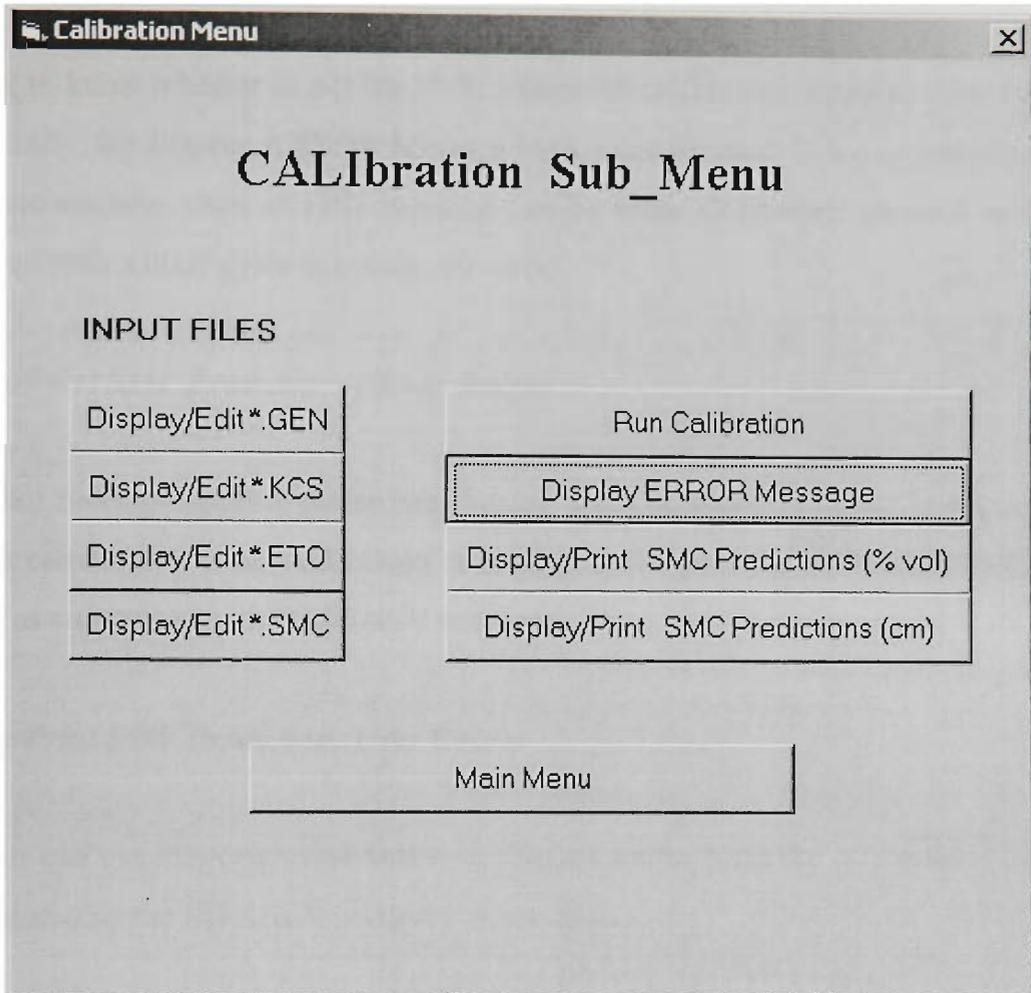


Figure C.28 CALibration Sub\_Menu of IRPSAEV Software

As can be seen from Figure C.28, there are nine command buttons to facilitate the operation of the CALI Sub-Menu. The four display/edit (i.e. Display/Edit \*.GEN etc.) command buttons on the left hand side of Figure C.28 can be used to edit the input data files relevant to this sub-menu. The other five buttons are described as below.

***Run Calibration Button***

By clicking this button, the IRPSAEV software computes the SMC values for calibration purposes.

### ***Display ERROR Message Button***

In order to know whether or not the SMC values for calibration purposes were computed successfully, the ***Display ERROR Message*** button can be used. If the computations were made successfully, then an OK! message can be seen. Otherwise, an error message is displayed with a brief guide to rectify the error.

### ***Display/Print SMC Predictions (%vol) Button***

If an OK! message appears (when the Display ERROR Message button is clicked), then the user can use this command button to display and/or print the calibration SMC (%vol) values, as computed by the IRPSAEV software.

### ***Display/Print SMC Predictions (cm) Button***

The user can use this command button to display and/or print the calibration SMC data, as computed by the IRPSAEV software in cm units.

It is important to mention that the output files of the CALI mode are similar to that of the EVAL mode except that the irrigation schedules (time and amount of irrigation) and the summary are missing in the CALI mode. Another point to note in this regard is that the SMC (%vol) given in the output file of the CALI mode is meant for single sub-layer shallow rooted crops. The SMC predictions in depth (cm) units represent the entire root zone SMC of multiple sub-layers, which can be used for calibration of multiple sub-layers deep rooted crops, as explained in Sections C.10.1 and C.10.2.

### ***Main Menu Button***

This button can be used to return to the Main Menu either to quit the IRPSAEV session, or to restart the session for the same farm to calibrate using data of another irrigation season or for another farm. However, before returning to the Main Menu, a message is prompted whether to store the current output files of this mode in the output storage bank for future reference. If YES option is selected by the user, the output files of this run are stored in the STOR sub-directory, which can later be displayed using STORE Sub\_Menu, as described in Section C.5.

### **C.10.4 Calibration Case Study**

To investigate the need for calibration of the IRPSAEV software, a case study was performed. The farm site selected for this case study was the same (i.e. Tongala) as described in Section 5.8.1. The 82-day period from 8<sup>th</sup> October 1997 to 28<sup>th</sup> December 1997 was used for this purpose. Graphical presentation of the measured SMC data for this period (i.e. Figure 5.7) revealed that the average value of ZERO\_ET DAYS parameter for this soil-crop system was 3 days. The required input data files were prepared as per Section C.4. After updating the input data files, the IRPSAEV software was run using the CALI sub-menu (Figure C.28) to give SMC (%vol) predictions on a daily basis. The graphical representation of both measured and predicted SMC data for this case study is shown in Figure 5.7. An excellent agreement between the two moisture use curves can be clearly observed from this figure. Further details of this figure have already been given in Section 5.8.3.

## **C.11 DOS VERSION OF IRPSAEV SOFTWARE**

As stated earlier in Section C.2, the IRPSAEV package can also be run in DOS environment. However, as will be shown later, both Windows and DOS versions do not

differ much in its operation. In order to run the IRPSAEV package under the DOS environment, the user is required to go to the sub-directory where the IRPSAEV software is (i.e. C:\DIS), and type DIS. This displays the Main Menu as shown in Figure C.29.

As can be observed from Figure C.29, there are eight function keys to facilitate the operation of this menu. These function keys are exactly same as the command buttons of the Windows version (Figure C.3), in Section C.2.

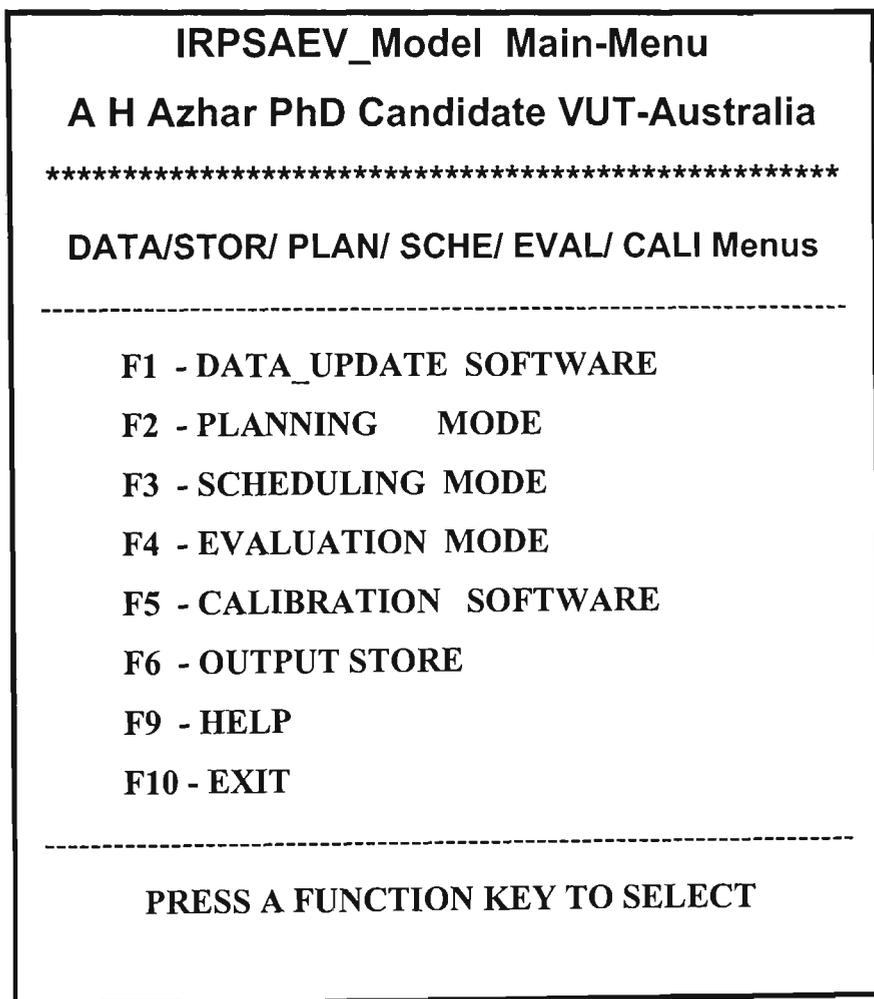


Figure C.29 Main Menu of IRPSAEV Computer Software DOS-Version

### C.11.1 DATA Sub\_Menu

The function key F1, when pressed, displays the data sub-menu shown in Figure C.30. This figure is similar to Figure C.4 of the Window version, the only difference being that the user needs to press the relevant function key from the keyboard to edit the input data files. In response, the user is prompted to type the name of the desired farm. The function of various keys is same as described for the command buttons of Figure C.4, described in Section C.3.

```

DATA Sub-Menu
** (Input Data files UPDATING) **
F9 -COPY as "ISMODEL .*" & Main_Menu
***** (Use SAMPLE.* file NEW farm)*****
F1 -List of Existing FARMS
F2 -EDIT *.GEN  General Inform Data
F3 -EDIT *.SMC  SMC Update Data
F4 -EDIT *.ETO  ETo & Rain Data
-----
F5 -EDIT *.KCS  Kc, Root, MAD ... Data
F6 -EDIT *.FET  OPTIONAL ETo_FORECASTs
F7 -EDIT *.CAL  Calibration SMC Data
F10 -HELP
-----
PRESS A FUNCTION KEY TO SELECT

```

Figure C.30 DATA Sub-Menu of IRPSAEV Package DOS-Version

### C.11.2 PLAN Sub\_Menu

The PLAN Sub-Menu is displayed as shown in Figure C.31, when the function key F2 is pressed from the Main Menu (Figure C.29). This sub-menu is similar to Figure C.11.

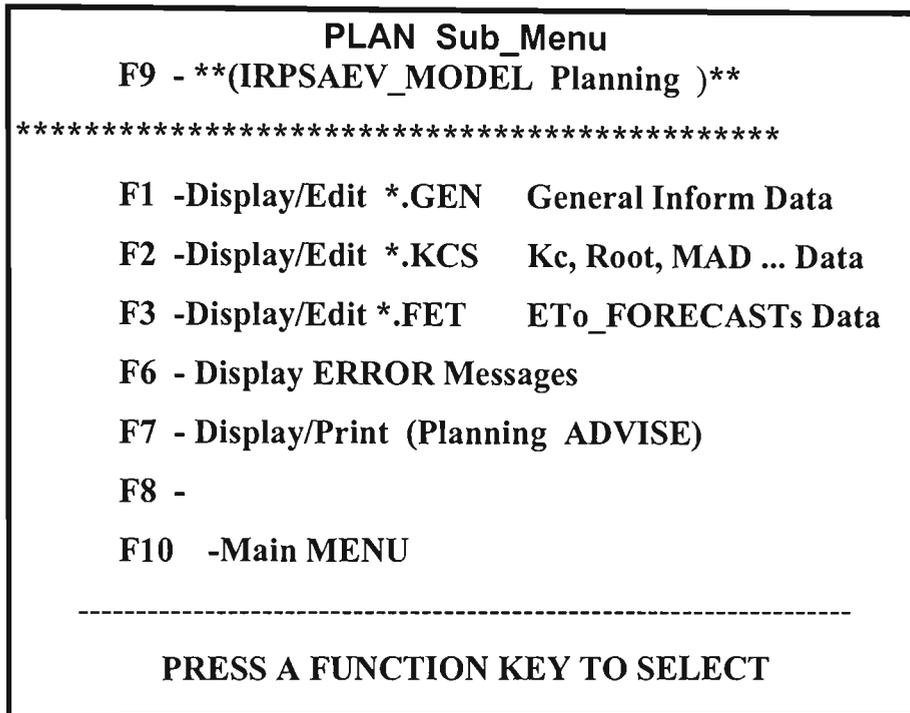


Figure C.31 PLAN Sub-Menu of IRPSAEV Package DOS-Version

### C.11.3 SCHEduling Sub\_Menu

Pressing the function key F3 from the Main Menu (Figure C.29) displays the SCHE Sub-Menu, as shown in Figure C.32. This sub-menu is similar to Figure C.14.

### C.11.4 EVALuation Sub\_Menu

The EVAL sub-menu is displayed as shown in Figure C.33 when the function key F4 is pressed from the Main Menu (Figure C.29). This sub menu is similar to Figure C.23.

```

SCHE Sub_Menu
F9 - **(IRPSAEV_MODEL Scheduling)**
*****
F1 -Display/Edit *.GEN   General Info. Data
F2 -Display/Edit *.KCS   Kc, Root, MAD, ... Data
F3 -Display/Edit *.ETO   ETo & Rain Data
F4 -Display/Edit *.SMC   SMC Update Data

-----

F6 - Display ERROR Messages
F7 - Display/Print Scheduling ADVICE
F8 - Display/Print GRAPH Output
F10 -Main_Menu

-----

PRESS A FUNCTION KEY TO SELECT

```

Figure C.32 SCHE Sub-Menu of IRPSAEV Package DOS-Version

```

EVAL Sub_Menu
F9 - **(IRPSAEV_MODEL Evaluation)**
*****
F1 -Display/Edit *.GEN   General Info. Data
F2 -Display/Edit *.KCS   Kc, Root, MAD, ... Data
F3 -Display/Edit *.ETO   ETo & Rain Data

-----

F6 - Display ERROR Message
F7 - Display/Print Evaluation REPORT
F10 - Main_Menu

-----

PRESS A FUNCTION KEY TO SELECT

```

Figure C.33 EVAL Sub-Menu of IRPSAEV Package DOS-Version

### C.11.5 CALibration Sub\_Menu

The CALI sub-menu is displayed as shown in Figure C.34 when the function key F5 is pressed from the Main Menu (Figure C.29). This sub-menu is similar to Figure C.28.

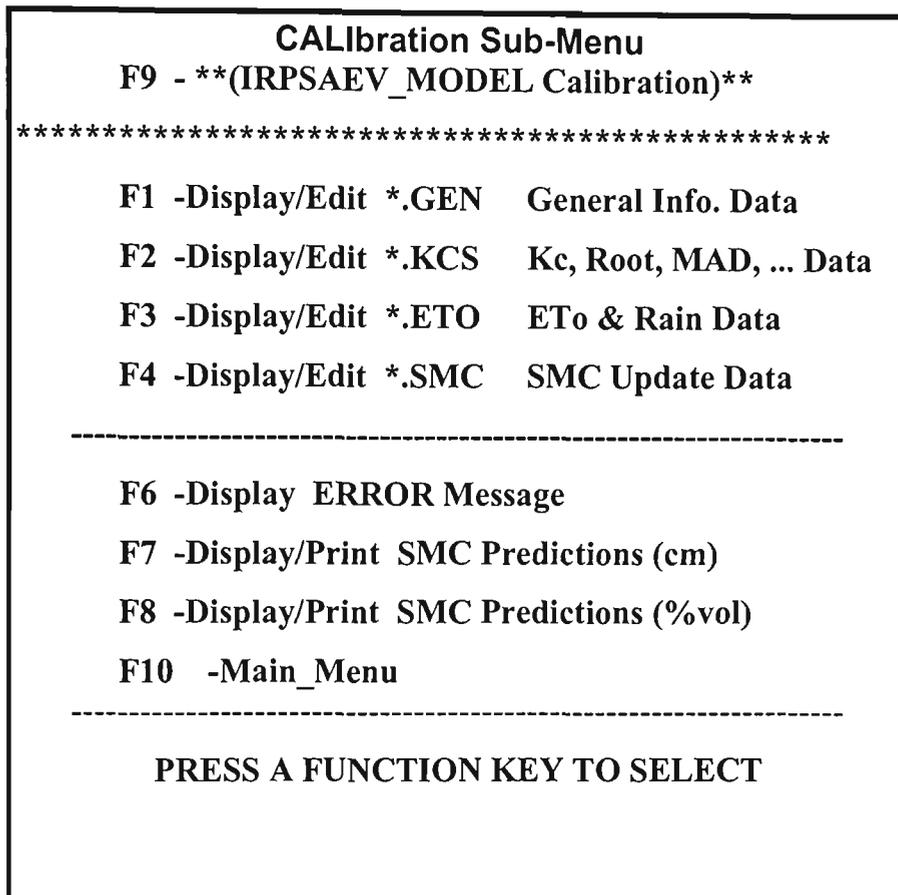


Figure C.34 CALI Sub-Menu of IRPSAEV Package DOS-Version

### C.11.6 STORE Sub-Menu

The STORE Sub-Menu is displayed as shown in Figure C.35 when the function key F6 is pressed from the Main Menu (Figure C.29). This figure is similar to Figure C.9 of the Window version.

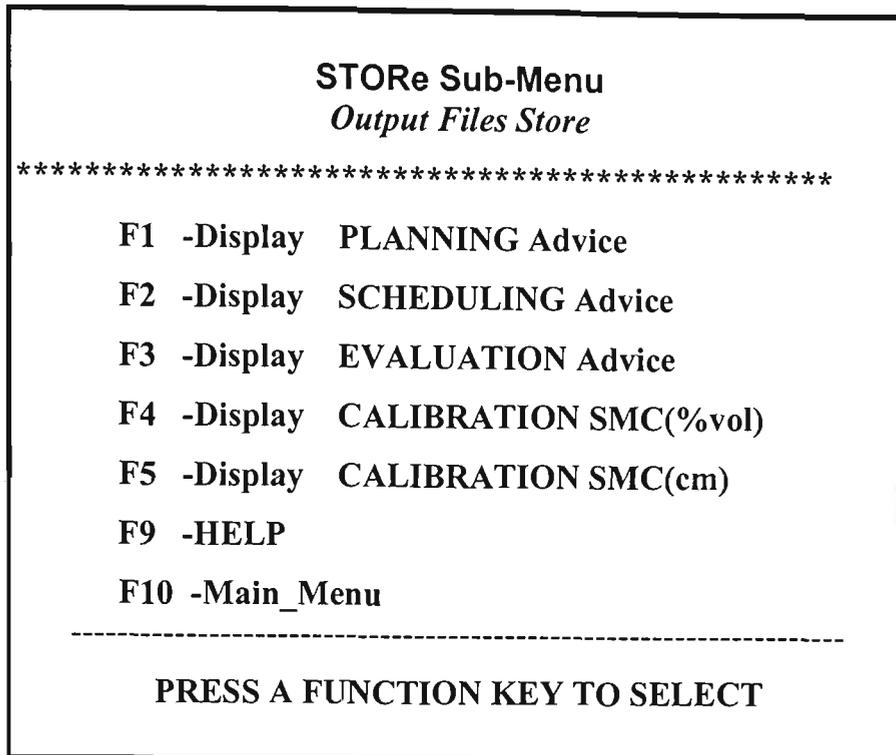


Figure C.35 STORE Sub-Menu of IRPSAEV Package DOS-Version

## C.12 LIMITATIONS OF IRPSAEV PACKAGE

It is important to appreciate that like all other computer models, the IRPSAEV package developed in this thesis has a number of limitations that can affect its application and accuracy. Since significant gaps remain in the understanding of the complexities of scheduling and distributing water in large irrigation systems, the IRPSAEV package attempts to provide a better tool with which irrigation professionals (as well as farm managers) can address some of these gaps. Although the IRPSAEV software can be effectively used for pre-season planning as well as for real-time scheduling (or operational planning) at the farm level, it cannot address many socio-economic issues that are just as important in irrigation management. Other improvements that can be incorporated into the package include: being able to take into account the effects of deficit irrigation (currently it is assumed that water is unlimited and is always available on request), allowing the multiple root zone sub-layers with variable depths, and including a component to factor the groundwater table contribution to crop water use.

Issues such as transferable water rights, water quality affects, economic returns and capacity constraints of the system can be addressed through other tools of analysis coupled with the IRPSAEV package.

### **C.13 SUMMARY**

A simple user-friendly menu-driven computer software (IRPSAEV package) was developed for the management and forecasting of irrigation water requirements at an on-farm level. The IRPSAEV package was developed by integrating the REF\_ET and RAIN\_PRE software with the irrigation scheduling model developed in Section 5.7 which includes an irrigation forecast module.

The developed package is comprehensive in considering a large number of soil-plant-atmosphere related factors and easy to operate. In order to make it usable and operative indistinct environmental conditions, some local calibration is required. As shown in the case studies (Section C.9.3 through C.9.5), many soil and crop data can be successfully adopted from the literature for use with this package, thereby reducing the cost of field experimentation. This provides the balance between flexibility required for operational use and the accuracy necessary for efficient use of available water at commercial farms.

The advantage of the developed IRPSAEV package over previous irrigation scheduling packages developed under Australian conditions is that it defines the irrigation scheduling problem from the farmer's viewpoint and adapt the interface to his/her concepts and needs - an important factor lacking in most software, which was responsible for slow acceptance of irrigation scheduling programs among the farmers.

The case studies carried out for planning and scheduling irrigations at a farm site in the Goulburn-Murray Irrigation Area in Victoria (Australia) demonstrated the usefulness of the IRPSAEV package. The results of the case study revealed that the developed IRPSAEV package can be effectively used as an operational as well as a planning tool at a farm level to reap significant water savings in addition to other environmental related benefits. The developed package has flexibility for its use under a wide range of soil, crop and climatic conditions.