REAL-TIME MONITORING AND CONTROL OF ON-FARM SURFACE IRRIGATION SYSTEMS

Final Report

July 1998

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National Program *for* Irrigation Research and Development

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Third Party: Goulburn-Murray Water

EXECUTIVE SUMMARY

This report outlines the work undertaken in project UME12. It is the final project report and covers all the work completed as part of the project. The heart of the report is section 7, it draws together all topics and field work completed as part of the project, and is probably where a reader familiar with the industry, or project, should begin. If further details are required on any topics then other sections can be referred to.

1. Introduction and 2. Irrigation and Dairy Farms in North East Victoria

The objective of this project was to develop a PC based approach to improve water use on dairy farms. The dairy industry in northeast Victoria was targeted because of the major role it plays in the regions irrigation industry. It has enjoyed continued expansion since the mid 1980's and currently consumes more than half the regions irrigation water. There has however been little use of modern irrigation timing and application management techniques on dairy farms.

3. The Basics of Irrigation Timing & Application

Irrigation timing and application are the two major components of irrigation management on dairy farms. Irrigation scheduling helps farmers determine when to irrigate and aims to prevent crop water stress caused by dry soil and water logging. Irrigation application describes how water gets from the farm channel and into the soil. Three performance measures of an irrigation application are irrigation requirement, application efficiency and application uniformity. They describe how much water is needed by the crop and for leaching of salts, what proportion of the total applied water serves its intended purpose and how evenly water infiltrates into the soil.

4. Monitoring Soil Water Content

A variety of sensors that measure the amount of water in the soil were surveyed at the beginning of the project and a number selected for laboratory and field testing. The Aquaflex[1] and Enviroscan[2], both based on dielectric techniques, were the two best performed sensors in an early field trial. The Aquaflex unit was chosen to use in expanded field trials. It was chosen because of its superior reliability, large sampling area and relatively low cost compared to instruments with similar sensitivity to soil water content changes. There were some concerns about the extent of soil structure disturbance during installation, but this is common with many soil based probes. The Enviroscan sensor also performed reasonably well but it is considerably more expensive and suited to higher value crops in horticulture and viticulture.

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[1] Aquaflex is a trademark of Streat Instruments Ltd
[2] Enviroscan is a trademark of Sentek Pty Ltd

5. Comparison of Aquaflex and Enviroscan

Soil water content measurements from the Aquaflex and Enviroscan sensors were compared with each other and with data from a simple water budget model. Once the effect of calibration equations was allowed for on the two instruments it was found that a reasonably strong relationship existed between the daily soil water use measured by each at soil water content levels below field capacity. Correlations of daily water content changes measured by the soil sensors and the water budget model were poor. This was because of the water budget models inability to adjust to the dynamics of soil water changes, which included shallow water-table contributions, and root water uptake. The results provide strong evidence that both devices are sensitive to soil water content changes and respond in a similar manner under the field conditions experienced in the study.

6. Forecasting Soil Water Content

Farmers in northern Victoria need to forecast crop water use because irrigation system management require at least four days notice prior to water delivery. Four forecasting methods, two using recent historical soil water content data from an Aquaflex probe and two using historical evaporation data, were tested to assess how accurately they could forecast four day soil water content. The basis for the reasonable performance of all methods was the omission of historical data above field capacity when deriving forecasting relationships.

The best performed method was the Adjusted Slope Method, which finds the slope of the observed soil water content curve for a period of days prior to the current day and uses this slope to estimate water use over the next four days. Its superior performance can partly be attributed to the application of an adjustment factor, based on soil water deficit values, that allows for changes in crop water uptake associated with changing soil water deficit values. On average the method was able to predict to within 1.1% the difference between observed and forecast soil water content at the end of four days.

7. Application, Benefits and Adoption

Five field sites were setup during the course of the project, each equipped with Aquaflex soil water sensors and some with groundwater loggers. Irrigations were scheduled on field sites by initially setting refill points from observations of the behaviour of water use by plants. A better method was to develop a field soil water characteristic curve by taking concurrent measurements of soil water content using Aquaflex sensors and soil matric potential using tensiometers. For the shallow water table regions of northern Victoria soil based sensors are a better option than water budget scheduling techniques because of their ability to incorporate water-table contribution to plant water requirements.

Using an understanding of irrigation application hydraulics two methods were proposed to improve application management. The approaches use either real-time or recent advance and depth data as inputs to a surface irrigation model, SRFR, which when combined with optimisation routines allows the determination of bay infiltration and roughness parameters. Once infiltration and roughness parameters are determined it is possible to use SRFR to identify the cutoff time that minimises irrigation water losses. Current testing is expected to show that real-time application management is achievable in the near future.

It was determined that by using irrigation scheduling techniques on dairy farms in northern Victoria it is possible to save one or two irrigations a year. The level of savings being dependant on the current irrigation management practices of irrigators. These savings equate to 5% to 10% of on-farm water use.

During the course of the project communication with farmers, extension staff and academics was maintained by attending farm walks, field days, conferences and workshops. Results from the project were disseminated using newspaper articles, farming magazines and seminars. Working with Goulburn-Murray Water staff, irrigators and an irrigation consultant ensured transfer of information out of and into the project as well as maintaining a balanced opinion of how the project was developing and how it should develop.

Low adoption of the techniques and equipment used in the project, despite positive response from most irrigators involved, was thought to result from the low priority given to water management by irrigators, the difficulty in understanding how environmental problems can effect individual properties and how changing management on an individuals farms will make any difference. The current climate of low water allocation resulting from two consecutive dry seasons and a capping of water allocations in the Murray-Darling Basin may well change the low priority given to on-farm water management.

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ACKNOWLEDGMENTS

Special thanks must go to Bill Heslop and Max Pleasance for their energy and cooperation throughout the project. If everyone in the irrigation industry was as dedicated and forward looking as Bill and Max there would be no doubts about its long term sustainability. I must also thank Derek Poulton for his contributions. Although I did not see him as often as Bill and Max his input during discussions was invaluable to me and the project. No doubt he will see his influence throughout this report.

Adrian Orloff, an irrigation consultant with Soil Water Monitoring Services, worked with me throughout the project with various instrumentation. He helped with field site installation and ideas on how best to present and use data for little financial return and I thank him.

I must also thank the following for their contributions throughout the project:

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Finally a special mention must go to the staff at the Irrigation Services Unit of Goulburn-Murray Water for services beyond the call of duty. Thanks to Wes Douglass for his more recent contributions, John Owen, Allen Lavis and Jacinta Corrie

1. Introduction

This report outlines the work undertaken in project UME12. The heart of the report is section 7, it draws together all topics and field work completed as part of the project, and is probably where a reader familiar with the industry or the project should begin. If details are required during reading then the appropriate sections can be referred to.

Salinity, waterlogging and nutrient runoff are major concerns for the irrigation sector of the farming industry in the Murray-Darling Basin. These three problems have partly resulted from the inefficient use of on-farm water resources. This report summarises investigations aimed at tackling these issues by designing a system to improve the on-farm use of irrigation water. The project focused on dairy farms in northern Victoria which use border check flood irrigation to irrigate perennial and annual pastures. Dairy farms were targeted because they are a major consumer of irrigation water and make little use of modern irrigation management techniques.

The objectives set out at the start of the project were to develop an affordable and reliable PC based approach to improve irrigation timing and efficiency of irrigation applications on flood irrigated pastures. To achieve this a system is required to enable irrigators to monitor and control, on a continuous basis, critical irrigation management variables including:

- Soil water status, to provide an indication of timing of application.
- Irrigation hydraulic variables, to provide an indication of the efficiency and uniformity of the on-going irrigation event and measures to improve its outcome.

The objectives were met by initially concentrating on the timing of irrigation events aided by the use of soil water sensors. This was followed by the formation of an approach to improve irrigation application efficiency by monitoring hydraulic variables during an application event. Ideally a single set of equipment is used to make irrigation timing and application management decisions.

Readers should note that the researchers involved in this project have no commercial links or obligations with any of the equipment suppliers mentioned herein.

2. Irrigation and Dairy Farms in North East Victoria

The Goulburn-Murray Water region is Victoria's major irrigation area. It covers more than 68,000 square kilometres of northern Victoria. The major storages for irrigation water in the region are Lake Eildon on the Goulburn River, Dartmouth Dam on the Mitta Mitta River and Hume Dam on the Murray River. Various other smaller on and off stream storages are spread throughout the supply system. Supply onto farm is either pumped, generally from natural supply channels, or via gravity flow from an extensive channel system. Surface supplies are the main source of irrigation water in the region. Because of the deficit between rainfall and evaporation in the region from August through to April (Figure 1) irrigation water is vital for agriculture. This is certainly the case for the dairy industry where much of the fodder production for stock takes place during this period.

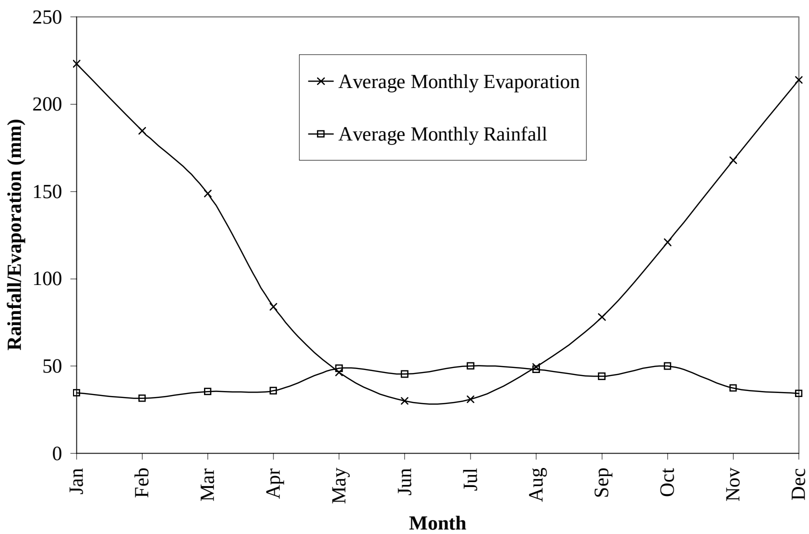

Figure 1 - Average deficit between evaporation and rainfall (E-R) for Tatura.

The major food supply for the dairy industry are annual and perennial pastures consisting mainly of clover, perennial ryegrass and paspalum. This remains the case even though high energy food supplements, mainly grain, are now common. Supplied supplements can vary between 0% and 70% of energy brought in (Armstrong et al. 1998). The growing of pasture is heavily reliant on irrigation water because of the low water stress tolerance of the clover component. In the height of summer clover requires watering every 5 to 10 days in many of the soils of northern Victoria and rainfall will not meet the necessary water requirement. Water use can vary between 6 ML/ha and 17 ML/ha (Armstrong et al. 1998) on properties growing perennial pasture depending on management, soil type, pasture species, rainfall amount and temporal distribution.

The dairy industry is the major consumer of irrigation water in the Goulburn-Murray irrigation area. Irrigated dairy pastures make up 41% of the total irrigated area and dairy consumes 56% (1,361,605 Ml) of water used for irrigation (Douglass et al. 1998). The high proportion of irrigation water use spreads right across the Murray-Darling Basin with Price

(1993) estimating that 50% of irrigation water used in the Murray-Darling Basin is for pasture and livestock production. These data show that the dairy industry is a large and over represented user of irrigation water.

It should also be noted that the dairy industry is expanding and so the demand for water is likely to increase. The irrigated area for dairy farming has expanded, in terms of area irrigated, 18% between 1993-97 (Douglass and Poulton 1998). The forecast figure for milk production in Victoria is 5,600 million litres in 2001 (a 60% increase since 1985). With the industry looking towards further expansion in the future one important focus will be the use and availability of water.

Currently water allocation levels in the Murray Darling Basin have been set at 1993/94 levels meaning greater production cannot occur as a result of larger areas of pasture irrigated with more water. The expansion will have to occur in part from better use of the current water resource. Dry seasons such as 1997-98 and 1998-99 where water allocations are low, estimated 40% of water right on the Goulburn system and 100% on the Murray, will see irrigators searching for new solutions to maintain, or increase, production with less resources.

With the high use of water in the dairy industry if improvement in water use is made then the whole irrigation industry benefits. Dairy farms were not only targeted because of the amounts of water they use. The dairy industry has a strong track record of adapting and improving production efficiency. Dairy farmers have proved they can adapt and improve with the average annual productivity per cow currently being 4,500 litres, up 32% since 1985. And total milk production is up despite a 50% reduction in the size of the state's dairy heard over the past 30 years (Victoria 1995). These improvements can be attributed to improved breeding, supplemental feeding and increased pasture area.

Unfortunately the industry has been slow to take new water management technology into the field. Reasons for this include:

- An inflexible delivery system eg. four days advance notice is required for water delivery.
- The lack of control that farm delivery systems have given farmers over application rates, application uniformity and irrigation efficiency.

However recent improvements to farm design, layout and planning, including widespread laser grading and the introduction of farm drainage systems, have lead to better on-farm water control. These changes mean that many irrigators are now in a position to implement improved irrigation management practices. This report contains information to aid production improvements by making better use of irrigation water on farms.

3. The Basics of Irrigation Timing & Application

Irrigation timing and application are the two major components of irrigation management on farms. This section describes the theory behind each component in preparation for the description of how the project went about improving each one on-farm. The irrigation timing problem is commonly referred to as irrigation scheduling.

3.1. Irrigation Scheduling

Irrigation scheduling is the decision making process used by irrigators to decide when to irrigate their crops and how much water to apply. The two main aims of scheduling are to control or eliminate:

1. Crop water stress caused by inadequate water supply.
2. Excessive periods of anaerobic conditions caused by water logging.

Meeting these two objectives may also provide the added benefits of limiting nutrient leaching, nutrient runoff and local salinity problems by reducing runoff and deep percolation. Another possible benefit from 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. Financial and environmental benefits stem from these improvements.

To obtain the best possible results it is important to tailor irrigation scheduling procedures to each individual situation. To do this information about the crop, soil, climate, irrigation system, water delivery and management objectives needs to be known and considered. Irrigation scheduling has its greatest effect, and so should be considered vitally important to farm managers when:

- Irrigation is a major feature of the farm.
- Restricted water supply limits production, ie. a larger area could be cropped and irrigated if water was available.
- The irrigation system allows for good control of application amount and uniformity (IAA 1990).
- Poor soil conditions restrict water movement or root development.
- Water or pumping costs are high (Jensen et al. 1970).
- Crop performance is particularly sensitive to water requirements ie. too much or too little water has a significant affect on crop yield or quality.
- Salinity or nutrient runoff issues are important.

3.1.1. Conventional Methods

The inherently quantitative nature of irrigation scheduling means it is well suited to computer based decision support (Plant et al. 1992). This is illustrated by the increase in the use of computers for irrigation scheduling since the mid to late 1960's. Decisions on when to irrigate can be made using:

1. Direct Approach Methods
    - Soil Indicators - these usually involve the measurement of soil water content or matric potential.
    - Plant Indicators - which usually involve the measurement of leaf water potential or canopy temperature.

2. Predictive Approach Methods
    - Water Balance Approaches - these involve calculating the depletion of soil water using estimates of soil storage capacity, rooting depth, allowable depletion and crop evapotranspiration. Examples well known in Australia are Right Amount Right Time (RART) produced by Agriculture Victoria and SIRAG Field from CSIRO.

More recent progress in computer aided scheduling has lead to the development of other approaches including:

- Simulation models.
- Optimisation models.
- Advanced water budget calculators (Plant et al. 1992).

These advances result from a combination of improvements in computer capabilities and the growing availability of databases supplying information about many of the variables related to irrigation scheduling eg. soil characteristics, crop information, meteorological data, economic data etc..

Computer based scheduling programs developed during the 1980's, mainly based on predictive approach methods, often scheduled irrigations when the estimated available soil water in the rooting layer fell below a predetermined level. Crop evapotranspiration was usually obtained by using a crop coefficient multiplied by reference evapotranspiration which was calculated using weather data (Clarke et al. 1992). These systems usually performed satisfactorily when the data required for their operation was readily obtainable. This data however is not always at hand as accessible climatic and crop data can vary widely from region to region. Clarke et al. (1992) comments on the lack of crop coefficient and rooting depth data as well as the large variation in available climatic data in the Ontario region of Canada. There are also other disadvantages discussed in section 7.4.

3.1.2. Real-Time Scheduling

Real-Time irrigation scheduling has been a major development in improving the accuracy of scheduling programs. It involves real-time monitoring of soil water content, plant water status or atmospheric evaporative demand which describe the actual conditions a crop is currently experiencing. The utilisation of forecast climatic data from a remote database enables a scheduling program to forecast future conditions and schedule irrigations. Forecasting can also be achieved without weather forecast information as described in section 6. Real-time monitoring requires the scheduling program to be adaptable to full automation with minimum maintenance, to have the ability to interact with computerised systems and use remote access through telecommunication systems (Phene et al. 1992). While Phene was referring to irrigation scheduling using remote weather stations, similar requirements apply for scheduling using soil water content sensors.

3.2. Irrigation Application

To date we have covered the problem of irrigation scheduling. Tackling the timing problem first is a logical step in the process of planning a system to aid irrigators. The final step towards completion of the system is finding a solution to aid irrigation application decisions. The application problem approach aims to maximise the use of the knowledge and data from the irrigation scheduling exercise ie. make use of the soil water content data and the associated instrumentation.

This section begins with outline of the basic concepts behind border check flood irrigation. For readers with knowledge of the terminology and processes involved there is no need to read section 3.2.1. A methodology on how to apply these concepts to improve irrigation efficiency is given in section 7.7.

3.2.1. The Irrigation Application Process

Surface irrigation methods depend on gravity to distribute water over the bay. Water enters the bay at a high point and it covers the bay via overland flow. An understanding of the approach outlined herein requires a basic knowledge of the different phases of an irrigation event. A typical irrigation event contains four main phases. These phases are:

1. Advance Phase - the advance phase begins when the inlet gate at the top end of the bay opens and water enters the bay. The water accumulates on the surface of the bay and moves forward as a wave. The advance front, or wetting front, are names given to the wave. As the wetting front moves forward some water infiltrates into the soil profile, and some evaporates (it is acceptable to ignore this component). Figure 2 illustrates this process. The advance phase continues until the wetting front reaches the far end of the bay, at which time the Storage Phase begins. The advance time, t_L, is the time it takes the wetting front to reach the far end of the bay.

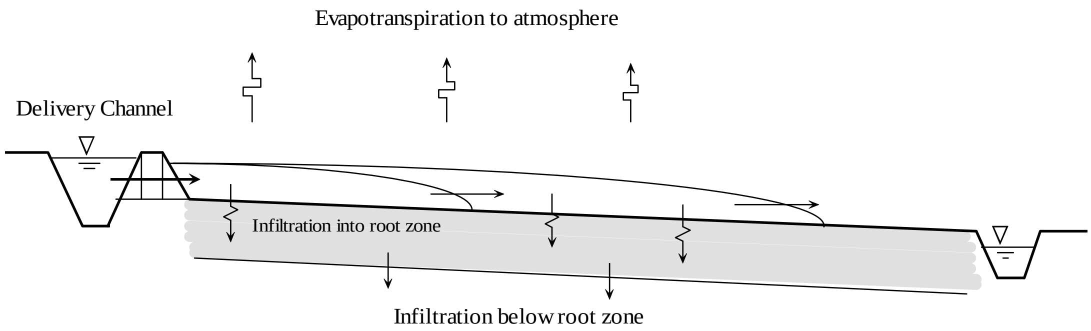

Figure 2 - The Advance Phase of an irrigation event.

2. Storage Phase - during the storage phase water is still entering from the inlet gate, infiltration is occurring and water is running off the bay and into the tail-water drain. The amount of water stored on the bay changes with time and is dependant on the boundary conditions at the bottom of the bay, the infiltration rate, and the inflow discharge. Generally in border check flood irrigation however there will be no storage phase. This is because inflow is cut-off before completion of the advance phase.

3. Depletion Phase - the depletion phase begins when the inlet gate closes. The cut-off time, t_{co}, is the time between inflow starting and inflow finishing. During the depletion phase the depth of water at the top of the bay and the surface storage volume is decreasing.

4. Recession Phase - the recession phase begins when the depth of surface water at the top of the bay becomes zero. In an ideal irrigation event movement of the recession front towards the end of the bay characterises the recession phase. The recession phase ends when zero depth of water remains on the surface of the bay. Figure 3 depicts the movement of the recession phase.

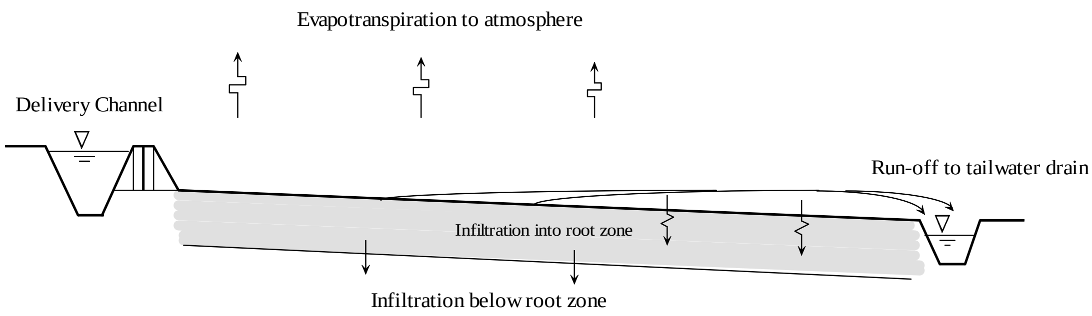

Figure 3 - The Recession Phase of an irrigation event.

Figure 4 shows each of the phases described above. It is simply a graph of advance and recession times versus distance down the bay. The advance and recession curves describe the front and rear of the irrigation wave as it moves down the bay. Also shown in the figure is the infiltration opportunity time, τ. The infiltration opportunity time is the time difference between the wetting front arriving at and the recession front passing a particular point. It represents the time available for water to infiltrate into the soil profile.

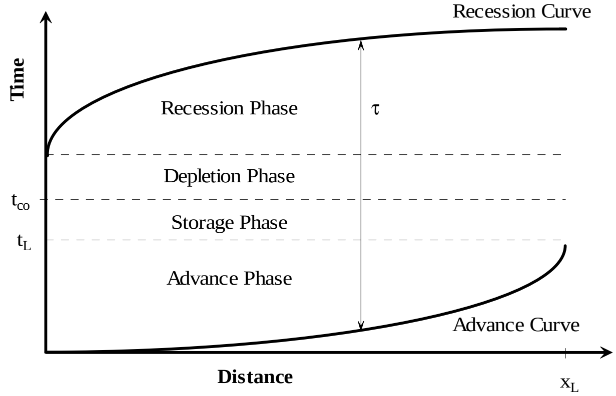

Figure 4 - Phases of a flood irrigation event.

3.2.2. Performance Criteria

There are three main parameters used to assess the performance of an irrigation application. The first, and most important for crop production, is the irrigation requirement. The irrigation requirement is simply the amount of water required to satisfy crop water needs and leaching fraction. The other two performance parameters are application efficiency and application uniformity.

Application efficiency is defined as:

$$E_a = 100\frac{(I+L)}{V}$$ **Equation 1**

where:
E_a = application efficiency
I = irrigation requirement for area
L = leaching fraction
V = total volume applied to bay

Application efficiency is a measure of the proportion of total applied water that serves its intended purpose ie. to refill the root zone or leach salts from the root zone. Any other water running off the end of the bay, or infiltrating below the root zone is a loss[3].

Application uniformity refers to how evenly water infiltrates into the soil profile. A criterion often used to represent application uniformity is distribution uniformity, DU, (Walker and

[3] Runoff is not a loss on properties with reuse systems.

Skogerboe 1987). Distribution uniformity is defined as the average infiltrated depth over the low quarter of the field, divided by the average infiltrated depth over the whole field. Both application efficiency and application uniformity can be high even when the infiltrated volume does not meet the irrigation requirement.

Figure 5 shows the total volume of water added to a field. It provides a good way of visualising the two criteria. The shaded section of Figure 5 represents the irrigation requirement and an allocation for leaching. The portion below this represents the water infiltrated below the root zone ie. deep percolation, and the tip represents the volume running off the end of the bay.

The shaded area of Figure 5, divided by the total area within the curve ABC, gives the value of application efficiency. If the infiltrated depth along the field is a constant eg. equal to Z_{Req}, then the application uniformity is high. However, due to differing infiltration opportunity times and spatial variability in soil properties along the length of the bay, the infiltrated depth will change with distance along the bay (see Figure 5). This change in depth with distance along the bay results in a lower application uniformity.

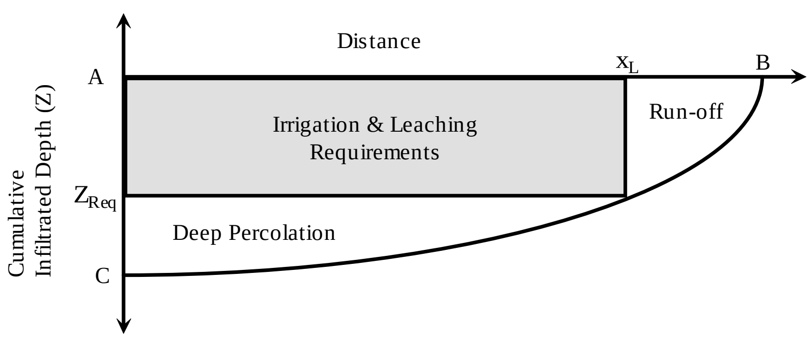

Figure 5 - Distribution of infiltrated irrigation water.

Maximising efficiency and uniformity minimises deep percolation and runoff losses. These factors are undesirable because:

1. Deep percolation leads to additions to the ground-water store and rising water-tables, and associated salinity and water logging problems.
2. Runoff wastes a valuable water resource (where re-use systems are not present). It results in the loss of nutrients from the bay and causes environmental problems in natural waterways (Austin et al. 1996).

4. Monitoring Soil Water Content

Soil water is an important controlling factor in plant growth and crop productivity. Water for plant growth is obtained from rainfall, irrigation, shallow water table or a combination of these. The primary objective of irrigation is to apply water to maintain crop evapotranspiration when precipitation is insufficient and water stored in the soil has been depleted below a level which decreases crop productivity significantly (Phene et al. 1990). Hence, measurement of soil water is of great importance for the process of decision making in irrigation.

The direct method of measuring soil water content is by gravimetric means. Great care is required when using gravimetric techniques since significant errors result from:

- The loss of the structural integrity of the soil sample prior to determining its bulk density.
- Soil loss between weighings.
- Weighing accuracy.

This method is commonly used today as a fall back technique and for evaluating or calibrating other means of soil water measurement. The limitations and difficulties inherent in the gravimetric method have led to a variety of inferential measurement devices.

The initial aim of the project was to set up a PC based soil water monitoring system for use on-farm to aid irrigation decision making. The precursor to setting up field equipment was to complete a survey of soil water monitoring sensors available at the time. From the survey a number of instruments meeting set criteria were selected for laboratory testing. Laboratory testing was undertaken to become familiar with the selected instruments and to eliminate problems associated with installation where access was good and help readily available. Field site testing was the final step in identifying which instrument/s were most suitable to use in setting up the PC based monitoring system on-farm.

The following sections describe the instrumentation identified in each of the above steps and the decision criteria used in choosing the Aquaflex as the most appropriate device for monitoring soil water content on dairy farms.

4.1. Market Survey of Soil Water Monitoring Devices

An extensive survey of soil water monitoring devices available on the market at the time resulted in the list of the equipment shown in Table 8 (Appendix 1). Please note that the details and prices quoted in the table are for 1992, this is to allow readers to understand the reasoning behind the original equipment choices. The rationale for selection was that the devices should be able to log data in their standard configuration, should not be subject to substantial temporal drift and that they be relatively inexpensive.

The devices selected from the survey for laboratory testing were the Aquaflex, Enviroscan, Microlink and tensiometers. Neutron probe measurements were also taken during the experiment to compare with readings from the other instruments. A description of the theory behind the various instruments and justification for why the Aquaflex, Microlink and Enviroscan were laboratory tested follows.

4.2. Measurement Principles

4.2.1. Dielectric Methods

The dielectric constant of a soil matrix is an electrical property of its soil, water and ion content. It is a measure of how strongly the soil matrix is polarised[4] when placed in an electric field. Dielectric constant values for water, soil and air are about 80, 5 and 1 respectively. Because of the large differences in their respective dielectric constant values by measuring the dielectric constant for the soil matrix the water content can be determined. To relate the measured soil matrix dielectric constant to water content some form of calibration equation is needed.

The calibration equation can be experimentally derived or developed from appropriate mixing theory. Often manufacturers include 'universal' calibration equations with instrument software and these are commonly used for a wide range of soils. Provided that absolute accuracy is not required for soil water content measurements, as is the case for irrigation scheduling purposes, then this approach is adequate.

4.2.1.1. Time Domain Measurements eg. Aquaflex

The Agricultural Engineering Institute at Lincoln University[5] New Zealand developed the Aquaflex soil water sensor. When the project began the Aquaflex was still being developed and only became commercially available in April 1998. The reason for the delay in commercialisation was Lincoln Venture's strong desire to ensure all possible problems associated with use of the probe would be eliminated before commercial release.

The sensors used in the testing program were prototypes of the commercial units. The instruments consist of a three metre long transmission ribbon and electronics to generate and

[4] Polarisation is an effect observed in a dielectric material when it is exposed to an electric field. It may be thought of as the tendency of the atoms and molecules in the dielectric to align themselves with the poles of the imposed electric field. Brownian motion, or random thermal motion, disrupts the alignment of atoms and molecules causing them to constantly move, so the alignment of a particular atom or molecule is constantly changing, but a dynamic equalibrium eventually results (Hilhorst 1998).

[5] The commercial arm of the Institute most involved in the development of the probe is called Lincoln Ventures.

monitor electrical pulses. Measurements commence once the transmission ribbon is buried within a crop root system. The Aquaflex device uses techniques similar to Time Domain Reflectometry (TDR) (Woodhead 1994), rapid voltage transitions pass along a transmission cable and electronics record their velocities (Woodhead 1991). The travel times of the voltage transitions enable the determination of soil water content. As with the Enviroscan, to obtain accurate soil water content values a user must develop a site-specific calibration curve.

The Aquaflex does not have a custom installation technique and the installation process disturbs the measurement area significantly. Figure 6 illustrates the steps involved in the installation procedure. The following lists the main steps in the installation procedure:

Step 1. Choose the placement of the protective box (containing the logger, battery and modem), erect the support pole and attach the box and solar panel.

Step 2. Dig a trench from the base of the pole into the irrigation bay to the installation position of the Aquaflex units (about half way across the irrigation bay). Note: To ensure the trench scar heels quickly remove pasture sods from the ground before trenching commences.

Step 3. Lay the cabling that connects the logger to the Aquaflex units. Lay the cable inside 25mm pvc conduit to decrease the chance of damage to the cable by stock or vehicle traffic.

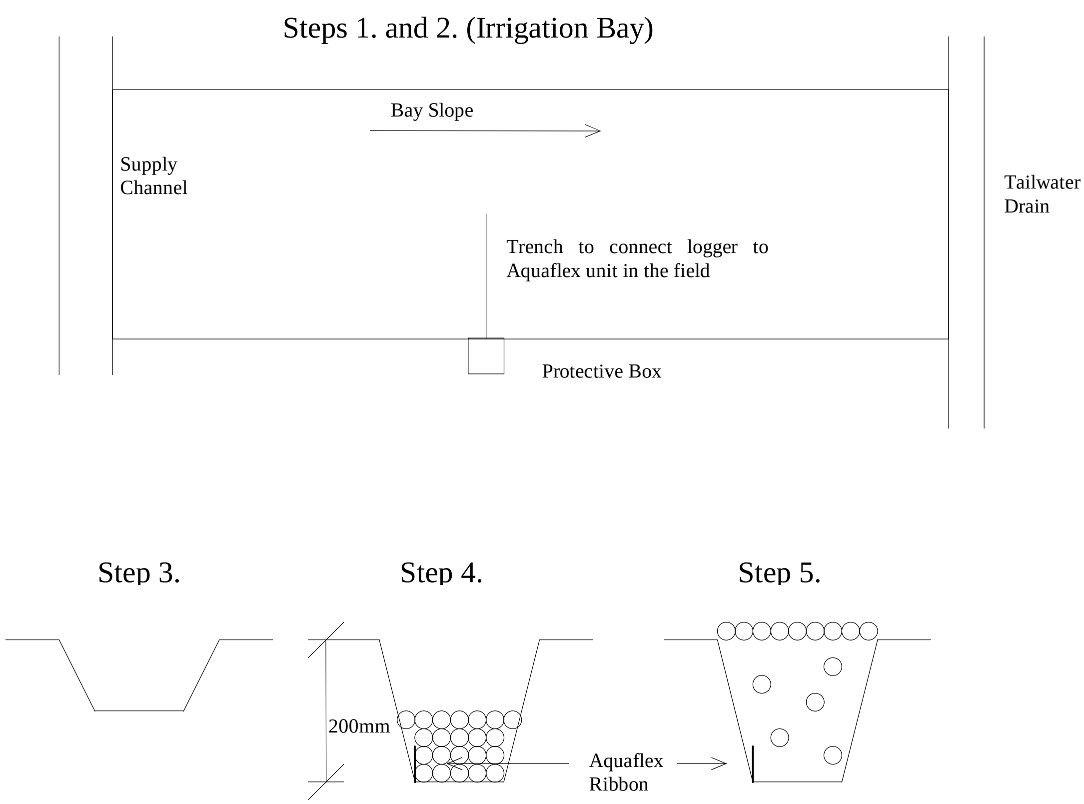

Figure 6 - On farm installation procedure for the Aquaflex device

Step 4. Installation of the Aquaflex ribbon. First remove soil sods from the installation position of the Aquaflex ribbon.

Step 5. Clean out a narrow trench to the desired depth and lay the Aquaflex ribbon along one side of the trench. Return the soil loosely around the ribbon (compaction could damage the ribbon). Note: If the soil type changes down the soil profile take care to separate the two soil layers to allow for correct replacement of each soil type when filling the trench.

Step 6. Return the soil to the trench and compact carefully. Finally, return the pasture sods to the trench. Usually the trench is slightly higher than the rest of the bay but after the first irrigation the soil consolidates well and returns to its original height.

The period of settling in before using the data to make irrigation timing decisions is dependent on soil type and application. For use with perennial pastures it is recommended that the instrumentation be installed at the end of an irrigation season in preparation for the following season. The period between installation and use allows the soil to consolidate and gives the crop root system a chance to recover. Ideally the sensors should be installed during initial sowing of pastures to ensure the site is representative of general soil conditions.

The advantages of this method include:

- Reliability
- Cheaper than TDR or Enviroscan
- Large sampling area
- Speed of measurement
- No radiation source
- High Resolution

The disadvantages of this method include:

- Non-linearity of calibration curve
- Soil Disturbance during installation
- Connected by cabling

4.2.1.2. Frequency Domain Measurements (Capacitance) eg. Enviroscan

The Enviroscan device, made by Watson and Buss in South Australia, uses the capacitive technique to measure the soil water content. The probe consists of copper plates that are lowered into a permanently installed PVC access tube. The Enviroscan measurement technique obtains an estimate of the dielectric constant of the soil and relates this to volumetric soil water content using an empirical calibration relationship. Obtaining the value of the dielectric constant of the soil requires incorporating the soil surrounding an access tube as part of the dielectric of a capacitor (Dean et al. 1987).

The part of the dielectric that changes over time is the soil phase and the change is predominantly due to changes in soil water content. The measurements are taken at high frequencies (150 MHz) this avoids:

- The interfacial polarisation effects in heterogeneous materials that occur at lower frequencies (<27 MHz).
- The increased dielectric loss factor associated with the relaxation time of water molecules at higher frequencies (>10,000 MHz). In this range the dielectric constant of water is essentially independent of the angular frequency, ω, of the applied electric field.

As with all soil water probes on the market the instrument calibration curve is dependant on soil type (Bell et al. 1987). The only way to measure actual soil water content is to develop a site specific calibration curve. Emphasis is placed on field rather than laboratory calibrations. The manufacturer curve for Enviroscan assumes an exponential relationship between soil water content and capacitance and is generally sufficient for irrigation scheduling purposes.

The measurement technique is slightly temperature dependant, in the order of 0.1% vwc (volumetric water content) per 10 ^{o}C. When considering spatial variabilities in soil water contents these temperature effects are negligible. Of more importance to this study are the significant effects that air gaps around an access tube have. Air gap effects result from the limited radial penetration of the measurement area and give undue weighting to the soil close to the probe. In swelling and shrinking soils these errors may be significant.

Tests done by Dean et al., 1987 show that an annular air gap of up to 0.5 mm has little effect on results. However, an annular gap of 3.0 mm causes effects that may result in significant errors in soil water content readings (certainly in the order of whole percentages). George (George 1994) notes that further research into the effects of electrical conductivity, temperature, and acid soil on measured frequency would better clarify the performance of capacitance probes.

It is a requirement with all in-situ measurements of soil water content that good contact with soil be maintained at all times. The sensitivity of capacitance probes requires that special care be taken during installation to ensure this contact. By only allowing trained personnel to install the Enviroscan probe the manufacturers limit problems caused by poor installation.

The installation technique is similar to that described in Bell et al. (1987). The technique involves inserting a PVC access tube vertically into the soil by passing it through a steel guide tube to ensure vertical installation and no lateral movement of the tube. The access tube has a steel cutting edge on the bottom. Insertion begins by driving the tube a small distance into the soil. A soil auger that fits neatly into the access tube removes the soil from inside the tube. The process continues until the access tube is at the desired depth. The next step is to seal the base of the tube by lowering a rubber bung into the bottom of the tube. The final step is to install the capacitance probes through the top of the tube and seal the top with a screw on PVC cap.

The advantages of this method include:

- Speed of measurements

- Lack of radiation hazard
- High resolution
- Adaptability for use with automatic logging equipment
- Absence of any random counting error
- Easy to log soil water data for a number of installation depths

The disadvantages of this method include:

- The non-linearity and soil dependence of calibration curve
- Care required in the installation of access tube
- Slight dependence on bulk density and temperature of the soil
- Some designs are sensitive to the salinity

4.2.2. Electrical Resistance Methods

Resistance methods of soil water measurement rely on the conductance of soil water to modulate current flow which is in turn used to give an indication of soil water content. The most common type uses a gypsum block which acts as a porous matrix although other materials such as ceramic, nylon, fibreglass and dental stone powder (Hayes and Tight 1995) have also been used. While there are some variations, most consist of two electrodes entirely buried within a porous matrix block. One reason for the success of the use of gypsum as the porous matrix material is its ability to negate the effects of salinity on the resistance measurements. When using materials other than gypsum it is the electrolytes in the soil water that provide conduction and thus they are sensitive to soil water electrolyte concentration. In the gypsum block however some of the block dissolves to provide the electrolyte and so it is less sensitive to soil water electrolyte concentration (White and Zegelin 1995).

The electrical resistance of dry gypsum is nearly infinite. When permeated with water, the electrical conductivity of gypsum approximates that of an average textured soil at the same water content (Phene et al. 1990). The principal of operation then relies on hydraulic contact between water in the porous block and soil water. Starting with a saturated soil and a saturated gypsum block the two systems are in equalibrium. As the soil dries its matric potential becomes more negative setting up a hydraulic gradient that results in water being removed from the gypsum block. With less water in the block the electrical resistance increases. The opposite happens when the soil water content decreases, the soil matric potential becomes less negative, water flows back into the gypsum block and the electrical resistance decreases. This hydraulic equalibrium is analogous to the operation of the porous cup in a tensiometer (section 4.2.5).

The operating range for resistance blocks is between -60 kPa and -1500 kPa. The -60 kPa limit allowing for the high variability of resistance measurements below this figure. The lower limit of -60 kPa would create problems when using them in the duplex soils of northern Victoria with shallow rooted pastures where the typical range of operation would be 0 to -80 kPa. They will however operate well in crops with higher water stress tolerance where tensiometers with a range of 0 to -80 kPa will not be of great use. A calibration curve is required that relates measured electrical resistance to soil water content or soil matric potential. As with many probes a manufacturer supplied curve is often adequate for irrigation scheduling purposes where absolute water content values are not vital.

Generally installation involves soaking the blocks in water for a day to saturate them and then burying the block at the required depth and connecting wires from electrodes in the block to an electrical resistance meter above the surface. Good soil contact is important to reduce lag times between soil wetting/drying and response within the porous matrix surrounding the electrodes. Trouble can occur in course soils and soils that exhibit shrinking and swelling because contact with the block and soil medium is difficult to maintain (Hayes and Tight 1995).

The advantages of this method include:

- Low Cost
- Improved resistance to influence of soil salts
- Simple technology

The disadvantages of this method include:

- Dependence upon the soil temperature
- Substantial dependence upon the degree of ionisation of the soil water
- Limited life
- Care required in installation
- Slow response to changes in soil water content

4.2.3. Heat Dissipation eg. Microlink[6]

The rate of heat dissipation in a porous medium of low heat conductivity has been shown to be sensitive to water content and this principle has been applied to a number of water sensors. Heat dissipation is determined by applying a heat pulse to a heater within the ceramic and monitoring the temperature at the centre of a ceramic before and after heating. The temperature difference is a function of thermal diffusivity, and therefore of the water content. However the accuracy of some sensors is poor and the reading is dependent on soil type and bulk density (Campbell and Gee 1986).

DRW Engineering of South Australia make the Microlink sensor, it works on the heat pulse principle. A pulse of heat of known energy is emitted from a sensor buried and in intimate contact with the surrounding soil. The time taken for this heat pulse to dissipate into the surrounding soil is proportional to the water content and so can be calibrated accordingly.

[6] Microlink is a trademark of DRW Engineering Pty Ltd

4.2.4. Neutron Probe

Neutrons tend to have elastic collisions with nuclei in the soil and when collisions occur neutrons lose some kinetic energy and the other nuclei gain it. The amount of energy exchanged in a collision between a neutron and a nuclide is dependant on the mass of the nuclide, the energy, or velocity of the neutron and the angle of the collision (Stone 1990a).

The hydrogen nucleus of a water molecule is the most effective element present in soil at slowing down fast neutrons. This property of hydrogen is the basis of the neutron method for measuring soil water content. Dickeyl (1990) stated that in the average soil 70% of the slowing effect of fast neutrons could be attributed to hydrogen atoms contained in soil water, 10% to oxygen and 20% to the remaining soil elements. Hydrogens' ability to slow fast neutrons can be attributed to the approximately equal masses of a hydrogen atom and a neutron. When a neutron collides with a hydrogen atom more kinetic energy is lost by the neutron than when it collides with other heavier nuclei in the soil. This is illustrated by the findings of Gardner and Kirkham (1952). They found that on the average a high energy neutron is thermalised after 17 collisions with hydrogen whilst on the average 136 collisions with oxygen are required to achieve thermalisation.

The neutron probe contains a source of fast neutrons, a detector of slow, or moderated, neutrons, a counter, a recorder, a display and a cable connecting the components. The cable is also used to lower the radiation source and the detector to the desired depth of measurement. Fast neutrons are emitted into the soil where they are scattered and slowed down by collisions with atomic nuclei (a process called moderation). A cloud of slowed or thermalised neutrons form around the source and some randomly return to the detector where they cause an electrical pulse which is counted by a rate-meter and shown on the display (James 1988).

The volume of soil sampled (sphere of influence) using the neutron probe is dependant on soil water content. It has been suggested that the "sphere of influence" or "zone of thermalisation" in wet soils (good moderators) has about a 15 cm radius which can increase to 50 cm in near dry soils (poor moderators). Stone (1990a; 1990b) however did not observe such large changes in the sphere of influence (Allen and Segura 1990).

The relationship between hydrogen concentration in the soil, and therefore water content, and slow neutron density is a linear one. Calibration curves usually plot the ratio of standard count over counts versus volumetric soil water content. A calibration curve for a neutron probe is not universal however and in the field there are many influences that will affect the slope and intercept of the curve.

The equipment needed to take soil water content measurements are:

- A neutron probe, a thin walled access tube (usually aluminium or steel, PVC tubes may be used where a soil contains minerals that could cause deterioration of aluminium or steel).
- A soil auger (to install the access tube) and calibration curves (Phene et al. 1990).

The access tube is sealed at the bottom to prevent water entering the tube from the ground and affecting the measurement, and is placed vertically in the ground to a desired depth. The top of the tube, or tubes, should protrude above the ground surface and when measurements are not being taken should be sealed. A rubber stopper is sufficient for this purpose. Note: all tubes should extend an equal distance above the ground to avoid having to move cable stops.

To take measurements the neutron probe is placed on top of the access tube, the neutron source and detector are then lowered into the tube. Cable stops are then used to keep the source and detector in place while the measurement is being taken. Measurements are usually taken at 15 cm increments throughout the depth of the soil profile. A standard count, taken with the probe inside the shield under "standard conditions", is usually taken at regular intervals.

Standard counts are taken too check if the probes detector and electronics are operating correctly by looking for excessive drift in the standard count readings (acceptable drift is usually specified by the manufacturer in the user manual) and to automatically correct for electronic drift and source decay. The most appropriate "standard conditions" are achieved by placing the gauge 1 to 2 metres above the ground surface on an access tube of the same material as the tubes used to take field measurements (Dickeyl 1990). The gauge is placed at this height to eliminate the effects of surface and soil water from the count. The probe should be at least 3 metres away from any objects that could reflect neutrons during counting to avoid affecting the count. Access tubes, typically made of aluminium, are buried vertically in the ground where measurements are to be made.

The calibration of the neutron probe is affected by factors such as neutron gauge characteristics (Dickeyl 1990), access tube characteristics (Allen and Segura 1990), soil type and chemicals (Stone 1990b).

The advantages of this method include:

- Non destructive testing
- Accurate when calibrated correctly
- Has a long history of good performance
- Can be moved around to a number of measuring sites

The major disadvantages of this method include:

- High cost
- Care required in operation because of the neutron source
- Must be calibrated for different soils
- Influenced by hydrogen and other small atoms which are not tied up in soil water
- In Australia operators are required to attend a training course prior to using probes
- Relatively slow measurement time
- Not designed for permanent installations where logging is required

4.2.5. Tensiometers

Tensiometers were developed in the late 1920's and have been used extensively for monitoring soil matric potential[7] directly and for irrigation scheduling. The tensiometer consists of a porous ceramic cup connected to a hollow tube that is sealed at the top. Often a pressure gauge is attached to the hollow tube to measure pressure changes in the tube. However the tube can also be sealed with a rubber stopper and a portable pressure gauge, with a hollow needle to insert through the stopper, is used to measure the pressure changes in the tube. Water is placed in the sealed tube and the ceramic tip is saturated and the tensiometer is inserted into the soil.

The principal of operation relies on hydraulic contact between the water in the ceramic cup and the water in the soil. Given this contact a state of equalibrium is maintained between the matric potential of the soil and the pressure depression inside the hollow tube. Equalibrium is maintained by water moving into and out of the tensiometer. Thus when a tensiometer filled with water is first inserted into a dry soil the pressure in the hollow tube is zero, but the soil matric potential is at some negative value. Water will move out of the hollow tube through the ceramic cup and into the soil matrix until the negative pressure inside the tube is approximately equal to the matric potential of the soil. The pressure inside the tube can then be read. If the water content of the soil rises, due to irrigation or rainfall, then the soil matric potential increases, water moves back through the ceramic tip into the tensiometer tube and the internal negative pressure increases.

The tensiometer gives readings of soil matric potential not soil water content, but soil water content readings can be obtained if a soil water characteristic curve, relating soil water content to soil matrix potential, is constructed. Soil matrix potential is however an excellent indicator of how difficult it is for plants to extract water from the soil and can be used to identify when to irrigate. The operating range for most traditional tensiometers is in the order of 0 to -80 kPa. This limit can be restrictive for some applications but given perennial pastures with shallow roots and the low water stress tolerance of white clover a tensiometer placed at around 200 mm will operate within this range.

The advantages of this method include:

- Low cost
- Relatively easy to install
- Gives a direct reading of soil matrix potential

The disadvantages of the tensiometer type of sensor include:

- Limited soil water range
- Hysteresis
- Regular maintenance is required
- Slow response time

[7] Often referred to as matric suction, soil water suction or soil water tension which all allow matric potential to be expressed as a positive figure ie. A matric potential of -10 kPa is equivalent to a soil water tension of 10 kPa (Hillel 1980). For an exact value of soil matric potential the height of the water column in the tensiometer should be subtracted from the internal pressure reading. However as for many applications the water column is short (100 to 200mm equivalent to 1 to 2 kPa) this term is often neglected in field use of tensiometers.

- Prone to damage by stock or vehicle traffic

4.3. Laboratory Tests

Paul Tyndale-Biscoe tested six soil water sensors in the laboratory. The instruments tested were Aquaflex, Enviroscan, Microlink, Trase (TDR), Neutron Probe and tensiometers. These six instruments covered a broad range of measurement principals (see section 4.2). The tests were conducted in a tank 1.5 m wide, 2.5 m long and 0.5 metres deep, filled with a sandy loam soil. Air could be circulated above and below the soil mass using a fan. The results of the tests were published in Agricultural Engineering Australia (Tyndale-Biscoe and Malano 1995).

The laboratory work concluded that Trase, Neutron Probe, Enviroscan and Aquaflex all responded well to changes in soil water content, displaying similar output form and good repeatability of measurement. The response of the Microlink was low with noise often being of a similar magnitude to measured soil water content changes. Tensiometers failed to operate in the light soil type.

The Trase and Neutron Probe were considered too expensive and impractical for use on farms (limited scope for multiple readings and logging) which meant the Enviroscan and Aquaflex were selected for field trialing. After some consideration the Microlink was also selected to be trialed in the field because it was reasonably cheap, was manufactured in Australia and used a completely different principal of operation to the other devices. It was thought that the heavier field soils may improve the response of the probe, although there were some doubts about keeping good soil contact in the swelling and shrinking soils of some parts of northern Victoria.

4.4. Initial Field Testing

4.4.1. Site Selection

The first field stage of the project was simply to trial the various instrumentation selected from the laboratory testing in the duplex soil of the Goulburn Valley and maybe in the grey clays around Kerang. From this testing a suitable soil water monitoring device would be chosen and used in the remainder of the project.

The decision was made to choose a site on the duplex soils and begin the experiment there before moving onto grey clays. The reasons for this were that the duplex soils would be easier to manage both from a behavioural point view (not having to deal with severe cracking) and a logistical point of view (closer to Melbourne and facilities) which would be beneficial during the equipment familiarisation stage. The irrigated duplex soils also represent a greater overall area than the grey cracking clays. In choosing the sight the following criteria were considered:

- Soil type be duplex and representative of the irrigated soils in the Goulburn Valley
- Soil type uniform throughout the bay
- Bay dimensions typical for flood irrigated dairying ie. approximately 400 m long by 40 m wide
- Longitudinal bay slope uniform with no transverse slope
- Irrigation bay be laser graded and top soiled (preferably)
- Crop be perennial pasture ie. clover, ryegrass, paspalum mix
- Head on inlet channel be sufficient for inflow monitoring using a flume
- Tail-water runoff able to be measured with a flume
- Site well maintained and all weather access available
- Site be reasonably close to resources eg. soil laboratories, equipment stores etc

4.4.2. Site Description

The first field site selected was the dairy farm at Victorian College of Agriculture and Horticulture (VCAH) Dookie. The farm has approximately 40 hectares of irrigated mixed perennial pasture (white clover, perennial ryegrass and paspalum) and a milking herd of 160 to 170 cows (both the irrigated area and stocking rate have increased since the site was first selected). The trial bay is part of the first of two irrigation management sections on the farm. The bay has an area of approximately one and a half hectares (40 x 365 metres) with a slope of 1 in 716. The farm was heavily landformed 15 years before the trial without being top soiled and so there is some variation in soil type across the bay.

The property's water supply comes from the Broken River. An axial flow pump supplies water at a rate of approximately 10 Ml per day (115 l/s) depending on river stage. An open channel system distributes water around the farm once it is pumped from the Broken River. The volume of irrigation water applied during each irrigation event is between 15 ML and 20 ML. Water originally flowed into the bay through three concrete inlets that were buried and replaced with one broad crested weir to allow inflow monitoring.

The test bay contained a duplex soil type with the following variation with depth:

0-15cm grey brown fine sandy loam to loam
15-25 cm light grey brown fine sandy clay loam
25-40 cm brown or grey brown medium clay
40-75 cm brown or grey brown heavy clay
75 cm $\rightarrow$ brown or grey brown heavy clay with slight lime

Monitoring equipment at the site is powered by 12 volt car batteries that are kept charged using solar panels. There was a weather station at the College but its reliability was in question so a weather station was installed on site.

4.4.3. Equipment Layout

Soil water sensors are located at one third and two thirds down the length of the bay to avoid end effects such as ponding and weed growth. Where possible the soil water sensors are located either side of the bay to monitor transverse variations and at two depths to measure infiltration characteristics. All cables are buried and access tubes protected against stock and machinery and kept in lines to minimise disruption to machinery operations. Inflow on and off the bay is measured using two broad crested weirs with two Dataflow capacitance probes measuring flow height across weir sills. Figure 8 shows a schematic of the irrigation bay and monitoring equipment.

4.4.4. Assessment of Reliability

4.4.4.1. Summary

The Microlink sensor performed poorly in the field trials, with only a very short period of data collected. Despite consultation with the local distributor and replacement of all components of the system the device proved unreliable. Keeping the joins between the probe inserted into the ground and the cable coming from the logger water proof seemed to be major problem (although the system could not be fully tested because it was so was not operating for any substantial period time).

The results collected in the first year of the field trial showed that the Aquaflex and Enviroscan respond well to changes in soil water content in the soils at Dookie. Although some question exists over the accuracy of the Enviroscan manufacturer supplied calibration equation in the heavy soils. A visual comparison of the results from the two devices indicates that there is a correlation between the volumetric water contents measured by each. This is evident since the devices responded to irrigation events at the same times and showed crop water usage over the same periods. The relationship between the volumetric soil water content results measured by the two devices also correlated quite well (see section 5)

The Aquaflex sensor was the favoured unit at the early stages as it had no direct operational problems and the large volume of soil that it sampled was seen as an advantage when the extent of spatial variability of water content in the bay was considered. It was decided to continue with the Aquaflex following the initial trials because:

- It showed superior reliability
- Was less expensive than the Enviroscan
- Sampled a larger area than the Enviroscan

It must be noted when looking at reliability results for the instruments that during the trial the Aquaflex sensors were an early prototypes that were not available commercially and had no custom logging system. Also although the Enviroscan was available commercially the manufacturers were constantly upgrading the equipment throughout the period of the trial. So in a sense it to was a prototype device and the sensors on the market in 1998 are superior to the test units.

To gain a quantitative idea of the reliability of the three soil water sensors a simple test was conducted. It consisted of dividing the number of hours that each device had logged rational results by the number of hours that each device had been installed. The numerical value is termed the reliability index. Although this gives a general depiction of the reliability of each device, malfunctions often resulted from system breakdowns eg. stock damaging cables, and not device error. Reasons for nonsensical results, or no results, are given for each case.

The performance of several probes is believed to have been effected by cut or pinched cables that had been trodden on by cattle. To eliminate the possibility of any recurrence of this during the next irrigation season all cables were relayed inside conduit during the first week of August 1994.

4.4.4.2. Aquaflex 1993-94 Irrigation Season

There were four Aquaflex units installed in the bay. Their locations and the value of the reliability index for each is given in Table 1.

Location	**Depth (mm)**	**Reliability index**
North	200	0.87
North	400	0.70
South	200	0.82
South	400	0.63

Table 1 - Reliability Index values for Aquaflex units.

The first and most important point to make about the reliability index values for the Aquaflex sensors is that on no occasion were the units found at fault. Any problems that occurred resulted from the fault of the overall system.

An initial problem with the two units at a depth of 400 mm was a short of some kind in the wiring within the logging device. The short caused the same value to be logged for both the units for a fortnight before the data was down loaded and the problem was recognised and fixed. This period of cognate data was the main cause of the comparatively low reliability index values for those two units. The variation in the reliability index values between the north and south Aquaflex units was the result of a severed cable running to the southern units.

Other problems that affected all the units included:

- A damaged pull up resistor, used to increase voltage supply to Aquaflex channels, which resulted in too low a voltage being fed to the Aquaflex units for them to function (a logger problem).
- A faulty power regulator used to limit the voltage entering the batteries from the solar panels to 24 volts. When checked the regulator was allowing 8 volts through to the batteries which was not sufficient to keep them charged (again a logger problem).

4.4.4.3. Aquaflex 1994-95 Irrigation Season

No reliability tests were carried out on the Aquaflex instruments for the 1994-95 irrigation season as they performed throughout the season without any problems. The one exception was the unit at north 100 mm, but this resulted from damage caused by farm machinery and was possibly compounded by poor installation. The damage was the result of the shallow depth of the unit and has led to planning the placement of future units at depths no shallower than 200 mm.

4.4.4.4. Aquaflex 1995-96 Irrigation Season

Four new field site installations were completed by September 1995. The timing was later than desirable and resulted because of production problems in New Zealand. The Aquaflex and associated equipment installed at each site was similar. Each Aquaflex consists of a 3 metre long ribbon and a control box. Each ribbon contains a hard plastic cover with three copper wires running longitudinally through it. Inside a control box, connected to one end of the ribbon, are software and electronics for measuring soil water and temperature. A 4 core cable connects the buried control box and ribbon to an above ground logger. The cable contains a clock-line, data-line, power-line and earth. A solar panel keeps a twelve volt battery, which powers the system, charged. A modem connected to the logger via an RS232 communication cable allows for remote access to the data stored in the logger. The modem is inturn connected to the local telephone network. Figure 7 illustrates the full setup.

The new version of the Aquaflex sensors measured soil temperature as well as soil water content. There were custom loggers that also measured the air temperature inside the protective box. Due to production problems in New Zealand there was little time to field test the Aquaflex units and loggers before they arrived in Australia. The result of the lack of testing was that shortly after the initial installation it became apparent that the time scale, or measurement window, of the units was not suitable for Australian soils.

The design of the units did not allow for adjustments to be made and researchers had to install replacement control box units. The replacement control boxes did not arrive until just before Christmas. A further fortnight of monitoring results followed the replacement of the units to ensure that the instruments were working adequately. The first opportunity to use the Aquaflex data was in early January, by which time a large period of the irrigation season had past.

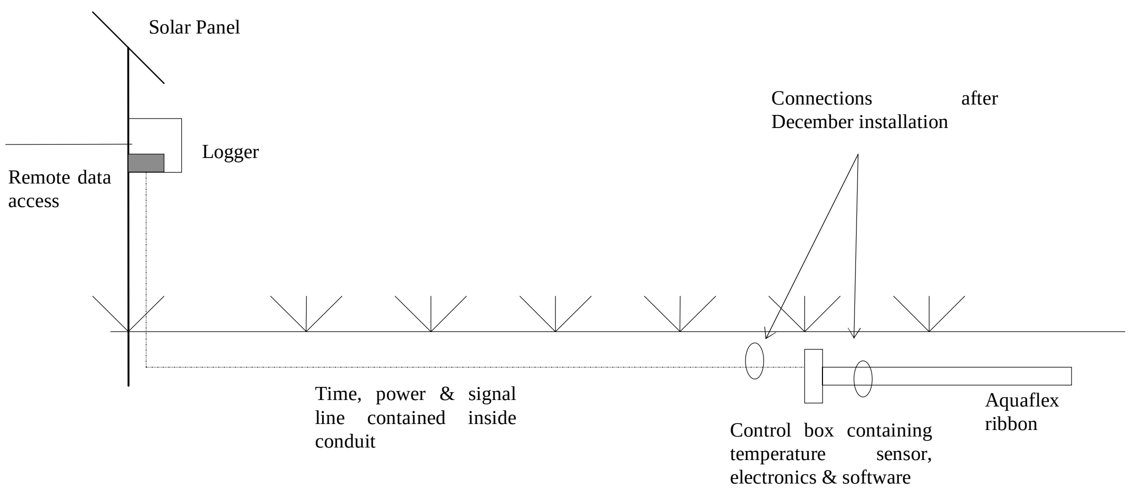

Figure 7 - New Aquaflex equipment field setup

When installing the new re-calibrated units only the control boxes were replaced. One connection joined the existing ribbons and the new control boxes with a further connection joining the control boxes to the cabling from the logger. Note: replacing the ribbons and cables meant that there was no further disturbance to the irrigation bay and no settling in period for the ribbons. Only replacing the control boxes introduced buried connections on both sides of the control boxes (see Figure 7). It was these connections that caused problems at two sites throughout the rest of the irrigation season.

After the second installation the sites at Tongala and Tragowel worked well for most of the season. The sites at Tatura and Calivil performed poorly for the rest of the season. The poor performance of these units was a result of the connections on either side of the control boxes not sealing. This conclusion was drawn from two observations:

1. When the connections were taken apart, dried and resealed the units would work for a day or two before water would find its way back into the connection and the unit would stop taking measurements again
2. Two units installed on vines at Woorenin and Tresco did not have the connections on the logger side of the control box that the pasture units did and worked without trouble throughout the entire season. The simple solution to this problem is to install any future units with the required length of cable to connect the control box to the logger already attached. By doing this no underground connection are necessary.

New units with attached cables were installed in mid September 1996 when equipment arrived New Zealand in preparation for the 1996-97 irrigation season. The new sensors were upgraded and have experienced no problems at any of the sights since (up to September 1998).

Two new sights have also been established by staff at Goulburn-Murray Water as part of research work being carried out by the Irrigation Services Unit. Reports to date are that apart from flat batteries the units have been operating well.

Lessons learnt in previous seasons with the basic setup and maintenance of equipment ensured no repeat of problems encountered during these seasons ie. loss of soil water data due to equipment problems. All loggers and probes at the seven sites operated without problems throughout the season.

The major problems experienced with the Aquaflex soil water monitoring equipment in previous seasons were:

- Water entering underground cable connections.
- Stock traffic causing deep pugging in saturated conditions, resulting in cable damage.
- Severing of cables by pests (rabbits and hares) chewing the cables where they emerged from the ground.
- Shorting out of loggers because of ant/spider nests inside logging units.

Overcoming these problems involved:

- Installing Aquaflex units with the required length of cabling attached, thereby avoiding any underground connections[8].
- Encasing cabling in conduit both above and below ground.
- Providing appropriate insecticides and/or poisons inside equipment boxes to kill any pests that could damage the logging equipment.

'Big Tip' whenever possible install soil water sensors during pasture renovation when the soil is ripped and seeds sown. In this way no settling in period is required and sensor conditions are assured of being representative of general field conditions. This applies to all soil based sensors. Of course this is easier in annual crops where installation can be considered part of planting and be done prior to each season.

4.4.4.5. Enviroscan 1993-94 Irrigation Season

There were 4 Enviroscan probes at the experiment site, each with sensors collecting data from depths of 100 mm, 200 mm and 300 mm. As all three sensors on each probe were usually affected by any problems that occurred with a probe, the reliability index values for probes and not individual sensors are listed in Table 2. The reliability index for the north east probe has not been presented in the table as the cable from the probe to the logger was pinched by stock early in January 1994 and did not operate after that. The cable was not replaced in case any other probes were disturbed.

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[8] Installing units with cabling attached is a good short-term solution, but causes problems in situations requiring long cable runs (the maximum length of attached cabling available last season was 50-m). To solve this problem Lincoln Ventures are introducing a waterproof connection for underground joints.

Location	**Reliability Index**
North West (1b)	0.91
South East (2a)	0.71
South West (1a)	0.93

Table 2 - Reliability Index values for Enviroscan Probes.

From a comparison of the reliability index values it would appear that the Enviroscan was the best performed piece of equipment. There are however other variables involved that make the performance of the Enviroscan look better than it actually was. Data for the Enviroscan probe was collected by the local agent for the probe, usually once or twice a week. Any problems that were affecting the probe were usually found within two to three days of the problem occurring. The Aquaflex data was being down loaded every fortnight to three weeks, so a problem could occur and not be detected for up to three weeks. Thus the Enviroscan had many short periods of unsatisfactory performance, which were usually a result of problems with the probe itself, each having little effect on the reliability index. The situation with the Aquaflex was the opposite with few problems occurring but when each problem occurred the delay until it was detected was much longer and had a significant effect on the reliability index. In addition the reasons for the Aquaflex problems were part of the system as a whole and not with the unit itself.

4.4.4.6. Microlink 1993-94 Irrigation Season

The Microlink controller, probes and cables that were installed after the 1993 flood did not provide any data. Over a period of six months a number of attempts were made, with the aid of the local distributor, to get the system working, with no positive results. All parts of the Microlink device were replaced at some stage during the first half of 1994 except for the telephone cable linking the power supply and logger to the heat pulse sensors. It has been arranged to replace the cables and lay them in PVC conduit during the first week of August 1994, when the Aquaflex and Enviroscan cables will also be replaced. No further data were gathered from the Microlink probes.

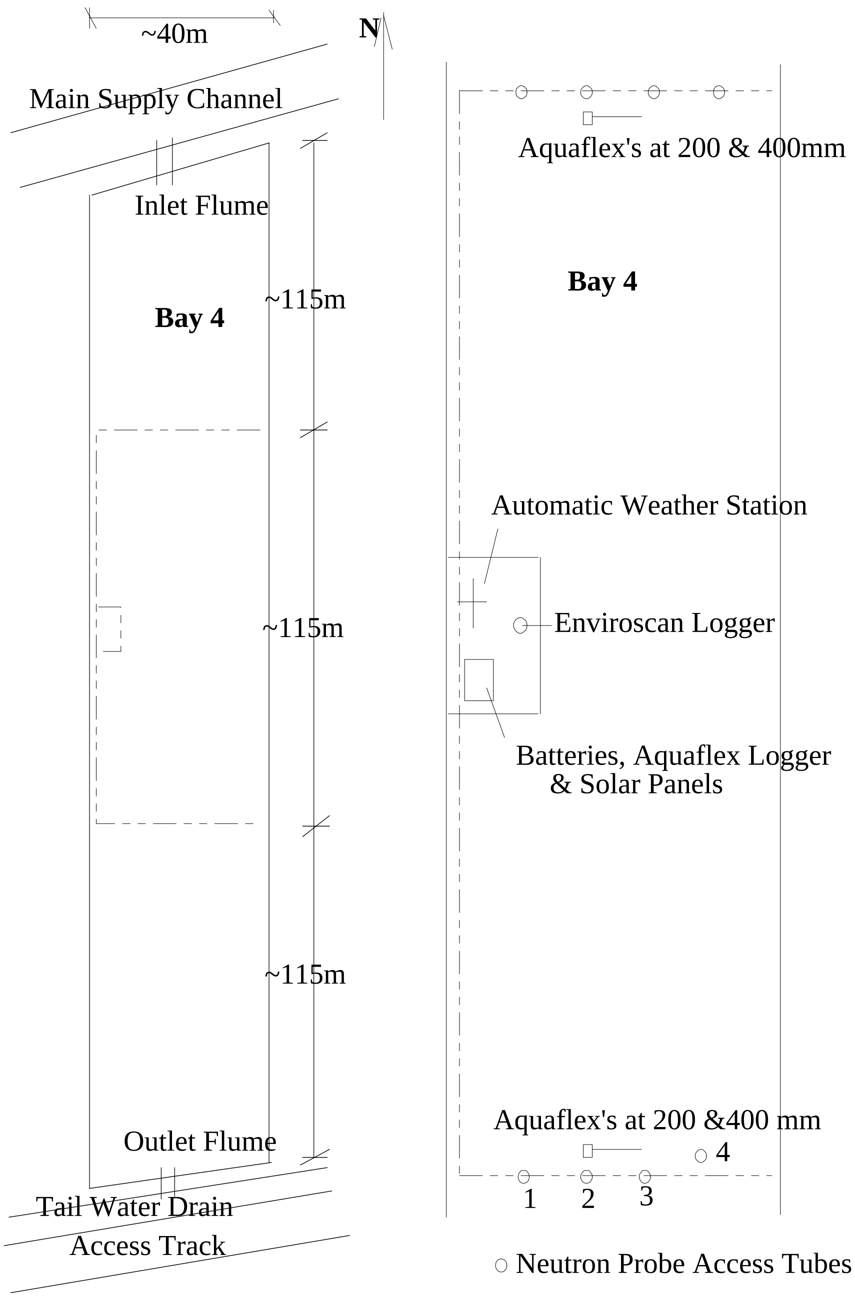


Figure 8 - Dookie College irrigation bay setup.

5. Comparison of Aquaflex and Enviroscan

The advent of new technologies for monitoring soil water has lead to instrument manufacturers putting new products on the market that are not always “commercially ready”. This section compares results from the Enviroscan and Aquaflex and assesses their performance and suitability for aiding irrigation scheduling decisions. Also used in the comparison was a water budget model. The dairy farm at the Dookie Campus of Melbourne University was the site for the trials during the 1994-95 irrigation season. Given here is a comparison of the data returned by the three methods, an assessment of the accuracy of the methods and a discussion of problems encountered.

Details of the Dookie site are given in section 3.4.2. so only a brief summary is given here. The trial bay is part of the first of two irrigation management sections on the farm. The bay has an area of approximately one and a half hectares (40 x 365 metres) with a slope of 1 in 700. A weather station was placed half way down the irrigation bay and the Enviroscan and Aquaflex units one third and two thirds of the way down the bay. The Enviroscan and Aquaflex were buried at a depth of 200 mm. The approximate spacing between the Aquaflex and Enviroscan probes at each position was 10 metres (measured across the bay).

The test bay contained a duplex soil type with an upper layer of grey brown fine sandy loam to loam and an underlying layer of brown to grey brown clay.

Both the Enviroscan and the Aquaflex logged soil water content data every hour. The weather station recorded daily maximum and minimum values of temperature, wet bulb and dry bulb temperature, daily wind run, rainfall amount and intensity, daily solar radiation. Additional temperature readings were taken at 09:00 and 15:00 hours. The weather station provided the input data required for daily evapotranspiration calculations.

Details of the Enviroscan and Aquaflex are given in section 3 and the reader is referred there for details.

5.1. Water Budget

The third technique used to measure soil water use was a water budget model. The water budget equation used was:

$$\theta_i = \theta_{i-1} - 100\left(\frac{ET - P_e}{D_{rz}}\right) \qquad \textbf{Equation 2}$$

θ_i,, θ_{i-1} = the soil water content in percent by volume at the end of day *i* and day *i-1*, respectively
ET = evapotranspiration (mm d^{-1})
P_e = effective precipitation (Irrigation or rainfall less runoff) (mm)

D_{rz} = depth of root zone (mm)

The depth of the root zone was taken as 400 mm as instrumentation at this depth was detecting a diurnal soil water pattern which indicates some root activity. A constant rate of soil water extraction was assumed throughout the root zone.

This simplified equation, which doesn't include deep percolation and runoff, was used due to data availability and the fact that using flood irrigation application techniques the soil is saturated during an irrigation event, so a known starting point is obtained after each irrigation. The effectiveness of a rainfall event is not known however and where rainfall has occurred it is assumed that all the rainfall is taken up by the soil. This leads to some inaccuracy in the water budget method.

The daily evapotranspiration was calculated using the Penman-Monteith combination equation (Smith et al. 1992). Variables measured at the on-site weather station and used in the equations were: global radiation, maximum and minimum temperatures, rainfall, wet bulb and dry bulb temperatures, wind run. The estimates of ET were calculated daily and no crop coefficients were used on the ET data.

To enable an accurate comparison of data from the water budget method to be made with the Aquaflex and Enviroscan the water budget data was broken up into hourly values by dividing the daily figure by twenty-four. When an irrigation was applied it could be accounted for in the water budget technique at the appropriate hour. The irrigation returned the soil to an assumed value of saturation (34% vwc) where it remained for twenty-four hours before returning to field capacity (30% vwc). From here the evapotranspiration (daily/24) was subtracted hour by hour from the previous hours total. The resulting comparison of volumetric soil water between the three techniques can be seen in Figure 45, Appendix .

5.2. Method and Results

The assessment program was designed to compare the relative performance of the two probes and the water budget model. Performance was primarily assessed by making relative comparisons of the soil water measurements, with some comments on reliability and service of equipment. Recommendations on the suitability for different applications are also made.

A destructive sampling program will be carried towards the end of the 1996-97 irrigation season to assess the performance of the methods against gravimetric results.

To make a comparison of relative changes in water use measured by Aquaflex and Enviroscan it was necessary to remove the effect of manufacturer calibration equations. Any relative differences in readings obtained could be a result of an inappropriate calibration equation. By removing the effect of calibration if the two probes were stable they should maintain consistent readings over future periods and give comparable results. The effect of calibration equations was partly removed by using the Enviroscan manufacturer calibration curve to obtain volumetric soil water content from the raw signal recorded by the Enviroscan probes. The raw output of the Aquaflex unit was then calibrated against the Enviroscan volumetric soil water content output to obtain a calibration curve for the Aquaflex. The period used for the calibration was from 16/11/94 to 28/11/94.

Figure 45 in Appendix shows the results from all three probes plotted on the same graph. A visual analysis of the figure reveals that all three methods follow the same general trend with good consistency in the relationships throughout the period (ie. Generally the Aquaflex records greater amounts of soil water use followed by the Enviroscan and the water budget approach. Also the values of vwc at saturation are constant over the period for the Aquaflex and the Enviroscan, indicating repeatability of the measurement techniques, or no temporal drift.).

The field capacity line on Figure 45 is an approximation based on the drainage characteristics of the curves. The refill point was set using a field determined soil water characteristic curve. The curve was constructed by taking concurrent measurements of soil water content and soil tension (using tensiometers). Work by Goulburn-Murray Water and the Kyabram Dairy Centre has shown that a soil tension value of 40 kPa at a depth of 200 mm is the optimum for white clover production in the poorly draining, low water holding capacity soils of the region. This value is a comprise between keeping enough water up to the white clover and allowing for drainage, stock rotation and delivery system constraints.

To confirm the visual analysis of Figure 45, ie. that the three curves are consistent in nature, the correlation coefficient of the daily change in volumetric soil water content (daily range) between each technique was determined (Table 3). The correlation coefficient of X and Y ($\rho_{X,Y}$) is defined as:

$$\rho_{X,Y} = \frac{Cov(X,Y)}{\sigma_X \sigma_Y} \qquad -1 \le \rho_{X,Y} \le 1$$ **Equation 3**

where:
σ_X , σ_Y = standard deviation of X and Y respectively
Cov(X,Y)= covariance between the two random variables X and Y

$$Cov(X,Y) = E[(X - \mu_X)(Y - \mu_Y)]$$ **Equation 4**

where:
μ_X , μ_Y = mean of X and Y respectively

In this experiment the X and Y are the daily range values of two of the three soil water measurement techniques.

The correlation coefficient values shown in column two of Table 3 are the values returned when all the data in Figure 45 (Appendix) is used in the analysis. The high values of the correlation coefficient reflect a strong positive relationship between all the variables tested. This can be seen in Figure 9, which shows that generally high values of daily vwc range measured by the Enviroscan correspond to high values of daily vwc range measured by the water budget technique. Likewise low and medium values also correspond. This plot is similar to the relationships existing between the Aquaflex and the Enviroscan and the Aquaflex and the Water Budget technique.

	$\rho_{X,Y}$ all data	$\rho_{X,Y}$ vwc < 30%
Aquaflex Enviroscan	0.94	0.66
Aquaflex Water Budget	0.93	0.41
Enviroscan Water Budget	0.97	0.34

Table 3 - Comparison statistics for the Aquaflex, Enviroscan and Water Budget measured daily range of soil water content.

Of greater importance to this study is how the daily range values from the three techniques correlate when the "working zone" (the region below field capacity) is considered. Column three in Table 1 shows the correlation coefficient values from an analysis of daily range data for days where the maximum vwc was below thirty percent (the approximate position of field capacity).

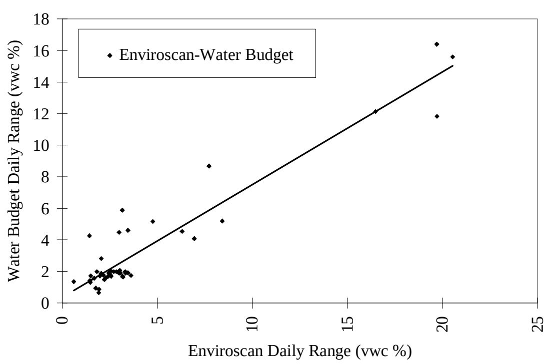


Figure 9 - Daily range in vwc measured by the water budget technique, plotted against Enviroscan daily range vwc values. All data was used.

The results show that a reasonably strong relationship exists between the daily range values of the Aquaflex and Enviroscan (Figure 10). This is not the case for the daily range values of the Aquaflex and Water Budget and Enviroscan and Water Budget techniques. The low correlation for the Enviroscan and the Water Budget techniques is shown in Figure 11.

The reason for the low value of the correlation coefficient is the difference in range values exhibited by the two techniques. The Enviroscan daily range values vary evenly between 0.5 to 3.5, whereas the values for the water budget technique are clustered between 1 and 2 % vwc.

The difference arises from an incorrect calibration for the Enviroscan, giving rise to an exaggerated spread of values and/or a false assumption of a constant root extraction rate with depth, leading to a narrower than actual spread of water budget derived values.

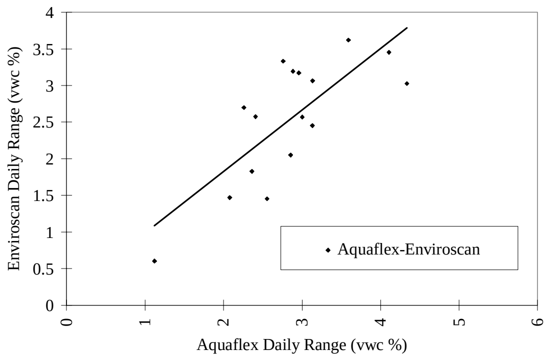


Figure 10 - Daily range in vwc measured by the Enviroscan, plotted against Aquaflex daily range vwc values. Only data from days where the maximum vwc was below 30% were used.

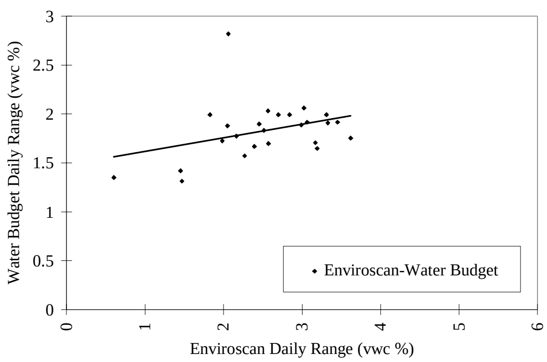


Figure 11 - Daily range in vwc measured by the water budget technique, plotted against Enviroscan daily range vwc values. Only data from days where the maximum vwc was below 30% were used.

The one prominent difference between the curves is the behaviour above field capacity. The water budget equation refills to an assumed saturation value (34%) for an estimated period (24 hours). The Enviroscan curve shows a higher saturation value than the Aquaflex. The difference probably results for two reasons:

1. The Aquaflex is averaging readings over three metres and some sensitivity to change on a small scale maybe lost.
2. Because soil contact is so important for the Enviroscan if an annulus develops between the soil and the probe, due to shrinkage of the soil, then at irrigation time the gap will fill with water and a higher than actual saturation point will result. The data in Figure 45 supports this hypothesis.

The figure shows that on 6 January 1995 a substantial rainfall event of 16 mm fell at the site. Because the soil was just below field capacity at the time of the rainfall no shrinkage of the soil from around the Enviroscan probe occurred before the rainfall event. Thus, the resulting saturation vwc reading for the Enviroscan was comparable to the Aquaflex reading (approximately 34 % vwc compared to 38 % vwc for applications applied to a drier profile). This supports the theory that the Aquaflex unit is representing the actual wetting and drying mechanics of the soil. Because the swelling and shrinkage do not influence the behaviour of the curve below field capacity the consequences for irrigation scheduling are not great.

Figure 36, Appendix 2 shows a plot of the cumulative difference between daily changes in soil water content measured by the Enviroscan and the Aquaflex against the daily maximum soil water value. From the plot it is clear that the major differences between the measurements made by the two instruments occur above field capacity. The same plot for the Aquaflex and Water Budget and Enviroscan and Water Budget techniques reveal the same trend (Figure 37 and Figure 38, Appendix 2) ie. small differences associated with soil water readings below field capacity and large differences associated with readings above field capacity.

Plots of the cumulative difference squared of the daily range in soil water content against time show that there was no temporal drift in the instrumentation readings ie. the slope of the curves are reasonably constant. Figure 39, Figure 40 and Figure 41 in Appendix 2 show the results of the comparison between the Aquaflex and the Enviroscan, the Aquaflex and Water Budget technique and the Enviroscan and Water Budget technique respectively. The sharp rises in the cumulative differences correspond to irrigation event days and arise because of the behavioural differences of the three techniques in the zone above field capacity. These jumps are not as apparent in Figure 40 because of the assumption that the saturation point for the Water Budget technique was close to the saturation value measured by the Aquaflex.

5.3. Discussion

The following discussion looks at the issues to consider when deciding which technique to use for monitoring soil water.

Conditions suited to the Enviroscan are those where measuring the infiltration of water through the soil profile is important, but a large sample area is not critical. The use of the Enviroscan in mixed pasture crops is not recommended as the dominance of one pasture species in the sampling area could give results that do not reflect the overall water use trends of the pasture.

Shrinkage of the soil surrounding the Enviroscan probe in some cases leads to an exaggerated saturation value. Following soil expansion upon wetting however, the probe resumes good contact with the soil and behaves consistently and repetitively when compared to Aquaflex.

Below the optimum soil water content range, the Aquaflex and Enviroscan soil water use curves exhibit a marked decrease in slope (Figure 12). In single species cropping irrigators use this decreased slope to identify the irrigation refill point. Irrigators should not use this method with a mixed species pasture when different species have different tolerances to water stress. The danger is that white clover is the least tolerant species in the pasture to water stress, but the most desirable. White clover production will decrease if the stress effects on the soil water use curve are not apparent until two or more species in the pasture become stressed. Also, complications in identifying the level when water related plant stress occurs result because of the influence of weather conditions, root density changes and pasture composition changes. Concurrent studies at other field sites have shown that a successful method for identifying the refill point is to obtain a field derived soil water characteristic curve and use this for scheduling.

The Aquaflex device samples a much larger area of soil to obtain a measurement of soil water content but it is more difficult to assess the movement of water through the profile using this instrument.

The installation process may lead to problems of increased root mass at depth due to the loosening of the soil, which may lead to easier root penetration on the clay soils. This could lead to greater water extraction rates than in other areas of the field and root water extraction from greater depths.

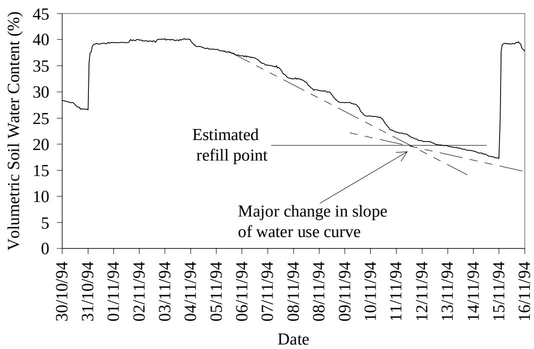


Figure 12 - A technique for identifying the refill point in crops. A rapid change in the slope of the soil water use curve identifies the position of the refill point.

On a practical application level, in border checked flood irrigation there are limits on how much control an irrigator has over applications. Thus there are restrictions on the full benefits to be derived from measurements of through profile flow. Another limitation on the use of infiltration data is that in the cracking soils of the test region, irrigation water can advance ahead of the surface wetting front via major cracks (Turral 1994). This phenomenon of rapid wetting at depth via cracks means that probes stationed vertically in the soil profile may not aid in the knowledge of infiltration characteristics. The reason for this is that simultaneous wetting of soil profile depths may occur.

A surface irrigation delivery system limits the flexibility irrigators have for managing the timing of irrigations and the amount of water applied at each irrigation event. This reduces the need for the extra information supplied by the Enviroscan (at considerable extra cost). In drip and spray systems this information is very desirable and in the future if farms become automated, with better control on application and smaller bays then the Enviroscan may be worth the further investment.

6. Forecasting Soil Water Content

Instruments for measuring real-time soil water content (swc) are readily available to irrigators in Australia. The instruments are excellent tools for aiding irrigation scheduling decisions. This section investigates and assesses methods to forecast four day swc to supplement real-time swc measurements. It identifies the most appropriate method to use in the soils of northern. Northern Victorian farmers need to forecast crop water use because irrigation system management require at least four days notice prior to water delivery[9].

Forecasting soil water use also allows for improved short-term planning by farm managers leading to the integration of the on-farm system with the main water deliver system. This precipitates real-time operation of the main system leading to more reliable deliveries to individual farms and allowing for real-time control on-farm. The need for constant delivery rates at required times is an important factor in realising real-time irrigation using automated equipment.

The basic concept of forecasting swc is a simple one. It involves estimating future swc given current observed swc. Irrigators inturn use the forecast to decide when to order water and irrigate (Figure 13).

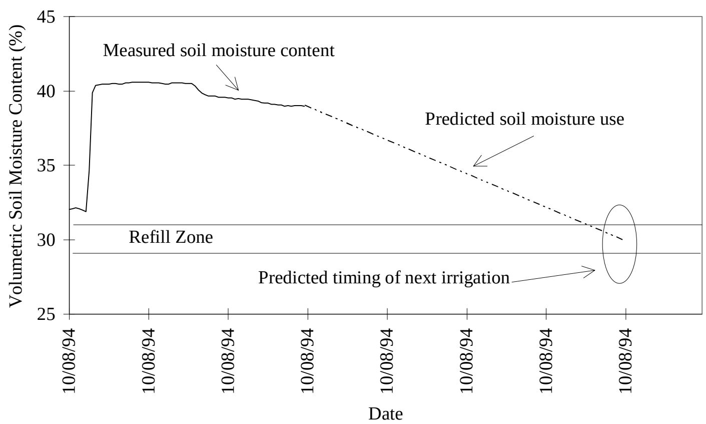


Figure 13 - Schematic diagram of the irrigation forecasting problem, illustrating the real-time and forecasting components of a swc curve.

The real-time swc data used to test the methods were obtained from an Aquaflex, but results apply to any instrumentation measuring real-time swc. A basic description of the forecasting methods are given below, with details provided in the next section.

1. Slope Method - find the slope of the observed swc curve for a period of days prior to today and use this slope to estimate water use for the next four days.
2. Linear Method - determine a relationship of the form y = ax + b, using linear regression, between the observed swc and observed evaporation, or reference evapotranspiration, for a

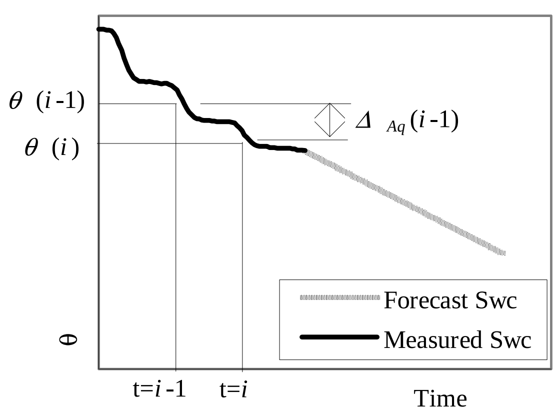
[9] Goulburn-Murray Water undertake to deliver 85% of orders on the ordered day and 93% of orders within one day of the day ordered, given the required four days advance notice (Water 1994).

period of days prior to today. Use this relationship to forecast swc given knowledge of weather conditions over the next four days.

3. Adjusted Slope Method - as per 1 except apply an adjustment to the observed and forecast swc changes. The adjustment compensates for the influence of the soil water deficit at the start of any hour on water content change during the hour.
4. Adjusted Linear Method - as per 2 except apply an adjustment to the observed and forecast swc data for the reasons described in 3.

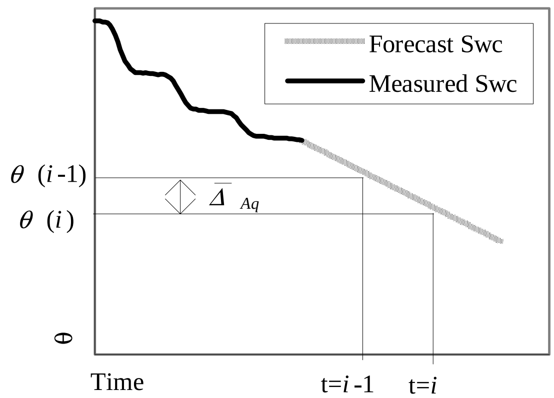
6.1. Methodology

This section explains the four methods employed to forecast hourly swc changes. Each method is split into two phases. Phase 1 is the formulation of a relationship to use when calculating forecast swc and Phase 2 is calculating the forecast swc values. The methods only use data below the Drained Upper Limit[10] (DUL) as gravity drainage, rather than crop water use, dominate changes in swc above this value (Figure 15). See Figure 14 for a diagram of the basic parameters used in all methods.



(a)

[10] This term is used when dealing with the duplex soils of northern Victoria (Poulton, D.C. 1997, pers. comm.). It is analogous to the field capacity point in free draining soils, but in duplex soils the low conductivity clay layers underlying the soil A-horizon, and high water-tables, result in water not bonded to the soil matrix remaining in the upper soil profile for extended periods. The difference between saturation and so called "field capacity" in the swc curves from the region is about 2% to 4% by volume, when for typical loam soils the expected difference is about 10% to 15%. Meyer et al. (1995) uses this term to describe the same point on the soil water curve.



(b)

Figure 14 - Parameters used to determine hourly changes in swc during (a) the development of a relationship for forecasting and (b) calculation of forecast swc values.

6.1.1. Slope Method

First calculate the slope of the observed swc curve for a number of hours prior to the current hour, then apply the slope to the forecast period. The one complication is that readings above the DUL are omitted from the process. If a reading at time, t = *i*, is above the Drained Upper Limit then the data for that hour is ignored. The calculation then moves backward to find two consecutive hours with readings below the Drained Upper Limit. This means that when finding the average slope for a given number of hours, *p*, the final swc reading may be more than *p* intervals before the current reading.

Given that the current time corresponds to the last observed swc reading and the beginning of the forecast period, when the calculation begins the:

1. time t=0,
2. observed swc is $\theta(0)$,
3. reading one hour prior to b) is $\theta(-1)$ and
4. change in swc during the past hour is $\Delta_{Aq}(-1)$

The change in swc for each hour of a given number of hours, *p*, is:

$$\Delta_{Aq}(i) = \theta(i) - \theta(i+1) \quad \text{for } i = -1, \ldots, -p$$ **Equation 5**

The average slope, or average hourly change in water content, $\overline{\Delta}_{Aq}$, over the entire period *p* is:

$$\overline{\Delta}_{Aq} = \frac{\sum_{i=-1}^{-p} \Delta_{Aq}(i)}{p}$$ **Equation 6**

The hourly swc values of the 4-day forecast are:

$$\theta(i) = \theta(i-1) - \overline{\Delta}_{Aq} \quad \text{for } i = 1,\ldots,96$$ **Equation 7**

6.1.2. Linear Method

First determine a linear relationship of the form y = ax + b, using linear regression, between observed swc and reference evapotranspiration[11] (Eto) or evaporation (E) data. The analysis extracts observed hourly swc changes from the soil water database and sums data from days with 24 hourly readings to get daily readings over the desired period, *p* days. Extracting corresponding readings from an evapotranspiration database is the next step, followed by the determination of the coefficients of the linear regression relationship, b_0 and b_1. The linear regression relation is:

$$\Delta_{DayAq}(i) = b_0 + b_1 \Delta_{ET}(i) \quad \text{for } i = 1,\ldots,-p$$ **Equation 8**

where Δ's are daily data for this method.

Determining the 4-day forecast estimates of swc changes involves calculating future daily Eto, using the Hargreaves equation and forecast weather data, and substituting these values into Equation 7. In a retrospective study this can be done using observed weather data. The forecast swc values are:

$$\theta_{Day}(i) = \theta_{Day}(i-1) - \Delta_{DayAq}(i) \qquad \textit{for } i = 1,\ldots,4$$ **Equation 9**

6.1.3. Adjusted Methods

In the adjusted slope and adjusted linear methods a correction is applied to data during both phases of the methods. The need for a correction is due to the complex and dynamic nature of the swc changes measured by the Aquaflex probes.

[11] The reference evapotranspiration data is calculated using the Hargreaves (Hargreaves et al. 1985) temperature based method. The choice to use the Hargreaves method was made because: 1. Irrigators have easy access to daily temperature data and can easily enter it into the model and 2. The FARMWEATHER forecast supplied by the Special Services Unit at the Bureau of Meteorology only includes temperature and basic wind data estimates. Therefore the choice of model to forecast evapotranspiration is limited to the Hargreaves or Blaney-Criddle models.

At the beginning of an irrigation cycle, immediately after the swc falls below the Drained Upper Limit, the amount of observed swc change is low, but increasing with time (Zone 2, Figure 15). The low increasing rate is due to the redistribution of water, mainly from downward drainage, and low root water uptake at depth when water is available closer to the surface. During the middle of an irrigation cycle water movement via drainage is low and the top layers of the soil are drying. This results in maximum water use at the depth of the probe (Zone 3, Figure 15). Finally, in the late stages of any irrigation cycle, given no water application, the soil at the depth of the probe becomes dry. Soil water tension values in the drying soil increase to magnitudes where roots find it difficult to extract water and water content changes begin to decrease (Zone 4, Figure 15).

Given the nature of the observed swc curve, it is likely that while deriving a relationship using observed data the data will come from more than one of zones 1, 2 and 3. Again during the forecasting the involvement of more than one zone is likely. Even if weather conditions are constant it is likely that the different water use characteristics of the three zones will result in significant forecasting errors.

The purpose of the adjustment methods is to provide a `standard` reading of the change in swc for a given hour, independent of the zone the reading comes from. Once developed the `standardised` forecasting relationship provides a method to forecast water use changes in any zone of a future irrigation cycle. It is necessary to consider which zone a forecast hour is in when applying the `standardised` relationship to estimate forecast data.

The above process is analogous to the concept of basal crop coefficients (ASCE 1990). Basal coefficients increase reference evapotranspiration when a surface is wet, to allow for increased evaporation, and decrease reference evaporation as the swc falls below a predetermined limit, allowing for crop water stress. The idea of correcting observed swc to obtain a `standardised` relation to use for forecasting however originated while reading (Jarvis 1989). Jarvis uses a stress index factor to allow for low root water uptake soon after an irrigation, because of oxygen deficiencies in the soil, and decreasing uptake following the onset of plant water stress. Jarvis' stress index is part of a larger model attempting to simulate changing root water uptake with depth.

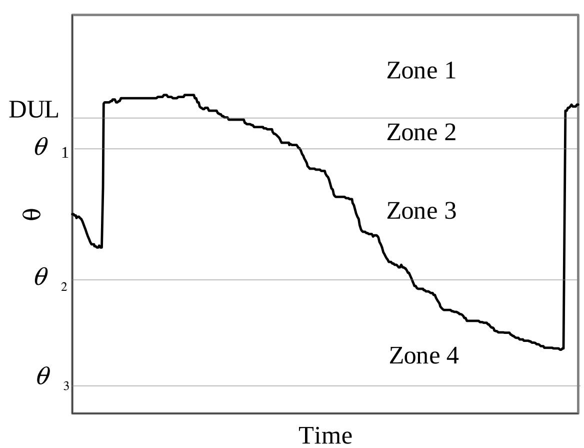


Figure 15 - Zones of the Aquaflex swc curve.

During the first phase of the adjusted methods a correction factor, α, is applied to hourly swc changes. This factor increases the observed changes while in zone 1, has no effect on the changes in zone 2 and again increases the changes in zone 3. α is a function of soil water deficit (SWD) and for Phase 1 varies as shown in Figure 16 (a). The SWD is equal to the Drained Upper Limit minus the swc at a given time. Three threshold limits, l_1, l_2 and l_3 mark the boundaries of zones 1, 2 and 3. Determining the limits involves studying the features of the observed swc curve (see Figure 15). From the figure the threshold limits are:

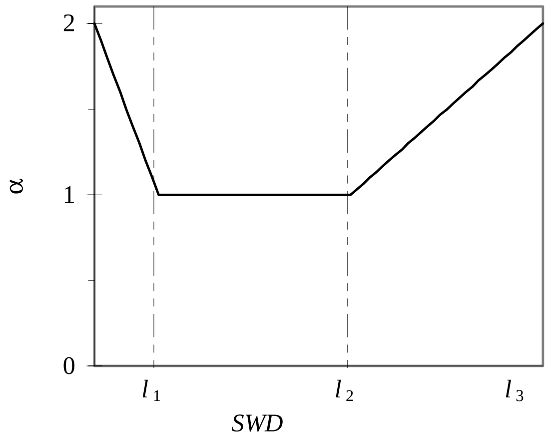
$$l_1 = DUL - \theta_1$$
$$l_2 = DUL - \theta_2 \qquad \textbf{Equation 10}$$
$$l_3 = DUL - \theta_3$$

The values of α in the three zones of the swc curve are:

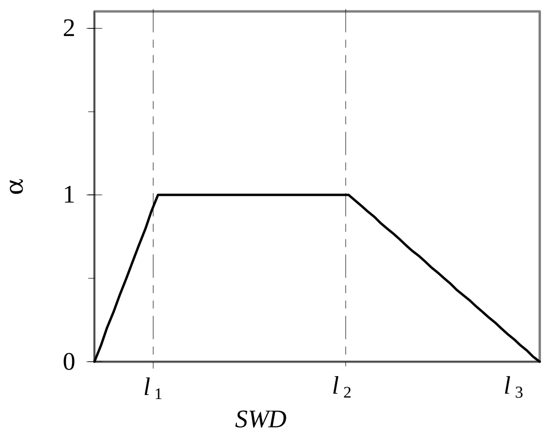
$$\alpha = 2 - \left(\frac{SWD}{l_1}\right), \qquad l_1 > SWD$$
$$\alpha = 1, \qquad l_1 > SWD > l_2$$
$$\alpha = 1 + \left\{\frac{(SWD - l_2)}{(l_3 - l_2)}\right\}, \qquad l_3 > SWD > l_2 \qquad \textbf{Equation 11}$$
$$\alpha = 0, \qquad SWD > l_3$$

During the Phase 2 of the adjusted methods, ie. using the derived `standardised` curve to forecast swc changes, α decreases hourly estimated swc changes in zone 1, has no effect on changes in zone 2 and decreases changes in zone 3. Figure 16 (b) shows the change in α with increasing SWD. The relative values of α in each of the regions are:

$$\alpha = \frac{SWD}{l_1}, \qquad l_1 > SWD$$
$$\alpha = 1, \qquad l_1 > SWD > l_2$$
$$\alpha = 1 - \left\{\frac{(SWD - l_2)}{(l_3 - l_2)}\right\}, \qquad l_3 > \mathrm{SWD} > l_2 \qquad \textbf{Equation 12}$$
$$\alpha = 0, \qquad \mathrm{SWD} > l_3$$



(a)



(b)

Figure 16 - α correction factor during (a) development of forecasting relationship and (b) calculation of forecast swc values.

6.1.4. Adjusted Slope Method

The analysis is similar to the Slope Method except that the correction factor, α, is applied to each hourly change in swc to give the adjusted change in swc, $\Delta_{Aq,Adj}(i)$, at time, t=i for a selected number of hours, p :

$$\Delta_{Aq,Adj}(i) = \alpha(i)\left[\theta(i) - \theta(i+1)\right] \text{ for } i = -1,\ldots,-p$$ **Equation 13**

The adjusted average slope, or adjusted average hourly change in swc, $\overline{\Delta}_{Aq,Adj}$, over p hours is:

$$\overline{\Delta}_{Aq,Adj} = \frac{\sum_{i=-1}^{-p} \Delta_{Aq,Adj}(i)}{p}$$ **Equation 14**

The adjusted hourly swc values of the 4-day forecast are:

$$\theta_{Adj}(i) = \theta_{Adj}(i-1) - \alpha(i)\overline{\Delta}_{Aq,Adj} \quad \text{for } i = 1,\ldots,96$$ **Equation 15**

The observed swc at time t=0, $\theta(0) = \theta_{Adj}(0)$. The soil water deficit value used to calculate $\alpha(i)$ is:

$$SWC = DUL - \theta_{Aq}(i-1)$$ **Equation 16**

6.1.5. Adjusted Linear Method

The Linear Method begins at Phase 1 with the development a linear relationship between adjusted observed daily swc changes, $\Delta_{DayAq,Adj}(i)$ and observed daily reference evapotranspiration, $\Delta_{ET}(i)$, using simple linear regression. The correction factor α is introduced prior to the summation of daily $\Delta_{DayAq,Adj}(i)$, during the process of extracting observed hourly swc changes (see equation (11)). The adjusted linear regression relation is:

$$\Delta_{DayAq,Adj}(i) = b_0 + b_1\Delta_{ET}(i) \quad \text{for } i = 1,\ldots,-p$$ **Equation 17**

Determining the 4-day forecast estimates of swc changes involves calculating for daily Eto and substituting the values into equation (15) to find the daily forecast swc changes. These daily values are divided into hourly values and the forecast swc content values, $\theta_{Adj}(i)$, are:

$$\theta_{Adj}(i) = \theta_{Adj}(i-1) - \alpha(i)\Delta_{Aq,Adj}(i) \qquad for\ i = 1,\ldots,96$$ **Equation 18**

where $\theta_{Adj}(0) = \theta(0)$, the last observed swc value.

6.2. Site and Methods

The observed swc data analysed in this study were measured at a property near Tongala, a small town in northern Victoria. The Aquaflex probe that measured the data is buried at a depth of 200 mm, in the root zone of a perennial pasture (white clover, perennial ryegrass and paspalum). Hourly observed swc readings were recorded from 25 August 1997 to 25 February 1998. The soil is a duplex soil consisting of Shepparton fine sandy loam to about 300 mm, underlain by a heavy red clay that restricts downward drainage and results in a perched water-table. The water-table rises to the surface during an irrigation event and drops to 700 mm of the end of each cycle. A small channel at the top of the bay conveys water to the bay. Water is applied using border checked flood irrigation. The slope of the bay is approximately 1 in 800.

The evaporation and weather data used in the analysis comes from Kyabram, 15 km to the south-west (latitude 36.34 South, longitude 145.06 East, elevation 104.5 m). Table 4 shows the climate averages for Kyabram.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall	mm	35.1	24.6	29.8	39.6	47.5	41.5	45.9	46.4	45.5	44.3	32	32.1	**464.5**
Evaporation	mm	8.6	7.9	5.6	3.3	1.7	1.1	1.2	1.8	2.8	4.4	6.5	8.1	**25.8**
Temperature	Max ^oC	29.5	29.6	26.3	21.5	16.9	13.6	12.8	14.5	16.9	20.9	24.4	27.6	**21.2**
	Min ^oC	13.8	14.6	12.3	8.8	6.2	3.4	2.7	3.7	5.1	7.4	9.8	12.2	**8.3**
Relative	9-am %	56	61	63	73	84	89	89	83	76	66	61	57	**72**
Humidity	3-pm %	33	36	40	49	62	67	66	60	57	49	39	34	**49**

Table 4 - Climate averages for Kyabram.

The analysis tested each method using a period between 1 and 20 days to develop a relationship from observed data. The analyses of the linear methods only used periods of 7 days or greater. Forecasts started at 7:00 PM on the evening of those days suitable for testing. Days not used in the analysis were:

- Days where swc was above the Drained Upper Limit at 7:00 PM.
- Dates occurring less than 3 days before an irrigation or rainfall event (to be enable comparisons between forecast and observed swc rainfall and irrigation events must not effect the data). The analysis included those days where an irrigation or rainfall occurred between 3 and 4 days after the forecast began. It was felt that including forecasts of less than 3 days would bias the results.

After eliminating the above, 61 days were available for analysis of a 4-day forecast. The Linear and Adjusted Linear Methods were tested using observed Hargreaves evapotranspiration and evaporation to determine the linear regression relation and in the estimation of forecast data. As an initial test, to see if results warranted further testing with forecast evapotranspiration, forecasting used observed data.

The retrospective nature of the study makes it possible to compare estimated and forecast swc during and at the end of each 4-day forecast. The tests statistics used to assess the forecast performances are:

- ME (% vmc) - (Mean Error) the average difference, in percent volumetric swc, between the final observed and forecast swc values of the 61 trials for each method. Units are percent volumetric swc. It indicates whether the forecast has a tendency to over-estimate or under-estimate the observed swc. A negative ME indicates the forecasts generally underestimated the final swc, a positive value indicates the forecasts usually overestimated swc and a value close to zero indicates that the forecasts varied evenly.
- ME (Day) - as for ME (% vmc) but the comparison is made in days rather than % vmc. The difference figure in days between the final forecast and observed curves is obtained

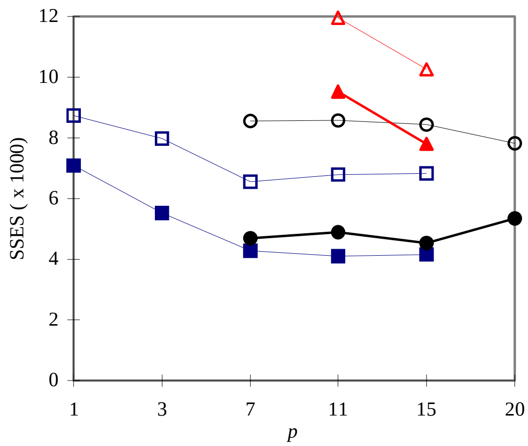
by dividing the error between the final forecast and observed figure by the average hourly observed swc change over the past 48 hours.

- MAE (% vmc) - (Mean Absolute Error) the average absolute difference, in % vmc, between the final observed and forecast swc values of the 61 trials of a particular method.
- MAE (Day) - as for MAE (% vmc) but the mean absolute error is expressed in terms of days.
- MAPE - (Mean Absolute Percent Error) the average absolute percent difference between the final observed and forecast swc values of the 61 trials of a particular method. This describes the average percentage difference, over the 61 trials, between the observed swc and the forecast swc, in terms of the absolute value of the observed figure.
- SSES - Sum of the Sum of Errors Squared is sum of the sum of errors squared for each of the 61 trials. The sum of errors squared for each of the trials is calculated by summing the squared errors between each of the 101 hourly forecast swc values and the corresponding observed values. It describes the total variation between the forecast and observed curve.
- MRS - the average coefficient of determination of the 61 regression analyses performed in each run of the Linear and Adjusted Linear Methods. It describes the strength of the relationship between observed swc changes and observed reference evapotranspiration during phase 1 of the linear models. A value close to 1 suggests a strong correlation while a value near 0 suggests a weak correlation between the two variables.

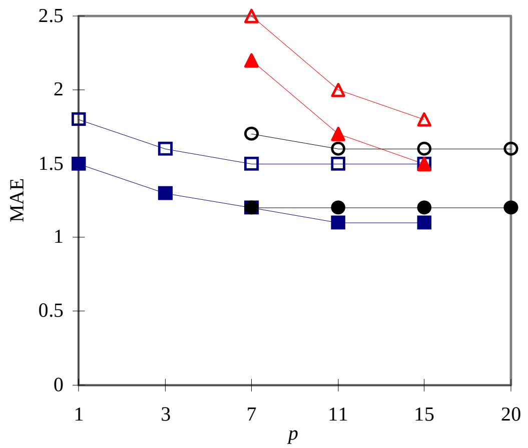
6.3. Results and Discussion

An assessment of the 4 zones on the swc curve found the values of the threshold limits as $l_1 = 2$, $l_2 = 11$ and $l_3 = 19$. The two adjustment methods use these limits. Table 9 in Appendix contains the results from the analyses.

Figure 17 (a) shows the SSES figures for all the methods (note the 7 day period results for linear Eto and adjusted linear Eto methods are omitted because they were very high and increased the scale too much). The data represents how closely the 96 hours of forecast soil water data matched observed data for the 61 trials. It is clear from the figure that all the adjustment methods (closed symbols) performed markedly better than the simple methods with the best performing technique being the adjusted slope. From the very low values of MRS, they vary between 0 and 0.4 (Table 9), the expectation is that the linear methods have no advantage over the slope methods.



(a)

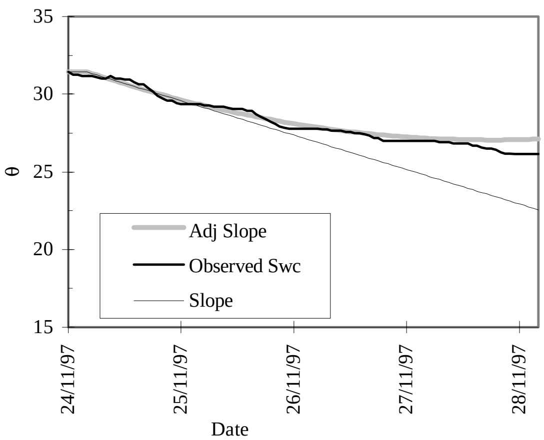


(b)

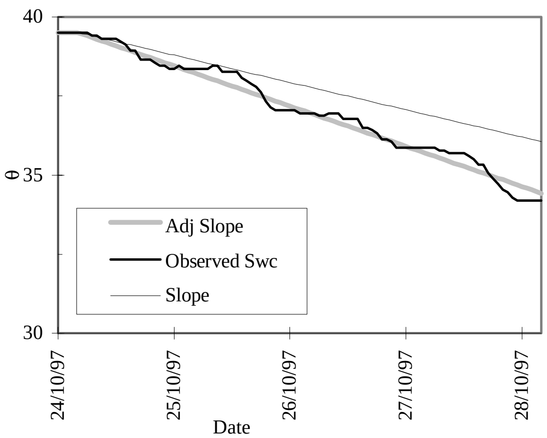
Figure 17 - Comparison of (a) SSES for Adjusted Slope (■), Slope (□), Adjusted Linear Evaporation (●), Linear Evaporation (❍) and (b) MAE for Adjusted Slope (■), Slope (□), Adjusted Linear Evaporation (●), Linear Evaporation (❍), Adjusted Linear Eto (▲) and Linear Eto (Δ).

The performance of the adjusted methods should be better because of their ability to describe the dynamic nature of the swc curve. Figure 18 (a) and (b) illustrate the ability of the adjusted slope method to adapt to the different conditions in each zone of the swc curve. Figure 18 (a) shows a forecast in zone 4 of the swc curve. The slope of the adjusted forecast line changes as the soil water deficit increases above the threshold limit l_1, but the forecast line of the slope method does not change as the deficit increases. Figure 18 (b) shows the benefits of deriving a standardised for forecasting. Many days of the observed data period used to determine the forecast line's slope lie within zone 1 of the swc curve. In this zone soil water changes are low and so the simple slope forecast underestimates the swc changes. The standardised curve adjusts any values from zone 1 and gives a more accurate forecast.

Extending the period of observed data used to develop a forecast relation provides no improvement for the linear evaporation (LEVAP), adjusted linear evaporation (ALEVAP), slope (S) and adjusted slope (AS) forecasts beyond 7 days. The best period to use with these methods is thus between 7 and 11 days. However, there is improvement in the forecast performance, ie. SSES values decrease, of the linear evapotranspiration (LET) and adjusted linear evapotranspiration (ALET) forecasts when the observed data period is extended from 7 to 11 (not shown Figure 17) and 11 to 15 days.



(a)



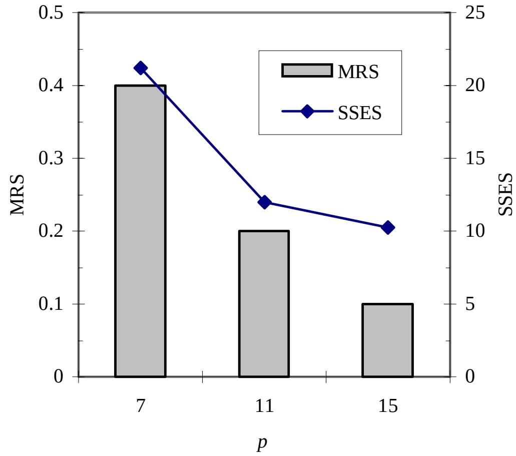
(b)

Figure 18 - Comparison of Slope and Adjusted Slope forecast for (a) 24 November 1997 and (b) 24 October 1997.

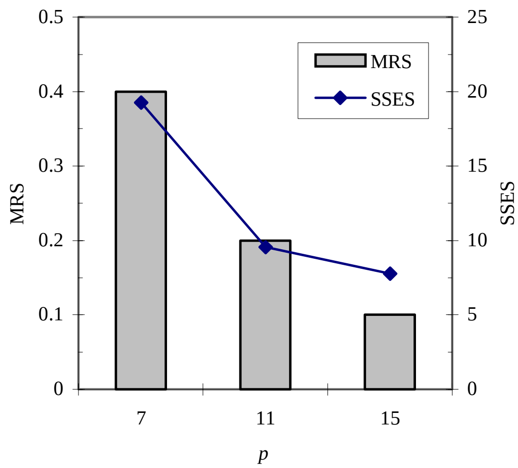
Figure 17 (b) strongly supports the observations made above. It shows the mean of the absolute error, in days, (MAE(%vmc)) between the final observed and forecast swc value for the 61 trials. The similarities between Figure 17 (a) and (b) indicate that better estimation of the total soil water curve leads to more accurate final forecast readings. For the best performed model, the AS, the average difference between the observed and forecast swc figure at the end of the forecast period is 1.1 % by volume.

Analysing the errors in terms of days, using the MAE (Day) statistic, gives virtually the same patterns as apparent in Figure 17 (b). The lowest error, obtained using the adjusted slope method, is 1.1 days. This says that on average at the end of fours days the forecast is within

1.1 days of observed conditions. The adjusted slope method MAE (Day) figure as an improvement of 0.3 days on the slope method figure.



(a)



(b)

Figure 19 - Relationship between the mean correlation coefficient (MRS) and sum of sum of errors squared (SSES) for (a) the linear Eto method and (b) the adjusted linear Eto method.

A most interesting finding to come from the analysis was the relationship between SSES and correlation coefficient values of the two linear evapotranspiration methods. The purpose of trialing the linear methods was to see if knowledge of future weather conditions, supplied by weather forecasts, could improve soil water forecasts. The thinking was that if a strong relationship existed between observed evapotranspiration and Aquaflex swc changes then forecasts using the relationship would improve. Figure 19 (a) and (b) disprove this hypothesis. The figures show that the opposite is true, as the correlation coefficient values for the observed ET v swc relationship increase so to do forecast errors. There are two reasons for this:

1. The higher correlation values do not mean that the derived relationship between observed ET and swc changes is representative of the general relationship between the two factors. It appears that the correlation coefficient values obtained from regressions on data sets with 7 or 11 points, are dominated by one or two points near the origin. These points are outliers that strongly influence the form of the linear regression equation and the correlation coefficient.
2. As the correlation coefficients decrease the regression relationship has a decreasing effect on the determination of forecast swc. When the correlation coefficient becomes 0 the regression relationship is a horizontal line. This means that the forecast soil water use is simply describing the slope of the observed swc. This is why in Figure 17 (a) and (b) the error values of the linear curves' move towards the error values of their equivalent slope methods.

6.4. Summary

The best technique to forecast swc with is the adjusted slope method. By describing some of the dynamics of swc curves during the formation of a forecasting relationship, and in the application of the relationship, it decreases forecasting errors. There appears to be little improvement in forecast performance once the period used to develop a forecasting relationship from observed data goes beyond 7 days.

Using the linear method approaches examined in this paper it was found that forecast weather data did not improve soil water forecasts. The problem being the poor relationship between observed Eto and observed soil based water content measurements made at a single depth. The poor relationship is a result of the complexities of water movement and plant water uptake at a single depth.

7. Application, Benefits and Adoption

If you have a particular interest in the benefits of Aquaflex soil water sensors, or sensors in general, and how practical they are to use on the farm then this section is for you. It covers the bulk of the on-farm work performed by project staff including:

- Field site descriptions and locations.
- Scheduling using soil water sensors.
- Advantages/Disadvantages in using soil water sensors over traditional water budget scheduling.
- A description and assessment of software developed as part of the project.
- Irrigation application management on the farm.
- Any financial or resource gains to be had from monitoring soil water content.
- Communication - how we went about 'spreading the word' on soil water management.
- Issues related to adoption of water management technology.

7.1. Field Site Details

Section 4.4, covering initial equipment field trials, described the Dookie College site and four other field sites setup during the course of the project. The process to identify the field sites initially involved Goulburn-Murray Water staff providing a list of potential candidates. Each of the potential candidates satisfied a number of criteria in addition to those specified in section 4.4. These were:

- They owned a computer.
- They were involved in some other committee, eg. water services committee or community salinity action group (this would enable them to discuss the project with a wider group of irrigators).
- They were energetic people and would commit time to the project eg. provide input on equipment performance.

Ten of the twenty-five irrigators approached said they would participate in the project. Mark Wood (Melbourne University) and Bill Heslop or Matt Nihill (Goulburn-Murray Water) visited the properties of the interested irrigators prior to the 1995-96 irrigation season and gave irrigators more information about their involvement in the project. Part of the information included a description of the commitment that irrigators would have to make to the project. The site visits also provided an opportunity to assess the amount of work involved in setting up the required field equipment at each site. The main requirements for the properties were that the irrigation bays were close to a telephone line (to allow remote data access) and that irrigation bays were laser graded.

All the sites, except for site 1, are owner operated dairy farms within the Goulburn-Murray Water irrigation region. Table 5 lists the five field sites and installed equipment directly associated with the project at the end of the 1997-98 irrigation season. All sites remain operational except for Site 5 where cows chewed and cut the cables linking the soil sensors to the logger. Figure 20 shows field site locations.

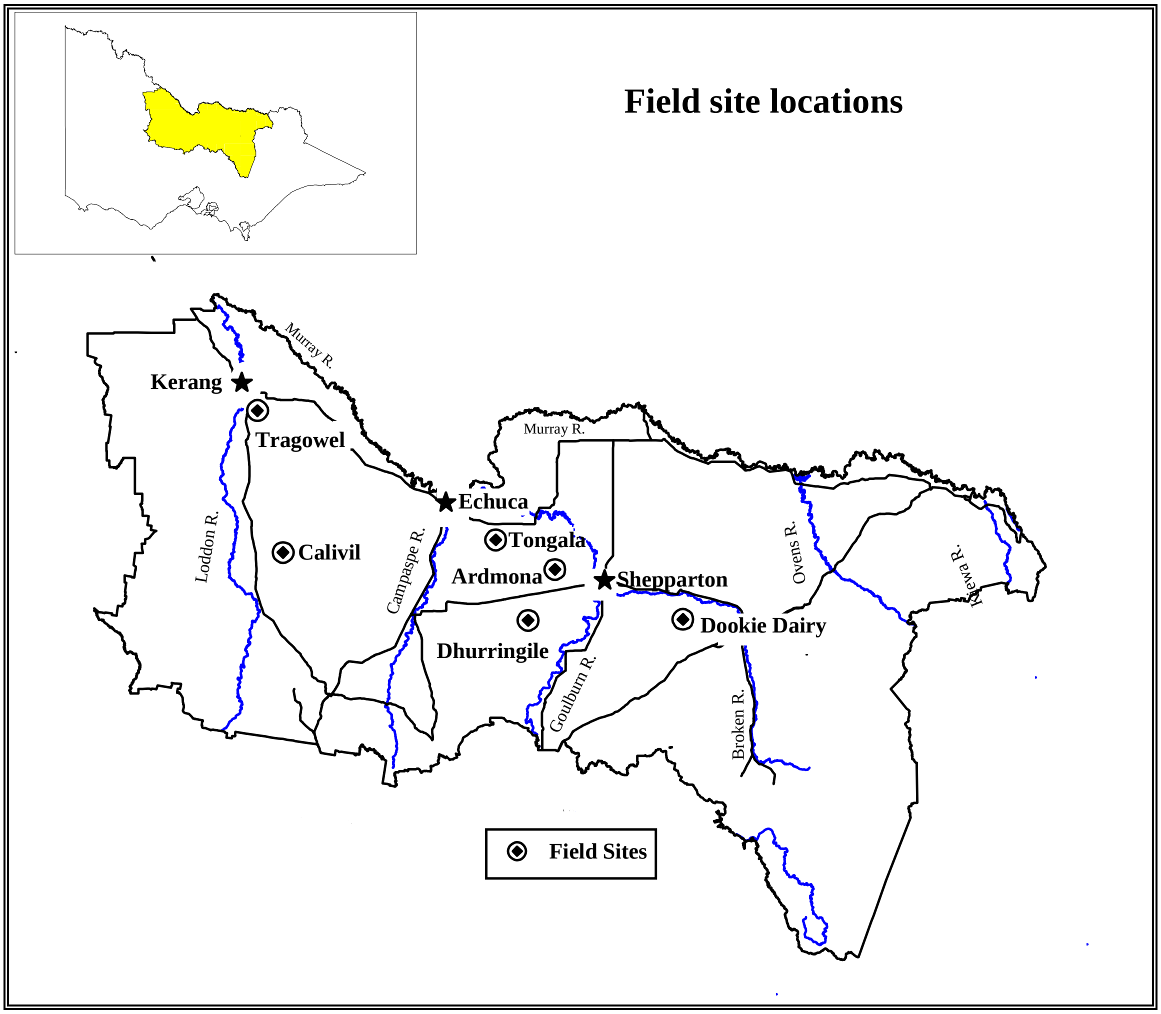


Figure 20 - Field site locations.

Location	Site ID	No. Probes	Depth of Probes (mm)	Other Instruments	Remote Access
Dookie	Site 1	4	2@200 2@400	Weather Station	No
Tragowel	Site 2	3	1@100$ 1@200 1@400	Water-table	Yes
Calivil	Site 3	3	1@100$ 1@200 1@400	Water-table	Yes
Tongala	Site 4	2	1@200 1@400	Water-table%	Yes
Dhurringile	Site 5	2	2@200		No

$ - Installed 18 March 1997
% - Installed 08 May 1997

Table 5 - Field sites.

7.2. Evolution of Field Sites

Refer to section 4.4.

7.3. Scheduling Irrigations Using Soil Water Sensors

In section 3.1 we reviewed the basics of irrigation scheduling. Now that an understanding of soil water sensors has been covered in section 4, it is time to see how they were applied on irrigation properties to gain insight into current irrigation management practices and to improve irrigation practices.

7.3.1. Technique

During the 1994-95 irrigation season the refill point was estimated by identifying the different stages in the soil drying process on graphs of volumetric soil water content versus time. The complete drying process begins at saturation following an irrigation or rainfall event and concludes when the soil is oven dry. As soils in the field will never be oven dry only part of this process is of interest in this instance. Important features that can be used to estimate the best time to irrigate from a graph of volumetric soil water content are saturation, gravity drainage, drained upper limit (field capacity, see Footnote 10 page 38) and readily available water.

The technique used to estimate the timing of an irrigation application from a plot of volumetric soil water content versus time is described by Buss (1994), who was using real-time data from an Enviroscan unit to estimate irrigation dates in hardwood plantations.

The technique involves identifying the volumetric soil water contents corresponding to saturation, gravity drainage, drained upper limit and the refill point. These points are shown on Figure 21.

Saturation - Saturation is reached after an irrigation or rainfall event. The saturation point is identified by peak plateaus (1. on Figure 21). The width of a plateau corresponds to the length of a rainfall or irrigation event.
Gravity Drainage - Saturation is followed by rapid draining of water from the soil which is seen as a steep decline from the saturation plateau (2. on Figure 21). The drainage is a result of gravity forces pulling the water in the soil through the profile. This rapid drainage is seen once the application of water is terminated.
Drained Upper Limit - Drained Upper Limit (Field Capacity) is reached when the water in the soil bonds to the soil with enough strength to hold on against the forces of gravity. On Figure 21 the drained upper limit (3.) occurs at the point where the steep gravity drainage curve flattens out and a diurnal water use pattern begins. A diurnal pattern is caused by the plants extracting more water from the soil during the day than at night and can be clearly seen as a series of steps on Figure 21.

Readily Available Water (RAW) - The RAW section of the volumetric soil water content versus time curve is the section where plants can easily extract water from the soil. While the soil water is in this zone the conditions for plant growth are optimum with neither oxygen or water availability restricting plant growth. During periods of stable weather conditions this section of the volumetric soil water content versus time curve appears as a line of reasonably uniform negative slope (4. on Figure 21).

Refill Point - The most important point on the volumetric soil water content versus time curve for determining when an irrigation should be applied is the point at which the water in the soil ceases to become readily available to plants (the refill point). If the amount of water in the soil falls below this point then plant growth will be reduced due the lack of freely available water. This point can be identified as it appears as a decrease in the slope of the soil water content curve. The drop in water use rate results from plants having to use more energy to extract water from the soil resulting in less water being removed. It is identified on the figure by a broken line (5.).

If the water content of a soil is allowed to continue below this point then plant water stress will occur. Ideally a farmer should apply irrigation water before or at the time this point is reached. Because of the difficulty in applying water at exactly the right time when water orders must be made 4 days in advance, this point should be set conservatively to avoid plant water stress should an irrigation be applied too late.

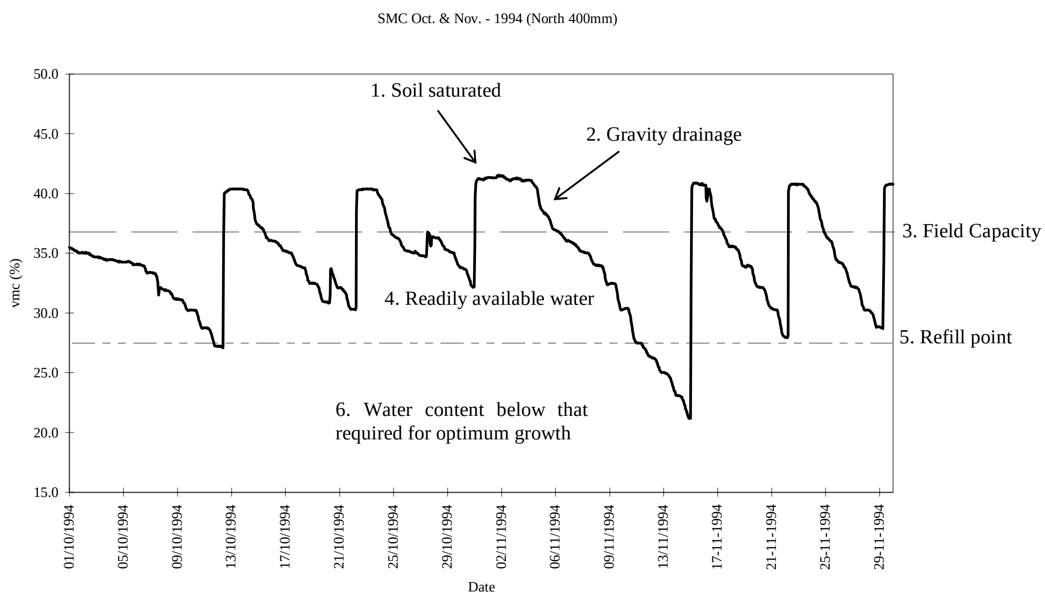


Figure 21 - Plot of volumetric soil water content versus time, showing the various features which allow for an estimation of irrigation timing to be made.

7.3.2. Discussion of the Technique

The technique to estimate the refill point described above has been successfully used by Sentek, the company that manufactures the Enviroscan soil water sensor (Buss 1994), in many different areas eg. turf, onions, hardwood plantations, carrots etc ... The difficulty in transferring its use in pasture monitoring is that no longer is there only one variety of plant to be monitored. In many pastures white clover, perennial ryegrass and paspalum will all be present, all react differently to soil water conditions and all have different root depths. Clover has the shallowest rooting depth and will suffer from water stress much earlier than ryegrass which will inturn suffer earlier than paspalum (Mulcahy and Schroen 1993).

If only one pasture species slows down its rate of removal of water from the soil then on the graph of volumetric soil water content versus time there may not be a clear change in the slope of the water use curve. The change in slope of the curve may not occur as the other two pasture species are still removing water from the soil. This could result in the irrigation period continuing beyond the point where clover is stressed and its yield will decrease as a result.

Another consideration is that the refill point may change during the irrigation season. Early in the irrigation season when clover shoot growth has been limited by the cold weather throughout the winter (Unknown 1993) root development will also have been restricted (Blaikie 1993). A shallow root system may mean that to allow optimum soil water conditions for growth to exist irrigations should be applied at a lower deficit than later in the season. This effect is amplified if the soil water instrumentation is below the level of the shallow early season root system and cannot accurately record the amount of soil water leaving the soil in the main root zone.

Weather conditions must also be monitored carefully when using the above technique. Cooler temperatures, cloud cover, high humidity and low wind velocities can all decrease the amount of water taken up by plants and cause a decrease in the slope of the soil water curve. If care is not taken to exclude changing weather conditions from causing a change in the slope of the curve then the refill point may be estimated incorrectly.

Despite the above problems with the technique it was used successfully during the 1994-95 irrigation season at site 1 to schedule irrigations. The success was not measured in pasture production but rather the positive response of the farm manager and liaison committee to the results recorded by the instrumentation. At worst they estimated that the pasture production was no lower than in recent seasons.

The restrictions on the use of the technique however lead to a different method being proposed to identify the refill point in the 1995-96 field trials. Personal communication with Bill Heslop and Derek Poulton identified the pasture refill point used by Goulburn-Murray Water as 40 kPa[12] with tensiometers placed at a depth of 200 mm. Personal communication with Kathy Kelly, from the Institute of Sustainable Agriculture in Kyabram, revealed that field experiments conducted at the institute used a value of 30 kPa for tensiometers placed at a depth of 300 mm as the refill point. Both values of soil water tension aimed to maximise pasture production. The refill point value used for this experiment was 35 kPa for tensiometers placed at a depth of 200 mm.

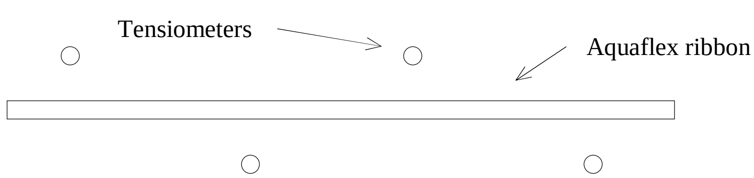
[12] The instrument used to measure pressure displays negative soil matric potential pressures as positive ie. as matric suction or soil water tension.

The field trial in 1995-96 monitored tensiometer readings in bays containing Aquaflex units during the first weeks of the irrigation season. When the tensiometers recorded a soil tension reading of 35 kPa the point corresponding to this date was marked on the Aquaflex soil water curve and used as the refill point for the remainder of the season.

The method used during the 1995-96 irrigation season was to develop a soil water characteristic curve for a field site by making concurrent measurements of soil water content (using the Aquaflex) and soil water tension (using tensiometers). Because the soil water tension is a direct measure of the energy required for the plant to remove water from the soil, it is an excellent indicator of the actual availability of water for plant use.

The field experiment to determine the soil water characteristic curve entailed placing four tensiometers at a depth of 200 mm alongside an Aquaflex unit (Figure 22). Bill Heslop and Gary Scot from the Kerang office of Goulburn-Murray Water and an irrigator, Max Pleasance, took tensiometer readings over two irrigation cycles. To limit the effects of soil heterogeneity readings were taken from four tensiometers.

To obtain the soil water characteristic curve shown in Figure 23 a plot was made of the average value of the four tensiometer readings for a particular date and time and the corresponding soil water reading. The curve shown in Figure 23 corresponds to the desorption (drainage) arm of the soil water characteristic curve. The curve will be different than one obtained from measurements in sorption. For most field cases the process will be that of desorption ie. soil water content starting at saturation and decreasing from that point. Further work during the 1996-97 irrigation season will investigate whether hysteretic effects have an influence on irrigation timing decisions.



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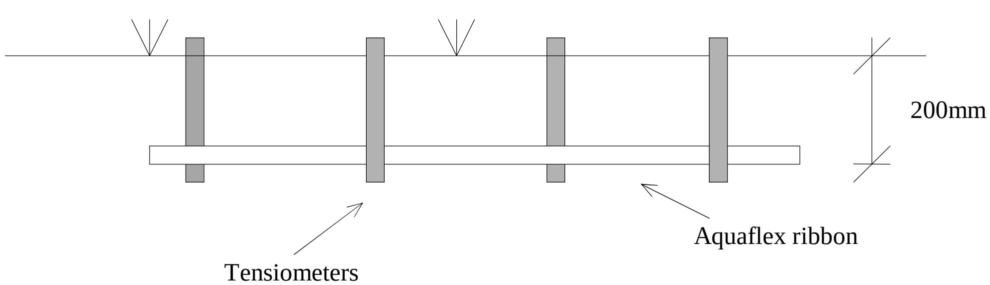

(b)

Figure 22 Field setup for the determination of a soil water characteristic curve (a) planview and (b) schematic.

After constructing the soil water characteristic curve a value of soil water tension, that aims to maximise pasture production, is marked on the curve. To express the refill point as a volumetric soil water content, simply select the value of soil water content corresponding to 35kPa on the soil water characteristic curve (Figure 23). To guide irrigation decision making mark the value of the refill point on the soil water versus time plots that the irrigator uses.

The above method requires little physical work. The process is simple and an irrigator, or the consultant who installs the equipment, can do the work. Using soil water content to determine the refill point requires the development of a calibration curve for each soil type and laboratory determination of the refill point. The soil water calibration curve is more difficult to construct than the soil water characteristic curve and the process involved is often destructive. Laboratory testing can introduce inaccuracies in measurements because of the difficulty in obtaining undisturbed samples. Compared to the soil water content calibration curve alternative the proposed method to define the refill point is simpler to perform, requires less time input, less expertise and no laboratory facilities.

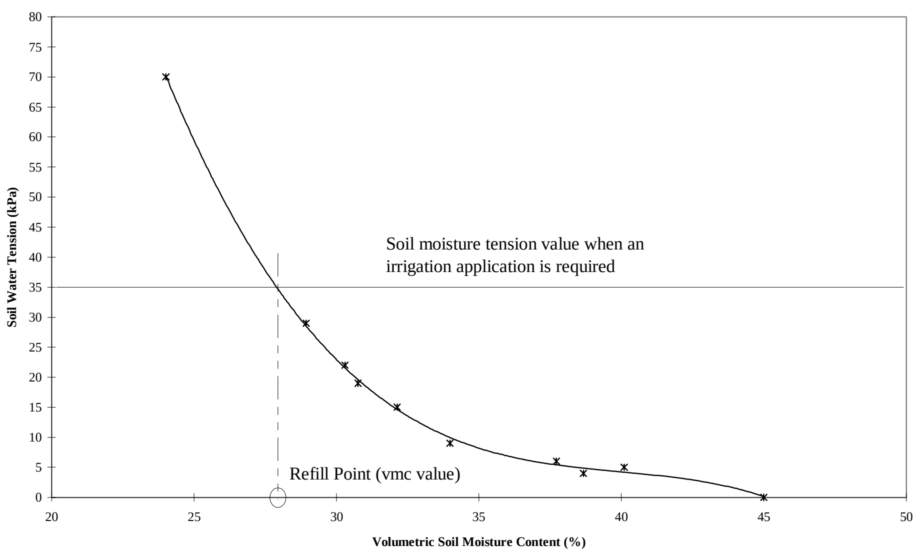

Figure 23 - Field determined soil water characteristic curve.

7.4. Comparing Probe Scheduling to Water Budget Scheduling

We make decisions every day and often have many options to choose from. This section is designed to give insight into what type, if any, of irrigation equipment or method is best suited to irrigators to improve the way they manage water. A comparison between various aspects of irrigation scheduling using a water budget approach and soil water sensors is given.

7.4.1. Site specific weather data

Water budget methods usually require weather station data to schedule irrigations. However, weather data from a local weather station are not necessarily representative of conditions on an irrigation bay many kilometres away eg. trees and a small range of hills surround the Dookie site, so wind conditions at the site could be quite different from those at the Lemnos weather station 30 km to the west. An on-farm weather station will overcome this problem. However, a private weather station requires constant monitoring, upkeep, an initial capital investment and a system to transfer data from the weather station to the home PC. These issues are common to both methods of irrigation scheduling, although often only associated with soil water monitoring equipment.

Water budget models provide a good, cheap way to introduce irrigators to the concepts of scheduling when weather stations, or on-sight evaporation pans, are available. Irrigators should always be aware of the problems associated with these methods however.

7.4.2. Site Specific Soil Data

Setting a refill point for use with water budget approaches requires knowledge of the soil water properties of particular soil types. Both water holding capacity and readily available water volumes change with soil type, and so on-site calibrations are desirable. Scheduling can be inaccurate on farms because irrigators do not investigate these factors.

Soil based monitoring equipment offers the advantage of measuring the water content of the soil directly. Combined with a few simple tensiometer readings, made concurrently with Aquaflex readings, irrigators can easily determine a reasonably accurate refill point (see section 7.3).Water budget methods can also use this approach ie. develop a relationship between soil water tension and E-R. This avoids the need to construct detailed information about the soil water holding capacities for different soil types.

By keeping historical records of crop water use soil water data can also provide a valuable tool for planning future irrigation requirements.

7.4.3. Water-table Contributions

In many areas of south eastern Australia shallow water-tables make considerable contributions to crop water requirements. It is very difficult to estimate the levels of contribution for specific sites, thus making it difficult to set refill points for water budget scheduling.

Stapper and Cruwys (1991) provide an option to allow for the contribution of water from a shallow water-table in the SIRAG-FIELD irrigation scheduling model. In the model however, users must enter the amount of the contribution, which they will generally not know. The program provides for a maximum allowance of 1.5 mm/day for grey soils and 0.6 mm/day for red soils, for water-tables within 1.5 m of the surface. A further complication is that water-table levels are dynamic, and so are their contributions to crop water requirements.

Soil based monitoring instrumentation includes any contributions from the water-table in all readings, and requires no direct knowledge of the contribution from water-tables. If an irrigator at the Tragowel site irrigated at a deficit of E-R[13] equal to 50 mm (recommended in (IAA 1990)), then for all but two irrigations in the period from late December 1996 to May 1997, they would have applied irrigations prematurely[14]. Figure 24 shows the ET_o-R deficits at the time of each irrigation during the period.

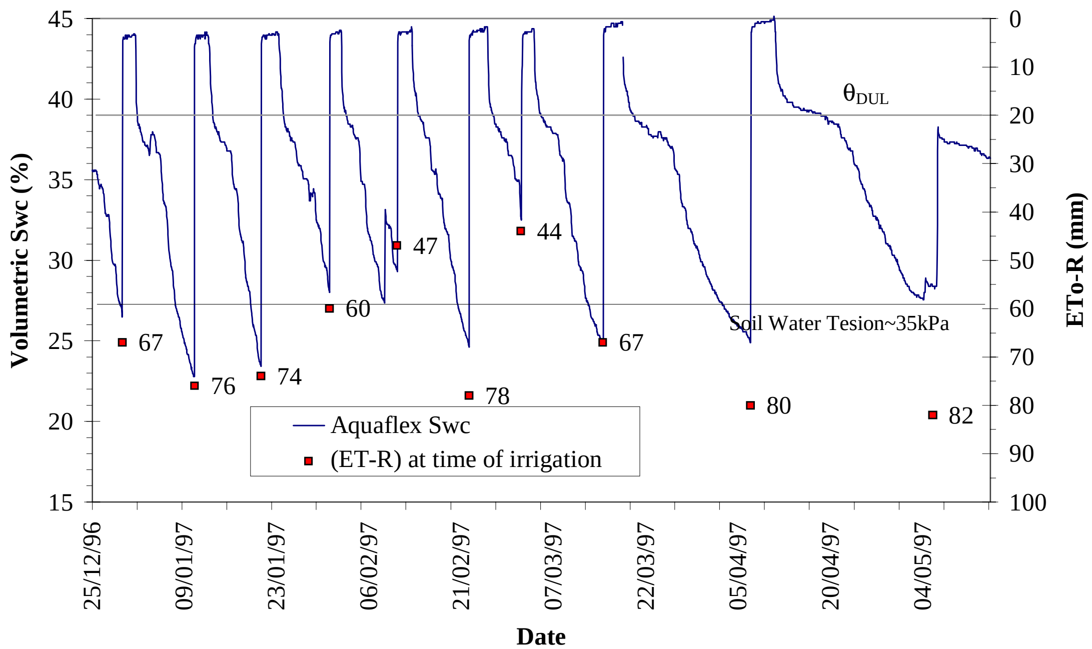

Figure 24 - Tragowel soil water content data showing irrigation timing and the corresponding ET_o-R deficits at the time of irrigation.

The reason behind the discrepancy in irrigation timing is most probably the contribution to plant water requirement from the shallow water-table. If there was no contribution from the water-table then the refill point of 35 kPa at 200 mm should coincide with an ET_o-R deficit of less than 50 mm (see Footnote 14). The water-table contribution to crop water requirement during this period is at least 20 mm (this is for a period of 12 days).

It is unlikely that an irrigator near Kerang would irrigate at an ET_o-R deficit of 50 mm. Irrigators have learnt over-time that a considerable proportion of crop water requirement

[13] Generally E in E-R refers to pan evaporation or reference crop evapotranspiration, with no crop coefficients applied (Lattimore et al. 1994) and (Blaikie et al. 1988).
[14] This comparison is based on experimental work carried out at the Kyabram Dairy Centre. The work showed that setting a refill point of 30 kPa at a depth of 300-mm approximated an E-R deficit of 35 mm (pers. comm. Kathy Kelly, Kyabram Dairy Centre). Allowing for differences in soil type a refill point of 35 kPa at 200 mm could at most be equivalent to an E-R deficit of 50 mm.

comes from the water-table, and have allowed for this effect. The argument is given here to emphasise the benefits in being able to quantify water-table contribution.

7.4.4. Crop Coefficients (k_c)

Water budget methods require reliable crop coefficients to relate reference crop evapotranspiration (ET_o) to actual crop evapotranspiration (ET_c), and ET_o equations that apply to local conditions. Meyer (1993) provides a locally calibrated evapotranspiration model, based on the Penman Equation, for the southeast region of Australia and so goes part way to solving this problem. Personal communication with Derek Poulton suggests that a k_c value of 0.8 to 0.85 is appropriate for use with this equation when pastures are being monitored. Unfortunately most crop coefficients apply to more widely used evapotranspiration models such as Penman-Monteith.

7.4.5. Saturation period

Different soils exhibit different drainage characteristics and these cause varying periods of saturation following the application of an irrigation. This period of saturation determines the starting time of any water budget calculation ie. the time it takes for soil water conditions to reach the Drained Upper Limit. The period of saturation alters throughout the season according to evaporative demand, time to cut-off and water-table depth. An irrigator must closely observe field conditions to accurately determine the length of the saturation period. An incorrect estimation of the saturation period causes inaccuracies in water budget calculations, and thus the scheduled irrigation date.

Figure 25 shows the differences in saturation periods for the Tongala, Tragowel and Dhurringile sites. The data is for late December and early January. At the Tongala site the soil remained saturated for 75 hours compared to 51 hours at the Tragowel site and 23 hours at the Dhurringile site.

The differences relate to soil type and structure, water-table depth and bay slope and length. The A-horizon soil type at Dhurringile is an Erwen loam and the underlying clay layer is not as heavy as that at the other two sites, thus drainage conditions are better. Also, the bay slope is reasonably steep (1:600). The bay is about 350 m long. The site is on a rise and so the water-table should be somewhat deeper than at the other sites (no water-table data is available). The Tragowel site water-table is within 1 m of the surface for most of the year and the A-horizon soil type is a McCorner Red Loam. The bay slope is 1:1000 and the bay is about 400 m long.

At Tongala the A-horizon soil type is an East Shepparton Fine Sandy Loam, but it is only about 0.3 m deep and underlain by a thin layer (~0.25 m) of red clay. This clay layer restricts downward drainage considerably. Water-table measurements made late in the season showed that the water-table was with in 1 m of the surface. The time of saturation at the Tongala site still seems unusually long. The cause is probably a long cut-off time, which results from a small inlet discharge onto the bay.

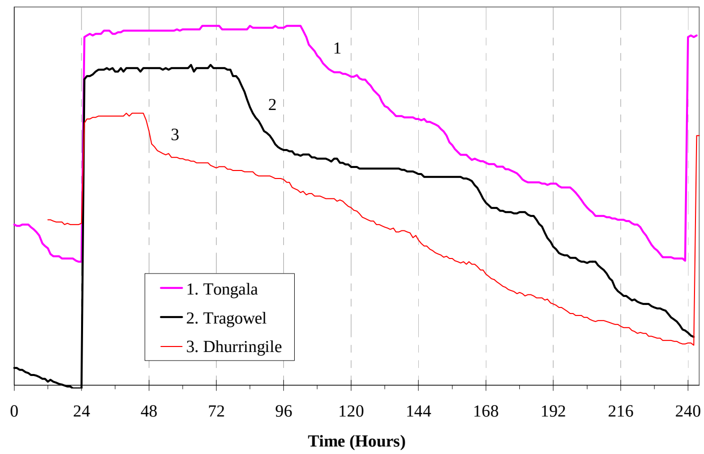

Figure 25 - Duration of saturation periods following an irrigation application.

7.4.6. Installation

A major disadvantage of soil based instrumentation is the disturbance to the soil structure during the installation procedure. Original Aquaflex installations involved placing probes into a trench. By digging up the soil not only is the soil structure altered, but preferential growth of roots also occurs, probably to greater depths than elsewhere in the field. This will give a biased account of both rooting depth and mass and so an unrepresentative view of conditions in other parts of the bay. Water budget methods of scheduling avoid this problem by not interfering with soil structure.

7.4.7. Settling in Time

Wood and Malano (1996) emphasises the need to allow time for newly installed probes to settle in. Data from the Tragowel site highlight this. The data from the Aquaflex probes did not settle at a constant value of the drained upper limit[15] until after the fifth irrigation. Figure 26 shows the effects that changes in soil structure have on soil water content as consolidation proceeds following an installation. In the figure the volumetric swc value of the drained upper limit after the first irrigation is 31%. However, at the end of the sixth irrigation of the season the value has moved to 39%. This phenomenon is dependent on soil type as Figure 27

[15] The DUL value may vary by small amounts during the season depending on water-table depth and evaporative demand. It will however remain reasonably constant from one irrigation to the next.

illustrates[16]. Figure 27 data are from the Tongala site and show little change in the value at which the drained upper limit occurs after early irrigations.

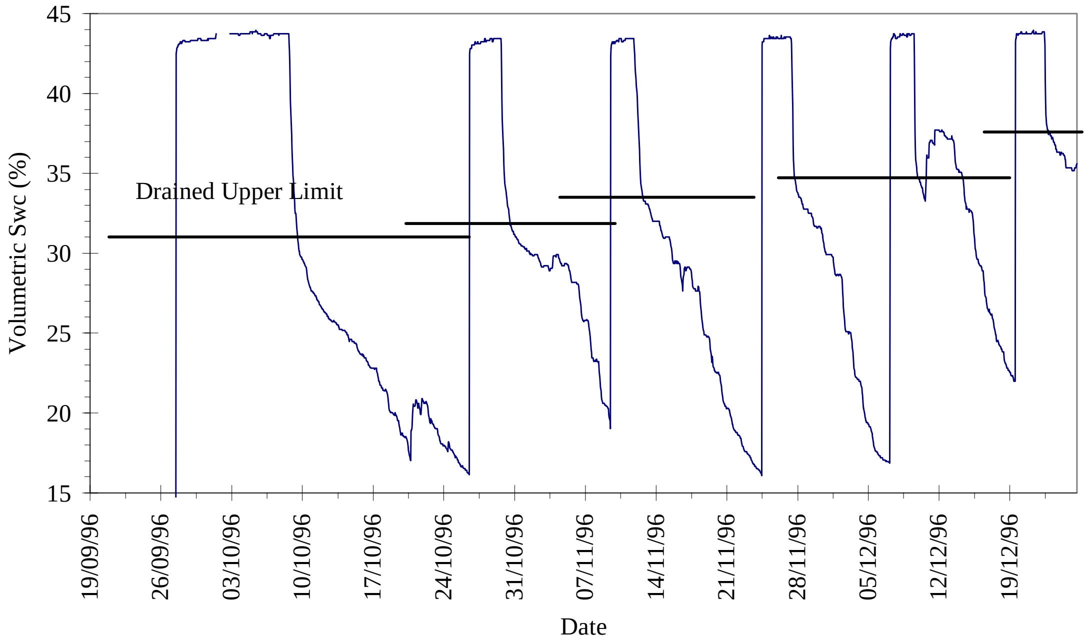

Figure 26 - Settling in time for a newly installed Aquaflex probe (Tragowel).

A different installation technique, to that described in Section 4.2.1.1 was employed to install probes at a depth of 100-mm at the Tragowel and Calivil sites. The technique involves making a thin slit in the soil with a flat shovel to the desired installation depth. The next step involves inserting the Aquaflex probe into the slit and compacting the soil back into place. This causes disturbance to a much smaller volume of the soil profile than digging a trench but it is difficult to ensure compaction around the probe. Also without some form of mechanical device to assist with installation, getting the slit much deeper than 200-mm would be very difficult. It is the opinion of the authors that the method described in section 4.2.1.1 is the preferred method.

Another issue related to settling time is the setting of refill points using concurrent measurements of soil matric potential with tensiometers and Aquaflex readings. The installation at the Tragowel site showed that calibration measurements taken too early result in the refill value being set too late. This occurs because the position of the DUL and refill point change over time as the soil consolidates. Therefore any calibration work must begin at the completion of consolidation of the soil.

[16] Shifting the drained upper limit to identify consolidation in the soil is not fool proof. This is because drainage amounts in some soils are very small and so exhibit little change in the DUL as the soil consolidates. This could well be the case for the Tongala site mentioned above.

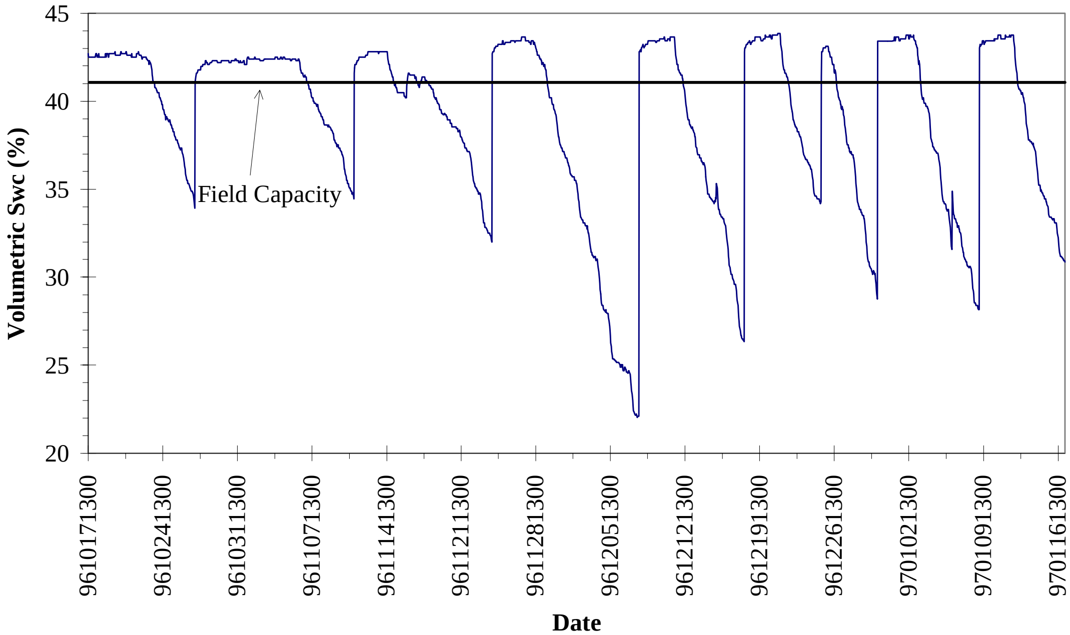

Figure 27 - Settling in time for newly installed Aquaflex probe (Tongala).

7.4.8. Overview

The data plotted in Figure 28 is provided to support previous discussion in section 7.4. The plot shows the Aquaflex soil water data and water budget data from the Tragowel site. The water budget ET[17] data is from the Goulburn-Murray Water weather station at Kerang. The figure shows an excellent relation between the two data sets. This proves that when the appropriate saturation period following an irrigation, and the correct crop coefficient value are known, then ET data is able to reproduce actual soil water changes very well. A closer look at Figure 28 however shows that the water budget approach tends to over estimate swc changes immediately following rapid drainage, and underestimates the changes later in the irrigation period.

The period between an irrigation application and the beginning of soil water extraction was kept constant, at 48 hours, for the water budget calculation. By doing this the last two irrigations in Figure 28 clearly show the effect of not identifying the saturation period correctly. During these irrigation periods the water budget approach starts calculating soil water extraction a number of days early, the result being that soil water deficits are over estimated. In the case of the last irrigation this effect is significant.

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[17] Meyer (1993) describes the procedure used to calculate ET data. Meyer uses a Penman type combination equation with locally developed coefficients for wind and solar radiation. The Irrigation Services unit, from the Tatura office of Goulburn-Murray Water, supplied the weather data for the calculations. A crop coefficient of 0.8 was applied to the ET_o data (pers. comm. Derek Poulton)

The conclusion is that the water budget data closely matches Aquaflex soil water data in the middle of the season, but it fails to capture the dynamics of soil water use processes early and late in the season, when saturation periods are changing.

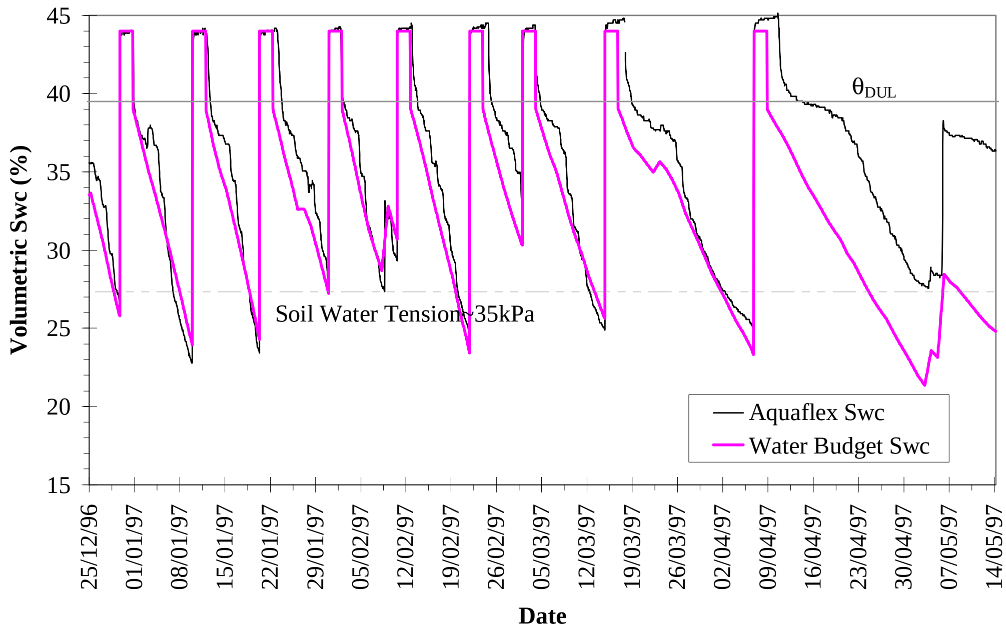


Figure 28 - Comparison of Aquaflex soil water content data and Water Budget data.

7.4.9. Summary

The fact remains that both probe and water budget scheduling methods offer advantages. For scheduling purposes however soil based methods offer:

- A better understanding of the processes of wetting and drying of the soil
- A more accurate method for timing irrigations in shallow water-table areas.

They also provide far greater possibilities for improving irrigation applications. They provide knowledge of infiltration into the profile and monitoring details of an irrigation event while it is in progress.

A major application of evapotranspiration techniques is in the planning and modelling of scenarios of different irrigation strategies. Work done using the SWAGMAN Destiny Model (Meyer et al. 1995), looked at irrigation strategies on scales larger than individual farms. Such work requires methods that provide long term knowledge of water use and are accurate over larger scales. Investigations such as the one described in Poulton (1996), require the use of water budget methods and provide important knowledge for long term planning decisions.

7.5. Irrigation Scheduling - Soil Water Sensors

Quantifying the benefits of irrigation scheduling is always difficult, especially in a field situation. If a comparison is made between yields under two irrigation regimes, where one uses a scheduling technique and the other a judgement approach, how does one determine whose judgement to use. Obviously someone with good knowledge of their soils and how plants use water, will do a better job than a novice. Other factors also play a role in irrigation performance for a given property:

- The presence of a water-table contributing to irrigation requirement always makes it difficult for irrigators to judge the magnitude of the contribution.
- Frequent rainfall means more difficult decisions, involving judgement of rainfall effectiveness must be made.
- A larger property often leaves little opportunity for flexibility in the irrigation schedule.
- A single manager has less time to consider water management than a property with multiple managers.
- Higher stocking rates mean faster rotations and again result in loss of flexibility with irrigation timing decision making.
- The amount of available water per hectare will often effect how often a property is irrigated ie. if there is plenty of water then frequent irrigations may result.
- Free draining soils result in less waterlogging problems which may simplify decision making.

Noting the possible influences on irrigation timing decisions let us compare the results from three properties to assess the benefits of irrigation scheduling. This gives some idea of what level of savings can be expected purely by improving application timing on dairy farms with heavy soil types.

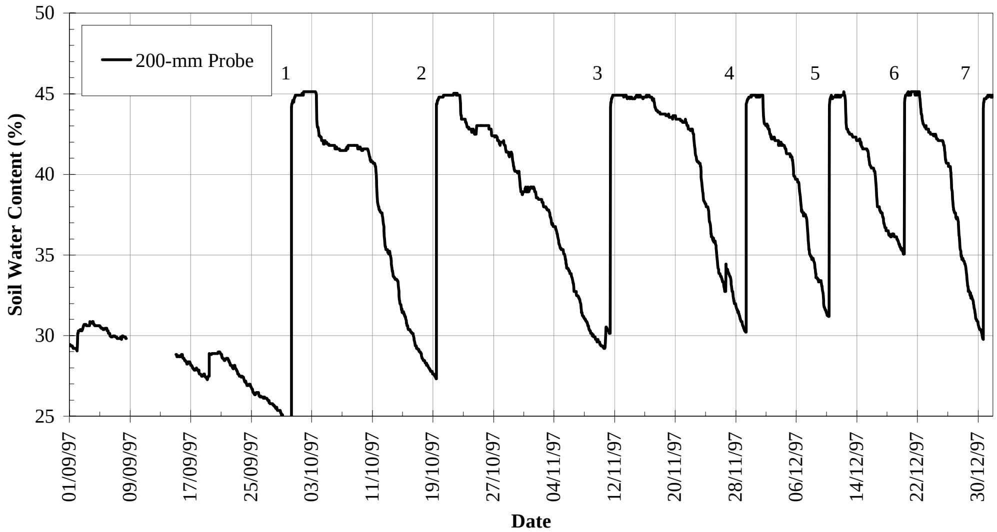
Note that all properties used in this analysis use approximately 10 ML/ha per annum for irrigating their perennial pastures. According to Armstrong et al. (1998) this puts them in the medium range of water use (the range varied between 6 ML/ha and 17 ML/ha). Therefore expected benefits, in terms of water savings, from these properties will be lower than at over irrigated farms.

Figure 29 (a) and (b) show site 2 soil water content data for 1997-98. This site scheduled irrigations using Aquaflex soil water sensors and it is immediately evident from looking at the two figures that the timing of irrigations, in terms of soil water content at the time of application, is reasonably uniform[18] ie. irrigation applications were applied at a constant soil water deficit. Applying irrigations at constant soil water deficits is achieved by understanding the dynamics of evaporative demand throughout an irrigation season and recognising when any changes in demand are occurring.

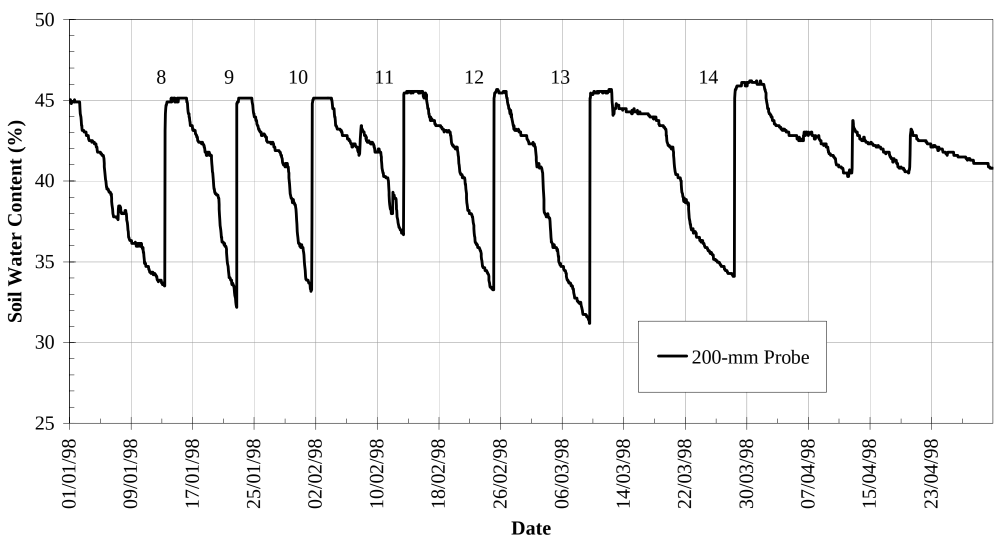
Thus when the season starts and evaporative demand is low the time between irrigations, the irrigation interval, should be reasonably long. As the days get longer and temperatures

[18] Please note that the refill point was adjusted up from 30% volumetric soil water content to 35% during the season because with the initial setting it was evident from looking at the 100 mm probes some stress was developing during the irrigation cycle. The data shown is for the 200 mm probe.

increase the evaporative demand increases and the length of the irrigation interval must decrease. The opposite occurs at the end of the season. Also it is easy to account for the contribution of any rainfall (not common during the 1996-97 and 1997-98 seasons due to dry years). The end of the season is also critical because if the bay is too wet when the winter arrives then stock traffic causes deep pugging over the winter months. There have been reports of cows disappearing into the mud on boggy paddocks around Kerang!



(a)



(b)

Figure 29 - Site 2 soil water data for 1997-98 irrigation season (a) September, October, November and December and (b) January, February, March and April

Figure 30 shows the data from site 1 for the first half of the irrigation season. The data are an average of the 200 mm and 400 mm probes. The difference between this figure and Figure 29 is obvious, the soil water deficit prior to irrigation is not constant because the period between irrigations early in the season is too short. Thus little of the available water is used by the pasture before the next irrigation application. It is apparent then that irrigations were applied when not required. This is a result of misinterpreting the evaporative demand changes throughout the season. Data for the second half of the irrigation season for site 1 are presented in Figure 47 Appendix 5.

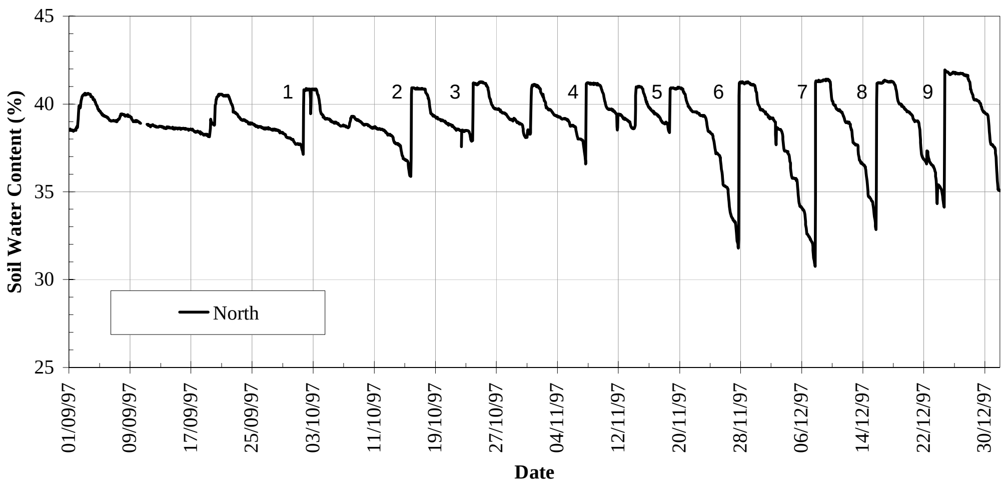


Figure 30 - Site 1 soil water data for 1997-98 irrigation season (a) September, October, November and December and (b) January, February, March and April

By reconstructing the soil water use curve and recognising that the refill point lies at 32% volumetric soil water content, it is possible to determine how many days could have elapsed between irrigations had an irrigation not been applied early. The reconstructed curve is shown in Figure 31 and the estimated water use was set either at the rate of the previous 24 hours or the final 24 hours of the previous irrigation cycle. Using the reconstructed curves it is apparent that 16 days elapsed when it was not necessary to irrigate when irrigations were applied. The average irrigation interval for the season at site 1 was 10 days meaning that approximately 1.6 irrigations could have been saved had scheduling technology been used.

Of course not all of this water would necessarily have been saved as more water would have to have been applied at each irrigation. But these irrigations cost money to buy the water, time to apply, add accessions to the water-table and effect pasture growth by saturating the root zone for up to three days. A similar analysis as this was performed for the 1996-97 irrigation season for site 4 in Wood and Malano (1996) and showed between one and two irrigations could have been saved at the sight.

The main reason for the early irrigation applications were the difficulty in assessing the effect of changing day lengths, and associated climate variable changes, on plant water use.

If we do a brief analysis of what financial or resource returns are involved with saving one, two or three irrigations we see that for a farm size of 50 ha one irrigation would conserve around 25 ML of water, assuming a seasonal water use figure of 10 ML/ha, or save $500 if water is valued at $20 per ML (about the price for permanently owned water). Of course if water is valued at temporary sales prices, around $60/ML, then the financial saving increases to $1,500/ML. Finally if a irrigator must buy permanent water at around $500/ML the saving jumps to $12,500/ML (Table 6).

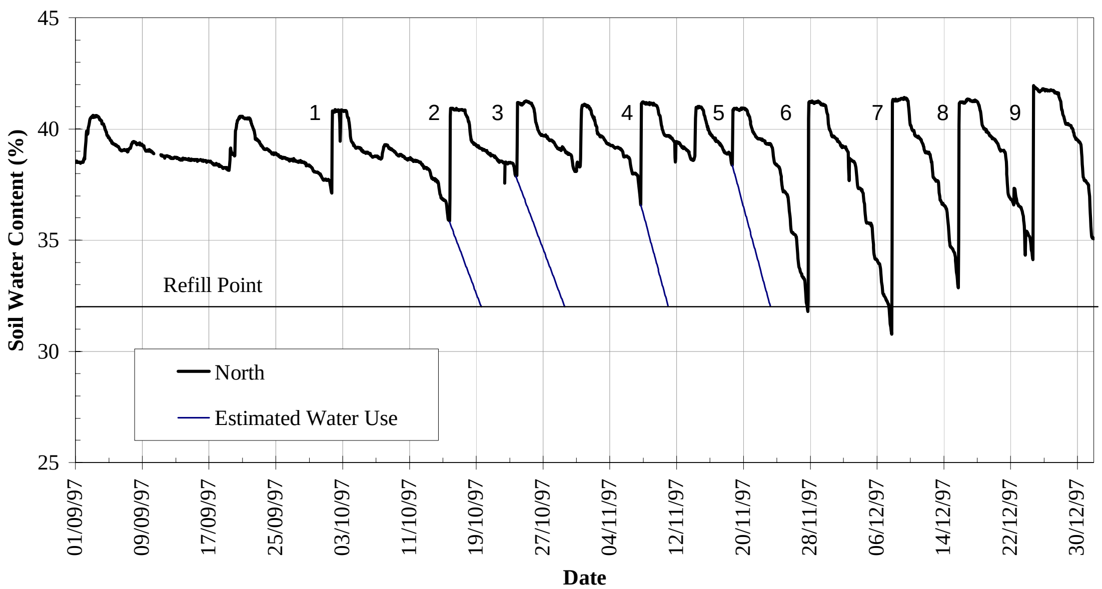


Figure 31 - Measured soil water content and estimated soil water content showing water use curve if irrigations had not been applied early at site 1

Daisy's Farm		Daisy's Savings			
Area of Perennial Pasture (ha)	50	No. Irrigations Saved	1	2	3
Water Used (ML)	500	ML Water Saved	25	50	75
Season Water Use ML/ha	10	% Total Water	5	10	15
Number of Irrigations	20				
Total Water Per Irrigation (ML)	25	Value of Savings	$	$	$
Application Rate (ML/ha)	0.5 (50 mm)	@ $20/ML pa	500	1,000	1,500
		@ 60/ML pa	1,500	3,000	4,500
		@ $500/ML pa	12,500	25,000	37,500

Table 6 - Details of Daisy's dairy farm with water and dollar savings for 1, 2 or 3 saved irrigations.

If the savings are compared to the cost of setting up a single site using Aquaflex equipment, estimated cost $4,000, then valuing water at $20/ML and saving 1 irrigation, it would take 8 years to recoup the capital (Table 7). Valuing water at $500/ML it would take a third of a year for the investment to pay off (Table 7).

Equipment Costs		Pay Off Period	
1 logger		Number Irrigations Saved	Pay Off Period (years)
2 Probes		1 @ $20/ML	8.0
Software	$3,000	2 @ $20/ML	4.0
		3 @ $20/ML	2.0
Installation			
Tuition		1 @ $60/ML	2.7
Site Visits	$1,000	2 @ $60/ML	1.3
Total	$4,000	3 @ $60/ML	0.9
		1 @ $500/ML	0.3
		2 @ $500/ML	0.2
		3 @ $500/ML	0.1

Table 7 - Estimated cost of setting up a single Aquaflex monitoring site and expected pay off period for 1, 2 or 3 saved irrigations.

Of course not all properties are using too much water for irrigation pastures. Armstrong et al. (1998) shows that the variation in water use per hectare of perennial pasture varied between 6 ML/ha and 17 ML/ha, meaning that some people put too much on, some not enough and others close to the correct amount, even without scheduling tools. The highest producing 10% of properties (in terms of milk produced per ML of water) used around 10 ML/ha. Figure 49 in Appendix 5, which contains the data for site 4 for the 1997-98 irrigation season, shows soil water data for a property that used no irrigation scheduling tools. The manager was able to account reasonably well for the changing evaporative demand throughout the season by altering the irrigation interval appropriately. The 1996-97 and 1997-98 irrigations seasons are an exception to most seasons due to very low rainfall which makes scheduling irrigations simpler because of a more consistent climate.

Irrigators currently at the low end of the water use per hectare range (6 ML/ha) generally produce low amounts of milk per ML of water. The low figure associated with under watering (Armstrong et al. 1998). Thus the benefits of scheduling for these properties will be increased production from using more water and getting a higher return per hectare. These savings, in the form of increased income, are however much more difficult to quantify than those from direct water use savings.

7.6. IRRIGATE Software

This section contains a description of the software for storing, displaying and forecasting soil water content data developed as part of the project. The software has come through several development stages since it was first proposed in Wood and Malano (1994). The changes are a result of a better understanding of the needs of irrigators. Irrigators and researchers directed the software improvements by making assessments of the performance of the initial prototype system.

The basic system architecture given in Wood and Malano (1996) still applies to the overall system, except that there is no longer any software to interrogate the remote dataloggers. In the current system when downloading from a remote site an operator will use a terminal emulator, such as Terminal, supplied with the Microsoft Windows operating system. Because a decision had not been made about the best method to use when retrieving remote data eg. via a radio telemetry system, laptop computer or the current method of telephone modem, IRRIGATE did not include software for remote data retrieval.

Figure 32 shows the style of graph presented to an irrigator when they select a plot of soil water data versus temperature data. The time scales available for plots are one day, one week, one month and the entire season. Or any period can be selected by manually entering the appropriate dates.

Figure 33 shows a schematic map of IRRIGATE in operational mode. The figure helps to illustrate how the IRRIGATE software works. An irrigator would start a work session with IRRIGATE by downloading the latest Aquaflex data from the field using a remote modem connection. Once transferred into memory the new data in the data file passes through a data filter which checks for problems with the data eg. missing data, and are then loaded into the Aquaflex soil water data database. Once in the database the Aquaflex data are available to the rest of the modules in the software system. Dates of irrigation events and forecast weather data are entered manually by the user.

After entering all the data the irrigator can choose whether to view plots of the available data, or find out when to irrigate next, by running a prediction model. To obtain a graph of soil water and temperature data the irrigator chooses the desired interval for plotting and waits for the graph to appear on the screen. IRRIGATE retrieves the soil water and soil temperature data from the Aquaflex database, formats the graph required and presents a full screen plot of the selected data to the irrigator.

To predict the timing of the next irrigation date the irrigator activates the Forecast Module. The methods are based on the description in section 6. The module carries out the prediction calculations and then displays a graph showing estimated soil water content in four days time.

Using the irrigate software is straight forward, but because of time restrictions an development it remains a fairly basic program. Despite this it has, and is still, being used at site 2 and serving the irrigator well. Other limitations on developments of the software include the initial database chosen for use with the system which is now obsolete, as is the data retrieval and graphing routines because they are no longer compatible with the data storage arrangement of the new Aquaflex sensors. Commercial developers are in a much better position to maintain and upgrade software and with good software available with the new commercial Aquaflex units there is no purpose in developing IRRIGATE any further.

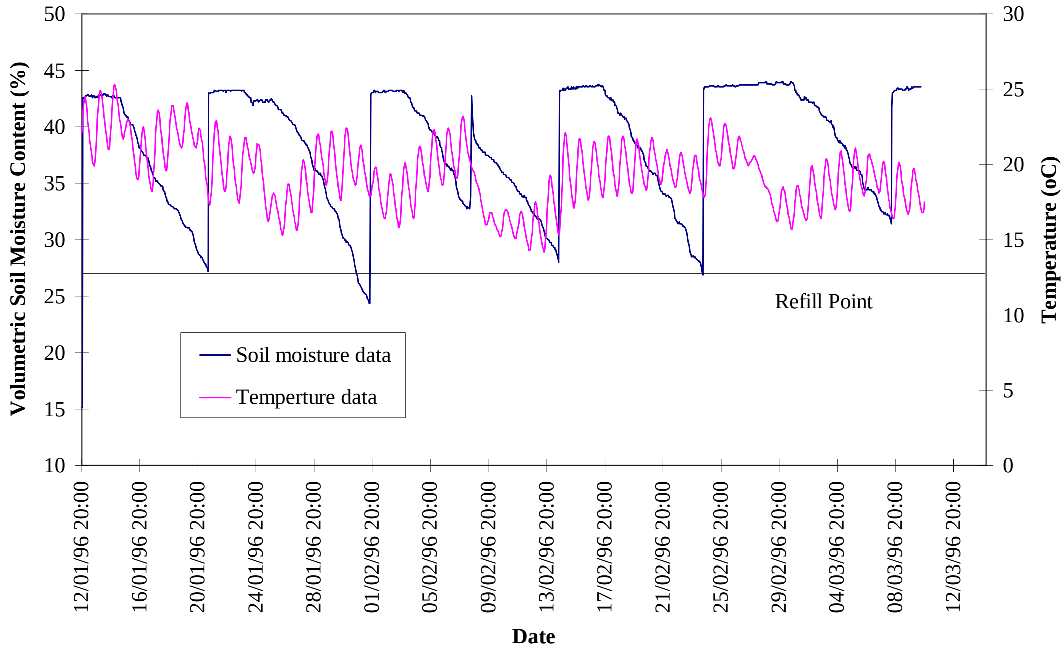


Figure 32 - Style of a soil water and temperature graph in IRRIGATE

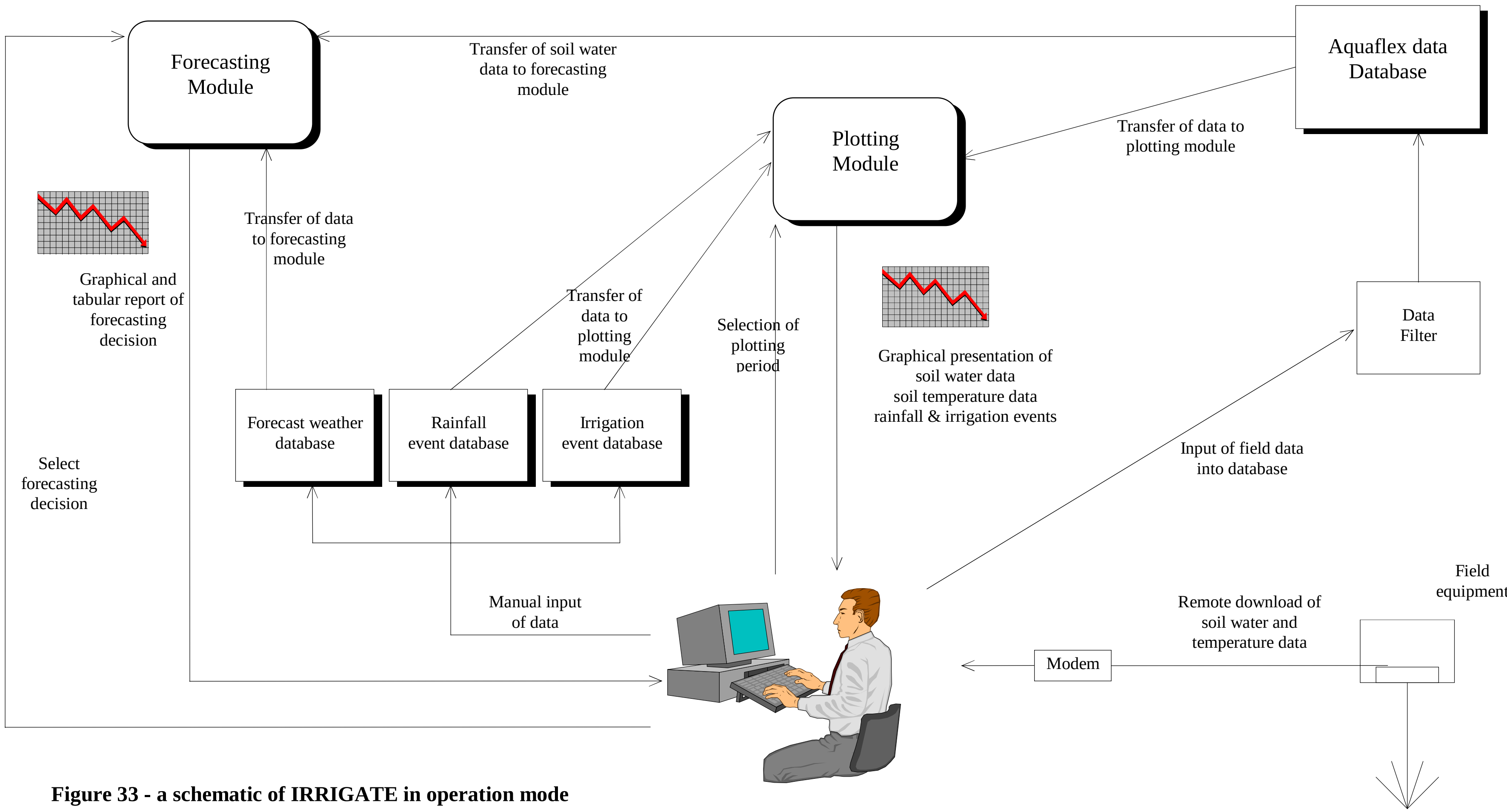


Figure 33 - a schematic of IRRIGATE in operation mode

7.7. Application Management on the Farm

Please note that an introductory description of application on flood irrigated dairy farms is given in section 3.

A property must meet a few basic requirements before it is worth trying to improve application performance. Bays need to be laser graded to allow a uniform application. A property should have good drainage from the bottom of bays to avoid ponding. Also, single gates on bay inlets are desirable. They allow for easy conversion to automatic control systems. However, most gates will still require some adjustments to allow for measurement of inlet volumes. The basis for the methodology in this section comes from work carried out by Hugh Turral during his Ph.D dissertation (Turral 1994).

7.7.1. The Modelling Exercise

Adjustment of an irrigation event in real-time requires the use of some form of model. Models can predict how an irrigation event will proceed when provided with data about how it has performed up to the current time. The four main approaches used in the past are the Full Hydrodynamic, Zero-Inertia, Kinematic Wave and Volume Balance approaches. The list is in order of decreasing complexity.

Constraints on processing capabilities and solution time often determine which approach to use. The initial work during 1997-98 concentrated on Zero-Inertia, as Turral (1994) used this approach. Turral based his work on the BRDRFLW model, a Zero-Inertia model developed by Katapodes and Strelkoff (1977). The work completed as part of this project used SRFR version 20.3, an updated version of BRDRFLW.

Zero-Inertia models are a simplification of Full Hydrodynamic Models. Hydrodynamic models employ all terms in the Saint-Venant equations to describe the flows of a surface irrigation event. The Zero-Inertia approach neglects all the acceleration (or inertial) terms of hydrodynamic approaches. The justification is that the velocities experienced in surface irrigation flows are small enough to make velocity changes negligible, when compared to the force terms.

Any worthwhile solution of a Zero-Inertia model requires an accurate description of the surface roughness and infiltration characteristics of the bay. As these parameters are difficult to describe, the initial step in the modelling problem is to determine values for them. Using either advance and/or depth data for an irrigation event it is possible, using the Zero-Inertia model, to find an inverse solution to the equations. The solution determines “best fit” values of roughness and infiltration for the current event. This process is achieved by coupling the

Zero-Inertia model with an optimisation algorithm[19]. The next involves putting the roughness and infiltration parameters back into the Zero-Inertia model, which then predicts the cut-off time that maximises performance criteria.

7.7.2. The Problem at Hand

The problem lies in making recommendations to an irrigator about how to achieve the desired irrigation requirement for a crop, while maximising efficiency and uniformity.

7.7.3. Solution Strategies

Primary factors that determine the performance of an irrigation event fit into two categories, those which effect the velocity of flow down the bay and those which effect infiltration rates. These factors are:

1. Velocity of flow down the bay - inflow discharge, bay slope, soil surface roughness, vegetation roughness and depth of water.
2. Infiltration rates - soil structure, soil texture, soil water content, temperature of soil, temperature of water, vegetation, depth of water on bay and conductivity of water.

The primary factors controlling an irrigation event are the quantitative differences between inlet flow and accumulating infiltration. Factors that can improve performance, and which an irrigator can control, are inflow discharge, $Q_{0,}$ and time of cut-off, t_{co}. Irrigators will only have limited control over Q_o because of irrigation system design, and so the following explanations only consider t_{co}.

There are two basic procedures to use when trying to set up an on-farm system to make recommendations to irrigators on how to apply water. The objective of both procedures is to assess the performance of an irrigation event and recommend the cut-off time to irrigators that will maximise performance criteria. The first procedure performs a retrospective analysis on an irrigation event and recommends actions to take for the following irrigation. The second procedure is a real-time procedure. It assesses an in progress irrigation event and provides advice on actions to take during the event.

Modelling an application event and optimising performance criteria requires field monitoring. Thus, for either approach it is necessary to monitor several variables during an irrigation event. Variables to monitor may include:

Inflow discharge (Q_o)

---

[19] Turral (1994) used a constrained simplex optimisation algorithm. The 1997-98 experiment combined an unconstrained simplex algorithm with a genetic algorithm. Convergence stability, convergence time, ability to converge to a global optimum and radius of convergence are factors to consider in a comparison of the methods.

Measurements of Q_o must be accurate as it has a major influence on the performance of an irrigation event. Q_o is generally measured using a weir or flume. A depth-discharge relation relates flow depth over the weir or flume to discharge through the inlet. A propeller meter can also measure inlet discharge. Remote access to discharge/depth readings is desirable for ease of operation.

Advance rate/Flow depth
Modelling of infiltration and roughness characteristics requires information about the advance rate of the wetting front, and/or the depth of flow of the irrigation wave. For this preliminary explanation consideration is only given to advance rate data[20].

Modelling constraints require advance time measurements at a minimum of three points in the bay (ie. at the inlet and two points further down the bay). An additional point at the bottom of the bay would provide valuable information in a retrospective analysis approach.

7.7.3.1. Real-Time Procedure

The real-time procedure requires monitoring of inflow discharge and advance time. Knowledge of the progress of the irrigation event allows for modelling of the event. The modelling procedure determines the time to cut-off, t_{co}, that will maximise performance criteria. The PC then sends a radio signal to close the inlet gate at the appropriate time.

A model requires time to process data, run various prediction scenarios and output the optimum time to cut-off. Therefore there is a time limit beyond which the model cannot use monitoring data coming from the field. If this limit is exceeded then recommended actions cannot be taken, because they will be too late.

The following explanation, of a real-time automated system, uses the simplest form of an automated system with the minimum monitoring requirements. Figure 34 shows the required field setup and equipment. Required equipment includes:

- A PC with radio communication capabilities to relay signals to field instrumentation.
- Two electronic advance water sensors with in built timers and radio communication to record and relay advance time data to the PC. Sensors placed approximately one quarter and half way down the bay.
- An inlet gate with radio communications that can open and close the gate. At the inlet gate a measurement of inflow discharge is also required. The system requires remote access to the discharge figures.

[20] The field trial will investigate many parameters to find the ones that best describe the infiltration and roughness characteristics of the irrigation bay. However, to simplify the description of the application process this discussion only considers advance.

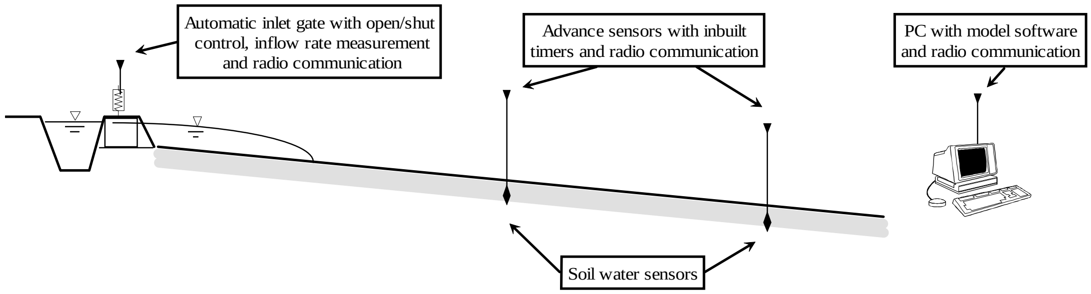
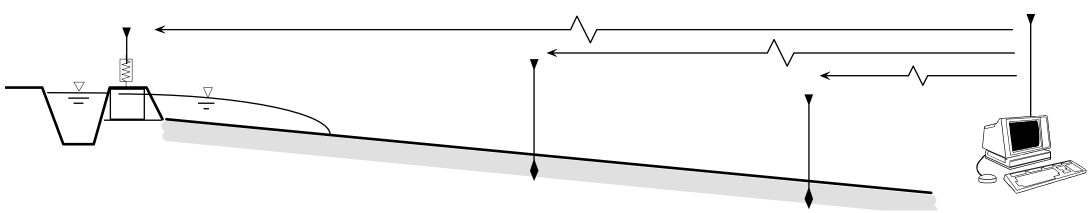


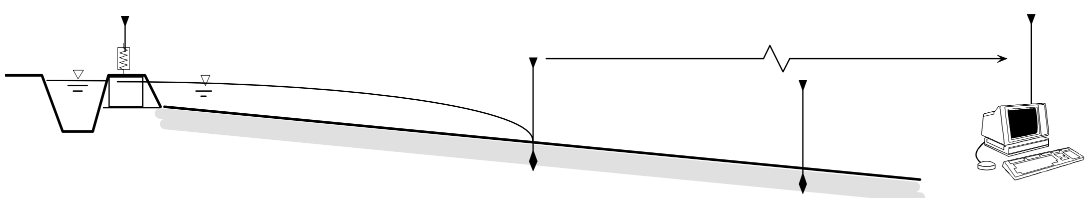
Figure 34 - Field equipment for real-time control of an irrigation event.

With this equipment in an irrigation bay the irrigation event would proceed as follows:

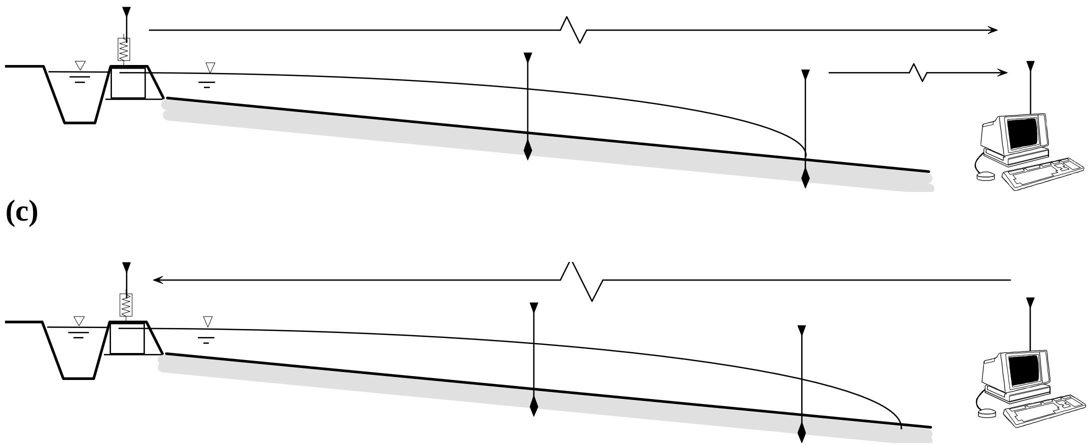
1. Irrigator initialises system by setting timers on advance sensors to $t = 0$ and starts discharge measurement at inlet. The inlet gate is open and the irrigation commences (see Figure 35 (a)).
2. The advancing wetting front hits the first advance sensor. The sensor records advance time, t_1, and relays time back to PC (see Figure 35 (b)).
3. Advancing wetting front hits second advance sensor. The sensor records advance time, t_2, and relays time back to PC. Inlet discharge data is transferred from the inlet gate to the PC (see Figure 35 (c)).
4. Software on the PC determines unknown model parameters required for simulation of the irrigation event. The software then runs through various scenarios of the irrigation event and determines the time to cut-off, t_{co}, that maximises performance criteria. At time t_{co} the PC relays signal to inlet gate to close and the irrigation cycle moves onto the next bay (see Figure 35 (d)).



(a)



(b)



(c)

(d)

Figure 35 - Schematic of a real-time controlled irrigation event (a) initialise system and open inlet gate, (b) Transfer time t_1 to PC, (c) Transfer time t_2 and Q_o to PC, (d) determine t_{co} and send signal to close inlet gate at appropriate time.

Ideally the results from one monitored bay will apply to a block of bays. The applicability of results will depend on other bays in the block having similar lengths and similar soil types. If bays are not the same length but contain similar soil types, it will still be possible to determine appropriate cut-off times. This can be done using the infiltration and roughness characteristics from the monitored bay. Different sections with substantially different slopes and soil types would need to be monitored separately.

The ideal field sensor for sensing advance would have the advance sensor and timer built into the soil water sensor. But as numerous soil water sensors are available on the market the best approach at this stage would be to develop a separate depth sensor that can work on the same communication network.

The main benefit of the soil water sensors in this process is to enable irrigation timing decisions to be made such that soil water conditions in the field are similar before each irrigation event. Similar soil water conditions in the field before each irrigation mean that infiltration rates will be similar from one irrigation to the next. This allows for a faster assessment of time to cut-off by the model software.

The time the model takes to make a recommendation about cut-off time is important because of the constraints discussed in section 7.7.3. It is envisaged that for the first few irrigation events of the season the model will take longer to run than in future events. This is because future runs can use knowledge of field conditions from the previous runs.

Retrospective Procedure

A retrospective procedure for improving irrigation application performance is simpler to achieve than the real-time procedure. This is because there are no time constraints on when recommended actions need to be available. Usually there will be a week between the event being modelled and when the recommended actions need to be available.

The field setup and instrumentation required are similar to the real-time procedure, except that an advance sensor could be placed at the end of the bay. Having a sensor at the end of the bay allows modelling work to account for any variability in advance rate at different distances down the bay. A description of variability is important if there are any changes with distance down the bay eg. soil type, vegetation type, soil water content.

With the field setup in place, the retrospective method would proceed in a similar way to the real-time procedure ie. inflow rate and advance times being fed back to the office PC. With no time restrictions on the modelling procedure however, advance data for the whole bay could be collected before modelling proceeded. Then, given the data from the irrigation event, the model would be run, performance criteria assessed and the recommended time to cut-off for the next event would be output. The time to cut-off would then be used by the irrigator during the next irrigation event. For this cut-off time to apply to the next event the inflow discharge, surface roughness and infiltration characteristics would need to remain similar to the modelled event.

Scheduling irrigations at a constant soil water deficit should ensure that infiltration rates at the start of each event are similar. However, pasture height will change from one event the next (it will grow or be grazed) and so surface roughness characteristics will change. Also, the delivery rate from Goulburn-Murray Water may change and so inflow discharge will also alter. Due to these possible variabilities it is best to aim towards a real-time approach.

A retrospective approach also introduces the possibility of improving application efficiency without automation. The concept is an alternative approach proposed by Nick Austin in his Murray Darling Basin Commission (MDBC) project, I7048[21]. Manual monitoring of advance will still enable the collection of any data required for irrigation event modelling. The irrigator will have to allocate time for data collection however. Given the appropriate data, recommendations about time to cut-off for the next irrigation event can be made.

Such an approach would allow an irrigator to improve application efficiency via a two stage approach. They could first trial the software using manual monitoring of irrigation events to see what advantages the model provided. If satisfied with the results, the irrigator could then install automation equipment on the farm and make full use of the model and lessen the time input.

7.8. Communication

The approach to communication throughout the project targeted irrigators, extension staff and research staff. For irrigators one approach was to select field sites whose managers were involved with committees throughout the industry who would be able to communicate any activities on their properties through the forums they were involved in. This was left at an

[21] The project title is “Development of a Decision Support Timer to Improve Flood Irrigation Management”.

informal level with no direction from project staff. Site 1 was an irrigation farm based at a teaching college. The farm has annual field walks and publishers activities in local newspapers. The owner at site 4 was on a water services committee and was also involved with the United Dairy Farmers of Victoria (UDV). The site 3 manager was on a water services committee. The manager of site 2 was not on any committees but has had a number of industry groups over the property in the last two years looking at the operation as a whole. The use of Aquaflex for irrigation timing has been of major interest to those touring. Articles in local and state papers have also been published to highlight work being done in the project.

As for the academic audience a number of seminars were delivered and several presentations made at both international and national conferences. Details of the main communication activities are given in the following section. The project also worked closely with a local irrigation consultant, Adrian Orloff, based in Shepparton who was regularly consulted about instrumentation and project direction. Adrian was an important information distribution source for work being carried out in the project.

7.8.1. Communication Activities

- **Irrigation Association of Australia Conference 1998**

Water is Gold, IAA 1998 Conference and Exhibition 19-21 May 1998 at Brisbane Exhibition and Convention Centre in Brisbane. Presented analysis on finalised approach for 4-day forecasting of Aquaflex soil water content.

- **The Age, I.T. supplement Tuesday March 17 1998, page 7e.**

"Water-management software on trial" by Glenn Mulcaster. The article covered the benefits to be gained from improved on-farm water management and gave details on equipment, installation and training costs.

- **Weekly Times, Farming Today Tomorrow, Wednesday February 1998, page 29**

"Keeping water cost at bay" by Genevieve Barlow. This article featured comments from a researcher involved with the project and covered the main objectives of the work. It also contained a description of equipment and training costs given by a consultant and a dairy farm manager gave his view of the value of the equipment on his property.

- **Victorian Farmers Federation (VFF) Information Technology Expo for Farmers**

Theme "The opportunities information technology offers to farmers to increase profitability" La Trobe University, Bendigo 19 February 1998. The workshop was structured as a gathering specifically arranged for information exchange with farmers. Two one hour sessions featuring presentation and discussion time were run and covered available soil water monitoring technology, how it is used on farm and the benefits to be gained from using the equipment.

- **Northern Times, Friday September 15, 1995 page 11 and 1997**

The 1995 article was published soon after the installation of equipment at site 2. It described how the equipment was installed and what information it provided irrigators with. The farm manager at site two gave his expectations of the benefits that the equipment would provide for aiding irrigation management.

- **Elmore Field Days, October 1997**

A display on the Goulburn-Murray Water stand outlined the basics behind the use of soil water monitoring equipment on-farm. It was part of a larger display arranged by Goulburn-Murray Water which also featured automatic irrigation equipment (inlet controls) and application efficiency work done at Institute of Sustainable Irrigated Agriculture in Tatura.

- **International Conference on Agricultural Engineering**

The 4-day forecasting component of the IRRIGATE software was presented at the International Conference on Agricultural Engineering, in Madrid during September 1996.

- **The Northern Irrigation Cropper**

An article describing the aims and progress of the project appeared in the Autumn 1997 edition of The Northern Irrigation Cropper Magazine. Farmers in northern Victoria and southern NSW receive the magazine.

- **Department of Civil and Environmental Engineering Seminar Series, 1995, 1996 and 1997**

General overviews of the project were presented as part of the departments postgraduate seminar series. Staff and postgraduate students from within the department attended the seminar.

- **Institute of Sustainable Irrigated Agriculture Seminar Series**

A presentation was made to about 30 staff, irrigators and extension officers at the Institute's Tatura office. The presentation gave a general coverage of the pros and cons of soil based monitoring technology and its application for irrigation scheduling.

- **Irrigation Association of Australia Conference 1997**

Although not directly related to the project, Mark Wood and Nick Austin presented a discussion session on the integration of automation with monitoring technology. The discussion covered many issues relating to the current study.

- **Dookie College Dairy Farm, Farm Walk, 1994, 1995 and 1996**

Descriptions of the instrumentation and the use of Aquaflex soil water data at the Dookie College Dairy Farm were presented at the farm walk. The data collected at the Dookie site were also presented at the farm walk by the farm manager Geoff Wilhelm. The walks were attended by about 40-80 farmers.

- **Approach for participation of Irrigators in the project, 1995**

Preparation for the 1995-96 irrigation season field trial of the scheduling system involved sending descriptions of the project to 25 dairy farmers in the Tatura and Kerang districts of northern Victoria. The descriptions were not only important to recruit participants for the project but also for raising the profile of the project in the general dairy community.

- **Sentek Software School, 1994**

The school was a chance to interact with others in the irrigation community interested in soil water monitoring. It also enabled discussions with a manufacturer about the direction of the project.

- **In house seminar at Burnley College, 1994**

The seminar was arranged primarily to discuss the experiences that a number of people had had with the Microlink. The seminar provided some excellent discussion of the problems that had been encountered with the sensor and also provided an opportunity to present a basic outline of the current project and get some input from those in attendance.

- **Contact with staff on related projects**

Derek Poulton (Goulburn-Murray Water, Tatura) organised several meetings with staff from related projects. No direct links between projects emerged from the discussions, but they gave valuable insights into how others in the industry are tackling related problems. Also there is better communication between personnel on the projects since the discussions.

7.9. Adoption

No broad recent survey of adoption of technology for irrigation management on farm has been conducted. From working within the industry however it is clear to the authors that there has been no significant increase in technology adoption. So although this project has raised awareness of available irrigation scheduling equipment and the benefits of equipment in the irrigation industry, there has been little effect on adoption. Similar problems were encountered in an irrigation scheduling program run by Goulburn-Murray Water in 1990-91 and have been met by many researchers in the past.

The Goulburn-Murray Water program was a reasonably successful program, conducted by the Loddon Torrumbarry Region of the Rural Water Commission of Victoria, during the 1989-90 irrigation season ran an irrigation scheduling service for irrigators in the Boort and Kerang areas (Heslop et al. 1990). The service involved farmers using a variety of methods on a diverse range of crops to try and better use their irrigation water. The service was well supported by farmers in the area who saw the major benefits of the service as increased awareness and understanding of the concepts and advantages of irrigation scheduling. Unfortunately after direct contact with extension staff was removed, the use of equipment eg. tensiometers, for scheduling soon dropped away. Although the information and techniques in this and the current program have yet to gain widespread acceptance they have introduced irrigators to the basic concepts and advantages of scheduling irrigations.

The next section looks briefly at possible explanations for the low adoption levels and what might change in the future to create an environment where adoption is more likely.

7.9.1. Why Low Adoption?

Although irrigation scheduling and application models have been widely used by "irrigation experts", farm operators (most often the intended users of the systems) do not regularly use them. Pleban and Israeli (1989) looked at why irrigation scheduling programs had not been widely used. They suggested possible reasons for this:

1. The programs were orientated toward research and for use by professionals and so looked at the scheduling problem from the point of view of the crop and the academic researcher and not the farmer. The article suggests that before scheduling programs are developed more consideration must be directed towards ensuring the final user can learn the basic concepts of irrigation scheduling from the program and thus feel comfortable using the program.
2. Personal time restrictions on the farmer who may not be able to irrigate when the program tells them to.
3. Scheduling of other farm activities that affect the time of watering eg. stock rotation and fertiliser application.

It has also been shown that computer systems which make radical changes to the existing practices of users will not be widely used or accepted (Adoum 1993).

It is for these reasons that improving crop water use efficiency by making irrigation scheduling and improved application techniques more accessible, accurate and flexible, is an increasing priority in many agricultural applications. To make this possible further development of computer tools, monitoring equipment and monitoring techniques required for on-farm irrigation scheduling is needed. To a large degree this project focused on determining difficulties involved in implementing such systems on-farm and has tried to answer the questions on how best to implement procedures.

The above comments indicate that if information is delivered in a clear, easily understandable and flexible format that most irrigators will implement irrigation scheduling and probably will not if the package is poor. Unfortunately the equation is much more complicated than this. No, irrigator's use of irrigation scheduling techniques will be determined by a variety of social, economic, cultural, perceptual and situational reasons (Vanclay 1992).

Having the correct product is no doubt important but the awareness and need for the product is also crucial. Vanclay (1992) points out, in the context of adoption of measures to improve land degradation, that farmers do not have environmentally hostile attitudes. Vanclay found in a survey of farmer's attitudes on the Darling Downs that most were aware of problems of land degradation and that they could lead to lower returns in the long term. However many farmers fail to recognise the early warning signs on their own properties and so failed to include management issues aiming at improving land degradation in their operations.

It is still unclear exactly why most irrigators fail to use any type of new methods to aid their irrigation timing decisions. The work by Rabi Maskey and Greg Roberts (LWRRDC project DAV 16) certainly indicates that reasons much closer to home eg. more sleep, are a greater driver for adoption of new technology than more abstract concepts such as increasing salinity and environmental degradation.

The most likely cure for low adoption could in part be the current restructuring of the water industry leading to limits on water availability and a greater price put on each unit of water. The current environment in northern Victoria is making water a higher priority on the agenda of irrigators. No longer is using too much water only a cause of long term problems such as salinity and waterlogging, it is an immediate problem effecting day to day operation of the farm. The changes will be devastating to some farmers but one positive aspect for the irrigation industry is that it could well be the driving force behind on-farm water management changes.

8. Conclusions

Monitoring of irrigation timing decisions at the trial sites clearly shows that in most cases one or two irrigations per season can be saved using technology to aid timing decisions. Low level technologies such as irrigation pans provide improved insight to irrigators about when to water, but sight specific variables such as water-table depth and soil type make it difficult to specify accurately the interval between irrigations.

Soil water monitoring equipment provide the added benefit of directly measuring the local variables such as soil type and water-table depth. This allows for more accurate decisions to be made with the added expense of equipment costs and greater maintenance. Also, to reap the full benefits of soil water monitoring equipment it is desirable for irrigators to undergo some initial training from a consultant and to liase with a consultant a couple of times a year.

During the past two years it became apparent that any software system designed during the period of the research would become obsolete quickly with the rapid development of sensing equipment. Also commercial interest in any probes made it difficult to work with any one supplier in the development of a decision support system. This lead to the approach of suppling a method best suited the use of soil water monitoring equipment in the dairy industry rather than a particular software package.

It was apparent from analysis of soil water content data that much care should be taken during installation of any soil based probe, with the ideal situation being an early installation of equipment during the season prior to its use. This allows for settling in of probes and for an assessment to be made of the behaviour of soil water changes at a particular site. This knowledge is invaluable when designing decision criteria for when to irrigate.

It is still unclear exactly why most irrigators fail to use any type of new methods to aid their irrigation timing decisions. The work by Rabi Maskey and Greg Roberts certainly indicates that reasons much closer to home eg. more sleep, are a greater driver for adoption of new technology than more abstract concepts such as increasing salinity and environmental degradation. The most likely cure for low adoption could in part be the current restructuring of the water industry leading to limits on water availability and a greater price put on each unit of water.

Approaches using on-farm monitoring of irrigation event hydraulic variables shows great promise for improving irrigation application efficiency. Unfortunately the technologies to achieve this, especially an on-farm communication system to return data from monitoring equipment, is only just becoming a reality. For the approaches outlined herein to become a reality further on site testing and integration of equipment needs to take place.

Appendix 1 - Soil Water Monitoring Equipment

Device Name	Water Monitoring Method	Permanent Installation	Sensor Installation	Logs Data	Reading Frequency	Response Time	Maximum Number of Sensors	Calibration Required	Soil Water Range	Affected by Salinity	Power Supply	Maximum Cable Run	Approximate Cost/Unit
Aquaflex Lincoln Ventures, NZ	Pulse Propagation	Yes	Buried Cable	Yes	Variable	1Hz Signal	4	Yes	All	No	12V	500m	~$1,500
Microlink DRW, SA	Heat Pulse	Yes	Buried Sensor soil contact important	Yes	Variable	Minutes	8	Yes	All	No	240V 24V	400m	$1600
Enviroscan Sentek, SA	Capacitance	Yes	Sensor in Access Tube	Yes	Variable	<1 Second	16	No	All	No	12V	100m	$3,400
Cambrone WMS Nutek, Qld	Heat Pulse	Yes	Buried Sensor soil contact important	Yes	Variable	15 Minutes	8	Yes	All	No	240V AC	200m	$8,500
WaterMatic Cumming & Ass, Vic	Porous Block	Yes	Block Buried soil contact important	?	?	10 Minutes	1	Yes	10-30 kPa	Yes	24V AC/DC	1.5km	?
Trase Irricrop, NSW	Time Domain Reflectometry	Yes/No	Buried/ Inserted Sensor	Yes/ No	n/a	Seconds	1	No	All	Yes	240V AC or Battery	Low Metres	$15,000
Neutron Probe	Neutron Scattering	No	Access Tube	No	n/a	~32 Seconds	1	Yes	All	Yes/No	Battery	n/a	~$5,000
Tensiometers	Water Tension	Yes	Inserted in Ground	Yes/ No	n/a	n/a	n/a	Yes/No	80kPa	No	n/a	n/a	~$60
Gypsum Blocks	Resistance	Yes	Buried	Yes	n/a	n/a	n/a	Yes	n/a	Yes	Battery	n/a	~$50

Table 8 - Details of surveyed soil water monitoring devices.

Appendix 2, Aquaflex Enviroscan Comparison Data 1

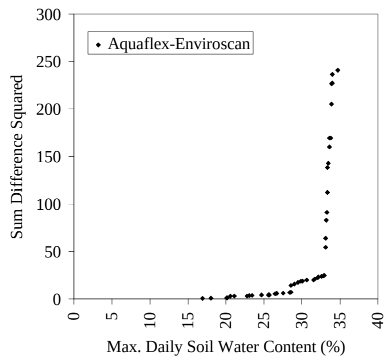


Figure 36 - Cumulative difference between daily soil water range measured by the Aquaflex and the Enviroscan against the maximum Aquaflex soil water reading for the day in question.

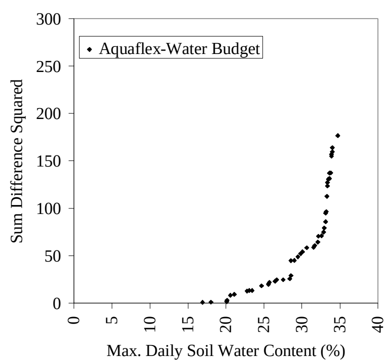


Figure 37 - Cumulative difference between daily soil water range measured by the Aquaflex and the water budget method against the maximum Aquaflex soil water reading for the day in question.

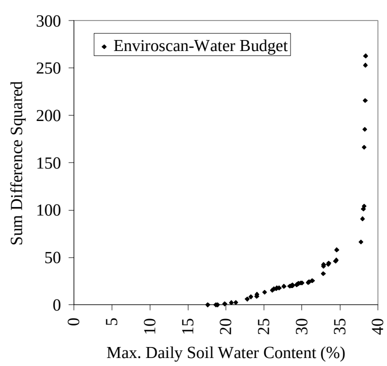


Figure 38 - Cumulative difference between daily soil water range measured by the Enviroscan and the water budget method against the maximum Enviroscan soil water reading for the day in question.

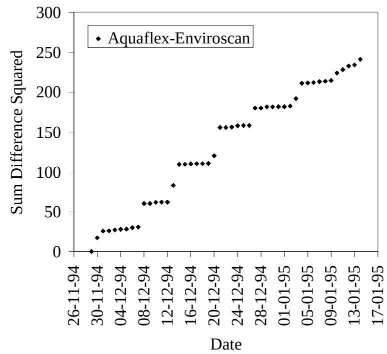


Figure 39 - Cumulative difference between daily soil water range measured by the Aquaflex and the Enviroscan against time.

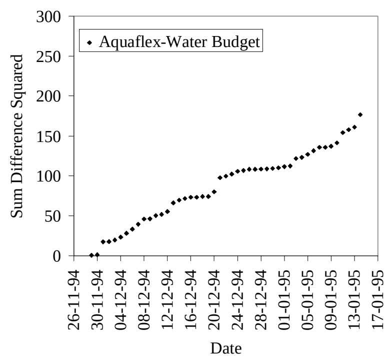


Figure 40 - Cumulative difference between daily soil water range measured by the Aquaflex and the water budget method against time.

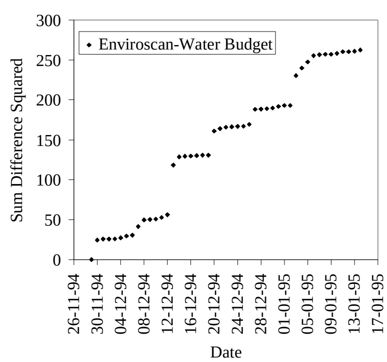


Figure 41 - Cumulative difference between daily soil water range measured by the Enviroscan and the water budget method against time.

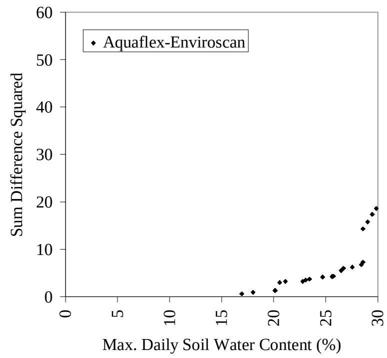


Figure 42 - Cumulative difference between daily soil water range measured by the Aquaflex and the Enviroscan method against the maximum Aquaflex soil water reading for the day in question (for readings below field capacity).

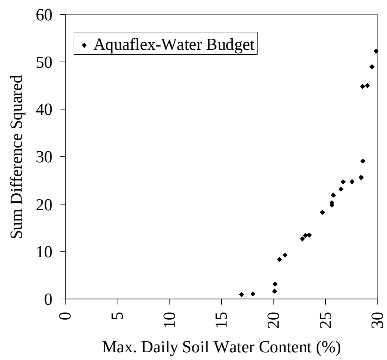


Figure 43 - Cumulative difference between daily soil water range measured by the Aquaflex and the water budget method against the maximum Aquaflex soil water reading for the day in question (for readings below field capacity).

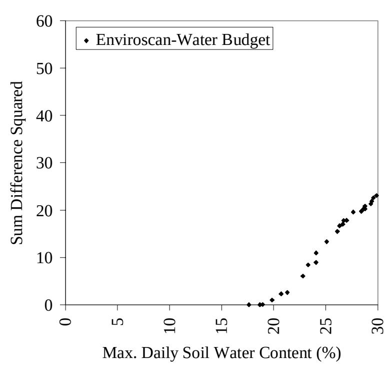


Figure 44 - Cumulative difference between daily soil water range measured by the Enviroscan and the water budget method against the maximum Enviroscan soil water reading for the day in question (for readings below field capacity

Appendix 3, Aquaflex Enviroscan Comparison Data 2

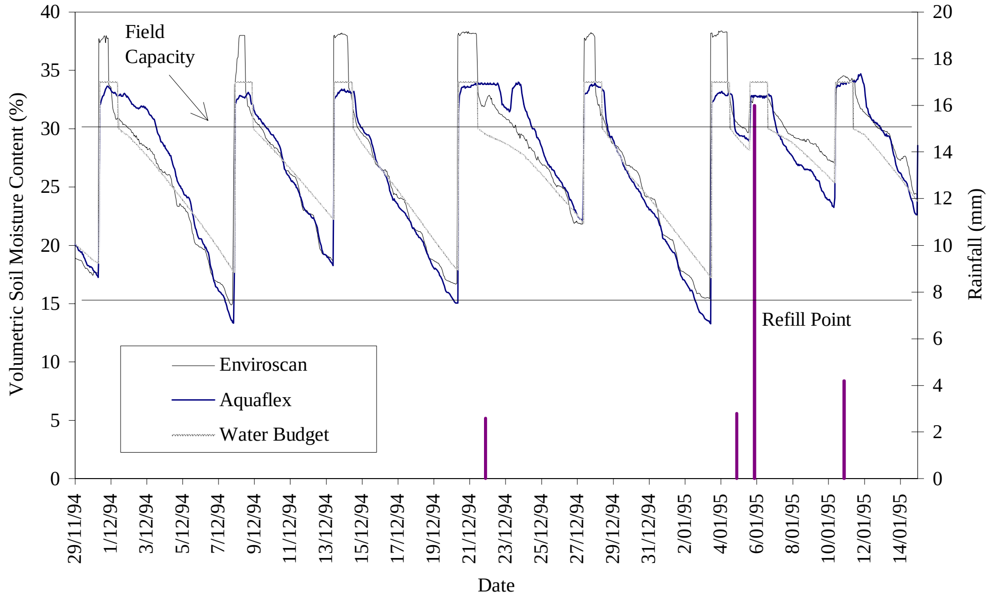


Figure 45 - a comparison of data for the three monitoring techniques. The period of data shown is from 29.11.94 to 14.01.96, covering a major part of the peak evaporative demand period of the season.

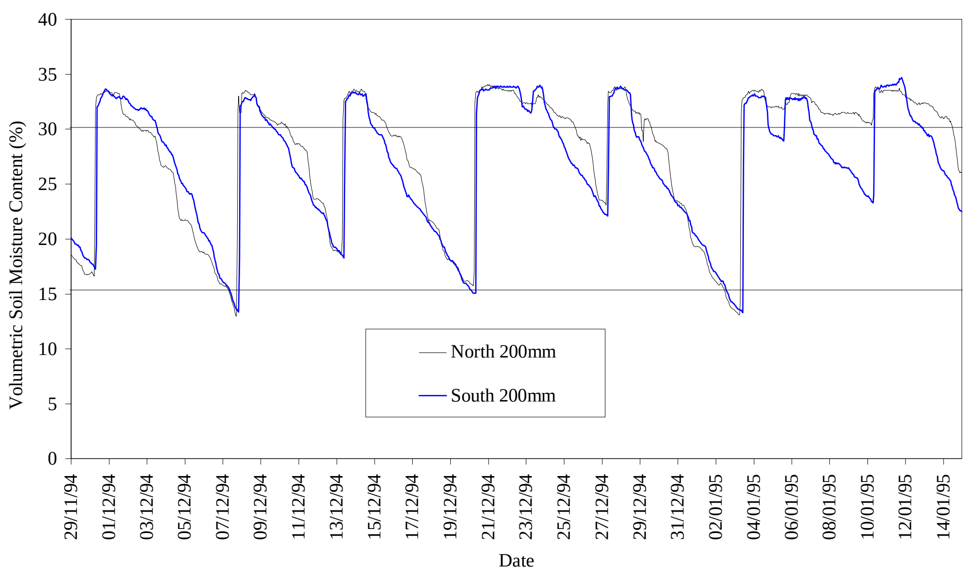


Figure 46 - A Comparison of data from the Aquaflex units placed at 200 mm. The north unit was set one third of the way down the bay and the south unit two thirds of the way down the bay.

Appendix 4 - Forecasting Soil Water Content Results

Period (Day)	Test Statistics	Slope	Linear ETo	Linear Evaporation	Adjusted Slope	Adjusted Linear ETo	Adjusted Linear Evaporation
1	ME (% vmc)	0.0			0.2		
	MAE (% vmc)	1.8			1.5		
	MAPE (%)	5.9			4.7		
	SSES (% vmc)	8730.6			7095.9		
	ME (Day)	0.8			0.7		
	MAE (Day)	1.9			1.9		
3	ME (% vmc)	0.0			0.1		
	MAE (% vmc)	1.6			1.3		
	MAPE (%)	5.2			4.2		
	SSES (% vmc)	7973.9			5516.9		
	ME (Day)	0.6			0.3		
	MAE (Day)	1.6			1.6		
7	ME (% vmc)	0.0	0.0	0.0	0.0	-0.2	-0.2
	MAE (% vmc)	1.5	2.5	1.7	1.2	2.2	1.2
	MAPE (%)	4.8	8.2	5.5	3.7	6.7	3.9
	SSES (% vmc)	6545.7	21199.8	8553.9	4270.8	19244.6	4692.1
	MRS		0.4	0.2		0.4	0.2
	ME (Day)	0.6	0.7	0.6	0.2	0.0	-0.1
	MAE (Day)	1.5	2.3	1.7	1.3	1.9	1.2
11	ME (% vmc)	0.0	0.1	0.1	0.0	0.0	-0.2
	MAE (% vmc)	1.5	2.0	1.6	1.1	1.7	1.2
	MAPE (%)	4.9	6.5	5.5	3.5	5.2	3.8
	SSES (% vmc)	6794.8	11964.6	8575.2	4097.9	9534.3	4889.5
	MRS		0.2	0.1		0.2	0.1
	ME (Day)	0.6	0.7	0.7	0.1	0.1	-0.2
	MAE (Day)	1.5	1.9	1.7	1.2	1.6	1.2
15	ME (% vmc)	-0.2	0.0	0.0	-0.1	0.0	-0.3
	MAE (% vmc)	1.4	1.8	1.6	1.1	1.5	1.2
	MAPE (%)	4.8	5.8	5.5	3.6	4.9	3.8
	SSES (% vmc)	6833.8	10260.2	8439.7	4161.6	7793.9	4528.1
	MRS		0.1	0.1		0.1	0.0
	ME (Day)	0.4	0.6	0.5	-0.1	0.1	-0.4
	MAE (Day)	1.4	1.7	1.6	1.2	1.5	1.1
20	ME (% vmc)			-0.2			-0.4
	MAE (% vmc)			1.6			1.2
	MAPE (%)			5.2			4.0
	SSES (% vmc)			7824.0			5342.2
	MRS			0.0			0.0
	ME (Day)			0.3			-0.4
	MAE (Day)			1.4			1.1

Table 9 - Results from analyses between observed and forecast swc data

Appendix 5 - Benefits of Irrigation Scheduling Data

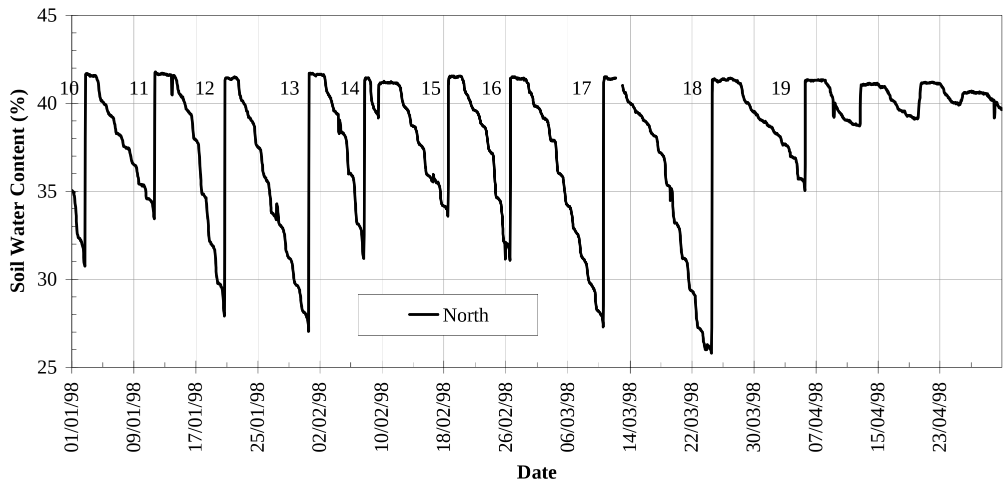
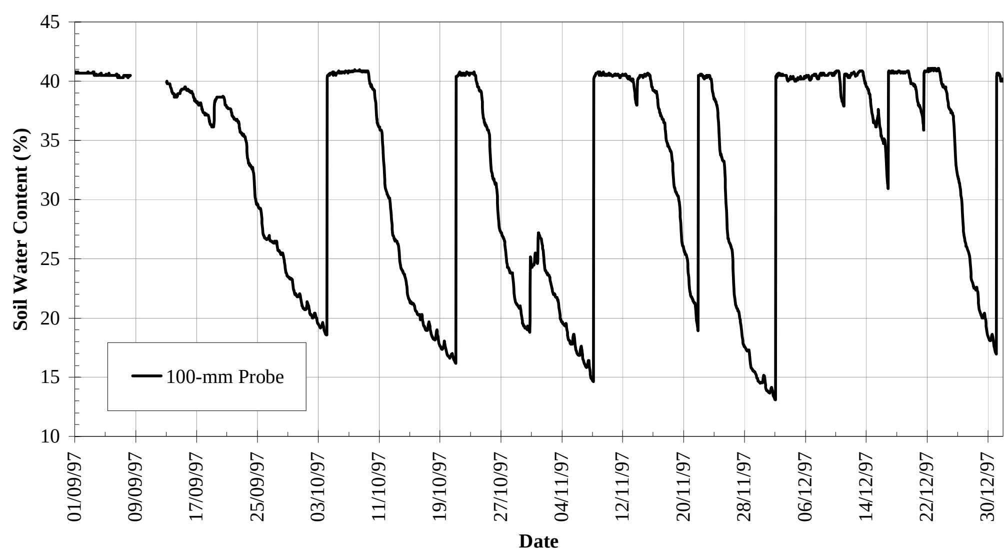
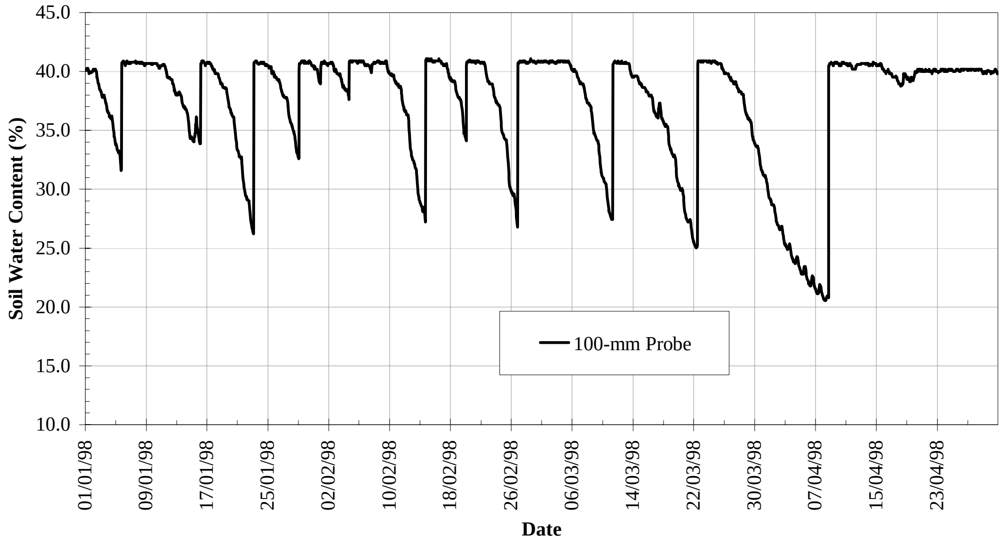


Figure 47 - Site 1 soil water data for 1997-98 irrigation season for January - April.

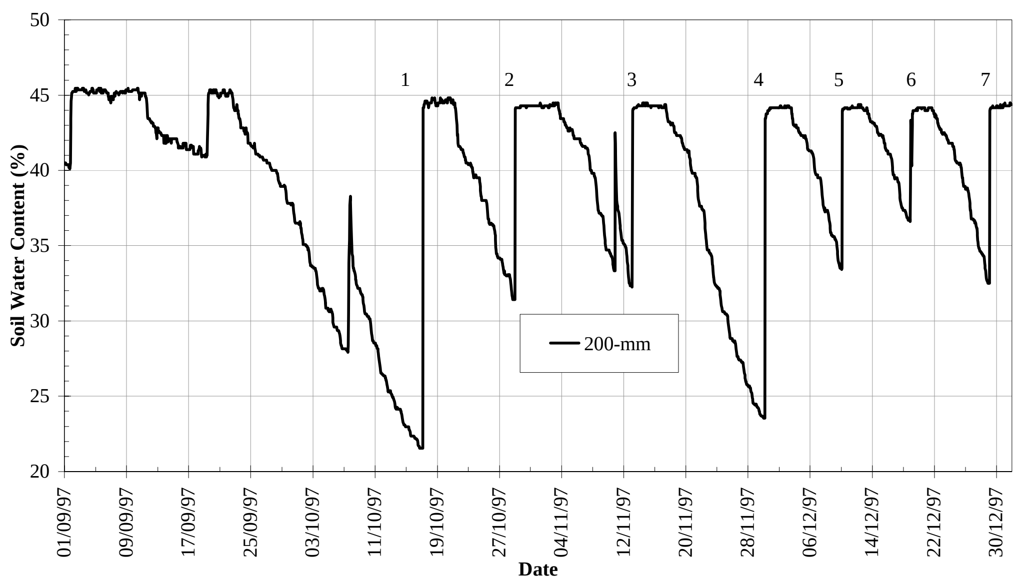


(a)

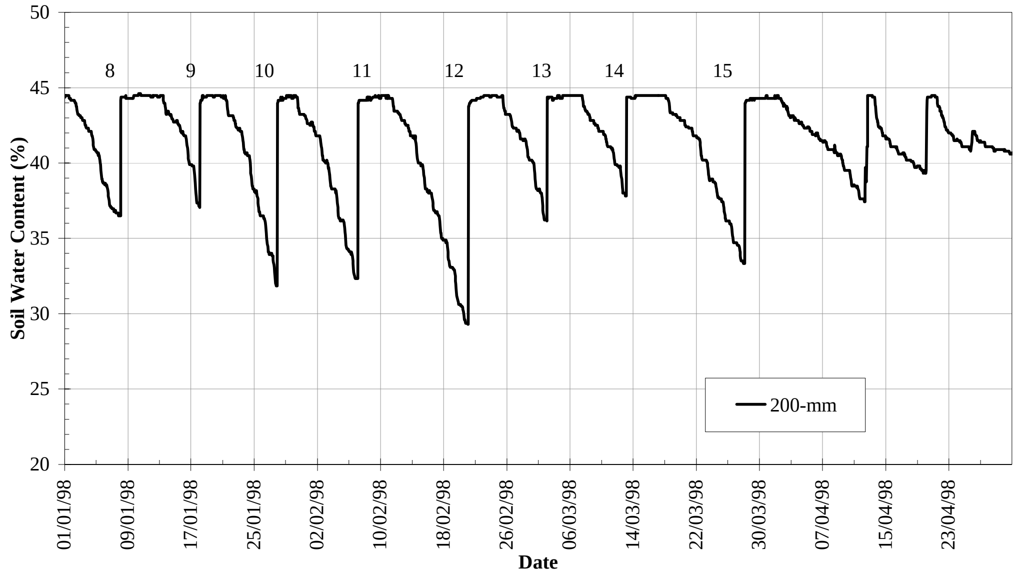


(b)

Figure 48 - Site 3 soil water data for 1997-98 irrigation season (a) September to December and (b) January to April

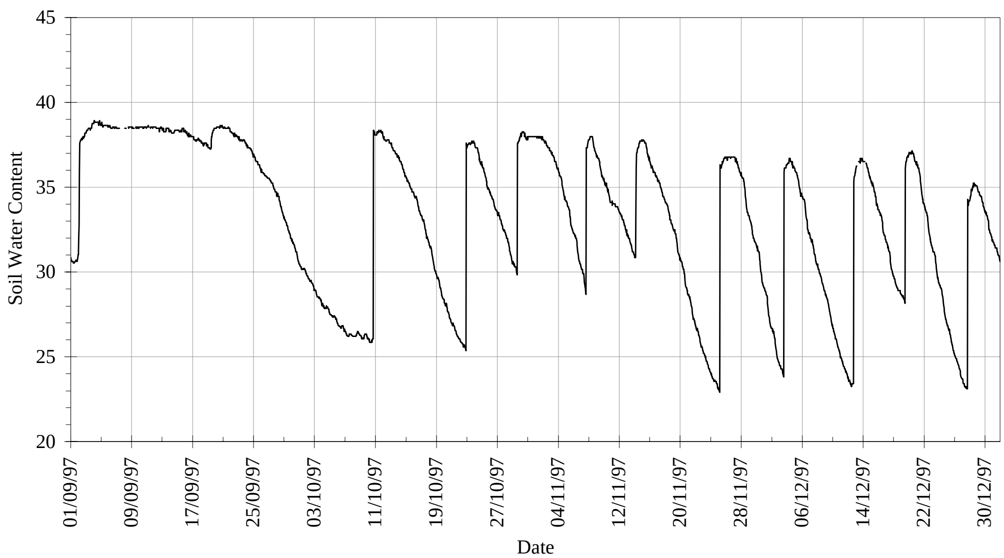


(a)

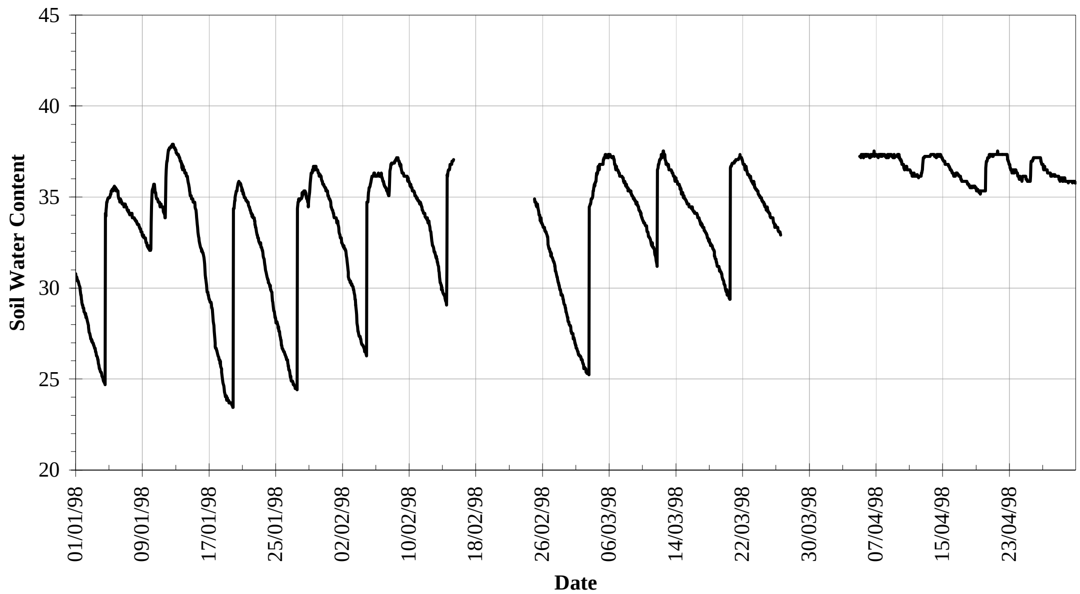


(b)

Figure 49 - Site 4 soil water data for 1997-98 irrigation season (a) September - December and (b) January - April



(a)



(b)

Figure 50 - Site 4 soil water data for 1997-98 irrigation season (a) September - December and (b) January - April

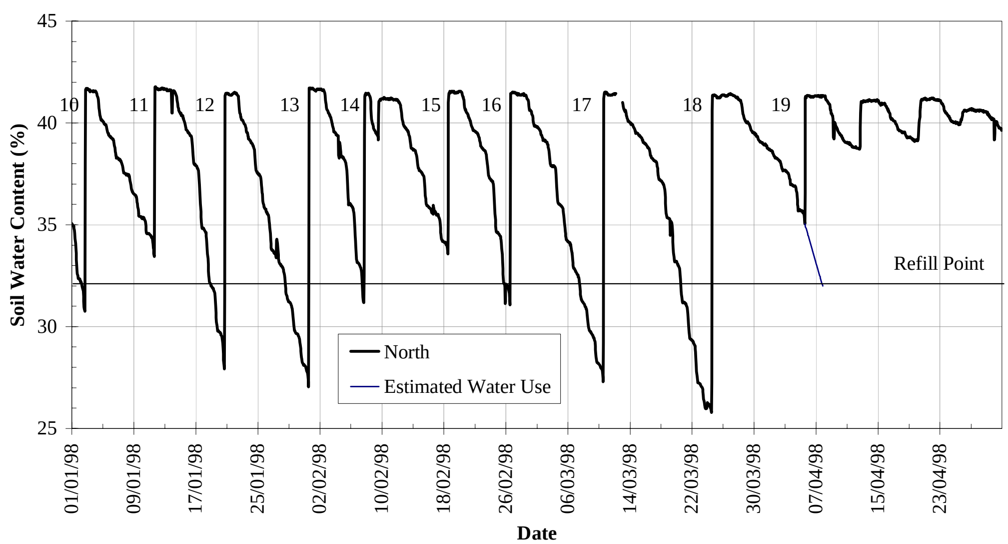


Figure 51 - Measured soil water content and estimated soil water content showing water use curve if irrigations had not been applied early at site 1, January - April.

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