An innovative way to manage irrigation using cheap and simple wetting front detectors

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ABSTRACT

The most common management problem associated with irrigated agriculture is knowing when to apply irrigation and how much of it is required. This is termed irrigation scheduling. Despite numerous techniques and tools developed by the scientific community to aid and improve irrigation scheduling, surveys have shown that farmers growing the same crops in the same region use different amounts of water. This is because of low adoption rates of available irrigation scheduling aids and/or their poor application for various reasons ranging from cost, accessibility and simplicity of the methods. So, as part of a WRC funded project on using *Wetting Front Detectors*, we seek a simple approach that can be used to better manage irrigation using wetting front detectors (WFD). This prototype WFD was developed in Australia, and was designed to be simple so that it can be understood and used by farmers at any level of training. There are two versions; one is electronic called a FullStop and the other is mechanical, called the Machingilana, a sePedi word for a *watchman*. The mode of operation of this WFD is based on the physical properties of water movement in the soil or a porous media. The tool give a 'Yes' or 'No' answer to whether the water has penetrated to a specific depth, and that's all the farmer needs to know to adjust his irrigation amount or interval according to a chosen algorithm.

This experiment on wetting front detectors was undertaken at the University of Pretoria experimental station to: (I) Evaluate two different methods of using electronic wetting front detectors, (II) evaluate two different methods of using mechanical wetting front detectors, and (III) to compare the accuracy of the wetting front detector method against the neutron probe and a computer-based irrigation-scheduling model.

Six treatments were evaluated. They were referred to as the Machingilana (MACH), crop factor (CF), FullStop 1 (FS1), FullStop 2 (FS2), neutron probe (NP) and Soil Water Balance model (SWB) treatment. The first four treatments used WFDs in different ways to manage irrigation. Lucerne (*Medicago sativa*, variety WL 525HQ) was chosen as experimental crop. The NP method was used as control treatment, given the acceptance and credibility this method has received from researchers. The aim was to use dry matter production per volume of water used as an indicator of treatment performance. However, it was later discovered that due to the extensive root system of lucerne, the crop could compensate for either under- or over-irrigation

and dry matter yield was not a good indicator of treatment performance. Statistical analysis of the dry matter yield data collected from three cycles revealed that the treatments were not significantly different at a 5% confidence level, although there was great variation in total amount of irrigation applied to each treatment per growth cycle. This is due to the fact that the crop was able to mine into deeper soil layers for water, although this strategy would not to be sustainable in the long run without extra irrigation applied. In the light of this, the trend in soil water deficit obtained with the neutron water meter for each treatment was used to evaluate the six treatments.

The four treatments based on WFDs (Machingilana, FS1, FS2 and CF) performed comparatively well to the control and SWB model treatments. However, this is not without discrepancies in all the WFD treatments or the control and SWB model treatment, but the problems associated with each treatment's successes or failures have been outlined, and with follow-up research, those problems can be rectified. It is concluded that WFDs can be valuable, simple and affordable tools to better manage irrigation, provided appropriate guidelines for using them are applied.

CHAPTER 1

INTRODUCTION

The needs of developing national economies demand the intensification of land and water use for the purpose of increasing and stabilizing agricultural production (Hillel, 1990). However, agricultural production is constrained by increasing water scarcity and competition for good quality water from industry and consumers in urban areas. Pressures on scarce water supplies are even more prevalent in rural communities of developing countries. Here, accessibility to fresh water, technologies and know how with respect to irrigation scheduling and management remain major obstacles to sustainable irrigated agriculture. The efficient use of water for agricultural production requires innovative and integrated approaches to ensure the sustainability of agricultural production to feed the increasing world population (Stockle and Villar, 1993).

Irrigation is applied to enable farming in arid regions and to offset drought in semiarid or sub-humid regions. Even in areas where total seasonal rainfall may seem ample, it is often unevenly distributed during the year, so that traditional dry-land farming is a high-risk enterprise and only irrigation can provide a stable system of crop production (Hillel, 1990). Irrigation represents a major resource investment in crop production that must be justified by commensurate returns in crop yield and quality. This means that water must be used wisely according to crop requirements to ensure high yields and the sustainability of irrigated areas (Seckler *et al.*, 1998; Mölders and Raabe, 1997; and Jensen *et al.*, 1990).

According to Deumir *et al.*, 1996, the cost of irrigation can vary between US$ 300 and US$ 600 per hectare, with a high proportion (80%) being due to infrastructure and equipment, compared to running cost of 20% over a growing season. Because of this high cost, the capacity of the equipment is never structured to manage dry years, and irrigation systems on farms do not

enable crop water requirements to be satisfied in all situations. Once this investment has been made, it is essential to manage irrigation carefully, as both over and under-irrigation result in reduced crop quality and yield. Whereas the effects of under irrigation are obvious, over-irrigation can be more damaging in the long term. Water logging, rising saline water tables and non-point source pollution of ground-water resources all result from incorrect amounts and/or timing of water application to agricultural fields.

The decision process related to 'when' to irrigate and 'how much' water to apply is termed "irrigation scheduling" (Heermann *et al.*, 1990, Hillel, 1990). Every irrigation farmer makes these decisions, be it by intuition, experience or measurement. According to Leib *et al.*, (2002), the main reason farmers are willing to put more effort into irrigation scheduling and pay more for irrigation water is to ensure high yields and good quality of high-value crops. Energy savings become important when water needs to be drawn or lifted considerable distances; however, water conservation, optimisation of yield, fertilization savings, and non-point source pollution are considered to be of secondary importance by farmers.

Research has made available a large number of irrigation scheduling tools including procedures to simulate crop water requirements, tools to measure soil water content or suction, and procedures to estimate the impact of water deficits on yield and economic returns. Many techniques and technologies for predicting irrigation needs that have been promoted by the scientific community are complex and require large amounts of information to operate. Moreover, most of the tools available do not cater for the financial situation of marginalized small-scale farmers. The small-scale farmer in South Africa uses less water than large commercial farmers. However, efficiency remains a big problem to both small-scale and large commercial farmers due to erratic supply of water, and even when water is consistently available, they often do not have or apply irrigation scheduling tools or technology, and therefore, this may lead to leaching of nitrogen and wastage of water. Moreover, there are 240 000 emerging and three million subsistence farmers as compared to 50 000 commercial farmers in South Africa, although not all are irrigation farmers

but to some extent they are water users, that's irrigated agriculture contribute 20 to 30 % of the annual gross production in South Africa (Backeberg, 2003). As such, the cumulative water use by both small-scale and large commercial farmers has financial and environmental implications to the ultimate national allocation and management of water resources.

Although there are documented difficulties in the use of irrigation scheduling technology, Koegelenberg and Lategan (1996), and Itier (1996), contend that scheduling methods must be simplified to match the time constraints, training level and income potential of producers. Such research is presented here, with the introduction of wetting front detectors (WFDs). Even in wealthier countries, the majority of farmers do not use the scheduling tools developed and promoted by the scientific community (Tollefson, 1996). If irrigation scheduling technology has eluded the wealthier farmers, what technology is available to adapt for resource poor farmers? To bridge this gap, Stirzaker *et al* (2000) sought the simplest method and device that could lead to improved water management. Should they prove to be accurate and acceptable to farmers, wetting front detectors are simple irrigation management tools that have the potential of being used by farmers at all levels of training with great ease.

The WFD has been designed to be as simple as possible for the user, but its mode of operation is based on solid soil physical principles. Water in the soil moves as a front, and therefore, a WFD tells the farmer if a wetting front has reached a particular depth in the soil or not. The WFD gives a 'Yes' or 'No' answer, and this is the information that a farmer must use to adjust the irrigation amount and/or interval. Farmers at all levels of training have shown great interest in the WFD because it "makes sense" to them.

The WFD was developed in Australia in 1997 (Stirzaker *et al.*, 2000) and performed comparatively well compared to the Time Domain Reflectometry method (TDR). There are two versions of the WFD, one electronic and one mechanical. Both have low initial and maintenance costs. However, research in Australia concentrated on the electronic version, which shuts off water

automatically once the wetting front reaches a prescribed soil depth. Little research has been conducted on the mechanical version of the detector.

For these reasons, this study was conducted to:

- Evaluate two different methods of using electronic wetting front detectors;
- Evaluate two different methods of using mechanical wetting front detectors, and
- To compare the accuracy of the wetting front detector methods against the neutron probe and a computer-based irrigation-scheduling model.

CHAPTER 2

LITERATURE REVIEW

IRRIGATION SCHEDULING

2.1 The Soil Water Balance

Irrigation represents a major resource investment in agricultural production. Every wise farmer that irrigates to enhance productivity considers the resource trade-offs: How much water is available? How much water will be needed and how much will it cost? When will irrigation be required and who will do the work? Where will the benefits be? (Hanks and Campbell, 1993).

When and how much to irrigate should be, but often is not, a scientific approach to determine irrigation requirements. Accurate irrigation scheduling requires that water be applied not on the day the soil simply appears to be dry or on the day that happens to be most convenient, but that the correct amount be applied when the crop requires it (Bailey, 1990). The correct amount should be applied at the correct time, based on the understanding of each individual crop's requirement, soil type and the practicalities of application (Bailey, 1990). Thus, irrigation scheduling aims at applying water *before* the soil becomes dry enough to affect the crop, and thereby providing an environment to maximise plant growth. This purpose, quite often, is constrained by the need to use a limited amount of water to stretch water supplies, and to reduce drainage and minimize pollution. To accomplish this it is necessary to quantitatively consider the soil water balance, as it is impossible to do so by visual examination of the crop or soil (Stockle and Villar, 1993, Bailey, 1990).

Numerous irrigation scheduling aids have been developed in the past. Every method follows the basic question of when and how much water to apply, and

focuses on the understanding of the soil water balance. It is evident that the goal of scientific irrigation scheduling is achievable, but there is a need for simple basic approaches that can be adaptable to practical situations at farm level. The understanding of the soil water balance in irrigation planning is fundamental. All aspects of irrigation management require an understanding of the soil water balance, which necessitates simulation or measurement of the amount of water in the root zone at any given time (Tollefson, 1996; Hanks and Campbell, 1993; Gardner, 1983).

The basic relation of field water balance components can be written as (*Allen et al.*, 1998, Hanks and Campbell, 1993):

$$I + P = E_S + T + R + D_r + \Delta S \quad (2.1)$$

Where:

I = irrigation

P = precipitation

E_S = soil evaporation

T = transpiration

R = run-off

D_r = drainage below root zone

ΔS = change in soil water storage (with a negative value for ΔS meaning that the soil became wetter).

From equation 2.1 it is evident that the amount of irrigation required for optimum plant growth depends on several factors. Soil water loss due to direct evaporation from the soil surface, drainage and surface run-off are not beneficial to dry matter production, but are components of the field water balance. Under water scarce conditions, the best management strategy would be one that aims at maximizing water loss through T, by minimizing the wasteful losses that do not contribute to yield, by irrigating to match the shortfall in precipitation with the losses due to evapotranspiration.

Climatic conditions dictate the timing and amount of precipitation, and it has a direct influence on potential evapotranspiration (PET), and hence actual evapotranspiration (ET_a), through evaporative demand. The rate of ET_a increases with an increase in net radiation and a decrease in relative humidity provided the soil water status can provide for water lost due to E and T, and if precipitation occurs in quantities greater than the soil water holding capacity, drainage will occur. Some of the water will be lost as run-off if the rate of water infiltration into the soil is low.

E_s is primarily depended upon soil water status and atmospheric conditions. If the soil is wet, E_s will be dependent on the climatic environment, and will be in the *"constant rate stage"* and will be at the potential soil evaporation rate (E_{sp}), (Hanks and Ashcroft, 1980). If the soil is air dry, Es will be less than E_{sp} and will be in the "falling rate stage". The value of E_{sp} depends on the crop because canopy properties, such as shading, will influence the microclimate (Hanks and Campbell, 1993). The value of E_{sp} might be measured approximately by a free water evaporimeter within the canopy or by measuring net radiation. Also, as first proposed by Boast and Robertson (1982) and described in detail by Boast (1986), measurements of soil evaporation, E_s, can be obtained with the use of microlysimeters (Kidman *et al.*, 1990). Hanks and Campbell (1990) found that for a field planted to sweet corn (*Zea mays*), the rate of E_s decreased rapidly early in the season followed by a moderate decrease later in the season. The moderate decrease in the later in the season was due to increased canopy cover unlike early in the season when the crop was still emerging. These complications were, therefore, found to make estimates of E_s in the field somewhat uncertain.

Transpiration (T) is more complicated to measure than E_s. This is because T involves biological as well as physical processes. Practical models for determining T include E, thus ET rather T alone can to some extent be easily determined with equations like the Penman-Monteith equation. This equation requires weather data to estimate ET (Hanks and Campbell, 1993).

Precipitation (rainfall) on the other hand, occurs uncontrollably, so irrigation planning has to adjust to it. Historical climatic data gives information as to what happened in the past, so there is a need to adjust to what can be expected. The amount of rain that can be stored by soil can only be effectively determined if the amount of drainage and run-off is known (Hanks and Campbell, 1993). An on-site measurement of rainfall gives certainty as to how much rainfall actually occurred.

Irrigation (I) has some of the same uncertainty as rainfall but can be managed with how much and when irrigation is applied. Irrigation has historically been applied in sufficient amounts to ensure good plant growth. This has undoubtedly resulted in excess leaching that needs to be minimized. Different irrigation methods may also have their own built in uncertainties, some leading to unequal distribution of water applied (Hanks and Ashcroft, 1980).

Drainage, D_r, is probably the most uncertain water balance component because it is so difficult to measure what is happening within the soil at the bottom of the root zone. Flow is very slow and may be highly variable and soil properties also may be highly variable. Use of models is probably the best approach to estimate D_r based on water balance concerns (Hanks and Ashcroft, 1980). However, the difficulty in estimating D_r with the water balance approach is that errors in estimations of ET would make large errors in calculations of D_r since D_r is estimated as the difference of all other components of water balance (Hanks and Campbell, 1993).

Surface run off, R, is also difficult to estimate in many instances. There are few measurements made of R in irrigation, it is difficult to estimate R, so additional uncertainty is introduced. However, there are many conditions where R is zero and can be predicted as such. R is usually zero if the field were irrigation is applied is in a confinement and or plots separated hydraulically, like in this experiment or in pot experiments. However, if R is not zero the amount is uncertain.

Technologies and know how exist for determining soil water depletion. Such tools involve the use of devices like the neutron probe for measuring soil water status at the beginning and end of a certain time period (Greacen, 1981). With the widespread use of computers and electronics in agriculture, models have been developed to simulate crop water use. Such models include the SAPWAT model by Van Heerden *et al* (2001) and the Soil Water Balance (SWB) model by Annandale *et al* (1999). The integration of the components of the soil plant atmosphere continuum (SPAC) through the use of computer simulation models provides a clear understanding of the field water balance and its influence on crop water uptake.

2.2 Practical Irrigation Scheduling Methods

Tighter competition for water use, as was projected in the past, is already evident (Amar *et al.*, 2002). Aside from the crop water requirements, water losses which are not beneficial to crop processes can add huge volumes to the total water usage in agriculture (Amar *et al.*, 2002). Water is a finite limited resource. Therefore, water utilization requires a rational approach (Seckler *et al.*, 1998, Molder, 1997). The ultimate goal is to ensure an optimum balance between the components of the field soil-water-balance (Equation 2.1), such that the storage is not over filled or under filled (Amar *et al.* 2002). Thus, the challenge of irrigation scheduling is to ensure this harmonious balance between the components of the soil-water-balance for optimum crop growing conditions.

More often than not, the goal of irrigation is met with constraints, as the amount of water that must be applied is wrongfully predicted due to uninformed use of available irrigation scheduling tools or a lack of appropriate irrigation scheduling technology (Brodie, 1984). Thus, the water requirements of crops grown at different times of the year and under different management vary considerably (Steiner and Howell, 1993).

There are three main approaches to scheduling - soil based, plant based and atmospheric driven. Each has strong and weak points, and there is a history

associated with each. For example, atmospheric based methods were the most common (because with E_{pan} it was reasonably easy to measure evaporation from a pan) but then the advent of the neutron probe and tensiometer made soil based measurements more popular (Greacen, 1981). For a while, (mostly in the 70's and 80's), plant based methods looked promising scientifically, but never took off in the marketplace (Evett and Steiner, 1995 and Greacen, 1981). Computers rekindled interest in atmospheric-based methods and a range of new soil monitoring tools have recently come on the market, which is reinvigorating soil-based irrigation scheduling (Mölder, 1997).

2.2.1 Soil-Based Approaches

These methods are based on measurements of soil water content and/ or matric potential, and other soil properties that influence the availability of soil water to plants. Campbell and Mulla (1990) describe three types of measurements relating to soil water as important factors for planning and management of irrigation. Those factors are the measurement of soil water content, soil water potential and hydraulic conductivity. Soil water content and soil water potential relate to the state (amount/availability) of water in soil, and soil water conductivity relates to the movement of water in the soil.

Water content is generally described in terms of the mass of water per unit mass of soil, or on a volume basis. This measurement describes the amount of water stored in the soil. Direct measurement of water content is possible by sampling the soil and weighing, drying, and reweighing the samples – gravimetric water content (gram of water per gram of soil). However, most literature cites water content on a volumetric basis because irrigation amount is commonly expressed as a depth of water.

Soil water potential is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at

atmospheric pressure to the soil water at a specified point (energy per unit quantity of soil water relative to that of pure free water at atmospheric pressure), and is useful for describing the availability of water to plants and the driving forces that cause water to move in soil (Campbell and Mulla, 1990).

The hydraulic conductivity of the soil is important for determining infiltration rates, field capacity, resistance to flow towards crop roots, and drainage of saturated soil (Campbell and Mulla, 1990). Water in the soil moves as a front because of the difference in hydraulic conductivity between the wet soil and the as yet unwetted deeper soil layer. That is the hydraulic conductivity of the unwetted soil is so low that water can only penetrate it when the gradient is very steep. Thus, it follows that the drier the soil is initially, the "sharper" must be the wetting front (Hillel, 1998).

Normally 24 to 48 hours after irrigation or rainfall, drainage rate drops such that all the water is presumably held by the soil particles. This drained upper limit is known as field capacity (FC). FC is defined as the amount of water held in the soil after excess water has drained away and the rate of downward movement has become negligible, while evaporation is presumed to be zero (Hillel, 1998; Bailey, 1990, and Campbell and Campbell, 1982). Water above this level is also available to plants, but only for a limited time depending on the rate of drainage. At field capacity, water is held at a matric potential around -10 J kg^{-1}. Water held in the effective root zone of a particular crop, and which is available for extraction through evapotranspiration is known as plant available water (PAW). The lower limit of PAW is referred to as the permanent wilting point (PWP). At this point, soil water is strongly held by the soil matrix and is not available for plant root uptake. This water content typically occurs at matric potentials around –1500 J kg^{-1}. The aim of irrigation scheduling is to prevent soil water content from decreasing below threshold water content at which yield losses and wilting occurs. The threshold water content is commonly known as allowable depletion level (ADL). In order to achieve optimal dry matter production and yield, as a good rule of thumb, it is a norm in irrigation scheduling to use an ADL of 50% (half way between FC

and PWP). This value, however, depends also on crop water stress tolerance and atmospheric conditions (Jovanovic *et al.*, 2003, and Kirkham, 1990).

The neutron scattering method is the most widely accepted method of measuring changes in the amount of water stored in the soil (Campbell and Mulla, 1990; Haverkamp *et al.*, 1984, and Greacen, 1981). This is a non-destructive method of measuring soil water content based on the slowing down by hydrogen of fast neutrons emitted by a radioactive source. The neutron probe consists of a radioactive source and a detector for detecting slow moving thermalized neutrons (Fig. 2.1). The neutron probe method is expensive and poses a radiation hazard to the user if not carefully managed. It requires calibration and therefore, some level of expertise is required to schedule irrigation using the neutron probe method (Hatfield, 1990).

Tensiometery is a popular and practical irrigation scheduling method. Tensiometers are used for measuring soil matric and gravitational potential, which determines the direction of water movement by measuring soil suction (Gaudin and Rapanoelina, 2002; Campbell and Mulla, 1990). Tensiometers are excellent at telling the farmer when to irrigate (because soil tension is what the plants actually experience) but it is not so easy to determine how much to irrigate. They need to be read on a daily basis and often need periodic servicing if soil dries out. Reliable measurements with tensiometers are limited to suctions of 0 to 80 kPa (Hoffman *et al.*, 1990). Tensiometers require considerable time for recording of observations and at a suction greater than 80 kPa, air is drawn in and the device must be refilled with water (i.e. the servicing described above). Unless the farmer is prepared to regularly refill tensiometers that have cavitated, the temptation is to keep the device reading at low suctions, often resulting in over irrigation (Gaudin and Rapanoelina, 2002; Tollefson, 1996; Hoffman *et al.*, 1990).

Other methods for estimating soil water status are based on the electromagnetic interaction between water and its constituents (water and soluble solutes). These include the use of Time Domain Reflectometry (TDR) (Robinson *et al*, 1999, and Campbell and Anderson, 1998). All above-

mentioned measurements like TDR, capacitance, and the heat dissipation sensor method are site specific. As such, they need many observations to properly characterize a field. In addition, methods like TDR and the heat dissipation sensor are laborious to install and have high initial costs. They also require tedious calibration procedures and constant supervision (Tollefson, 1996).

The capacitance method (which is similar to TDR but much cheaper) is becoming very popular with several new products on the market. It is likely that these methods will replace neutron probes on farms – and they can give a continuous trace rather than just the intermittent measurement of the soil water content, which is a big advantage compared to the neutron method.

Figure 2.1 *Neutron probe placed on the access tube. The probe is lowered down the access tube without exposing the operator to the radioactive source.*

2.2.2 Plant-Based Approaches

Visual examination of plant responses to soil and environmental conditions can serve as a logical indicator for irrigation scheduling (Hsiao and Bradford, 1983). These methods are based on the delicate balance between crop water uptake from the soil and water loss (Hsiao and Bradford, 1983) through ET. Water stress occurs when atmospheric demand exceeds water supply from the soil. Plants draw quantities of water in excess of their essential metabolic needs; this water is transmitted to an unquenchably thirsty atmosphere through the stomata as transpiration (T) (Hillel, 1998). This loss of water by plants is a process driven by a gradient in water potential between the normally water-saturated leaves and the often quite dry atmosphere, and therefore, is not an active plant process. This water moves from high to low water potential (Hsiao and Bradford, 1983).

Upon interception of solar radiation, the stomatal pores open to assimilate CO_2 needed for photosynthesis, and simultaneously water evaporates (in the opposite direction) from the sub-stomatal cavities (Hsiao and Bradford, 1983). This water loss lowers the leaf water potential, which in turn causes water to move from the stems to the leaves, thereby, lowering the potential in the stem. Water then moves from the root system to the stems, in turn lowering root water potential. Soil water potential is now higher than root water potential and so water moves from the soil into the roots. Since the lowest potential in the system is in the atmosphere, the atmospheric demand is therefore the primary driving force for water movement.

This water movement through the soil plant atmosphere continuum is subject to certain resistances. In wet soil, soil resistance is small because the soil matrix does not hold water tightly. However, as the soil starts to dry the major resistance is located in the soil just around the roots (Jovanovic *et al.*, 2003). Irrigation keeps the soil resistance at a minimum. For a given atmospheric demand and canopy size, the plant resistance determines the rate at which water will be transported to the leaves, and it increases with an increase in

soil resistance. The stomatal resistance is at the leaf atmosphere interface, and it determines the rate of water loss (which also depends on the atmospheric demand) from the leaf into the atmosphere. When leaf water potential is low, stomata will close to prevent water loss thereby increasing stomatal resistance. T is the price plants pay for photosynthesis; any water loss due to transpiration is productive water use (Hillel, 1998; Hsiao and Bradford, 1983).

An indicator of water availability is whether or not the plant can transpire (T) at the potential rate (PT), which is determined by the atmospheric evaporative demand. When water is freely available and the potential transpiration is not excessive, then T relative to PT is 1, showing that the root system is able to keep up with the atmospheric evaporative demand and thereby preventing wilting. If T/PT drops below 1, it means that the root system can no longer supply water fast enough to keep up with demand and the soil water can be seen to be less available. So, it is clear that the water between FC and PWP is not equally available to the crop, although it is all available to the crop. Therefore, yield losses and wilting will occur if the field is dried below ADL. This threshold point, ADL, is dynamic and depends on rooting density, canopy resistance to water loss, hydraulic conductivity of the soil and atmospheric demand.

The purpose of irrigation is to maintain optimal plant water status in order to achieve optimal yields. Under intense evaporative demand with shortages of soil water, the plant loses water faster than it takes it up, and the leaf water potential (Ψ_L) decreases (Kirkham, 1990). Leaf water potential is, therefore, a measure of plant water status (Hsiao, 1990). Leaf water potential can be measured with a pressure bomb (Phene *et al.*, 1990). This method is not easy to determine on a large field scale, and it is expensive. The main problem is that leaf water potential and stomatal conductance change rapidly throughout the day. It is difficult to relate a measurement taken at one point in time to the "stress" that the plant is experiencing (Stirzaker *et al.*, 2000).

Often times under conditions of severe water stress, the plant allows the leaves to remain turgid at low water potential by accumulating solutes into leaf cells. This phenomenon is termed osmotic adjustment and it is a long-term strategy for avoiding desiccation (Radin, 1983). It enables the plant to reduce its water potential to enable water uptake from very dry soil. The decrease in leaf water potential creates a gradient for water uptake against plant resistance. Plants can use this mechanism for short-term survival against water stress. Another plant-based approach is that of determining stomatal resistance. When transpiration begins to exceed water uptake due to water shortages in the soil under high evaporative demand conditions, the plant closes stomata as a mechanism for preventing desiccation. This occurs when leaf water potential is reduced, and the stomatal cells dehydrate. This leads to closure of the stomatal pores, which increases stomatal resistance. A measurement of stomatal resistance provides an index of plant water status, and can be obtained with a gas diffusion steady state porometer (Phene *et al.*, 1990).

In hot climates when the canopy temperature is high, plant transpiration provides a mechanism for cooling themselves down which is an added advantage of transpiration to plants - evaporating water takes energy (heat) out of the system. When only a little transpiration takes place because the plant is stressed, the incoming energy heats up the canopy and increases canopy temperatures. Canopy temperature of a well-irrigated crop is similar to field canopy temperature, and therefore, can be an indicator of water stress. Portable infrared thermometers measure radiation emitted from all parts of the canopy within the field of view of the instrument (Phene *et al.*, 1990). This method requires a well-irrigated canopy transpiring at the maximum rate for the particular atmospheric demand conditions, to be adequately applied as an index of water stress. That is the canopy temperature of a well-irrigated (uniformly rather than inconsistently) crop is similar to field canopy temperature. The setback is that a well-irrigated canopy is generally not available in commercial fields, so this method is suitable mainly for research and not field applications.

There are numerous methods, destructive and non-destructive, for determining plant water status, like thermocouple psychrometry, which measures leaf water potential (Campbell and Mulla, 1990). These methods are labour intensive and require many samples. Measurements must be normalized with well-irrigated fields for accurate estimations (Phene *et al.*, 1990). Plants can also be used to schedule irrigation through visual observation. However, visual indicators of plant stress are often an after the fact method of scheduling, and thus considerable dry matter loss may occur before being noticed. Plants can indicate when to irrigate, but we still need to know how much irrigation water to apply. Most of the techniques mentioned above are not practical as they are too difficult for use in the field on a routine basis.

2.2.3 Atmospheric-Based Approaches

The effect of climate on crop water use has long been recognized. As such, the atmospheric-based approach follows a meteorological imposed evapotranspiration demand that varies over time. The irrigation requirements are determined by the rate of evapotranspiration (ET) (Hatfield, 1990). The level of ET is related to the evaporative demand of the atmosphere and the supply rate of water from the soil/root system.

ET is directly inferred from the residual of the soil water balance after all other components have been measured in equation 2.1 and is given as:

$$ET = I + P - R - D_r - \Delta S \quad \text{.....(2.2)}$$

The evaporative demand can be expressed as the internationally standardized reference evapotranspiration (ET_o) (Allen *et al.*, 1998). ET_o represents the rate of evapotranspiration of an extended surface of an 8 to 15 cm tall green grass cover, actively growing, completely shading the ground and not deficient of water. Methods to calculate the reference evapotranspiration include the Penman-Monteith grass cover equation, and

the Pan evaporation of water is also used as a reference method of estimating ET_o (Allen *et al.*, 1998, and Doorenbos and Kassam, 1979).

ET_o is related to maximum crop evaporation (ET_m) by an empirically determined crop coefficient (K_C) when water supply fully meets the water requirements of the crop. The relation is obtained by (Allen *et al.*, 1998, and Doorenbos and Kassam, 1979):

$$ET_m = K_C ET_o \quad (2.3)$$

The value of K_C varies with crop, development stage of the crop, to some extent with wind-speed and humidity, and management (irrigation frequency). For most crops, the K_C value increases from a low value at the time of crop emergence to a maximum value during the period when it reaches full development, and declines as the crop matures. K_C values of different crops have been developed (Allen *et al.*, 1998).

ET_o is a dynamic process driven by the available energy, and can be limited by the ability of the plant to conduct water from the soil to the leaf (Steiner and Howell, 1993). To compute ET_o one requires; minimum and maximum temperature, solar radiation, minimum and maximum relative humidity, and average wind speed. However, some of these parameters cannot be obtained in some localities due to inaccessibility to automatic weather stations, in which case they can be estimated following guidelines of Allen *et al.*, 1998.

In the past the pan evaporation method has been widely used (Green, 1985), although, with less accuracy, because it requires application of empirical coefficients to relate pan evaporation to ET_o (Allen *et al.*, 1998, and Doorenbos and Pruitt, 1977). This is due to the fact that the positioning of the pan may not reflect the same situation as the field where the crop is growing, and in some cases, shading may occur giving unrealistic evaporation values. Data required with the pan evaporation method is mean pan evaporation from a class A pan (E_{pan} in mm day^{-1}), and information on whether the pan is surrounded by a cropped or dry fallow area.

ET_o, representing the mean value in mm day^{-1}, over the period considered is obtained by:

$$ET_o = K_{pan} E_{pan} \quad (2.4)$$

Where E_{pan} is evaporation in mm day^{-1} from a class A pan and K_{pan} is a pan coefficient (Allen *et al.*, 1998). The approach for estimating crop water requirements using ET_o becomes very useful when used in combination with other methods like computer crop simulation models.

The class A pan method has the advantage that it provides an index of the integrated effects of radiation, air temperature, air humidity and wind on ET. However, this method is disadvantaged by the fact that the crop factors are not always transferable from district to district or season to season and depend heavily on the irrigation method used. Errors in crop factors are always cumulative, so that the farmer tends to consistently over irrigate or under irrigate (Stirzaker *et al.*, 2000). Its downside also lies in the significant differences in water loss between the cropped and water surfaces. The rate of water loss from a cropped surface is not the same as from a water surface. Hence, this method requires correction coefficients to adjust evaporation values obtained from a pan to crop ET (Allen *et al.*, 1998).

To employ the pan/crop factor method, the farmer needs to be able to perform the calculations and read and maintain the pan. With the aid of computers and availability of weather data for various locations in South Africa, it becomes easier to compute reliable ET_o values. However, the majority of producers are computer illiterate or some use computers but not for irrigation scheduling (Botha *et al.*, 2000), so determination of accurate ET_o values is restricted.

The pan method has lost popularity because reliable ET_o estimates are now more available than in the past decade or so. Weather parameters for determining ET_o can be obtained from a network of automatic weather stations available. However, the complexity of processing this enormous amounts of data impair the adoption of the developed computer simulation

models by farmers, especially resource poor farmers. Hatfield (1990) further adds that the limitations within the models are mostly associated with instrumentation and the collection of data. Accurate measurements are required of several parameters to run these models.

2.2.4 Model-Based Approaches

The soil-plant atmosphere-continuum (SPAC) is an integrated system that constitutes physically integrated and dynamic components of the soil, plant, and ambient atmosphere, which mutually attribute to soil-water extraction and utilization by plants. With the aid of computers and electronics, several irrigation scheduling models based on evapotranspiration (ET) have been developed to quantify the SPAC, for the betterment of irrigation scheduling, in terms of accuracy when estimating crop water requirements (Hatfield, 1990). Such models in South Africa include the Soil Water Balance (SWB) model (Annandale *et al.*, 1999), and SAPWAT by Van Heerden *et al* (2001). The SWB model is a mechanistic, real-time, generic crop, soil water balance, irrigation scheduling model, which gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data (Annandale *et al.*, 1999). On the other hand, SAPWAT has been developed for the purpose of planning irrigation and to estimate crop water requirements (Van Heerden *et al.*, 2001).

These computer models are developed to ease the burden of computing complex mathematical equations for determining crop water requirements. As an integrated approach, computer models have a great degree of accuracy in estimating crop water requirements.

Mohan and Arumugam (1997), define systems that provide an efficient means of providing decision support that require experience-based knowledge as expert systems. So, it is quite notable that these models require an in depth understanding of the SPAC and a good level of training experience for on-farm irrigation scheduling purposes. Reliance on experience and experts is

necessary for effective decision-making in the complex domain of irrigation management (Mohan and Arumugan, 1997). Some of the computer simulation models, like SWB, although not designed as an expert system (Annandale *et al.*, 1999), can be used for real time scheduling and provide reliable and accurate measurements of crop water use and water requirements (Annandale *et al.*, 1999).

For these models to be effective in determining crop water use, they require several input variables. Accurate and reliable inputs may not be available at the farm level, like crop parameters, soil data and many other variables depending on the type of model (Tollefson, 1996). Models must provide farmers with the daily information needed to make timely decisions. The disadvantage with these models includes development of appropriate crop parameters suited for different areas and crop types. Most farmers' perception is that, models were meant for precision farming and scientific research, not for on-farm application. The concept of models is difficult to implement in small scale farming, even for commercial farmers of developed countries, due to a lack of appropriate infrastructure and skills (Botha *et al.*, 2000, and Tollefson, 1996), and most notable the reluctance to try out the new technologies available.

2.3 The Use Of Scheduling Aids At Farm Level

Despite numerous and varied scheduling aids, the majority of farmers, especially small-scale farmers, do not utilize available irrigation scheduling services (Pereira, 1996). According to a study by Leib *et al.* (2002), most farmers are likely to use irrigation scheduling tools based on their simplicity and cost. For instance, a 1997/8 survey showed that all farm size groups in Washington, USA, reported high utilization of the feel/ appearance method (71%) to determine the status of soil water. As for sensors, the large farms were likely to use a neutron probe and one very large farm was the only one to indicate the use of TDR. Although, these results were obtained from a developed foreign country, a logical comparison of the use of irrigation

scheduling tools by producers under South African conditions can be made out of these results. It is also evident that most farmers are likely to use less complicated scheduling methods to monitor soil water status. As an example, 76% of small-scale farmers in Washington reported using the feel/appearance method on a total of 300 ha, while none of them used TDR. This observation may be attributed to the fact that TDR is more of a scientific tool rather than an on farm tool. In the same study, nine smallholder farm groups out of 23 farms reported the use of tensiometers to schedule irrigation, and the generally observed pattern is that more farmers are likely to adopt an easy to employ tool to schedule irrigation.

Determination of crop evapotranspiration is another important approach in scientific irrigation scheduling. From the survey in Washington, smaller farms (16 – 405 ha) reported greater use of on-site evaporation pans to estimate ET than the very large farms (> 405 ha). However, the overall adoption rate of crop water use information was greater in the large farm groups, with 61% reporting the use of nearby weather stations on 19 102 ha while 9% of small farms used nearby weather station information on 62 ha. The survey also revealed that 77% of all operators indicated ownership of computers, however, only 5% of all respondents used their computers to schedule irrigation (Leib *et al*, 2002). Data from a local weather station may require some pre-processing and computation before one can use it, so this might be the reason for not utilizing the nearby weather station data to a greater degree.

In a South African context, irrigation scheduling is perceived by the majority of farmers as a tool for precision farming, and which is not intended for farmers but rather for research purposes (Botha *et al.*, 2000). This is mainly because most of the farmers are still emerging, 3.24 million or subsistence as compared to 50 000 commercial farmers (Backeberg, 2003). Thus, most farmers are mainly smallholder producers who do not rely solely on income from agricultural production but are working elsewhere, and only practice crop production for food security on small food plots (Backeberg and Odendaal,

1998). However, the common practice of the smallholder and commercial farmer is that irrigation is applied based on experience acquired over the years and the advice obtained from neighbouring farmers (Botha *et al.*, 2000). According to Jovanovic *et al* (2003), such a practice of 'gut feeling' irrigation scheduling is thought to be accurate, however, decline in agricultural production, destruction of arable lands through urban development and increasing groundwater pollution are some of the facts that exist to prove the inaccuracy of this method.

To ensure an increase in efficient water use, government policies have increased the price of water on irrigation schemes, cutting down governmental subsidies and shifting water ownership rights from farmers to water boards through water use licenses (Botha *et al.*, 2000 and Backeberg and Odendaal, 1998). However, some farmers can afford to over irrigate in the short term, but may later be affected by previous mismanagement. Technologies to improve water productivity exist, however, most of the tools are difficult to implement and expensive to employ. Moreover, quite often, the advice of local extentionists is ignored. For instance, in a study conducted by Botha *et al* (2000), 51.2% of the 43 respondents from the Riet River irrigation scheme in South Africa indicated that they first heard of irrigation scheduling from the local Co-operative. However, the consistency of the visits to the farmers by the extentionist played a vital role to the continual use of the irrigation scheduling technology rendered to the farmers. For this particular survey there were originally 78% of farmers who indicated the use of an irrigation scheduling service from the local Co-operative or extentionist, but when the extentionist stopped his regular visits this number declined to 65.2% (Botha *et al.*, 2000). This can be attributed to the fact that the farmers were not adequately informed about the benefits of irrigation scheduling. Instead, the farmers reverted back to their usual practices, gut feeling or no irrigation scheduling at all (Botha *et al.*, 2000).

The use of computers in irrigation scheduling was low (8 out of 28 farmers indicated ownership of computers and not all used them for irrigation scheduling purposes), mainly because the local farmers believe that

computers are complex and costly to operate and others were just satisfied with their current practice ('gut feeling'). However, 32% of the 43 farmers indicated interest in employing computer-based irrigation scheduling models because they believed that the computer models are more accurate than conventional methods in determining irrigation requirements. Most farmers, however, cited problems of computer literacy, availability of results on time and applicability to local conditions (Botha *et al.*, 2000).

The main reason for poor adoption of most irrigation scheduling techniques or tools is that their cost does not really reflect the extent to which they can be easily applied under field conditions - they are expensive and difficult to implement. According to Burt (1996), many of the irrigation scheduling methodologies developed could be associated with training and or educational but have little or no practical use in implementing a desirable schedule of water delivery if the goal is to maximize yield with increased efficiency in water use in irrigated agriculture. To the irrigation farmer all capital expenditure on irrigation scheduling and any other production input must be compensated by commensurate returns in income. Van der Westhuizen *et al* (1996) found that in South Africa, the primary reason farmers do not schedule irrigations is that they do not perceive the net benefit to be positive.

Both over and under-irrigation can reduce the effectiveness and sustainability of irrigation. Historically, more attention has been given to the problems of under-irrigating than to over-irrigating. The effects of under-irrigating are generally exhibited on a field level often within the immediate growing season, while the problems associated with over irrigation are exhibited on a regional basis over a longer time period (Steiner and Howell, 1993).

With increased pressure from other water users, specifically through domestic and industrial consumption, there needs to be major improvements in water use by irrigation farmers. This is because irrigation is the dominant user of water, especially in developing countries, currently estimated at 80% of the total annual water budget (Hennessy, 1993). There are numerous irrigation scheduling aids available, however, the overall adoption rate is limited. Some

of the constraints encountered include; flexibility, cost of scheduling and many others. Flexibility in irrigation scheduling is essential. Irrigation scheduling becomes redundant if water is not available when required or if supplied on a rigid schedule without due consideration to crop requirements. This is common in areas where water is delivered to farmers on a predetermined schedule. These conditions of rotational supply render many of the modern irrigation scheduling technologies impractical. This necessitates development of viable methodologies to adapt to these situations.

Irrigation scheduling methods can be costly and time consuming. Unless properly monitored and maintained, they can be unreliable (Tollefson, 1996). Many farmers will continue to execute conventional native irrigation scheduling methods with limited decision-making skills, unless new technology developed provides directly perceived benefits with minimal costs or demand for time. If the benefits are not evident, the acceptance and use will be limited unless highly subsidized.

Given all the discrepancies and complexities attached to various scheduling devices and approaches, the WFD aims at balancing cost, simplicity and accuracy in irrigation scheduling. Thus, the WFD is a simple affordable tool. Its mode of operation is based on sound soil physics and water movement in the soil. However, the farmer does not have to be a soil physics scholar to use a WFD. The tool gives an indication of whether or not water has reached a certain depth in the soil, and then the farmer can follow a chosen algorithm to adjust his irrigations (Stirzaker, 2003, and Stirzaker *et al.*, 2003).

CHAPTER 3

THE WETTING FRONT DETECTOR

3.1 Introduction To The Wetting Front Detector

The wetting front detector (WFD) is a simple user-friendly device designed to help farmers' better management irrigation. It is a funnel shaped device that is buried open end-up in the soil (Fig. 3.1). The wetting front detector is buried in the root zone and gives a signal to the farmer when water reaches a specific depth in the soil. Farmers can use the detector to know whether they are applying too little or too much water (Stirzaker *et al.*, 2000).

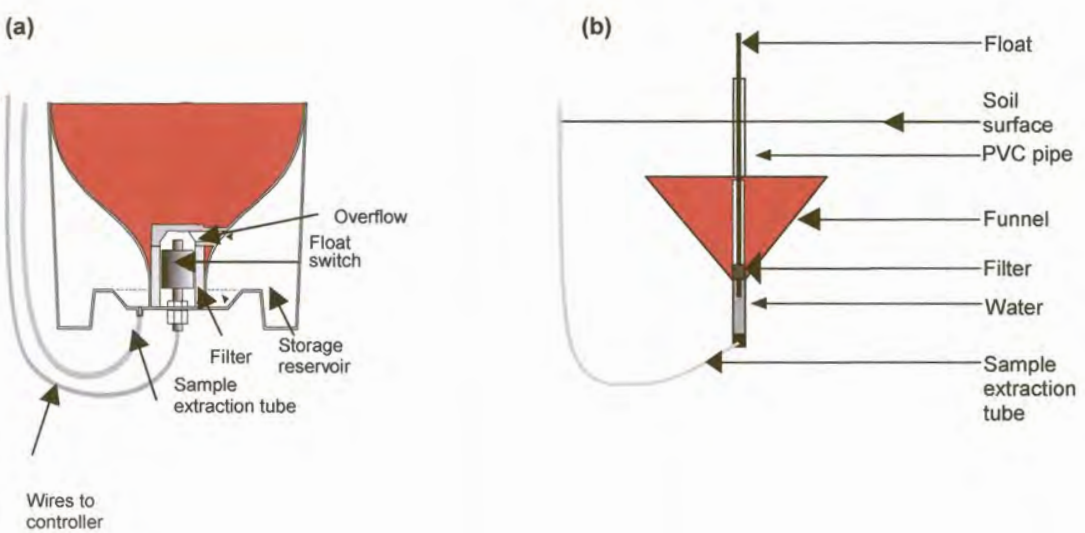


Figure 3.1 *(a) Electronic (FullStop), and (b) manual (Machingilana) version of the newly patented wetting front detector.*

As indicated in Figure 3.1, there are two versions of the newly patented wetting front detector; one is called a FullStop, which derives its name from a logical combination of the words 'full' and 'stop'. A FullStop can stop an irrigation event by breaking the circuit to a solenoid valve when the soil is 'full' of water to a required depth, hence the name "FullStop".

The other simpler purely mechanical version is called a Machingilana (MACH). A Machingilana is a sePedi word for a *watchman,* who stands at the gate to monitor the people going through. Similarly, the Machingilana is placed at a specific depth in the soil and indicates whether a wetting front has passed this depth or not. The principle of operation of both versions of the WFD is the same; the only difference lies in the way they provide a signal to the farmer.

3.2 How The Wetting Front Detector Works

Water in the soil moves as a front, except for cases of preferential flow. This front is a resultant difference in wetness between the wetted upper zone and the drier unwetted soil below the wet zone. The area between the wet and dry soil is characterized by rapid change in wetness and is called the wetting front. At the wetting front, the moisture gradient is so steep that there appears to be a sharp boundary between the moistened soil above and the initially dry soil beneath. This is because the hydraulic conductivity of the as yet unwetted soil is so low that water can only penetrate it when the gradient is very steep. Hence, it follows that the drier the soil is initially, the "sharper" must be the wetting front (Corradini *et al.,* 2000, and Hillel, 1998).

The WFD is buried open end up at a certain depth in the soil, and gives a signal that the wetting front has reached a specific depth or not. The dimensions of the WFD are such that when the wetting front reaches the detector the unsaturated flow streamlines are diverted towards the centre of the funnel due to convergence. Free water is then produced at the centre of the funnel, which then flows through the filter into the PVC pipe (Fig. 3.1b) or into a chamber surrounding the electrical switch (Fig. 3.1a). For instance, a dry soil would be at a certain matric potential before irrigation, say 50 cm (Appendix A), and the tension would decrease steadily from the soil surface downwards upon irrigation application or rain. As the wetting front reaches the top of the wetting front detector, water will converge towards the centre of the funnel due to its shape. In an initially dry soil, this convergence is also due to

the high suction by the soil in the WFD. With more rain or irrigation, free water would then be produced at the base of the funnel as water content increases (Appendix A). The free water would escape through the filter into the chamber to activate the switch, in the case of the electronic WFD or into the bottom section of the PVC pipe in the case of the mechanical version to activate a polystyrene float. However, some of the water moving down will not be caught by the WFD and will continue to move down even when irrigation has closed. In both versions, it would take about 20 *mℓ* to activate either the lightweight rod or electrical switch (Stirzaker *et al.*, 2000). The fundamental logic behind the operation of this WFD is directly related to the physics of the downward movement of water in the soil.

Once free water is produced and stored in the reservoir, the lightweight rod will remain activated until the farmer chooses to reset the detector (Fig. 3.1b). In this prototype of the mechanical version, water must be sucked through the sample extraction tube to reset the detector (Stirzaker *et al.*, 2000). The extracted sample can also be used to monitor fertilizer leaching or salts.

In the electronic version, FullStop, water stored in the float chamber can be withdrawn upward by capillary action when the soil above the detector dries out. In this way the float switch will fall down or reset, rendering the detector ready for the next irrigation. This is because if the float switch is down or reset the irrigation controller is turned on, the detector then completes the circuit between the irrigation controller and the solenoid valve. In this way the FullStop has the risk of running an extended irrigation if the run time set on the irrigation controller is too long. For instance, if an irrigation controller is set to run three hours of irrigation and it takes one hour to activate a detector connected to the solenoid valve. It is possible that after the first activation the detector can reset before the set run time elapses (water sucked out of the device by capillary action), and in this way the circuit between the irrigation controller and solenoid valve will be reconnected, thus *reactivating* the device *and* allowing for extended irrigation. This led to the notion that the FullStop *"wanted"* a certain amount of water but the controller *"gave"* a certain amount

predetermined by the programmed time on the irrigation controller. This will be discussed in detail in Chapter 5.

Water collected in the storage reservoir of the FullStop, can be emptied by sucking it out through the extraction tube, and it can also be used for monitoring nutrient leaching.

3.3 How To Use A Wetting Front Detector

Early research work done with this WFD, has given hope for the adoption success of the tool; hence, this follow up research work has been undertaken. In earlier work, the electronic version connected to an irrigation controller was used to irrigate turf grass by sprinkler. Four detectors were used to control irrigation. Irrigation was automatically started every four or five days and shut off by the detectors when three of the four had detected the wetting front. The experiment was run over two summer seasons and gave excellent results (Stirzaker and *et al.*, 2000).

The usual practice is to install a pair of detectors (shallow and deep) in one location at a horizontal spacing of 60 – 90 cm: the first about half way down active root zone and a deeper detector towards the bottom of the active root zone. The active root zone was defined as a layer of soil containing most of the roots that we wish to replenish with water. For a lucerne crop we chose to manage a root zone of about 60 cm deep. The ideal depth of placement for the shallow detector would be such that it is 20 cm from the lip of the funnel to the soil surface, because the distance from the float switch to the lip of the funnel is 10 cm, and this is the depth that the wetting front has reached when a signal is received (Appendix A). The wetting front speeds up a bit inside the funnel due to the convergence, so the wetting front is about 10 cm below the lip when the float rises or switch floats. This implies that when a detector is installed at 30 cm it is 20 cm from the soil surface to the lip of the funnel. The point of detection for the wetting front will be at about 10 cm below the lip of the funnel. The deep detector at the bottom of the root zone would be installed

at 50 cm from the lip of funnel to the soil surface (60 cm from the soil surface to the measuring point). By following the number of detectors responding the farmer can then adjust his irrigation application and timing according to a chosen algorithm, so as not to consistently over or under-irrigate. In this manner, the farmer can use this WFD to ensure a minimum wastage of water past the root zone.

In terms of the irrigation management strategy chosen by the farmer, a FullStop can be used to control irrigation (that is in *'control'* mode), as was the case with one of the treatments of this experiment. The FullStop is connected to an irrigation controller via an irrigation solenoid valve.

The MACH type WFD that was used for this experiment can only be used in *'feedback'* mode. Thus, the number of detectors responding can be used to adjust irrigation according to a chosen algorithm. The ideal algorithm would be to increase irrigation quantities (or shorten irrigation cycle) if few shallow detectors are activated and to decrease irrigation quantities if many deep detectors (or lengthen the irrigation cycle) are activated. The FullStop can also be used in feedback mode by logging the activation and resetting using a data logger.

3.4 Depth Of Placement Of The Detector

Choosing the appropriate depth of placement and the irrigation interval are important factors in determining the accuracy of this method of irrigation scheduling. Most irrigation equipment applies water at a fairly high rate (compared to say a light drizzle). Under commercially available irrigation equipment, most wetting fronts move at suctions between 2 kPa and close to zero. This is well above field capacity, which is somewhere between 5 and 10 kPa. The wetting front will therefore continue to move below the detector after irrigation has stopped when used in control mode, as the water content above the detector drops towards the drained upper limit or field capacity. To compensate for this, the shallow detectors should be placed about halfway down the root zone for light soils and two-thirds of the way down the root zone

for heavy soils (Stirzaker *et al.*, 2000). This is to ensure minimum water draining below the root zone after irrigation was stopped, i.e. to reduce drainage.

Knowledge of soil properties is useful for determining depth of placement of the detector and the appropriate irrigation interval. One can define the active rooting depth as the zone of soil containing sufficient roots to dry the soil at potential rates. The active rooting zone may be a function of soil properties (e.g. shallow topsoil). In other cases, farmers have a preference for frequent small irrigations or infrequent larger irrigations, which will determine the active root zone.

If the detector is to be placed with the top of the funnel at 20 cm to the soil surface then you need to dig a hole about 30 cm deep and 30 cm wide at the surface. Keep different soil layers in separate piles. In the centre of the hole drive in a stake or crowbar a further 10 cm. Move the stake from side to side to make a hole with a diameter of about 5 cm to accommodate the narrow end of the funnel and the PVC pipe. Holes can also be dug with augers, 20 cm diameter for the large hole and 5 cm diameter for the small hole.

Fill the neck of the funnel with washed sand (up to where the funnel widens). This will settle around the mesh and act as extra filtration. It is essential that the sand is washed, otherwise fine material will block the mesh filter. Lower the detector into the hole and pack soil under and around the sides of the funnel until it is firmly in place.

Pour soil into the detectors and press down lightly. Do not compact the soil over the top of the funnel. The hole should be filled with soil in the same order as it was removed.

The detector is best installed into freshly ploughed soil. If the soil surface sinks a bit after watering, rake the soil above the detector to make the soil surface even again. If water collects in a depression above the detector, it will signal early and not be representative of the whole field.

An example of calculating depth of placement for the detector and irrigation interval is given below for the site where this project was carried out. The management root depth was chosen at 600 mm. The depth to the shallow detector (d_d) was halfway down the active rooting depth or 300 mm. From soil water retention curve measurements it determined that the water content at the wetting front θ_{wf}, drained upper limit θ_{dul}, refill point θ_{rf}, and lower limit θ_{ll} were, 0.21, 0.18, 0.14 and 0.09 m m^{-3} respectively (Table 3.1 and Appendix B). The water content for wetting front (θ_{wf}) and refill point (θ_{rf}) was estimated from the water retention curve following determination of the drained upper limit and lower limit. Thus, it is theoretically accepted wetting front water content occurs above FC and that refill point should be between lower limit and FC (at least 50% below FC). This assumptions were followed simple theory on FC and lower limit, as such may not hold for any soil type or any situation.

Table 3.1 *Water content for different levels or points obtained from the soil moisture retention curve (Appendix B).*

Threshold	Water Content (m m^{-3})
Wetting front (θ_{wf})	0.21
Drained upper limit (θ_{dul})	0.18
Refill point (θ_{rf})	0.14
Lower limit (θ_{ll})	0.09

The amount of water, I, applied to a crop with a detector in control mode would be,

$$I = d_d (\theta_{wf} - \theta_i) \quad \text{.....(3.1)}$$

where θ_i is the water content before irrigation.

Assume θ_i was the refill point or 0.14, then the amount of irrigation applied by a control detector would be 300 mm x (0.21 – 0.14) = 21 mm. If initial water content was at PWP then 36 mm would be applied (300 mm x (0.21 – 0.09) = 36 mm). This would represent the most water one could apply.

If irrigation was stopped automatically as soon as the wetting front reached the detector, then some water would redistribute below the detector. This is called the overhead.

The overhead, ***O***, or the amount of water that moves below the controlling detector is;

$$\boldsymbol{O} = d_d (\theta_{wf} - \theta_{dul}) - T_d \quad (3.2)$$

Where T_d is daily transpiration (T_d is included because transpiration and redistribution take place simultaneously). For example, if most of the redistribution took place in 24 hours and crop water use was 8 mm day^{-1} then the overhead would be 300 mm x (0.21-0.18) – 8 mm day^{-1}= 1 mm. However, if ET was only 3 mm day^{-1} overhead would be more (6 mm). The overhead will also depend on the speed of redistributing water as well, so this calculations serves to give a rough estimate of what can be expected thereof.

Using the above equations and rough estimates of ET, we can calculate appropriate irrigation intervals. We know that in reality the amount of water we irrigate is the wetting front water content minus the refill water content times the actual depth of the detector (300 mm) and the amount of water between wetting front water content and refill point is 0.07 m m^{-3}. So;

$$\text{Irrigation Interval} = d_d (\theta_{wf} - \theta_{rf}) / ET \quad (3.3)$$

In summer when the ET may average 8 mm day^{-1}, the interval should be 3 days (300 mm (0.07)/8 mm day^{-1} = 3 days). In winter where ET may be 3 mm day^{-1}, the interval should be lengthened to 7 days (300 mm (0.07)/3 mm day^{-1}= 7 days).

The above points are theoretical and only serve to illustrate that detectors could be used incorrectly. If the irrigation interval for a given depth of placement was too long in summer the crop would run into stress, because there is a limited amount of water that can be added before the wetting front reaches the detector. Conversely, over irrigation is possible if irrigation is carried out too frequently, particularly in winter when ET is low. It is not expected that farmers, operating at any scale should go through the above calculations.

By using detectors in pairs, one placed halfway down and the other towards the bottom of the active root zone, farmers can work out if they are over irrigating or under irrigating. For example, we advise farmers that it is best that the shallow detector is only occasionally activated when the crops are young, assuming they show no visual signs of stress. This helps to minimise fertilizer leaching when the crop is still young. As the crop grows it is important that the shallow detectors respond regularly, to ensure that more than half the active root zone is rewetted with every irrigation. The deep detectors should respond from time to time, demonstrating that we are not drying out the lower half of the active root zone. However, if deep detectors respond regularly, it is likely that over irrigation is occurring. Much of the aim of this thesis is to test these ideas. It is usually advisable that the farmer gets the shallow detector going off or activated more often than the deeper ones bottom of the root zone. In this way irrigation water is contained within the effective root zone, the crop will neither be consistently under nor over - irrigated.

CHAPTER 4

EXPERIMENTAL MATERIALS AND METHODS

4.1 Experimental Background And General Layout

The WFD experiment was conducted with lucerne (*Medicago sativa*, variety WL 525 HQ) as experimental crop (Fig. 4.1). This work was carried out at the University of Pretoria's experimental farm in Hatfield (South Africa). The crop was planted on the 16th of October 2001 (DOY 289). The experimental design was a completely randomised block with six treatments, and each treatment replicated five times. Sixty hydraulically separated plots were set up under a rain shelter with a drip irrigation system, of which the 30 outer plots served as border plots. The plots were divided at the edges with 1.2 m deep asbestos plate (and the edges rising above the soil surface by 20 to 25 cm). The experiment was conducted on a Hutton soil form, according to the Soil Classification of South African: A Taxonomic System For South Africa. (1991). Six different irrigation-scheduling methods were applied to the 30 internal plots (Fig. 4.2; see also Appendix C). The treatments investigated were scheduling using the neutron probe soil water measurement method (NP), a soil water balance model treatment (SWB) and four different ways of using wetting front detectors. The wetting front detector treatments were split as two types of automatic control FS1 and FS2), and two types of feedback control. That is building a crop factor using wetting front detector (CF) and a feedback treatment (Machingilana - Mach). These will be discussed in detail later.

Each experimental plot had an area of 5 m^2 (length = 2.5 m and breadth = 2 m), and 4 rows of 2.0 ℓ h^{-1} dripper lines. Each dripper row had seven emitters (30 cm spacing between emitters). The three cross pieces at each end contained one emitter each (Fig. 4.3). The total number of emitters per plot was therefore 34, giving a flow rate of 68 ℓ h^{-1}. The irrigation system therefore, had a delivery rate of 13.6 mm h^{-1}. The wetting pattern was one dimensional

with a wetted diameter of 25 to 30 cm covered by each emitter. However, the 13.6 mm h^{-1} drip tape was later replaced with 18.4 mm h^{-1} (thus with 2.7 $\ell\ h^{-1}$ dripper lines) pressure compensated drip tape, because we needed pressure compensation to ensure that flow rates did not change too much when plots were automatically shut off by a FullStop.

Figure 4.1 *The lucerne crop with the rain shelter open to allow exposure of the crop to ambient environmental conditions.*

Soil preparation was done by loosening the topsoil with a garden fork and then broadcasting 2:3:4 (30) NPK fertilizer at a rate of 500 kg per hectare. The fertilizer was evenly distributed and worked slightly into the soil using a rake. Lucerne seed was treated with 20 $m\ell\ kg^{-1}$ of Seedflo®, an inoculant with the active ingredient sodium molybdate, which acts as a stabilizing and binding agent, and also for the prevention of molybdenum deficiency, an ion important for nitrogen fixation. Seed was planted at an inter-row spacing of 24 cm at a rate of 40 kg ha^{-1}. After planting, 35 mm of irrigation was applied using a

sprinkler irrigation system. This was followed by daily irrigations of 10 mm during the first week, and changed to 10 mm every second day from the second week after planting until the crop had fully emerged.

For this particular study, the R and P components of the field water balance in equation 2.1 were eliminated because the plots were hydraulically separated (raised edges so no runoff could occur) and under a rain shelter. The field water balance equation for this study can therefore be written as follows:

$$ET + D_r = I - \Delta S \quad (4.1)$$

Where;

$$ET = (E_s + T) \quad (4.2)$$

As drainage was not quantitatively determined, the drainage component was added to ET. This is of course not applicable to all treatments, as it will come clearer later. However, there was a possibility of over irrigation with all the other treatments except (theoretically) the treatment scheduled with the neutron probe method (NP treatment). This is due to the fact that the NP treatment was irrigated according to the measured soil water deficits, whereas for the other treatments their set methodologies were applied.

The irrigation system had 14 solenoid valves connected to an irrigation controller. Ten solenoids were connected to 10 shallow FullStops in the five replicates of the FS1 and FS2 treatments. Each of these solenoids supplied water to one treatment plot plus three other border plots, giving a total flow rate of 272 $\ell\ h^{-1}$each but later 368 $\ell\ h^{-1}$. The remaining four solenoids each controlled one experimental treatment (5 plots), giving a flow rate of 340 $\ell\ h^{-1}$ each (but later 460 $\ell\ h^{-1}$) (Appendix D). This meant that for the Machingilana, NP, CF and SWB treatments, all five replicates (plots) received the same amount of water per irrigation event. However, for the FS1 and FS2 treatments, each replicate (plot) was connected to its own solenoid valve, and

therefore, each replicate received different amounts of irrigation depending on the time that the FullStop was activated. The reason that the FS1 and FS2 treatments also controlled the border plots was that we needed a certain flow rate for the pressure controller to operate within.

Figure 4.2 *The 30 external plots around the edges (without treatment labels) served as border plots, whilst the 30 internal plots were treatment plots.*

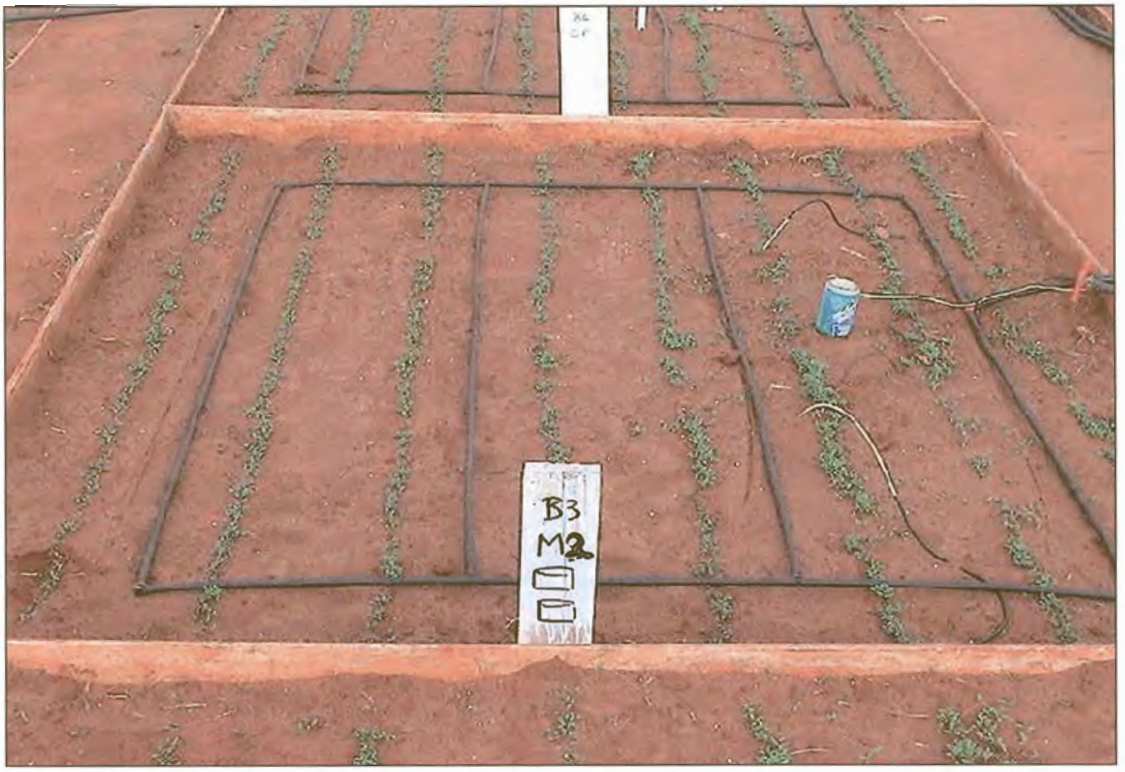


Figure 4.3 *An experimental plot with drip set-up. Each plot had four drip lines and three cross pieces at each end. Lucerne was planted in two rows between each dripper line.*

4.2 Experimental Procedures

4.2.1 Machingilana (MACH) Treatment (Feedback With A Mechanical WFD)

This treatment consisted of two mechanical WFDs installed in each replicate plot. One detector was placed at a shallow depth of 30 cm to monitor the wetting front within the upper most part of the active root zone (the effective root zone), and one at 60 cm for monitoring the bottom part of the active root zone. Of course we understand that lucerne roots penetrate much deeper than this, but are using it as an experimental crop and treating it as a crop with most of the active roots in the top 60 cm. Lucerne was also chosen because it could provide regrowth allowing for repeated measurements and sampling over different seasons.

This treatment was irrigated twice weekly at an interval of three or four days. An algorithm was developed to calculate the irrigation amount based on the number of detectors that responded to the previous irrigation. At the beginning of each growth cycle, an initial irrigation was 'estimated', after which irrigation amounts were adjusted by either increasing or decreasing the previous amount by 30%, depending on the number of deep detectors responding.

If out of the five replications;
0 or 1 deep detector responded, increase previous irrigation by 30%;
2 or 3 deep detectors responded, then give the same amount as the previous irrigation; and
4 or 5 deep detectors responded, then decrease next irrigation by 30% of the previous amount.

This treatment assumed we initially had no knowledge of the required irrigation, and had to iterate, to find a reasonable amount to apply.

4.2.2 Crop Factor (CF) Treatment (Using A Mechanical Detector To Modify A Crop Factor)

The CF treatment plots contained two mechanical WFDs placed at two depths, similar to the Machingilana treatment. It was also irrigated twice weekly. Initially the treatment was irrigated according to an estimated crop factor (e.g. 0.4). Crop water-use was then calculated using ET_O and crop factors. The crop factor was continuously adapted as the season progressed, based on the observations made from the deep WFDs. Depending on the WFD response, the crop factor was adjusted as follows:
If;
0 or 1deep detectors were activated by the previous irrigation, the new crop factor was increased by 0.05,
1 deep detector was activated; the crop factor was increased by 0.05,
2 or 3 deep detectors were activated; there was no change in crop factor,
4 deep detectors were activated, the crop factor was decreased by 0.05, and

5 deep detectors were activated; the crop factor was decreased by 0.1.

This treatment was an attempt to see if additional knowledge of the atmospheric demand improved our estimate of crop water use. It was a predict-feedback-adjust, approach to irrigation scheduling. The treatment aimed at getting the wetting fronts, on average, to 60 cm, and it also was a build-up of a crop factor curve through iteration. The potential evapotranspiration (ET_o) was calculated from automatic weather station (AWS) data using the FAO 56 Penman – Monteith ET_o calculator of the SWB model. Every Monday and Thursday the AWS data would be collected and imported into SWB for calculation of ET_o. For instance, if the cumulative ET_o for a 3-day period totalled 20 mm, with a crop factor of 0.4, the irrigation amount would be 8 mm.

4.2.3 Fullstop 1 (FS1) Treatment

The FS1 treatment plots contained one electronic detector (FullStop) buried at a depth of 30 cm. Each detector controlled a solenoid valve. Twice a week, the irrigation controller (control station 1 – 5) (Appendix D) would be programmed to give 180 minutes (equivalent to 41 mm, and later 55 mm at 130 to 150 kPa after changing the drip system) of irrigation. The 130 to 150 kPa pressure was measured at the inlet supplying water to the drip system, and it is the pressure at which the delivery rate of the drip system would be 13.6 mm h^{-1} (then later 18.4 mm h^{-1}). However, each replicate could get different amounts of water, depending on the time it took the wetting fronts to reach the detectors. When the wetting font reached the FullStop, the float would be activated, and because it was connected to the solenoid valve via the controller, it would immediately cut the electrical circuit to the solenoid valve and stop irrigation.

Irrigation start times were manually written down into the *'field book'* on all occasions and the times when the detectors tripped were recorded for each individual plot by data loggers connected to the FullStops.

This treatment was based on the assumptions that, by the time a wetting front have reached detection depth, there was enough water in the soil to carry the crop for 3 or 4 days till the next irrigation.

4.2.4 Fullstop 2 (FS2) Treatment

The FS2 treatment plots had two FullStops in each plot: one at a shallow depth of 30 cm (controller detector) and one deep detector at 60 cm for feedback. Initially a run time of 180 minutes was set for each of the five solenoid valves on the controller. Each plot was turned off individually when the float switches in the control detectors were activated. However, before the next irrigation, the data logger record for the deep feedback detectors was downloaded to check if they responded from the previous irrigation. If they responded, it was assumed that water redistributed from 30 cm to 60 cm after irrigation. The assumption then was that not much water was being used between the detectors (30 to 60 cm), or that the soil profile between 30 and 60 cm had enough water. Therefore, for that particular plot the next irrigation was skipped. This would allow the subsoil to dry out a little more, and when the next irrigation was applied, the wetting front would not penetrate as deep. This treatment tested the assumption that irrigating to a fixed depth might cause over irrigation if the redistribution of water below the detector exceeded the uptake of water below it. Overall, each plot would potentially get different amounts of water, depending on when the shallow detector shut off the water and whether a deep detector response forced the next irrigation to be suspended or not.

4.2.5 Neutron Probe (NP) Treatment

The NP treatment was scheduled using the neutron scattering method of measuring soil water content. The neutron scattering method provides an indirect measure of volumetric soil water content (θ) (Haverkamp *et al.*, 1984, and Campbell and Mulla, 1990).

The relationship between the count ratio (***N***) and volumetric soil water content is represented by a linear calibration function of the form (Gardner, 1986 in Campbell and Mulla, 1990):

$$\theta = a + bN \quad \text{.....(4.3)}$$

and $$N = \frac{I}{I_{std}} \quad \text{.....(4.4)}$$

Where I is the count rate, I_{std} is the standard counts, ***a*** is a constant that depends upon substances in the soil, other than protons, that are capable of thermalizing neutrons, and ***b*** is the slope of the linear regression function.

The field capacity of plots was determined before the start of this trial. This was done by irrigating all the plots to excess, and then took the neutron measurements after 24 hours. Gravimetric samples were at the same time collected from one of the border plots for the determination of volumetric water content and bulk density at FC. Measurement for a dry point was taken from a border plot that was left to dry out by a crop.

Soil water content measurements were conducted twice weekly, from which the deficits were calculated with reference to the initially determined FC for each plot. The FC points were calculated for the entire profile 0 to 120 cm and then later partitioned for the different layers, 0 to 60 cm and 60 to 120 cm for comparison of soil water distribution between the different layers. The average deficits for all plots of the NP treatment were then converted to a run time for input into the controller. Thus, all five plots of this treatment received the same amount of water per irrigation event. This treatment was a test of a conventional soil-based irrigation scheduling method, with a fixed frequency.

4.2.6 Soil Water Balance (SWB) Model

The SWB model treatment was scheduled using the SWB model (Annandale *et al.*, 1999). SWB uses Penman-Monteith reference crop evaporation (ET_o), together with a mechanistic crop growth model to calculate crop water use, using weather, soil and management data as inputs (Annandale *et al.*, 1999).

Each Monday and Thursday, the AWS data was collected and imported into the model that was used to calculate the growth stage and water use by the crop. The growth model option of SWB was used in this case, and the model would estimate deficit to field capacity and present it in graphical and numeric format. The irrigation controller was then programmed accordingly.

4.3 OBSERVATIONS

The neutron scattering method is a widely employed tool for irrigation scheduling (Campbell and Mulla, 1990). As it is often regarded as the standard method for irrigation scheduling, this treatment was chosen to be a control treatment for this experiment. For that reason, neutron probe access tubes were installed in all the other treatment plots. Moreover, the NP treatment was seen as one treatment where we thought that there would be no deep percolation. Each treatment was, however, scheduled according to the method described above under section 4.2. Neutron probe measurements were made on NP treatment plots, and other treatment plots as well. These measurements were used to calculate soil water deficit of each treatment from the determined FC points. This data was used to calculate ET + D_r for each treatment according to equation 4.1, and ET_o was calculated from AWS data using the ET_o calculator of the SWB model.

A plant sample of 1 m^2 was collected from all treatment plots for dry matter yield determination at the end of each growth cycle. The dry matter yield was determined from the leaves and stems of mature lucerne.

Several cycles were harvested from the lucerne crop. However, only three cycles were considered adequate for the evaluation of the experimental objectives. These include the summer period (January/February), early autumn (March/April) and an early winter (April/May) cycles. The first growth cycle was excluded from this analysis as the crop was initially uniformly irrigated for good crop establishment. The lucerne was cut when it reached 10% flowering, and the dry matter yield was determined by weighing oven dried samples (for 24 hours at 100 °C) collected from each experimental plot. During transition between the cycles, the lucerne was allowed to grow, although the treatments were not applied. There was no irrigation between the cycles, except at the beginning of treatment application when we wanted to bring the soil profiles to field capacity. During the Feb/March transition, the old (13.6 mm h^{-1}) dripper system was replaced with a new pressure compensated dripper system (18.4 mm h^{-1}).

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 January/February Lucerne Growth Cycle

Overview

This cycle was the first to be harvested for statistical analysis and evaluation of the six treatments. The very first cycle was not included as the lucerne was allowed to establish itself prior to testing of the different treatments. The results obtained with FS1, FS2, SWB and the control treatment (NP) will be discussed here. The results for the CF and MACH treatments will not be discussed because during this cycle the wires between the controller and the solenoid valves that supplied water to the CF and MACH treatments were accidentally swapped. In the light of this, these two treatments were excluded for this cycle.

The results obtained show that FS1, FS2 and SWB used less water than the control (NP) to produce statistically similar dry matter yields (Table 5.1 and Fig. 5.1). The FS1 and FS2 treatments received similar amounts of water, both less than the SWB treatment. Before the first cycle, the plots received 45 mm of sprinkler irrigation in an attempt to start the treatments at the same soil water content. However, this irrigation did not rewet the subsoil in the FS1 and FS2 treatments, so they started-off drier and remained so throughout the cycle (Fig. 5.2). The NP treatment served as a control treatment. Irrigation was applied according to the average soil water deficit measured across all NP treatment plots. The deficit was determined from the difference between the measured soil water content before irrigation application and the original field capacity values determined before the experiment began (described under 4.2.5), and then averaged over five plots.

Table 5.1 *Dry matter yields obtained, cumulative irrigation applied to, and calculated ET + D_r, as well as change in soil water storage (*ΔS) for the entire soil profile (0 to 120 cm) *for the FS1, FS2, SWB and CF treatments throughout the January/February growth cycle.*

Treatment	Dry matter (t ha^{-1})	Cumulative irrigation (mm)	ΔS (mm) (0 to 120 cm)	Estimated ET + D_r (mm)
FS1	4.2	137	-22	159
FS2	3.7	140	2	138
SWB	4.2	154	-21	175
NP	4.0	196	-19	215
$LSD_{p=0.05}$	Not Significantly Different			

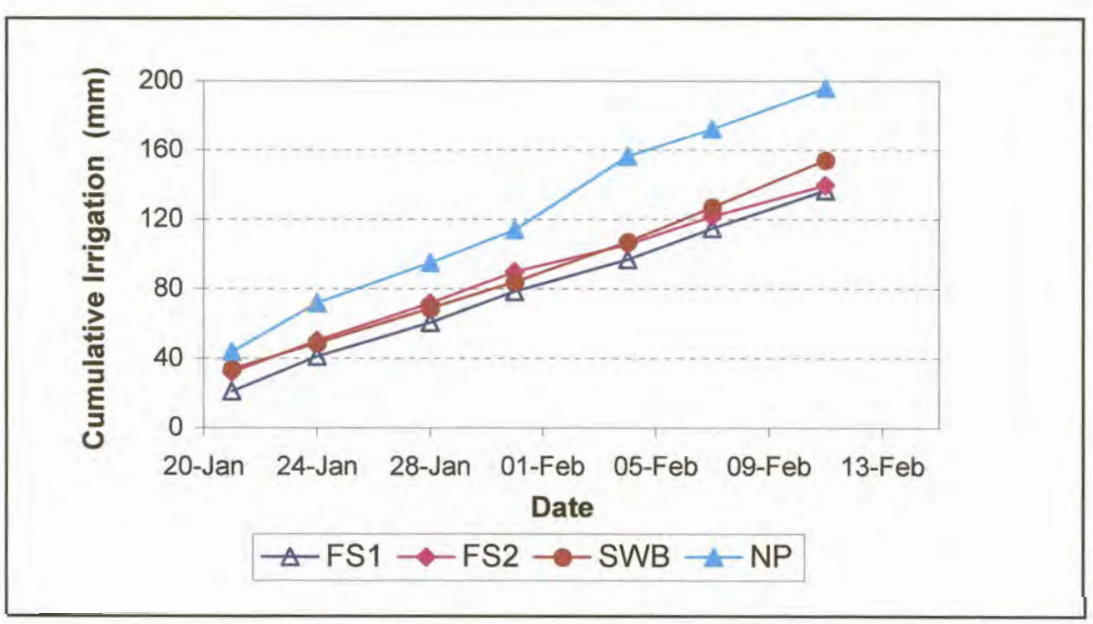


Figure 5.1 *Cumulative irrigation applied to the FS1, FS2, SWB and NP treatments throughout the January/February growth cycle.*

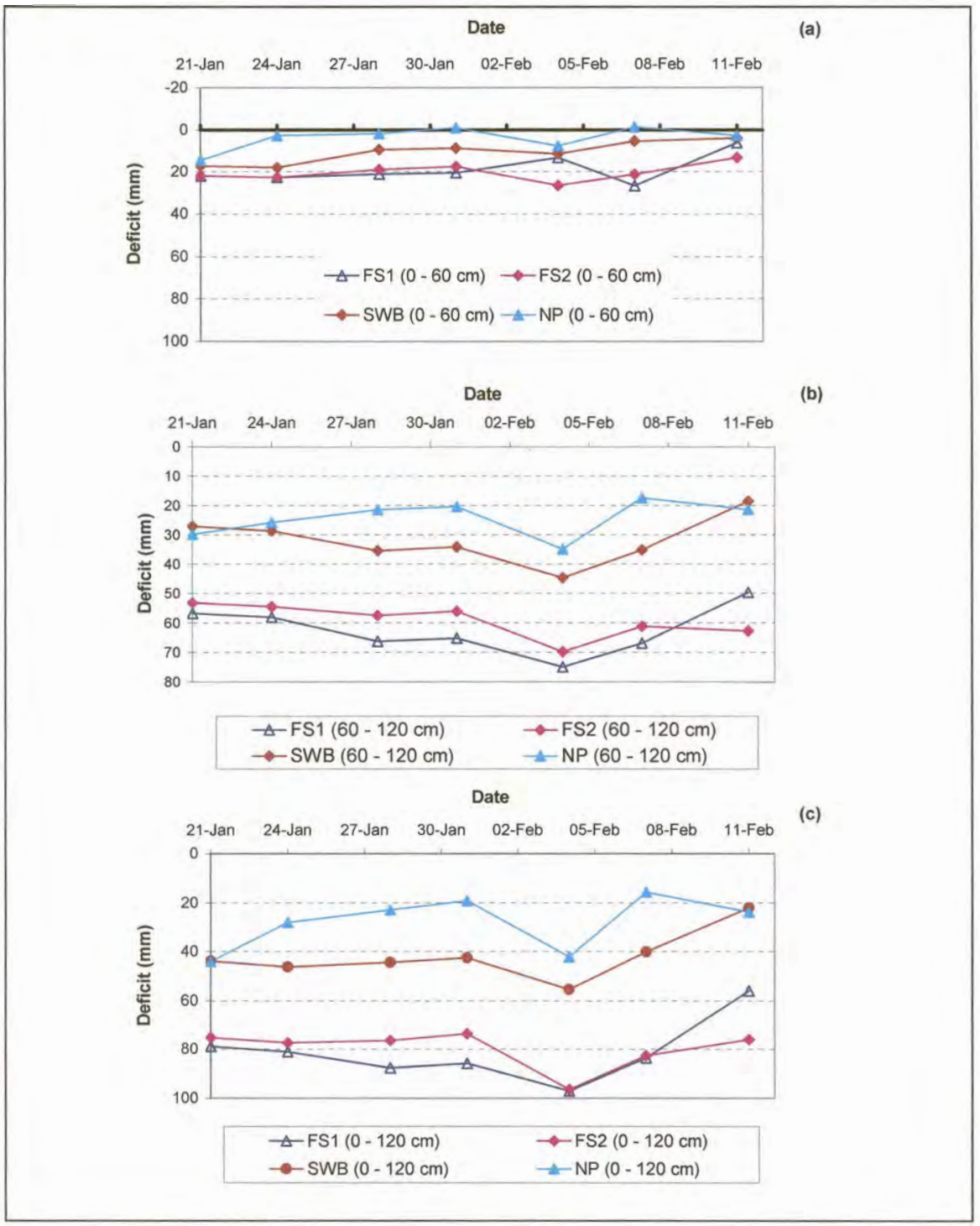


Figure 5.2 *Soil water deficit measured (a) within the "managed effective root zone" (0 - 60 cm), (b) below the root zone (60 – 120 cm) and (c) for the entire soil profile (0 – 120 cm) for the FS1, FS2, SWB and NP treatments during the January/February growth cycle.*

In the NP treatment, the measured water deficit shows that the topsoil root zone was kept at or near FC throughout the cycle (Fig. 5.3a). The aim was to refill the whole profile to field capacity. So, before irrigation, when the neutron

probe measurement was taken, the soil water content should have been three days of water use below field capacity. The amount of water applied per irrigation indicates that it was in accordance with the averaged measured deficit. However, the cumulative irrigation received by the NP treatment was higher than that of the other treatments, this indicates that the FC value was over estimated. Thus, the topsoil in the NP treatment remained constantly around FC throughout the cycle (Fig. 5.3a).

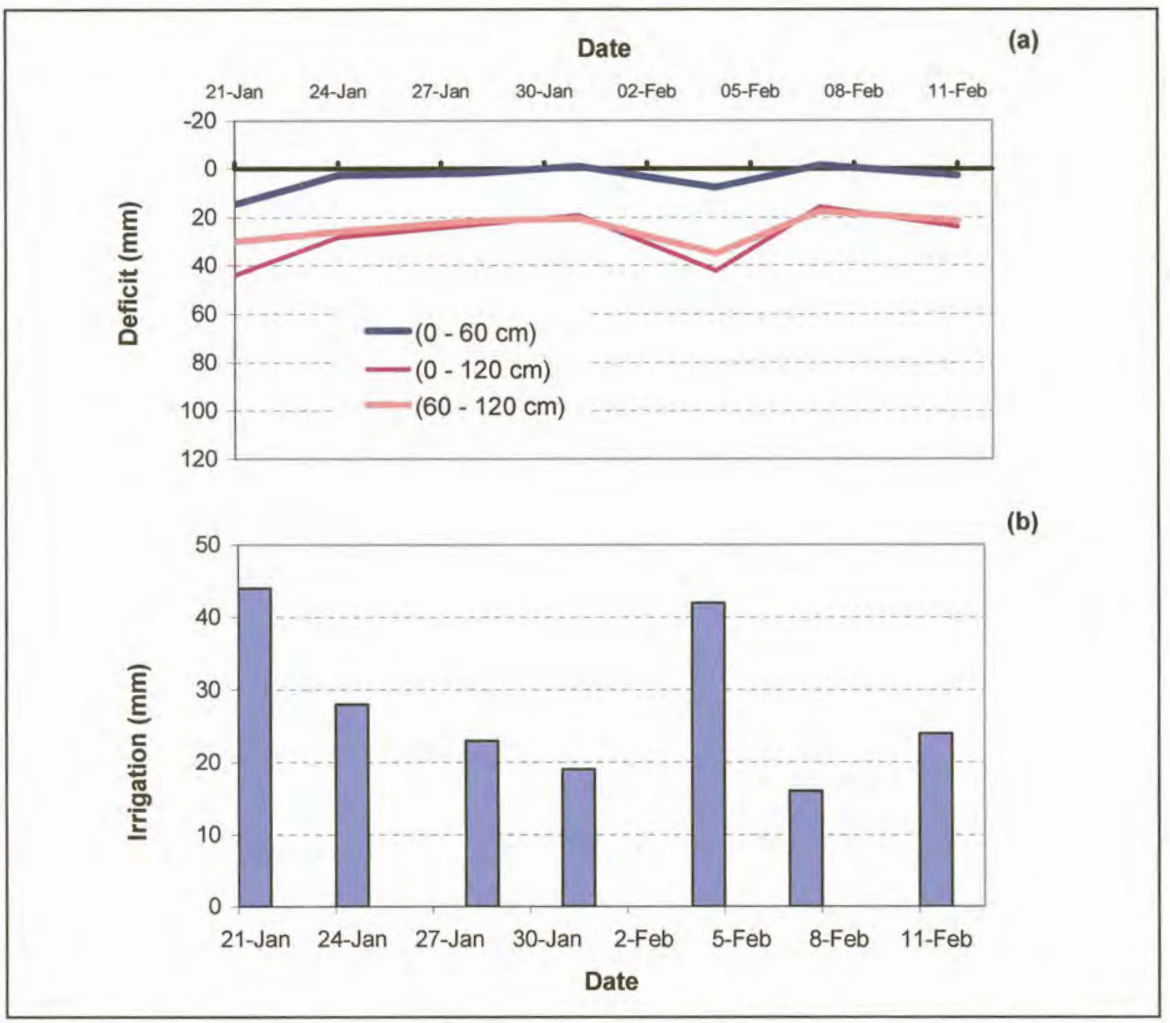


Figure 5.3 *(a) Measured soil water deficit and (b) amount of water applied per irrigation event to the NP treatment during the January/February growth cycle.*

5.1.1 FS1 Treatment

The individual plots of this treatment received different amounts of water, depending on the time when the control FullStop at 30 cm stopped irrigation.

This treatment's total irrigation is an average over five replicates. The dry matter yields from each replicate were therefore, added together as a treatment mean for statistical comparison to other treatments, and so was the water use.

Although Table 5.1 shows that the total amount of water applied was 137 mm, the control FullStop *'wanted'* 120 mm, 76 mm less than the control treatment (Table. 5.2). The 137 mm total resulted because of reactivation of the control detector after the first activation. This means that shortly after irrigation was stopped, the FullStop was emptied through capillary action, causing the float switch in the detector to drop, and in that way completing the circuit between the solenoid valve, the irrigation controller and the detector thereby allowing for continual irrigation. The reactivation was recorded with the dataloggers, and it was a result of a long irrigation run time of 180 minutes, set on the irrigation controller. However, the extended irrigation was fortunately not long enough to have caused over irrigation. As such, this treatment received less water than the control treatment. This is further confirmed by the measured soil water deficit for FS1 as compared to NP (Fig. 5.2a).

At first, there was no increase in soil water deficit, but towards the end of the cycle there was a decrease in soil water deficit. Measured soil water deficit within the effective root zone, 0 to 60 cm, never exceeded 28 mm from field capacity (Fig. 5.4a). The deficit in the whole profile, 0 to 120 cm, neither drastically increased nor decreased. Moreover, there was a dry layer of soil below the effective root zone (60 to 120 cm), and this confirms that irrigation application was good enough not to result in drainage below the root zone.

Table 5.2 *Amount of water that the treatment 'wanted' and that the control detector 'gave', and observed detector response for the FS1 treatment during the January/February growth cycle.*

Date	Irrigation *'wanted'* (mm)	Irrigation *'given'* (mm)	Number of shallow detectors responding
21-Jan	20	21	5
24-Jan	17	20	5
28-Jan	17	19	5
31-Jan	15	18	5
04-Feb	16	19	5
07-Feb	16	18	5
11-Feb	19	22	5

All detectors (shallow) responded to irrigation throughout the cycle (Table 5.2 and Fig. 5.4b), and although there was no *'feedback detector'*, the amount of water redistributing below the control detector could not have been large because the water content of deeper soil layers did not increase. That is why the layers of soil below the root zone was constantly dry throughout, except towards the end of the cycle when the deficit decreased due to a decreased atmospheric demand, whilst the irrigation quantities were increasing (Fig. 5.4b).

FS1 produced a dry matter yield of 4.2 t ha^{-1}, which is not significantly different from the other treatments at a 5 % confidence level (Table 5.1). The

FS1 treatment, however, used less water (137 mm) than the control treatment, NP.

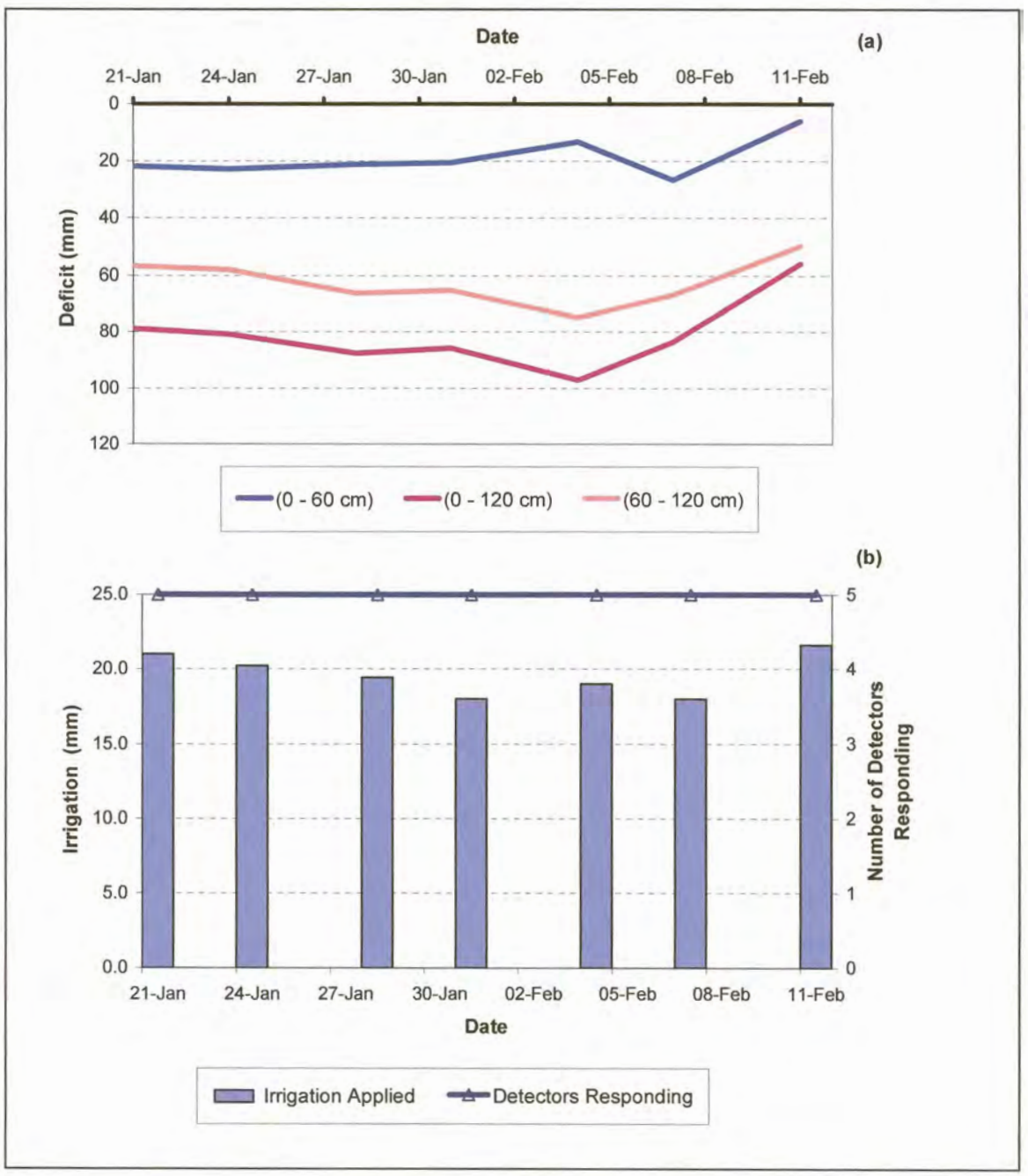


Figure 5.4 *(a) Measured soil water deficit, and (b) detector response, as well as the amount of water applied per irrigation to the FS1 treatment during the January/February growth cycle.*

5.1.2 FS2 Treatment

The total amount of water applied and yield obtained with this treatment has been averaged over four replicates out of five because the wires between the solenoid valve and the detector in the 5th replicate were accidentally cut-off, and as a result received no irrigation.

Table 5.1 shows that FS2 irrigated a total of 140 mm, whereas the control FullStop *'wanted'* 132 mm (Table 5.3), 64 mm less than the control treatment. The 140 mm resulted from *"reactivation"* of the control detector due to a prolonged run time set on the irrigation controller. However, in this case it was a minor problem. As with FS1, irrigation was controlled at a 30 cm depth. However, FS2 had feedback, which required that if a deep detector was tripped, that treatment plot missed the next irrigation. However, no deep detectors responded to irrigation during this cycle of seven irrigation events (Figs. 5.5a and b). This treatment can therefore be taken as a replicate of FS1. Hence, both treatments used similar amounts of irrigation water to produce similar dry matter yields.

The measured soil water deficit within the effective root zone (0 to 60 cm) indicates that the water deficit never exceeded 27 mm throughout the cycle (Fig. 5.5a). In this case, just like with FS1, there was a dry layer of soil below a wet effective root zone, and this implies that there was little water redistributing below the control detector. There was no response from the feedback detectors at 60 cm. This is an indication that there was not much water redistributing to deeper soil layers, which is in agreement with the neutron probe data (Fig. 5.5b). FS2 produced a dry matter yield that was not statistically different from the other treatments (Table 5.1). However, FS2 used less water to produce a similar yield to the NP treatment.

Table 5.3 *Amount of water that the treatment 'wanted' and that the control detector 'gave', and observed detector response for the FS2 during the January/February growth cycle.*

Date	Irrigation *'wanted'* (mm)	Irrigation *'given'* (mm)	Number of shallow detectors responding	Number of deep detectors responding	Replicate skipped
21-Jan	32	32	4	0	None
24-Jan	17	19	4	0	None
28-Jan	19	21	4	0	None
31-Jan	18	18	4	0	None
04-Feb	15	16	4	0	None
07-Feb	14	16	4	0	None
11-Feb	17	18	4	0	None

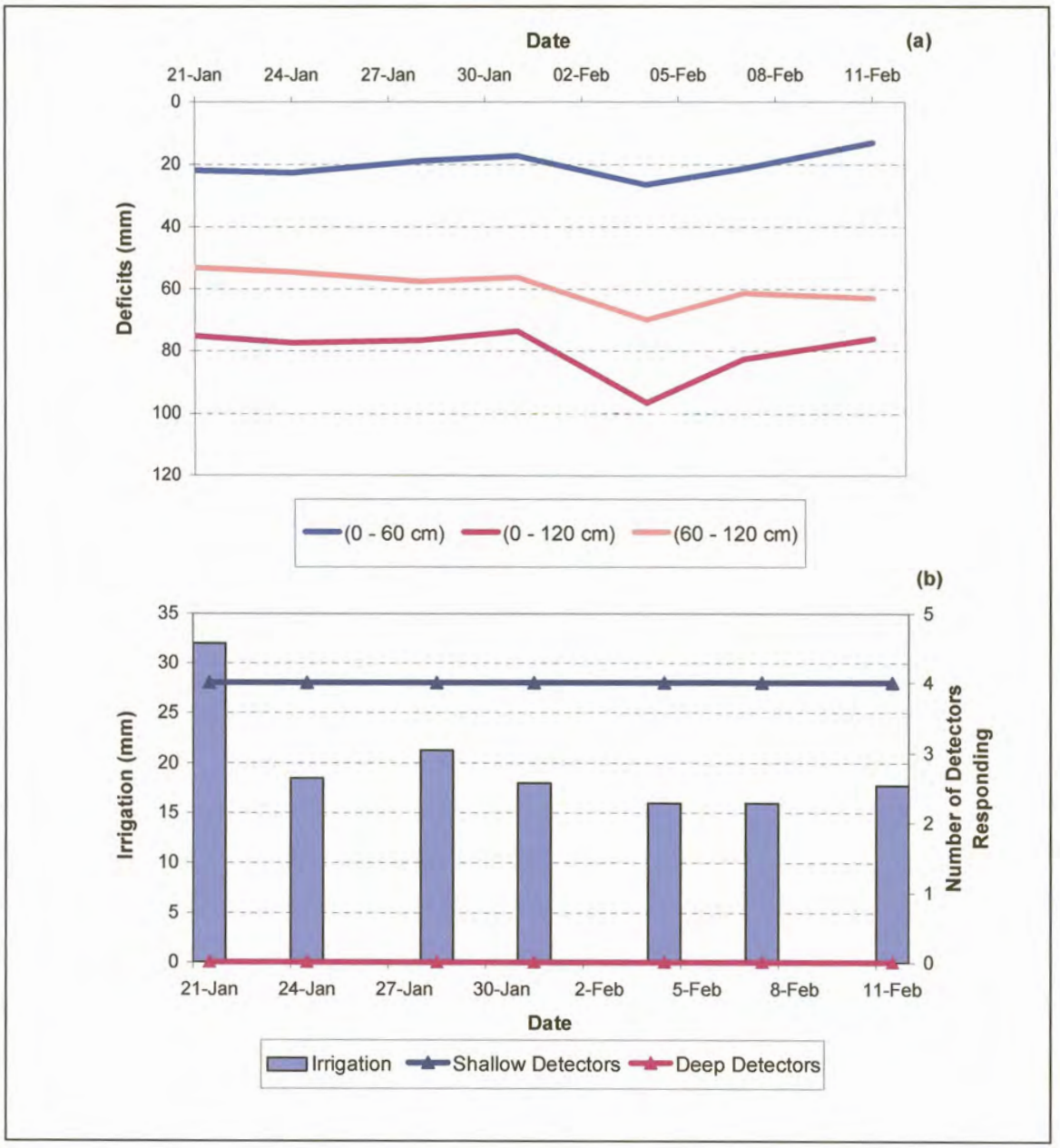


Figure 5.5 *(a) Measured soil water deficit, and (b) observed detector response as well as water applied per irrigation event to FS2 during the January/February growth cycle.*

5.1.3 SWB Model Treatment

This treatment was irrigated according to the irrigation depth (mm) recommended by the SWB model, and water deficits were also monitored with the neutron probe for comparison purposes.

Out of the seven irrigation events, the highest amount was 34 mm and the lowest 5mm (Fig. 5.6b). The 154 mm cumulative irrigation predicted by the model was 42 mm less than that of the control treatment - NP (Fig. 5.1).

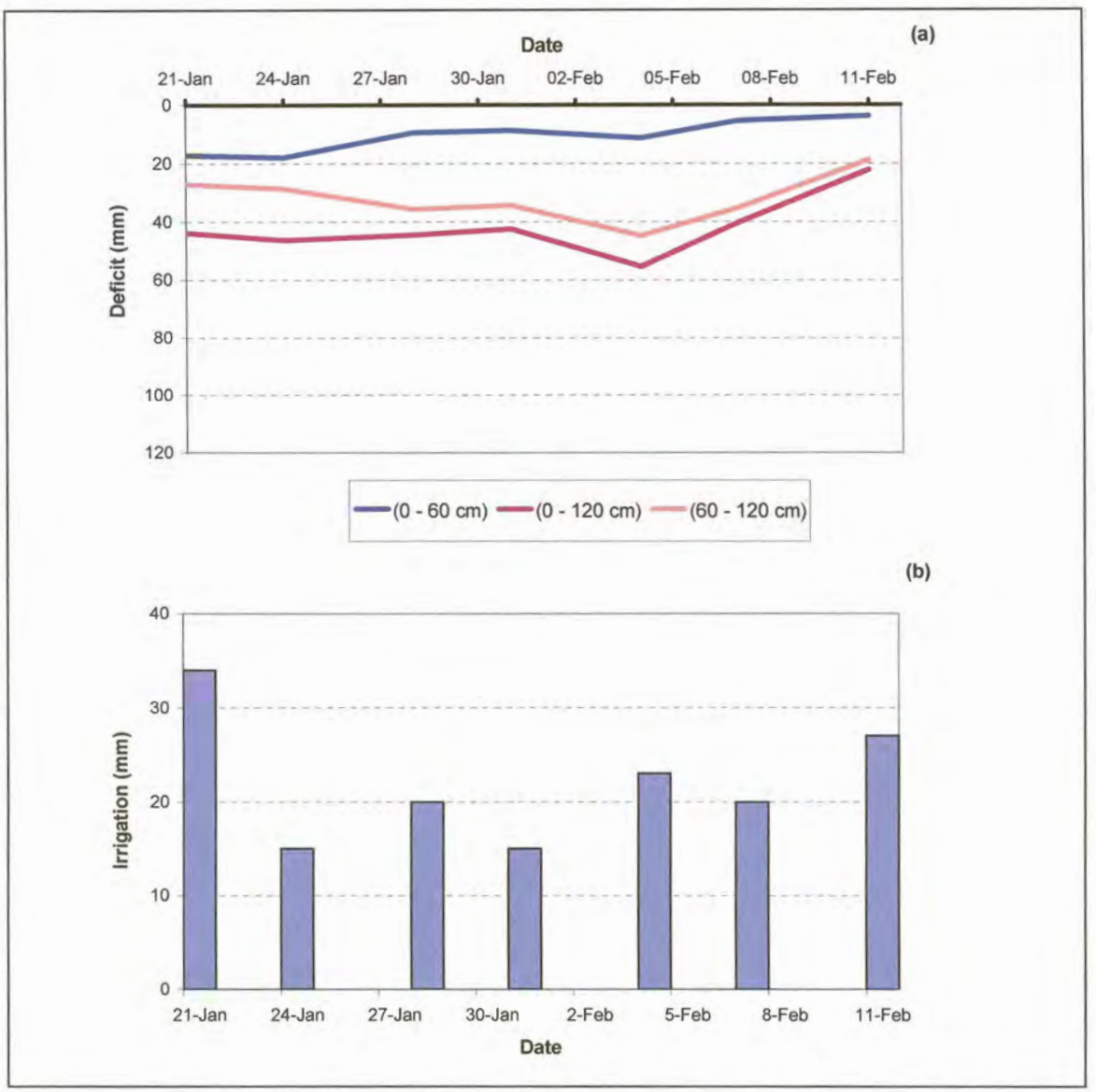


Figure 5.6 *(a) Measured soil water deficit and (b) irrigation amount applied per irrigation event to the SWB treatment during the January/February growth cycle.*

The treatment started off with a 17 mm deficit in the effective root zone and ended with water content near FC (Fig. 5.6a). The topsoil deficit decreased over time, like the FS1 and FS2 treatments. The yields were also not statistically different at a 5% confidence level, but this was achieved with 21% less water than the NP treatment.

5.1.4 CONCLUSIONS

The amount of water applied to the FS1, FS2 and SWB treatments was 137, 140 and 154 mm respectively. The FS1 and SWB treatments ended the cycle 22 and 21 mm wetter than they started. The FS2 was 2 mm wet. Using equation 4.2 we can see that ET + D_r was 159, 138 and 175 for FS1, FS2 and SWB respectively. Since the water content below 60 cm did not increase substantially (Fig. 5.2a), and was well below FC, we conclude that drainage was low. Therefore, the calculated ET + D_r was largely ET. The fact that ET + D_r for the NP treatment was 215 mm suggests that this treatment was over-irrigated, although the graph of deficit does not show that (Fig. 5.3a). Maybe the calibration or FC determination for the NP profile was incorrect (too high FC). Thus, the soil water status measurements said there was a deficit, but maybe there was not or the deficit was lower, thus over irrigation (and drainage) occurred.

5.2 March/April Lucerne Growth Cycle

Overview

This cycle proceeded after replacing the 13.6 mm h^{-1} drip system (2 ℓ h^{-1}) with 18.4 mm h^{-1} pressure compensated drip system (2.7 ℓ h^{-1}). This was to ensure a uniform water application rate when irrigation switched-off between the solenoid valves of the different treatments. Before the start of treatment application, the crop was given a sprinkler irrigation of 64 mm. This was an attempt to bring the soil profile back to FC in all treatments, so that all the plots started at a uniform soil water content. All treatments were well executed except SWB. The SWB model was not updated for each irrigation, so with time the computer programme assumed that the crop was drier, and therefore recommended a higher irrigation amount than it actually required. As a result, the SWB treatment was excluded from the analysis for his growth cycle.

The MACH, FS1 and FS2 treatments received more water than the control (NP), whilst the CF treatment received less than the control (Table 5.4 and Fig. 5.7). The measured soil water deficit shows that CF, NP and FS2 dried out their soil profiles, whereas there was no increase in deficit for the FS1 treatment (Fig. 5.8). There was a large variation in cumulative irrigation applied among the treatments (143 mm applied to the CF, 149 to NP, 172 to FS2, 183 to FS1, and 255 mm to the MACH).

Table 5.4 *Dry matter yields, cumulative irrigation to, calculated ET + Dr, as well as change in soil water storage for the FS1, FS2, MACH, NP and CF treatments for the March/April growth cycle.*

Treatment	Dry matter ($t\ ha^{-1}$)	Cumulative irrigation (mm)	ΔS (mm) (0 to 120 cm)	Estimated ET + D_r (mm)
FS1	2.8	183	-15	198
FS2	2.8	172	17	155
MACH	2.8	255	-20	275
NP	2.8	149	-4	153
CF	3.4	143	10	133
$LSD_{p = 0.05}$	Not Significantly Different			

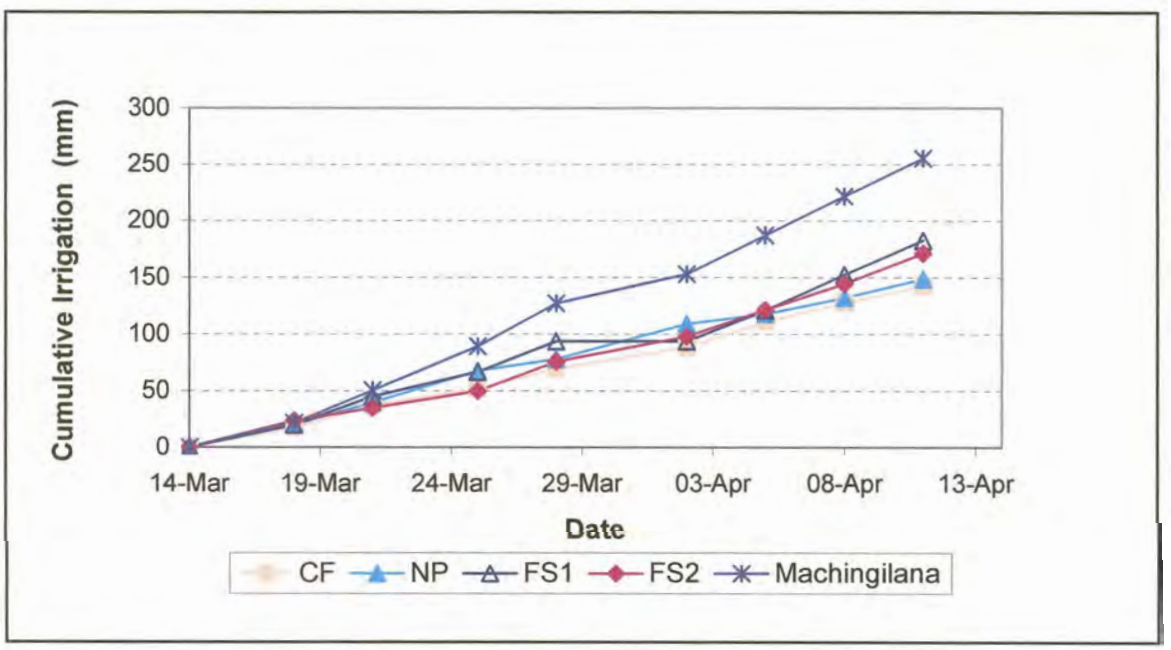


Figure 5.7 *Cumulative Irrigation applied to the MACH, CF, NP, FS1 and FS2 treatments throughout the March/April growth cycle.*

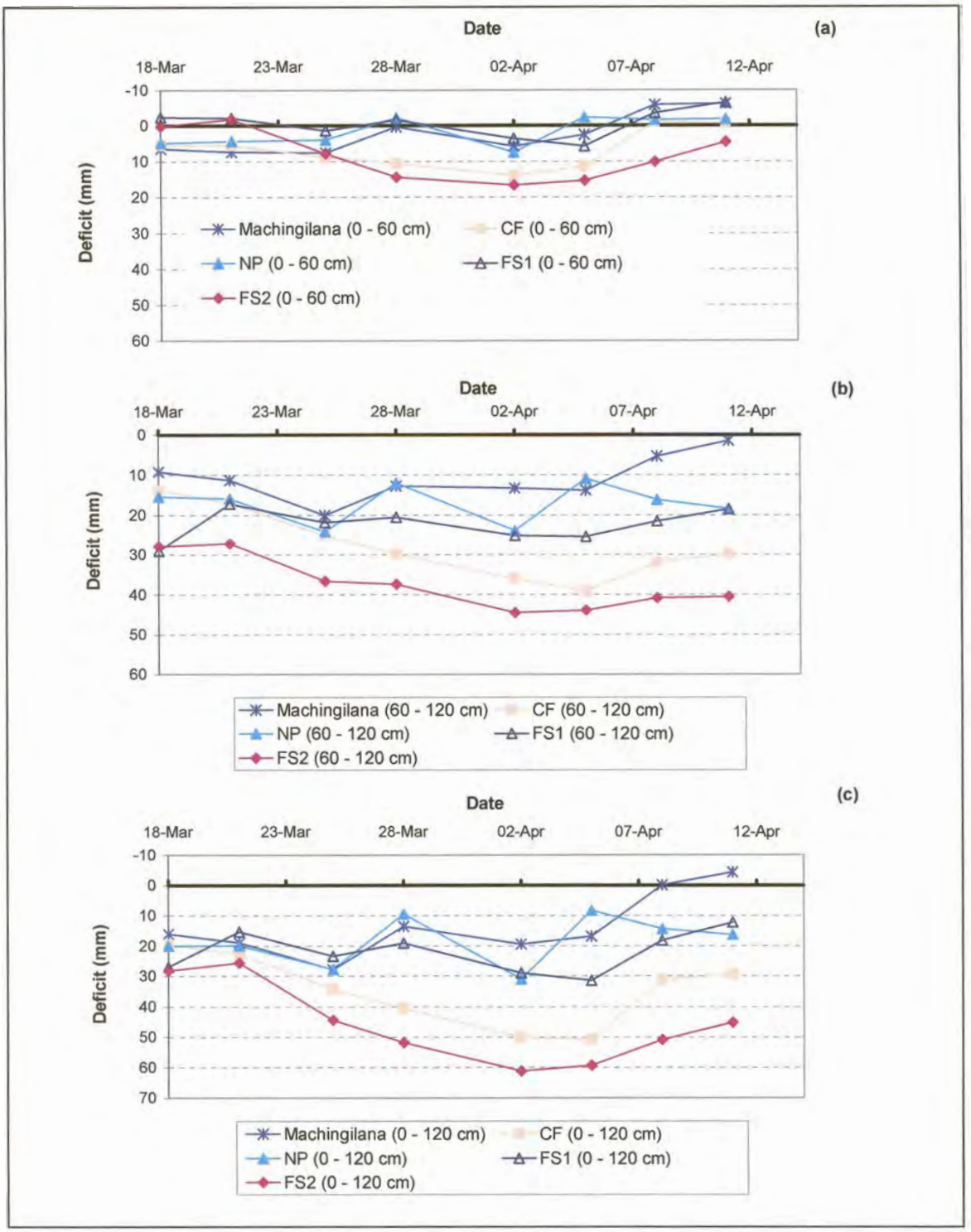


Figure 5.8 *Soil water deficit measured for the MACH, CF, NP, FS1 and FS2 treatments (a) within the effective root zone (0 - 60 cm), (b) below the root zone (60 – 120 cm), and (c) for the entire soil profile during the March/April growth cycle.*

The soil water deficit measurements for NP show that there was a substantially drier layer of soil below a wet managed root zone (Fig. 5.9a).

Bearing in mind that the control treatment was irrigated to refill the entire profile to field capacity, irrigation was applied based on the averaged deficit over the replicates (Fig. 5.9b). According to Fig. 5.9a the deficit at the beginning and at the end were not substantially drier, there should have been no drainage. The dry matter obtained with NP was also not different from the other treatments, which indicates that this treatment used water efficiently, the profile was not overfilled or under filled during this cycle (Table. 5.4).

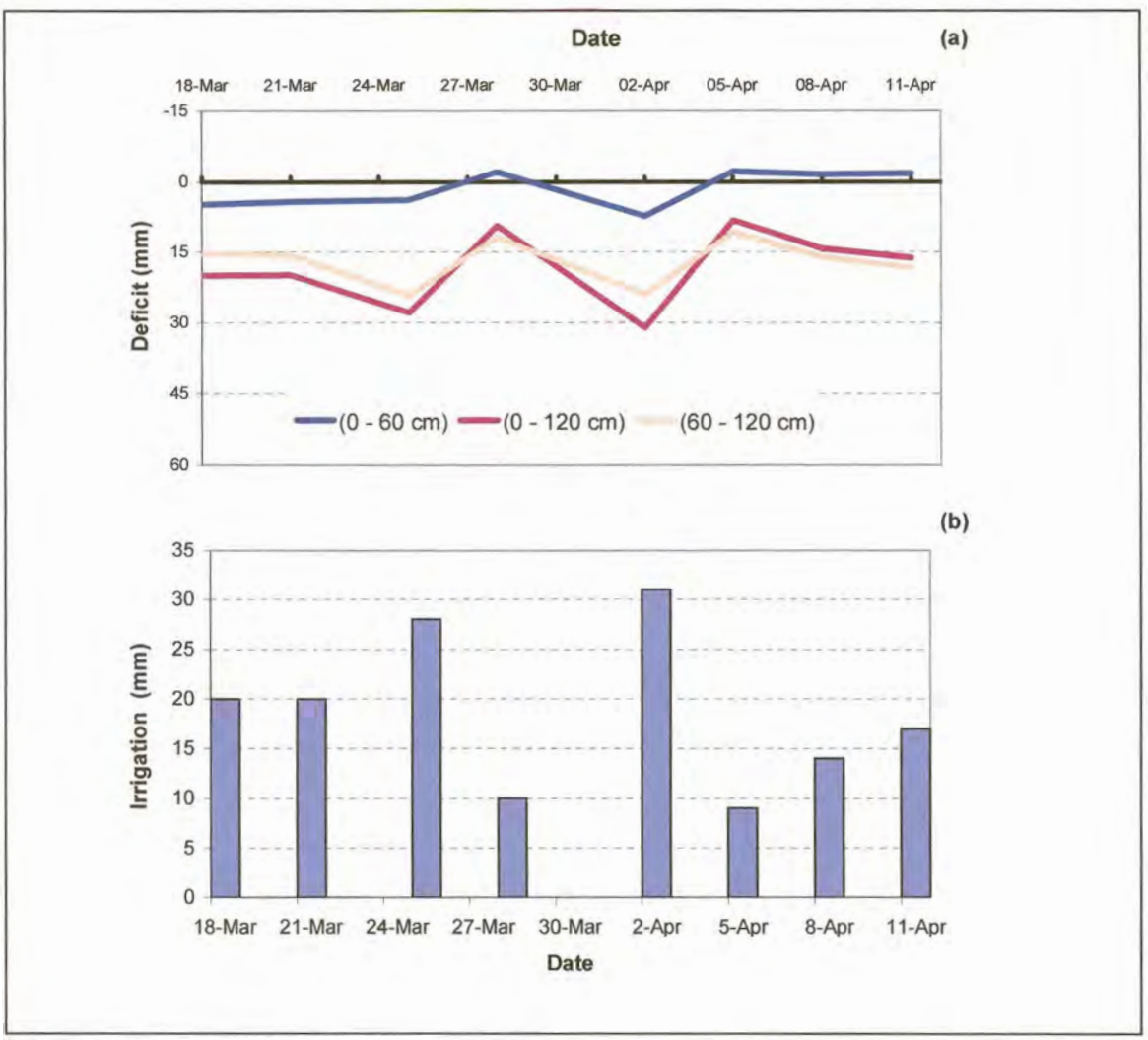


Figure 5.9 *(a) Measured soil water deficit and (b) water applied per irrigation event to the NP treatment during the March/April growth cycle.*

5.2.1 MACH Treatment

This treatment received 255 mm of irrigation, 106 mm more than the control. However, the yields obtained with this treatment were similar to other treatments, indicating that the treatment was over irrigated (Table 5.4).

Irrigation amounts were controlled from deep detector response. There were 8 irrigation events with the highest being 38 mm and the lowest 22 mm (Table 5.5 and Fig. 5.10b).

Table 5.5 *Amount of water applied, observed detector response as well as algorithm followed for the MACH treatment throughout the March/April growth cycle.*

Date	Irrigation applied (mm)	Number of shallow detectors responding	Number of deep detectors responding	Irrigation adjustment
18-Mar	22	0	0	30% Up
21-Mar	29	5	1	30% Up
25-Mar	38	5	1	30% Up
28-Mar	38	5	3	Same
02-Apr	26	5	5	30% Down
05-Apr	34	5	1	30% Up
08-Apr	34	5	3	Same
11-Apr	34	5	3	Same

The first three irrigations did not go deep enough to activate the required number of deep detectors (Table 5.5), and thus the chosen algorithm required an increase in irrigation amount. However, all shallow detectors were activated at all times, except from 22 mm irrigation on the 18th March (Fig. 5.10b). After the 38 mm irrigation on the 28th March the algorithm required that the next irrigation on the 2nd April be reduced, and then only 1 deep detector responded which required that the next irrigation amount be increased again. From there onwards, the algorithm required that irrigation be kept constant at 34 mm throughout, because 3 deep detectors were responding. As a result,

the MACH treatment was over irrigated, with a large contribution being from the last three irrigations (with a total of 102 mm).

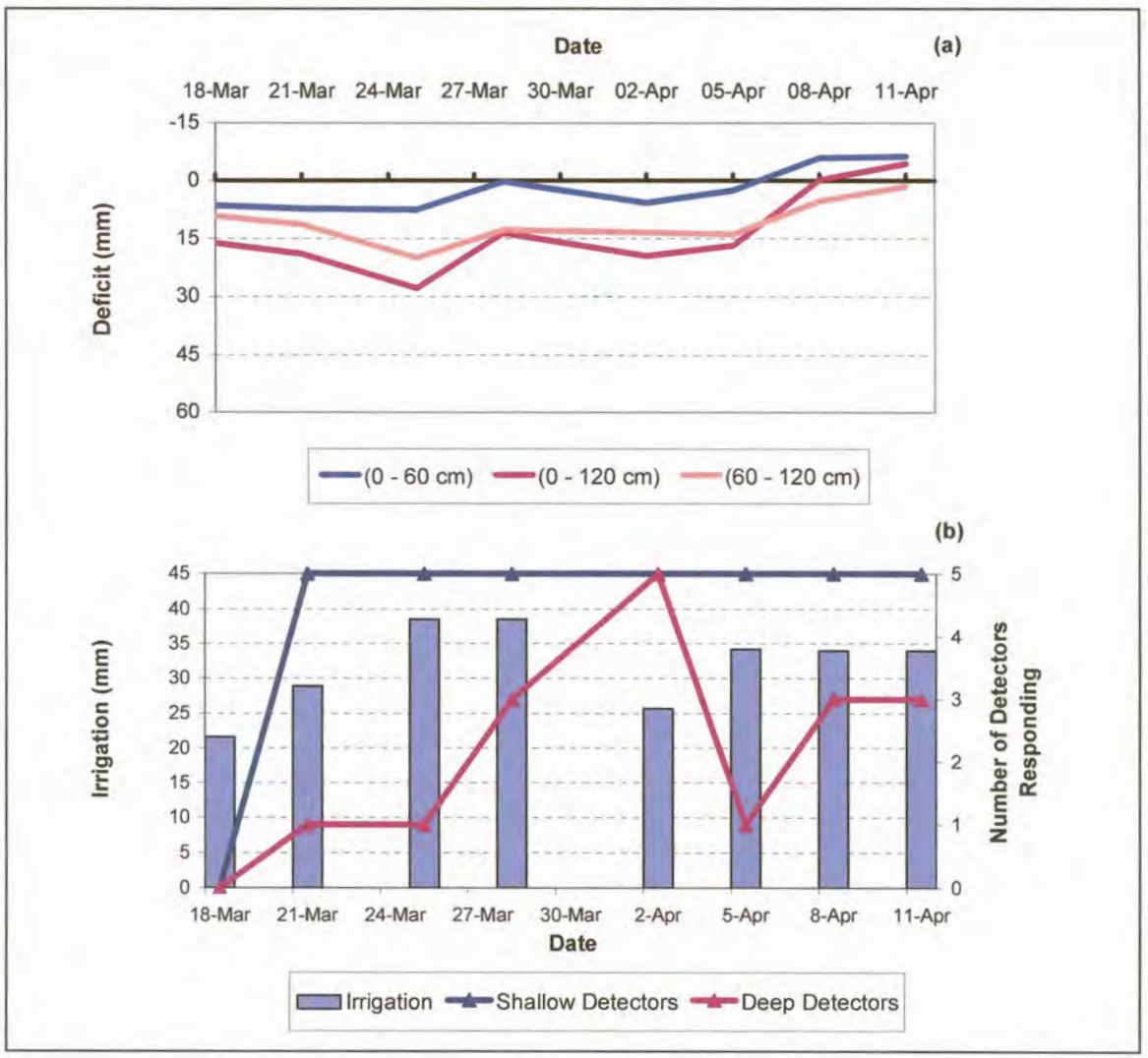


Figure 5.10 *(a) Measured soil water deficits, and (b) amount of water applied per irrigation as well as the observed detectors responding for the MACH treatment during the March/April growth cycle.*

The reason for over irrigation is that irrigation was controlled from the 60 cm detector. So, the soil had to be filled with water up to 60 cm to cut down the irrigation. However, deep detector response was not enough to cut down irrigation as required by the chosen algorithm. Theoretically, the WFD will trip if it experiences a wetting front having a water potential of -2 kPa. The measured soil water deficit graph shows that there was water redistribution to deeper soil layers (Fig. 5.10a); however, it was not detected by all the WFDs.

As a result, soil water deficit for deeper soil layers decreased with time. This is due to *'weaker'* wetting fronts resulting from frequent irrigation applications under conditions of decreasing atmospheric demand. This aspect of *'weaker'* wetting fronts still needs to be investigated more fully.

5.2.2 CF Treatment

This treatment received 6 mm less water than the control, to produce a dry matter yield not significantly different to the control or other treatments at a 5% confidence level (Table 5.4). There was an increasing deficit from the beginning of the cycle (Fig. 5.11a). This is because the initial crop factor was underestimated (Fig. 5.11c), and this led to continual under irrigation of the crop throughout the cycle. The chosen algorithm required an increase in irrigation amounts, but the crop factor increment was not high enough to even activate a single detector during the first four irrigations (Table 5.6 and Fig. 5.11b).

Table 5.6 *The calculated ET_O, adjustment in crop factors based on deep detector response and irrigation amounts applied to the CF treatment during the March/April growth cycle.*

Date	$\sum ET_o$ Between irrigations (mm)	Crop factor	Irrigation Required (mm)	Amount according to water meter(mm)	Number of shallow detectors responding	Number of deep detectors responding	Adjust crop factor
18-Mar	22.42	0.60	13	17	0	0	Up
21-Mar	22.05	0.70	15	20	0	0	Up
25-Mar	14.67	0.80	12	15	0	0	Up
28-Mar	14.59	0.90	13	17	2	0	Up
02-Apr	14.59	1.00	15	19	0	0	Up
05-Apr	20.7	1.10	23	23	5	2	Same
08-Apr	15.14	1.10	17	17	4	0	Up
11-Apr	12.63	1.20	15	15	3	0	Up

There were eight irrigations in total, and irrigation was adjustment took into account deep detectors response. However, it took till the sixth irrigation (Fig. 5.11b), before any deep detector could respond. This was after the crop factor had increased to 1.1 (Table 5.6), indicating full canopy cover. The soil water deficit then started decreasing due to four large irrigations towards the end of the cycle, when the daily ET_o was decreasing (Table 5.6 and Fig. 5.11c). The soil water content therefore, increased because crop uptake was low when the crop had already reached maturity. This is clearly visible with the soil water deficit trend (Fig. 5.11a), which shows that there was a sudden decrease in soil water deficit towards the end of the cycle.

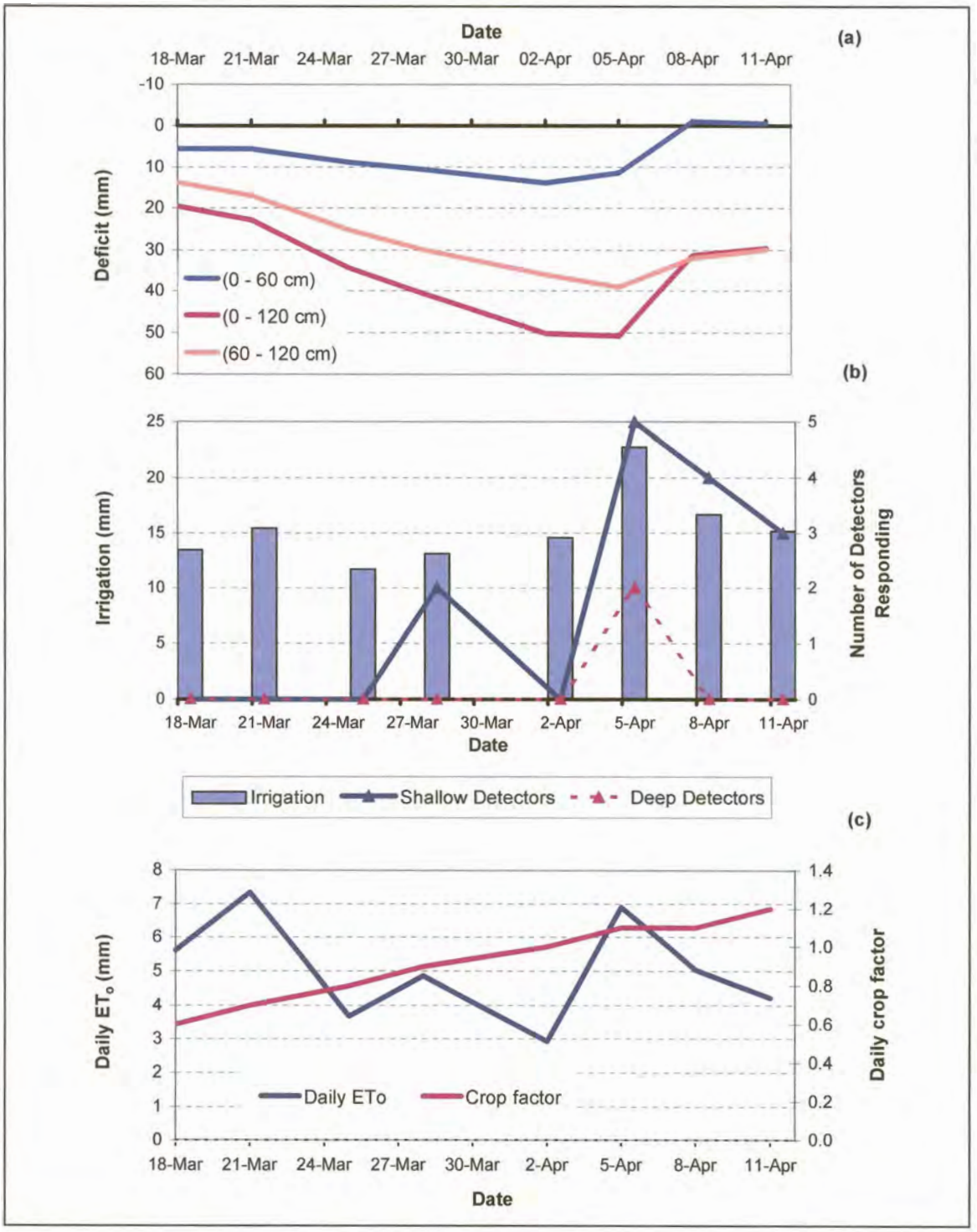


Figure 5.11 *(a) Measured soil water deficit, (b) observed shallow and deep detectors responding as well as the amount of water applied per irrigation and (c) crop factor and ET_o plotted against time for the CF treatment during the March/April growth cycle.*

5.2.3 FS1 Treatment

Due to *'reactivation'* of the control detector a total of 183 mm was applied to this treatment. However, the control FullStop at 30 cm *'wanted'* 173 mm (Table 5.7). This treatment received the second highest amount of irrigation water (after MACH, Fig. 5.7) to produce similar yields to the other treatments.

Table 5.7 *Amount of water that the treatment 'wanted' and that 'given', as well as observed detector response for the FS1 treatment during the March/April growth cycle.*

Date	**Irrigation *'wanted'* (mm)**	**Irrigation *'given'* (mm)**	**Number of shallow detectors Responding**
18-Mar	19	20	[a]4
21-Mar	22	25	5
25-Mar	20	22	5
28-Mar	25	27	5
02-Apr	[b]0	[b]0	[b]0
05-Apr	26	28	5
08-Apr	31	31	5
11-Apr	30	30	5

[a] *One of the five replicates was not turned on due to broken wires.*
[b] *There was no irrigation on this day because the irrigation controller was not turned on.*

The measured soil water deficit suggests that the treatment was slightly over irrigated (Fig. 5.12a). The deficit fluctuated around field capacity in the effective root zone (0 to 60 cm), and the water content in this zone ended up wetter than at the beginning of the cycle. The measured deficit (Fig. 5.12a) for the 60 to 120 cm layer started at 29 mm and ended at 19 mm, so there was substantial decrease in water deficit below the root zone. There might have been drainage to the deeper soil layers. Up to the third last irrigation on the 5th April (Fig. 5.12b), the soil water deficit over the entire profile seemed to be consistently decreasing, which suggests the crop was not over irrigated.

However, the treatment did use 34 mm more water than the control, so we expect that over irrigation occurred right at the end of the cycle. These results show that irrigation interval is of great importance when using FullStops to control irrigation, because water can redistribute below the control depth after irrigation was stopped. Thus, the interval should be long when using FullStop to control irrigation without any means of monitoring redistribution.

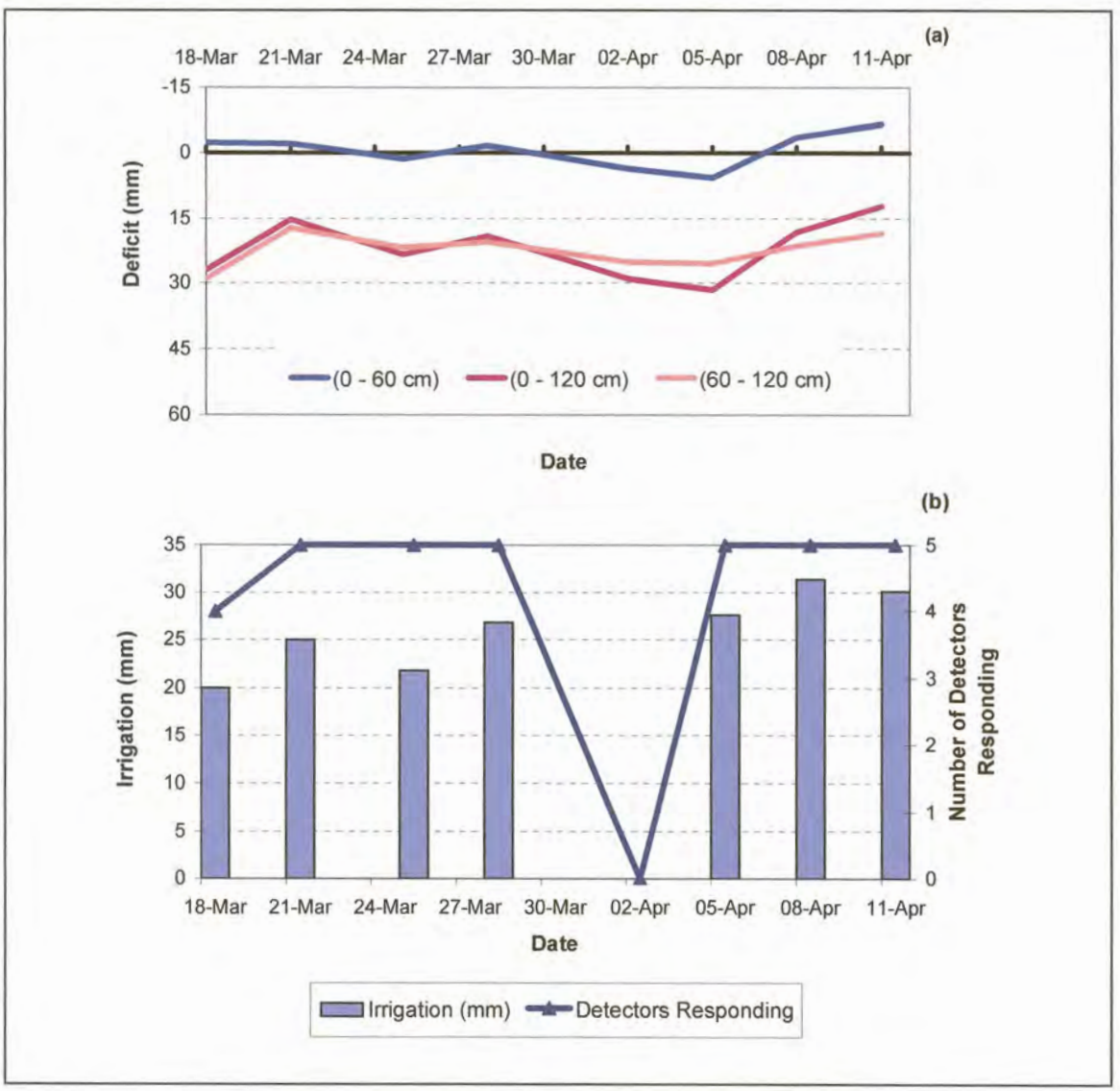


Figure 5.12 *(a) Measured soil water deficit, and (b) observed detector response as well as amount of water applied per irrigation to the FS1 through the March/April growth cycle.*

5.2.4 FS2 Treatment

This treatment received 172 mm of irrigation (Table 5.4), 23 mm more than the NP treatment (Table 5.8 and Fig. 5.7). Irrigation was controlled at 30 cm, like for FS1, however, a feedback detector placed at 60 cm was used to monitor water redistributing below the managed root zone.

Table 5.8 *Amount of water that the treatment 'wanted' and that 'given', as well as observed detector response and the replicate that skipped irrigation for the FS2 treatment during the March/April growth cycle.*

Date	Irrigation *'wanted'* (mm)	Irrigation *'given'* (mm)	Number of shallow detectors responding	Number of deep detectors responding	Replicate skipped
18-Mar	24	24	5	3	1, 2 & 3
21-Mar	11	11	2	0	None
25-Mar	[1]15	[1]15	0	[2]2	[2]1 & 2
28-Mar	26	26	0	[2]2	[2]1 & 2
02-Apr	22	22	3	3	3, 4 & 5
05-Apr	24	24	2	1	3
08-Apr	23	23	[3]No Data		
11-Apr	27	27	[3]No Data		

[1]*On this day the shallow detectors did not respond to irrigation, however, the irrigation was turned on and water meters recorded the given amount of water.*

[2]*Although replicates 1 and 2 were not turned on, on this date; the deep WFDs malfunctioned and were not irrigated.*

[3]*Logger files lost due to power failure of the notebook used to download data.*

Whenever the wetting front was detected at 60 cm, that particular plot skipped the next irrigation allowing it to dry out before applying water (Table 5.8), and this prolonged the irrigation interval to 7 days. This treatment was not over irrigated (Fig. 5.7), as was the case with the MACH treatment.

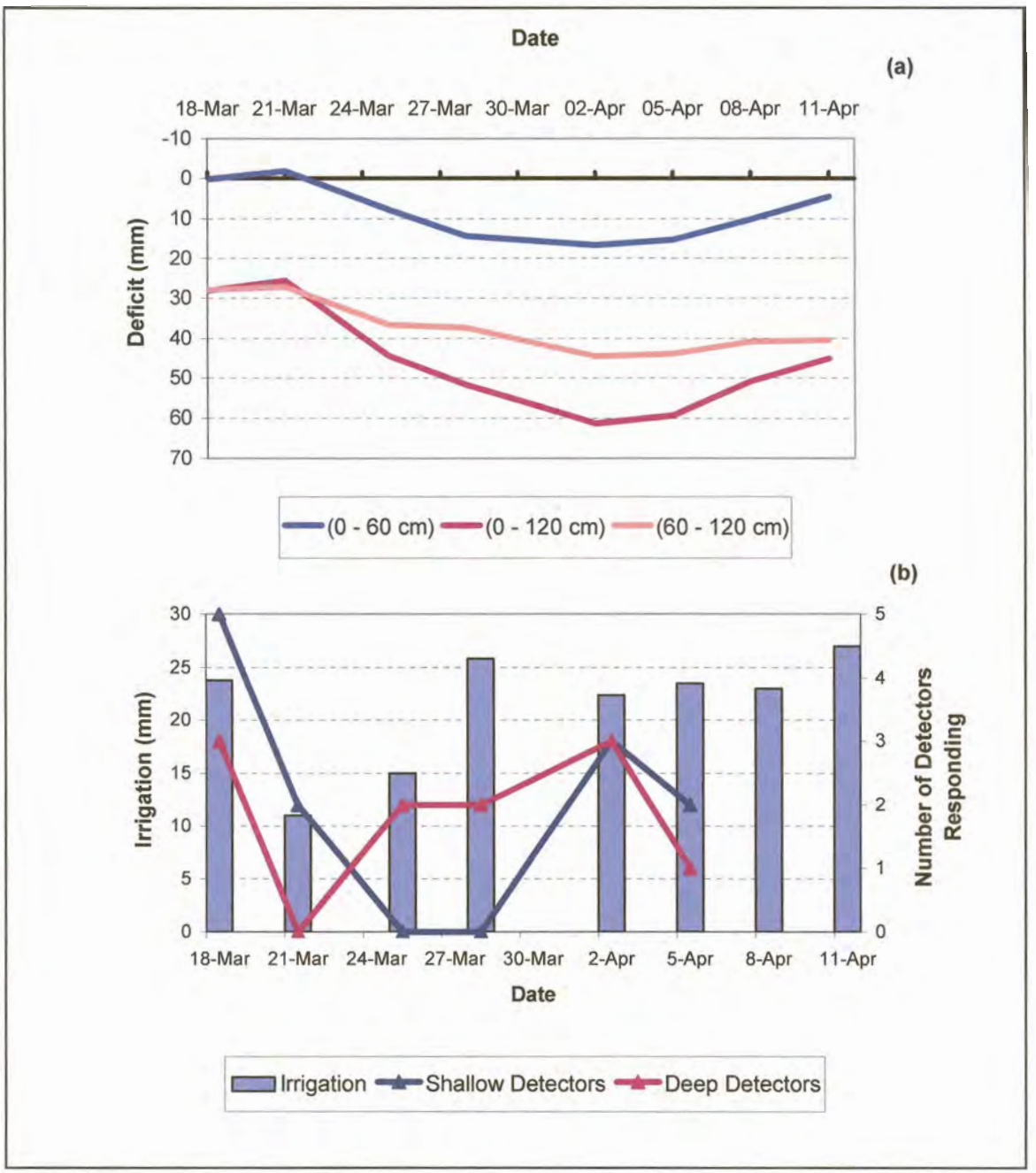


Figure 5.13 *(a) Measured soil water deficit, and (b) irrigation amount applied per irrigation event as well as, observed detector response for the FS2 treatment through the March/April growth cycle.*

The first 24 mm irrigation on the 18th March activated 5 shallow and 3 deep detectors (Table 5.8 and Fig. 5.13b). The algorithm required that the three plots skip the next irrigation, and this then led to a decreased averaged irrigation amount for FS2 on the 21st March, because only two of the five plots were irrigated.

From the measured soil water deficit, it is evident that water drainage from the management root zone (0 to 60 cm) was minimal, as there was a continuous increase in deficit below the root zone (60 to 120 cm) (Fig. 5.13a). However, the last two irrigations commencing from the 8th of April increased the profile water content significantly, as noted by the decrease in profile water deficit towards the end of the cycle (Fig. 5.13a and b).

5.2.5 CONCLUSIONS

The trend in soil water deficit measurements was that the soil profiles became generally drier as the cycle progressed, which suggests that the D_r component was relatively low and the calculated ET + D_r was mostly ET. FS2 treatment did dry out the profile by 20 mm. However, there was a slight decrease in soil water deficits towards the end of the cycle. The NP treatment on the other was better irrigated than FS2. The FS2 treatment had a dry subsoil throughout the cycle (Fig. 5.13a), which implies that the crop had to use water from the subsoil due to insufficient water supply from within the topsoil or managed root zone. FS1 was probably managed close to correct, as it did receive a little bit more water and did not experience an increase in deficit. So, it seems that an ET of around 180 mm is probably right. In the MACH treatment, an inappropriate choice of irrigation interval and controlling depth and also the algorithm for increasing irrigation, led to over irrigation of this treatment.

5.3 April/May Lucerne Growth Cycle

Overview

All treatments were executed according to plan. However, the solenoid valve in one replicate of FS2 (replicate 5) and the detector in one replicate of FS1 (replicate 4) malfunctioned and therefore, they were omitted from the analysis of water use and lucerne growth for this cycle.

The MACH and FS1 treatments put on more water than the control, and FS2, CF and SWB treatments put on less water than the control (Table 5.9 and Fig. 5.14). The measured soil water deficit shows the all treatments except for the MACH had an increase in soil water deficit throughout the cycle, and it was even more conspicuous with the CF and SWB treatments (Fig. 5.15). Treatment application started on the 29th April and ended on the 30th May, however, there were NP measurements taken on the 26th April following 47 mm sprinkler irrigation the previous day.

Table 5.9 *Dry matter yields, cumulative irrigation applied, change in soil water storage, and estimated ET + D_r for the NP, FS1, FS2, MACH, CF and SWB treatments for the April/May growth cycle.*

Treatment	Dry matter (t ha^{-1})	Cumulative irrigation (mm)	ΔS (mm) (0 to 120 cm)	Estimated ET + D_r (mm)
NP	2.5	211	3	208
FS1	2.5	254	8	246
FS2	2.4	193	5	188
MACH	2.7	285	0	285
CF	2.6	92	37	55
SWB	2.5	123	21	102
$LSD_{p=0.05}$	Not Significantly Different			

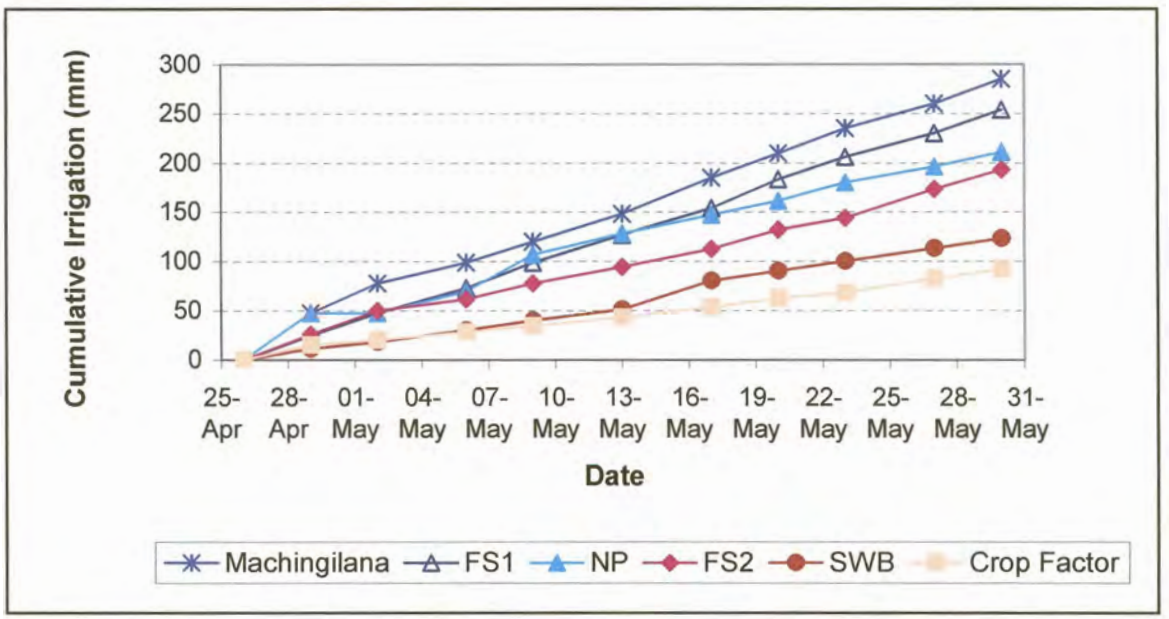


Figure 5.14 *Cumulative Irrigation applied to the MACH, CF, NP, SWB, FS1 and FS2 treatments throughout the April/May growth cycle.*

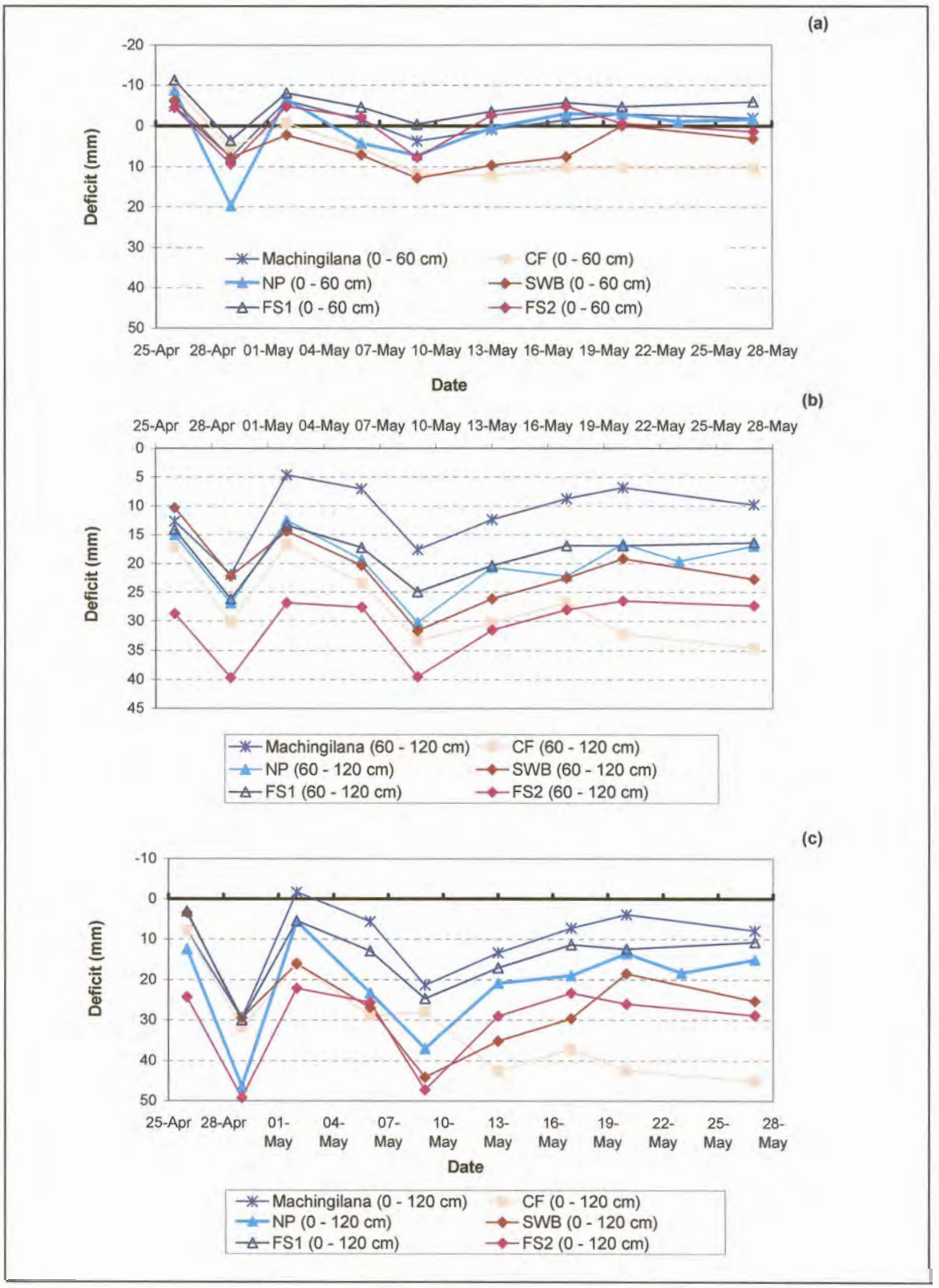


Figure 5.15 *Soil water deficit measured for the MACH, CF, NP, SWB, FS1 and FS2 treatments (a) within the effective root zone (0 - 60 cm), (b) below the managed root zone (60 – 120 cm), and (c) for the entire soil profile (0 – 120 cm) during the April/May growth cycle.*

The control (NP) treatment received 211 mm of irrigation. Since the soil water storage increased by 3 mm between the beginning and end of the cycle we calculate ET plus drainage to be 214 mm (Table 5.9). The soil water deficit measurements (Fig. 5.16a) show that although water content within the effective root zone started 9 mm above FC, it was later maintained within the range of FC for most of the cycle. However, the aim was to refill the whole profile to field capacity. So, before irrigation soil water content should be 3 days of water use below field capacity, because water application was based on averaged deficit of the NP replicate plots (Fig. 5.16b).

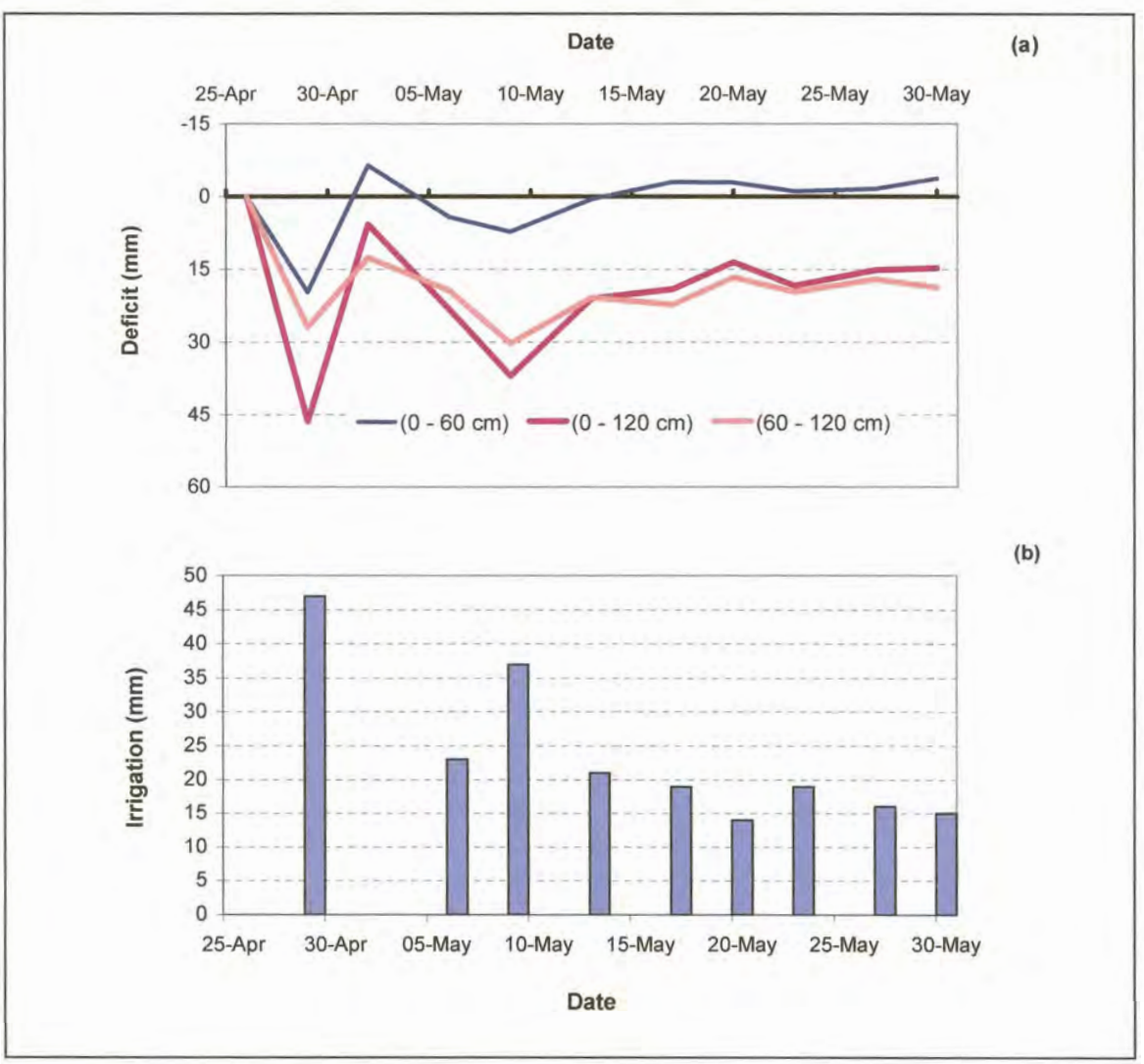


Figure 5.16 *(a) Measured soil water deficit and (b) amount of water applied per irrigation to the NP treatment during the April/May growth cycle.*

Theoretically, there should have been no drainage in this treatment, assuming the FC values are correct and the probe accurately measured the deficit. Since the soil remained fairly wet throughout the cycle we can say that this treatment was not under irrigated. However, if similar soil water deficit graphs are obtained for treatments that had less irrigation we could deduce that this treatment (NP) was over-irrigated.

5.3.1 MACH Treatment

This treatment received 285 mm, 74 mm above the "control", NP treatment (Fig. 5.14). There were 10 irrigation events with the highest being 47 mm and the lowest being 21 mm (Table 5.10 and Fig. 5.17a). The first irrigation on the 29th April (Fig. 5.17a) was made on freshly cut lucerne. All treatments received 47 mm four days earlier on the 25th April in an initial attempt to start the experiment on a full profile (FC). The first irrigation on the 29th April was clearly too much for freshly cut lucerne on a nearly full profile in late autumn. This large initial irrigation resulted from the fact that 47 mm was the last irrigation entered into the spreadsheet on the 25th April and the algorithm *"used it"*. Thus, the first reason for over irrigation is that wrong data was fed into the algorithm. If the first irrigation had been 20 mm and three deep detectors were activated, then about 40 mm would have been used before the 6th May.

The first two irrigation events activated four deep detectors (Fig. 5.17c) and the algorithm reduced the irrigation from 47 to 21 mm by the 6th May. However, 21 mm was not sufficient to get many deep detectors responding. The algorithm increased the irrigation from 21 to 37 mm over the next seven days (Fig.5.17a and Table 5.10). This caused five deep detectors to respond on the 17th May and so, the irrigation was again reduced by 30%. The last four irrigations were all 25 mm with only two deep detectors responding – not reaching the threshold of four detectors needed to bring the irrigation down by 30%. It is most likely that over irrigation occurred from the 17th May onwards. The measured soil water deficit shows that soil water content increased with time even for deeper soil layers (Fig. 5.17b). The measured deficit clearly

shows that there was an increase in profile water content, but the algorithm was not sensitive enough to ensure a reduction in irrigation amount to minimize drainage (Fig. 5.17b).

Thus the algorithm had three mistakes. Firstly, it would have been better to base the algorithm on the shallow detectors. Secondly, an irrigation interval of 3 to 4 days was too short for this time of year when evapotranspiration rates are low. Thirdly, the first irrigation of 47 mm was made on an already near full or full profile and it definitely contributed to this over irrigation.

Table 5.10 *Amount of water applied, observed detector response as well as algorithm followed for the MACH treatment throughout the April/May growth cycle.*

Date	Irrigation applied (mm)	Number of shallow detectors responding	Number of deep detectors responding	Irrigation adjustment
29-Apr	47	5	4	30% Down
2-May	31	5	4	30% Down
6-May	21	5	2	Same
9-May	21	5	1	30% Up
13-May	28	5	1	30% Up
17-May	37	5	5	30% Down
20-May	25	4	2	Same
23-May	25	5	2	Same
27-May	25	5	2	Same
30-May	25	5	2	Same

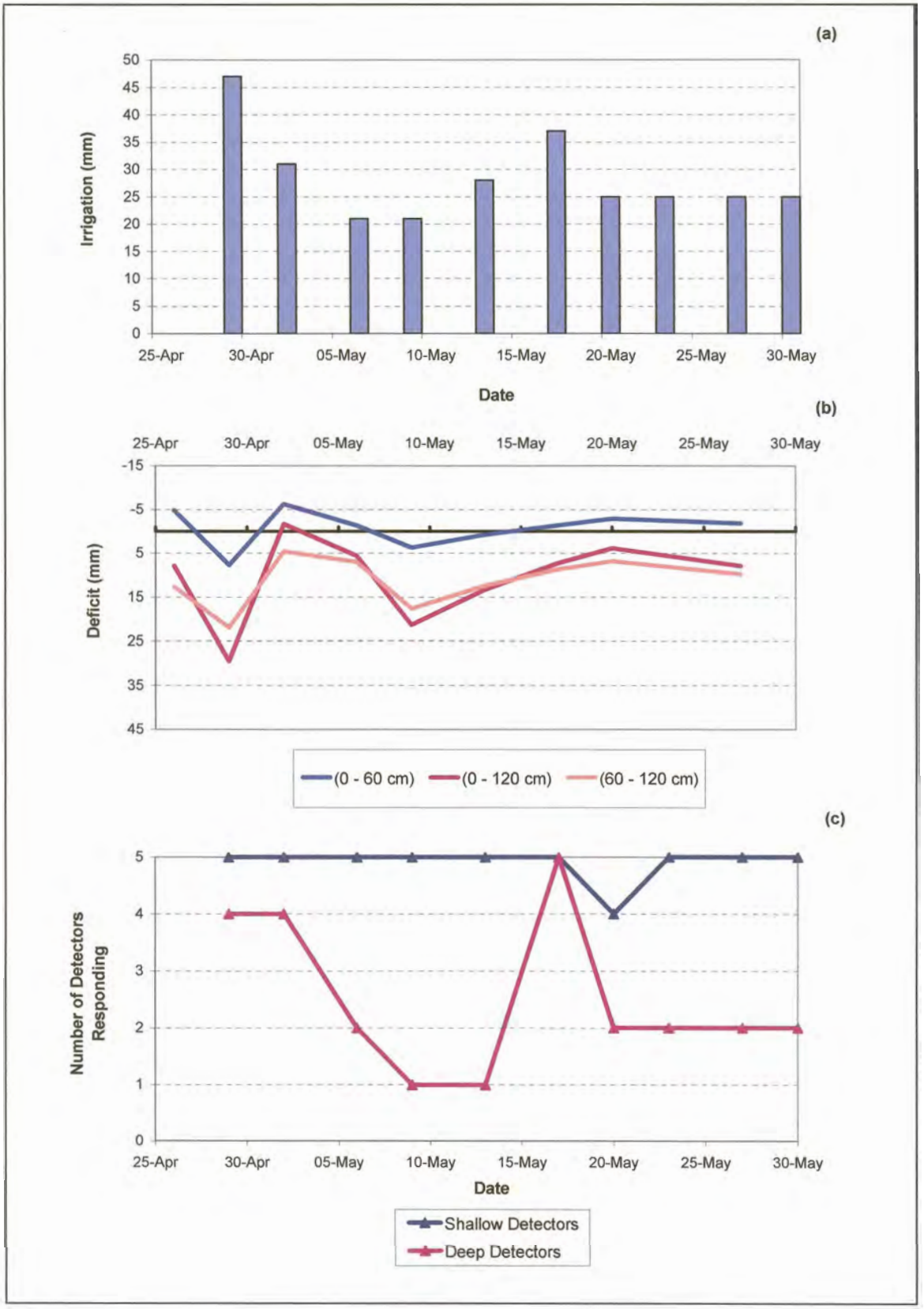


Figure 5.17 *(a) Amount of water applied per irrigation event, (b) measured soil water deficit and (c) observed detector response for the MACH treatment through the April/May growth cycle.*

5.3.2 CF Treatment

This treatment *'wanted'* 92 mm of irrigation, 119 mm less than the control treatment (Fig. 5.14 and Table 5.9). There were 10 irrigation events with the highest being 15 mm (Fig. 5.18a). The reason this treatment was under irrigated relative to the control is clearly because the algorithm could not increase the crop factor fast enough (Fig. 5.18c). The algorithm increased the crop factor with every irrigation event, but it was never able to get the application high enough to set off a single detector (Table 5.11 and Fig. 5.18a). The crop factors were increased by 0.05 and not by 0.1 as stipulated in the treatment methodology (spreadsheets not updated). The increasing soil water deficit confirms that the detector response was correct (Fig. 5.18b).

Table 5.11 *Measured ET_o and methodological action taken for the CF treatment as well as irrigation applied and observed detector responding throughout the April/May growth cycle.*

Date	$\sum ET_o$ (mm)	Crop factor	Irrigation Applied (mm)	Number of shallow detectors responding	Number of deep detectors responding	Crop factor adjustment
29-Apr	32.6	0.45	15	0	0	Up (0.05)
2-May	10.1	0.50	5	0	0	Up (0.05)
6-May	13.9	0.55	8	0	0	Up (0.05)
9-May	10.2	0.60	6	0	0	Up (0.05)
13-May	12.1	0.75	9	0	0	Up (0.05)
17-May	11.9	0.85	10	0	0	Up (0.05)
20-May	9.7	0.95	9	0	0	Up (0.05)
23-May	5.9	1.05	6	0	0	Up (0.05)
27-May	12.3	1.15	14	0	0	Up (0.05)
30-May	8.3	1.25	10	0	0	

A second problem may have been that the calculated ET_o (108 mm) was too low, and this is also observed with the SWB treatment. However, CF produced yields similar to other treatments and was not significantly different at a 5% confidence level. This implies that the crop was able to *'tap'* into

deeper soil layers for water, hence the profile got drier (Fig. 5.18b). More importantly, the treatment may have used water from below the depth of the neutron probe measurements, which would lead to an underestimate of ET.

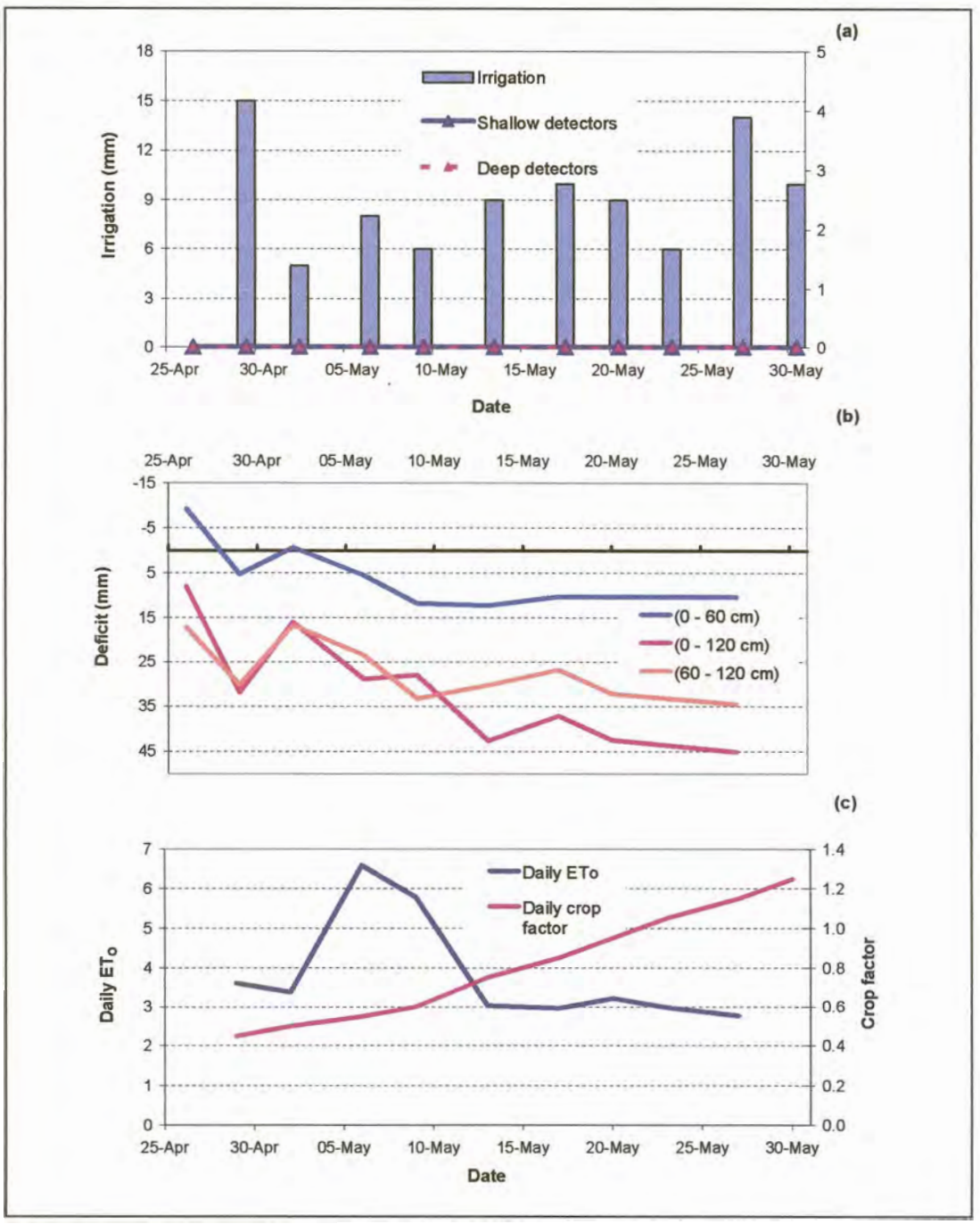


Figure 5.18 *(a) Observed detectors responding as well as amount of water applied per irrigation event, (b) measured soil water deficit and (c) daily crop factor and measured average daily ET_o for the CF treatment during the April/May growth cycle.*

5.3.3 FS1 Treatment

The control detector *"wanted"* 216 mm, 5 mm above the control treatment (Fig. 5.14 and Table 5.9). However, the cumulative water *"given"* was 254 mm. This is because of *'reactivation'* of the control detector as a result of too long an initial irrigation run time (180 minutes) set on the irrigation controller.

Table 5.12 *Amount of water that the treatment 'wanted' and that the control detector 'gave', as well as observed detectors response for FS1 during the April/May growth cycle.*

Date	Irrigation *'wanted'* (mm)	Irrigation *'given'* (mm)	Number of shallow detectors responding*
29-Apr	21	24	4
2-May	19	23	4
6-May	23	26	4
9-May	23	26	4
13-May	24	28	4
17-May	23	27	4
20-May	21	29	4
23-May	20	23	4
27-May	21	24	4
30-May	21	24	4

**Note that only 4 replicates were operating.*

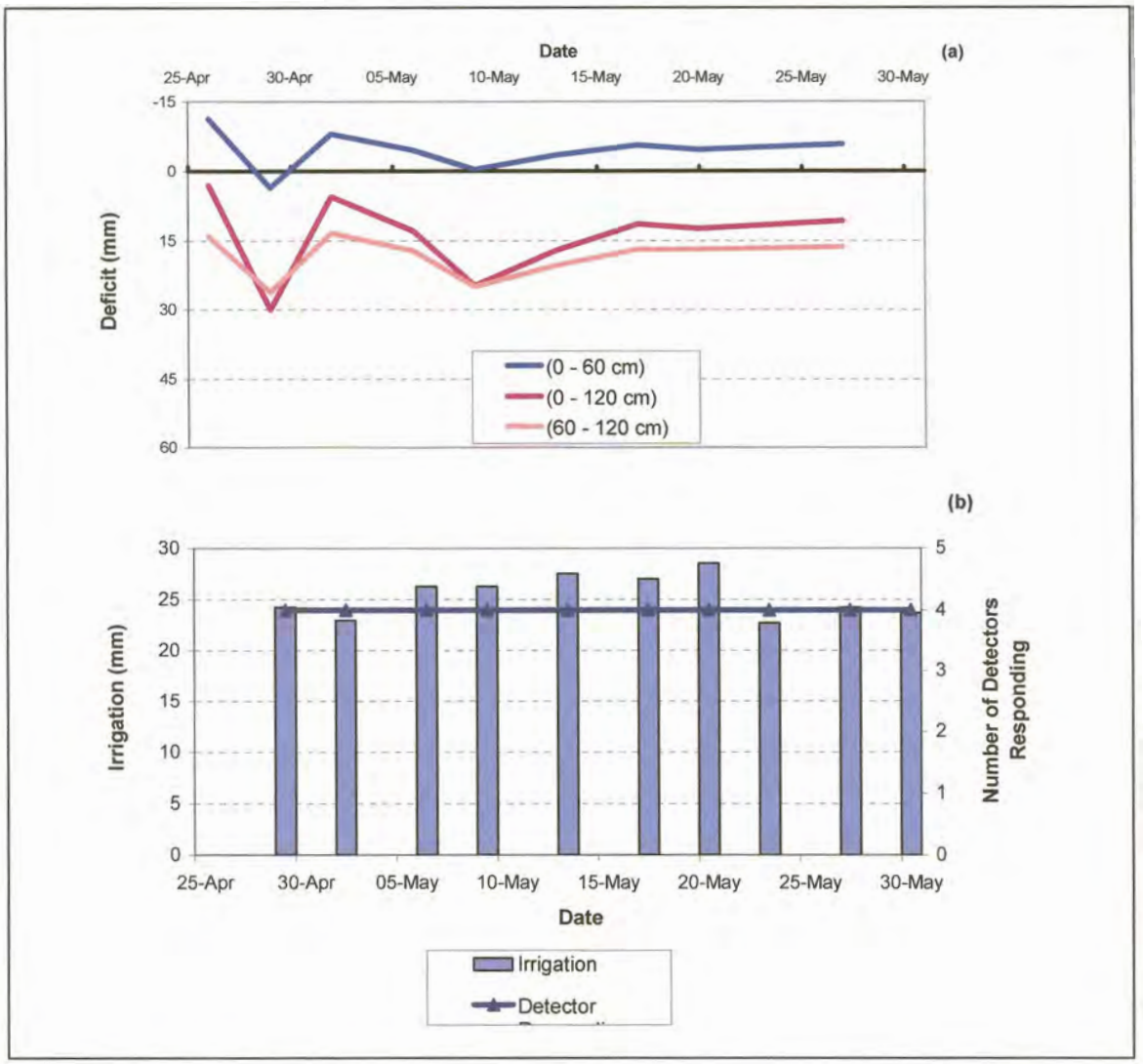


Figure 5.19 *(a) Measured soil water deficit and (b) observed detector response, as well as the amount of water applied per irrigation event to FS1 treatment during the April/May growth cycle.*

The measured soil water deficit shows that soil water content was above FC within the effective root zone, and as a result, the deeper soil layers also got wet due to drainage from the root zone (Fig. 5.19a). This treatment did not get drier, so it was probably over irrigated. Since the NP treatment was given less water and also did not get drier we can say the treatment was over irrigated relative to the NP. The reason for over irrigation is that the run time on the controller was too long so more irrigation occurred after the reset. The treatment actually *'wanted'* 216 mm, which is close to the 208 that the NP *'wanted'*. The detectors were responding to irrigation all the time, however, the depth of redistribution was not monitored (Fig. 5.19b).

5.3.4 FS2 Treatment

This treatment received 193 mm (Table 5.13), 18 mm less than the NP treatment (Fig. 5.14 and Table 5.9). However, FS2 produced statistically similar dry matter yields to the other treatments.

Table 5.13 *Amount of water that the treatment 'wanted' and that the control detector 'gave', as well as observed detector response and replicates that 'missed' irrigation after responding to irrigation for FS2 treatment during the April/May growth cycle.*

Date	Irrigation *'wanted'* (mm)	Irrigation *'given'* (mm)	Number of shallow detectors responding	Number of deep detectors responding	Replicate(s) skipped
29-Apr	25	25	4	0	None
2-May	21	24	4	2	1 & 2
6-May	11	12	2	0	None
9-May	10	16	4	1	2
13-May	17	17	3	2	1 & 2
17-May	18	18	Lost data file, all replicates were irrigated		
20-May	16	19	4	2	1 & 3
23-May	11	12	2	0	None
27-May	29	30	4	1	3
30-May	19	20	3	1	1

In the FS2 treatment, irrigation was controlled at 30 cm like with FS1. The FS2 treatment, however, used the extra information provided by the feedback detector to lengthen the irrigation interval by skipping irrigation if the deep detector was tripped. This mechanism allowed the soil profile to dry out before applying irrigation. As a result, FS2 received less water than FS1 (Table 5.9). There were deep detectors responding during this growth cycle (Fig. 5.20b).

This method had the effect of lengthening the irrigation interval, the prime cause of over irrigation in the MACH treatment. The measured soil water deficit (Fig. 5.20a) indicates water content fluctuated around FC in the active root zone, and due to prolonged irrigation interval, less water was draining to the deeper soil layers.

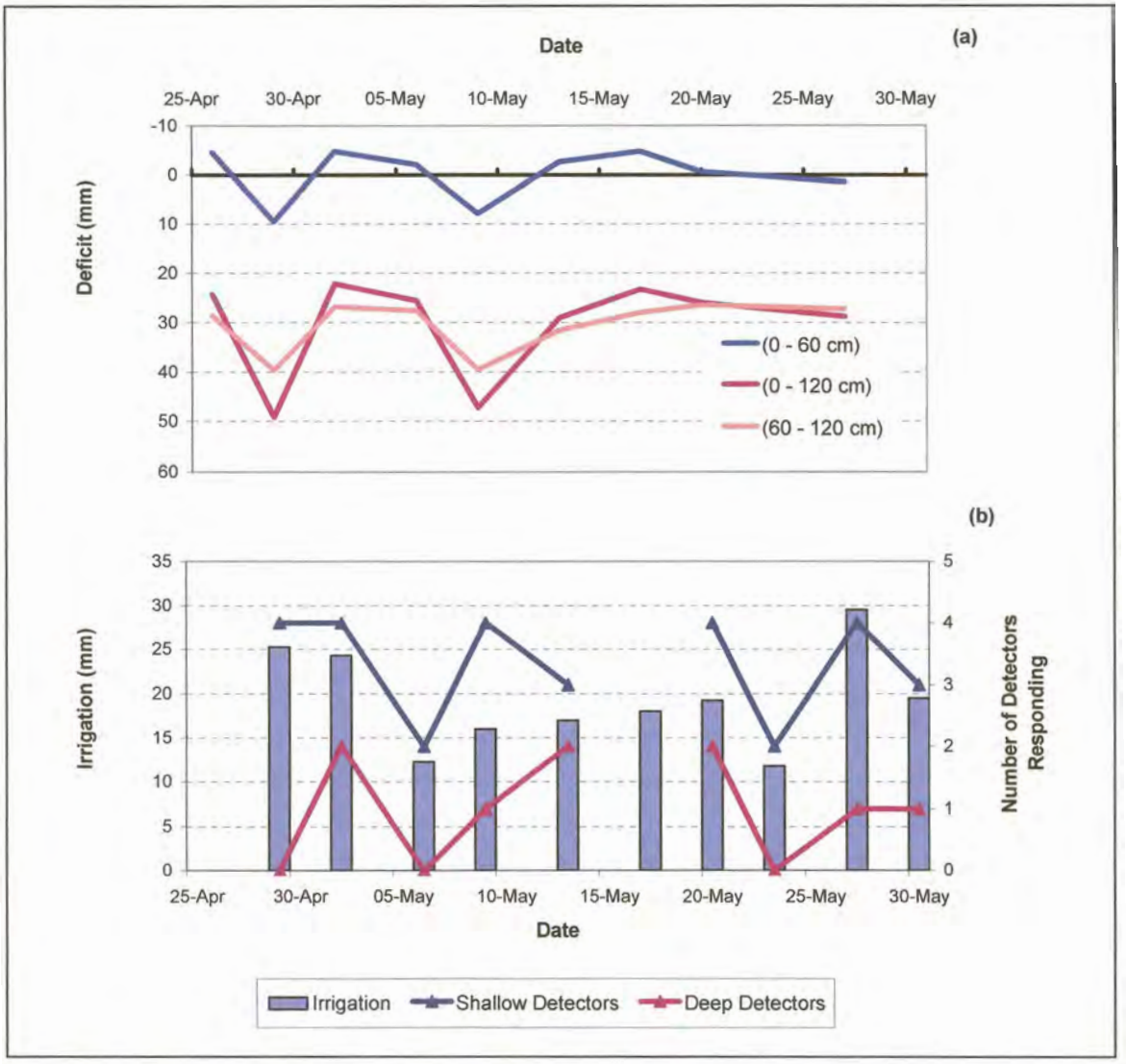


Figure 5.20 *(a) Measured soil water deficit, and (b) observed detector response as well as the amount of water applied per irrigation to the FS2 treatment during the April/May growth cycle.*

5.3.5 SWB model Treatment

This treatment received 123 mm of irrigation, 88 mm less than the control (Fig. 5.14 and Table 5.9). There was an under irrigation early in the season, which is confirmed by the soil water content measurements made in the SWB treatment (Fig. 5.21a).

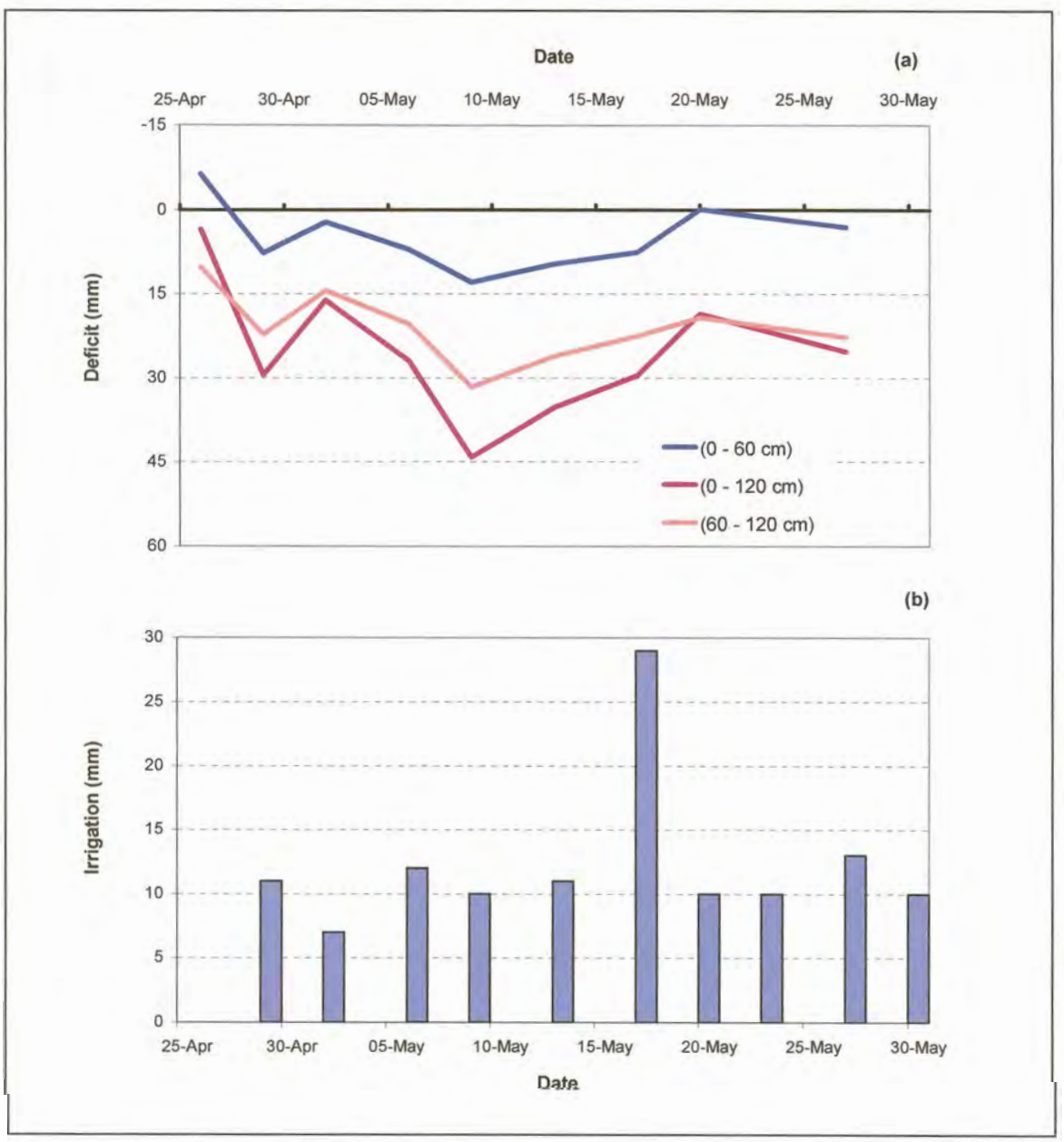


Figure 5.21 *(a) Measured soil water deficit and (b) irrigation amount applied per irrigation to the SWB treatment during the April/May growth cycle*

This is because the initial leaf area of the crop may have been underestimated and, as a result, the crop growth model 'grew' the leaf area too slowly. These mislead the model to estimate that the crop was adequately irrigated, however, the irrigation increments were too small for the ever-increasing canopy. Therefore, this led to underestimation of the crop water requirements, especially for the period between 4th April to 10th May as depicted by the measured soil water deficit within and below the managed root zone (Fig. 5.21a). This was due to inadequate irrigation applied per irrigation event (Fig. 5.21b). However, like in the CF treatment the crop was able to mine water from deeper soil layers.

5.3.6 CONCLUSIONS

The soil water content data shows that the SWB and CF treatments were under irrigated because the soil ended substantially drier than it started. There was little change in soil water content in the other four treatments. Since, FS2 received the least irrigation of these four treatments (193 mm) we conclude that the actual crop water requirement was between 55mm (CF) and 188 mm (FS2). However, it was closer to 188 mm (FS2) because water taken up from below 120 cm soil depth in SWB and CF would result in an underestimation of ET. The MACH treatment was over irrigated, as irrigation was controlled from deep detector response, like in the previous cycle. Depth of irrigation control and irrigation interval had an enormous impact on water applied to the MACH treatment. FS1 was also slightly over irrigated, as there was no feedback mechanism like in FS2. It is, therefore, highly recommended that there should be a feedback detector when using FullStops to control irrigation.

CHAPTER 6

GENERAL DISCUSSIONS AND CONCLUSIONS

6.1 General Discussions

The dry matter yields obtained with all treatments per growth cycle were similar, although with very different amounts of irrigation water (Tables 6.1 - 6.2). However, growth may have not been a good indicator of irrigation treatment success because treatments were wet up before each cycle, and towards the end of the experiment, lucerne probably grew roots below the depth of measurement. Thus, the lucerne was able to temporarily mine the soil storage and obtain good yields, but this strategy would eventually fail without the extra irrigation applied.

The soil at the experimental site is well drained, and there was no further fertilizer application after planting (leguminous crop), so leaching or water logging was unlikely to be a problem. The over irrigation also did not seem to affect yields. This is because the dry matter yield per cycle was not significantly different for different treatments whereas each treatment used varying amount s of water. As such, we use the water content trend measured by neutron probe in each treatment to make judgements about the most accurate treatment. Figure 6.1 is typical soil water content trends we will use to evaluate the experimental treatments. Each treatment will be evaluated for two soil layers, that being the topsoil (0 to 60 cm) and, the subsoil (60 to 120 cm). This is to serve as an indicator of whether the treatment was well irrigated or not.

The results obtained during the January/February cycle when the atmospheric demand was high, with ET averaging 6 to 8 mm day^{-1} indicate that, the FS1, FS2 and SWB treatments were better irrigated than the control. The control (NP) treatment was irrigated 196 mm, and since the profile was refilled to FC per irrigation, it is apparent that the crop was not under irrigated because the

subsoil was uniformly wet throughout the cycle (Fig. 5.3a). Water content within the topsoil fluctuated around FC. This is an indication that the FC points determined at the start of the experiment may have been overestimated, so when the soil should be 10 or 20 mm below FC, indicated that it was at FC because the full point was set too high. Also, the FC of the 60 to 120 cm layer might have been overestimated.

Table 6.1 *Dry matter yield (t ha^{-1}) obtained with each treatment per growth cycle.*

Cycle ID/ Treatment	January/February (cycle #1)	March/April (cycle #2)	April/May (cycle #3)
NP	4.0	2.8	2.5
MACH	-	2.8	2.7
FS1	4.2	2.8	2.5
FS2	3.7	2.8	2.4
CF	-	3.4	2.6
SWB	4.2	-	2.5
$LSD_{p=0.05}$	Not Significantly Different	Not Significantly Different	Not Significantly Different

So, for the first irrigation on the 24th January (Fig. 5.3b) was applied more water than the actual profile deficit, and therefore, the irrigations that followed was just additions to a nearly full soil profile. Hence, NP treatment received too much water during the January/February cycle.

The pattern in soil water deficit depicted by the topsoil or managed root zone in the NP treatment is similar to scenario 1 in Fig. 6.1 for the January/February cycle, which in this case can be argued to be a reflection of an over irrigation because the amount of water used by the treatment did not have a significant positive effect on dry matter production, and other treatments with similar neutron probe reading trends and yield required less water.

Table 6.2 *Cumulative irrigation (mm) applied to each treatment over the three growth cycles.*

Cycle ID/ Treatment	January/February (cycle #1)	March/April (cycle #2)	April/May (cycle #3)
NP	196	149	211
MACH	-	255	285
FS1			
"Gave"	137	183	254
"Wanted"	120	173	216
FS2			
"Gave"	140	172	193
"Wanted"	132	172	177
CF	-	143	92
SWB	154	-	123

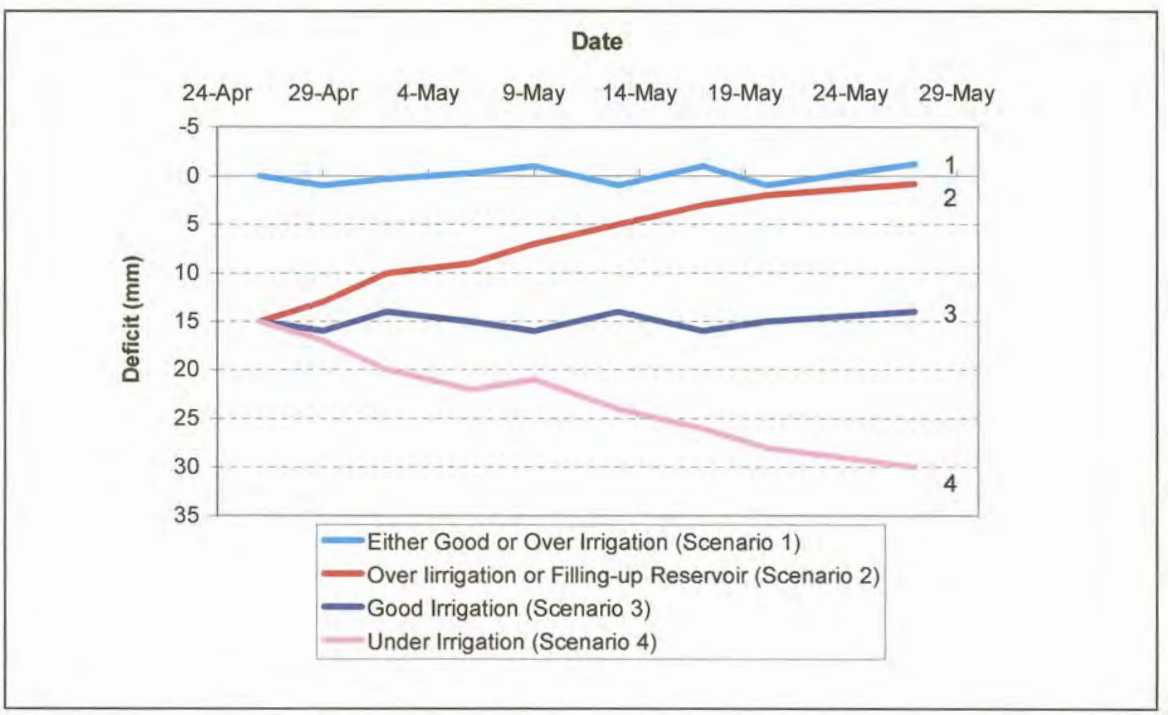


Figure 6.1 *Trends that depicts possible scenarios that can be obtained with the measurements of soil water deficit.*

During the March/April cycle, the soil water content in the topsoil stayed around FC for NP, and total water applied was 149 mm, as compared to 183

During the March/April cycle, the soil water content in the topsoil stayed around FC for NP, and total water applied was 149 mm, as compared to 183 mm for FS1 (Table 6.2) with the same yield of 2.8 t h^{-1} (Table 6.1). The trend in soil water content for FS1 treatment shows that the water content within the active root zone fluctuated around FC and the soil layers below the root zone remained dry. However, FS1 might have been over irrigated towards the end of the cycle with water content exceeding FC (Fig. 5.12a). The NP treatment during the March/April cycle received less water than during the January/February cycle. Before the start of treatment application during the March/April cycle, all the plots received 64 mm sprinkler irrigation in an attempt to start the profile at uniform water content. During the January/February cycle, all treatments started off drier, unlike during the March/April cycle, and therefore, in an attempt to bring the soil water content to FC more water was applied during the January/February to an already full or near full profile. This happened because of over estimation of the determined FC points.

The first irrigation applied to the NP treatment on the 18th March was applied to a fairly wet soil, unlike during the January/February cycle, which started drier. This may have been an over irrigation dictated by an overestimated FC, as happened in the previous cycle. The pattern of soil water deficit for the NP during the March/April (Fig. 5.9a) is similar to scenario 1 for the active root zone (0 to 60 cm) (Fig. 6.1). The NP treatment produced similar yields as the other treatments, so it can be concluded that growth and/or yield was not a good indicator of irrigation accuracy because different treatments used different amounts of water produce statistically similar dry yields.

The cumulative irrigation received by the NP treatment during the April/May cycle (211 mm), was reasonably close to the presumably correct ET of 198 mm for FS2 (Table 6.3). Soil water deficit was decreasing with time, the excess irrigation can also be attributed to faulty FC points. The difference in cumulative irrigation applied for the NP during the January/February cycle (over irrigation), March/April cycle (good irrigation) and April/May (good irrigation) can be attributed to errors in calibration of the neutron probe. The

differed for each cycle. For instance, cycle 1 started drier (no sprinkler irrigation), cycle 2 received 64 mm and cycle 3 received 47 mm of sprinkler irrigation.

Table 6.3 *Estimated crop water requirements plus drainage (ET +D_r) (mm) for all treatments per growth cycle calculated from equation 4.2.*

Cycle ID/ Treatment	January/February (cycle #1)	March/April (cycle #2)	April/May (cycle #3)
NP	215	153	208
MACH	-	275	285
FS1	159	198	246
FS2	138	155	188
CF	-	133	55
SWB	175		102

Thus, if according to the determined FC points, the deficit for the top 0 to 60 cm was 100 mm but the real number should be 110 mm. If the NP measurement before irrigation was 90 mm, 10 mm will be irrigated to refill the profile to 100 mm, but the plants actually used 20 mm. This would cause an under irrigation. If according to the determined FC points, the deficit for the 60 to 120 cm is 110 mm but the real number should be 100 mm, the deficit will be overestimated. Thus, if the NP measurement before irrigation is 100 mm, 10 mm will be irrigated on an already full profile because the plants did not use any water. This would cause an over irrigation. Fortunately, the errors in the top and subsoil layers appear to have largely cancelled each other out.

For both cycles that good data was collected for the MACH treatment, this treatment was irrigated more water than all the other treatments and, as a

For both cycles that good data was collected for the MACH treatment, this treatment was irrigated more water than all the other treatments and, as a result it can be deduced that the MACH treatment was over irrigated. Data was collected for the last two cycles under conditions of decreasing ET.

From knowledge of the possible overhead when controlling irrigation from 60 cm at a transpiration rate of 3 to 4 mm per day, about 15 mm could drain past the detector after a front was detected (Equation 3.2). Thus, **O** = 600 mm (0.21 – 0.18) – 3 mm, and therefore **O** equals to 15 mm. This means we would have to use at least 15 mm below the deep detector before the next irrigation if we wanted no drainage. However, plants use water from the topsoil first – the ET was too low and the interval too short for this growth cycle (March/April cycle). So, because the crop was not allowed enough time before the next irrigation, the MACH treatment was over irrigated mainly because the crop could not use all the water at deeper soil layers. This is because irrigation was controlled from deep detectors – at the bottom of the managed root zone.

The chosen algorithm required four or five deep detectors to respond before it would reduce irrigation, and this was far too strict. The measured soil water deficit during the March/April cycle indicates that for the entire profile (0 to 120 cm), soil water deficit never exceeded 30 mm, and in fact, it was above FC towards the end of the cycle (Fig. 5.10a). The flat NP trace near FC means we either over-irrigated or were exactly right, and other treatments have flat traces with less irrigation – so we can confidently assert that this treatment was over irrigated. This implies that there was drainage from the topsoil to the deeper soil layers. This is exactly a depiction of scenario 1 in Fig. 6.1, and in this case, it can be ascertained that there was over irrigation.

For the April/May cycle, the over irrigation that occurred with the MACH treatment was partly due to an error in updating data to be used in the chosen algorithm. It is observed that large irrigation amounts were applied at the beginning of the cycle on freshly cut lucerne, and it is expected that the crop water requirement was not high at this point. The first irrigation on April the

29th took into account the previous irrigation amount applied with sprinklers because only 3 deep detectors were activated from the sprinkler irrigation (Table 5.10) The algorithm required that the first irrigation be kept the same as the previous one if 3 deep detectors responded to the previous irrigation in (that being the 47 mm sprinkler irrigation applied four days earlier). As a result, this treatment was over irrigated, and so did drainage occur.

Another contributing factor for over irrigation with the MACH treatment during the April/May cycle, just like during the March/April cycle, is that irrigation was controlled from deep detector response and we know for a fact that the wetting front will continue to move after the detector has detected it. The soil behind the wetting front will be near saturation because θ_{wf} occurs at suctions wetter than -2 kPa (Hillel, 1998). With redistribution, the excess water would definitely be pushed to deeper soil layers (Stirzaker *et al.*, 2000, and Zur *et al.*, 1998). The chosen algorithm permitted this to happen because until the wetting front had activated at least 2, 3, 4 or 5 detectors it would receive the same or an increase in irrigation. This over irrigation scenario is further outlined by the measured soil water deficit that fluctuated around FC with a wet layer of soil below the managed root zone indicating that there was water drainage to deeper soil layers (Fig. 5.17b). A typical scenario 2 (Fig. 6.1), would best suit the soil water deficit pattern depicted by the top 60 cm soil layer of the MACH treatment.

As it happened during the March/April cycle it appears that there were weaker redistributing wetting fronts that all deep detectors could not detect, such that the number of responses from deep detectors was not enough as required by the chosen algorithm to cut down irrigation quantities. The MACH treatment was not scheduled accurately because more water was applied to produce statistically similar dry matter yield to other treatments at a 5% confidence level (Table 5.4).

In the FS1 and FS2 treatments irrigation was controlled from a 30 cm depth, thus the top 30 cm was at wetting front water content, (θ_{wf}), immediately after irrigation. However, FS2 had a feedback detector at 60 cm to monitor

redistribution. During the January/February cycle, FS1 and FS2 treatments became replicates because there were no deep detectors responding. These treatments received similar amounts of water during this cycle (137 and 140 mm respectively), although the soil storage in FS1 increased by 22 mm. So, the soil water deficit in the FS1 treatment was decreasing with time, unlike FS2 that had a constant deficit over time. The soil water deficit pattern for the FS1 and FS2 treatments is a close approximation of scenarios 2 and 3 (Fig. 6.1), for FS1 and FS2 respectively. So, there might have been drainage with FS1 but very unlikely with the FS2 treatment. In fact, both ended with relatively dry subsoil, so there was little likelihood of drainage.

As the season progressed into the cooler times during the March/April cycle, there were deep detectors responding to irrigation in the FS2 treatment, so the feedback detector prolonged irrigation by at least 7 days for the particular plot whenever it had responded to previous irrigation. In this way, the crop had to mine water from the deeper soil layers, hence, the soil profile dried out with time in FS2. On the other hand, in the FS1 treatment, the soil water deficit for the topsoil and subsoil neither drastically increased nor decreased, except towards the end of the cycle due to three large irrigations (Fig. 5.12b). The most notable feature about the FS1 and FS2 treatments is that the feedback detector in the FS2 treatment provided additional information by monitoring the depth of redistribution, whereas FS1 treatment did not. The benefit of the feedback mechanism was more pronounced during cooler times when ET was low.

Theoretically, the cooler time of the year means that less water would be used below the 30 cm detector between irrigations and less ET on the day of irrigation means that there is more water to redistribute, so we would expect fronts to travel deeper. Thus, the feedback provided a mechanism of allowing the profile to dry out before irrigating. This was observed during the April/May cycle, when the FS2 treatment received substantially less water than FS1. The measured soil water deficit shows that, in the FS2 treatment, water content within the topsoil fluctuated about FC whilst the subsoil was dry. In FS1, the subsoil was getting wetter whilst the topsoil was often above FC. The

soil water deficit pattern depicted by the two treatments is similar to scenario 1 (Fig. 6.1). However, there was definitely drainage in FS1 whereas in FS2 drainage, if any, was minimal

The SWB model made a reasonably good prediction of the crop water requirement compared to NP during the January/February cycle. The estimated crop water requirement plus drainage was 175 mm according to equation 4.4, and the model predicted 154 mm for the same period. It can be assumed that the greater proportion of the 154 mm irrigation was used for dry matter production with little water lost due to drainage. However, the possibility of drainage to subsoil cannot be completely dismissed because the topsoil got wetter with time (Fig. 5.6a). The estimation of crop water requirements, according to equation 4.2, indicates that SWB was over irrigated by 21 mm. Perhaps the model's prediction of crop water requirements was not that accurate but because we started off dry it was fortunate that we slightly over irrigated as opposed to under irrigate. According to scenario 2 Figure 6.1, this is an indication that we were filling up the resevoir. During the April/May cycle, SWB treatment was under irrigated relative to the control, as confirmed by the soil water deficit measurements. The SWB treatment was under irrigated by at least 21 mm according to the soil water balance equation (equation 4.2). This under irrigation can be attributed to the fact that the initial updated leaf area of the crop may have been underestimated and this led the crop growth model in the SWB model to under estimate the leaf area. Therefore, the model under estimated the actual crop water requirements. During cycle 1, the initial leaf area may have been over estimated, and therefore the treatment was slightly over irrigated.

When using the SWB model to run crop water requirement simulations, it is important to make a proper update of the input variables, like initial leaf area of the crop grown.

The patterns depicted by soil water deficit measurements for the CF treatment (Fig. 5.11a and Fig. 5.18b), show that the soil profile was increasingly drier throughout the cycles, except towards the end of the cycle during the

March/April cycle. Scenario 4 (Fig. 6.1) best describes this situation (under irrigation). This is an indication that the crop had to tap water stored below the root zone because of its extensive root system. Hence, this resulted in 10 mm and 37 mm depletion of soil water storage by the crop during the March/April and April/May cycles respectively.

Although the crop factors were increased with each irrigation episode, the increment was not enough to cause a large enough increase in irrigation amount. Moreover, during the April/May cycle the increment used was by 0.05 instead of 0.1. In addition, the calculated ET_o may have been too low. The pattern depicted by WFD response during the April/May cycle, shows that the irrigation quantities were too low to initiate detector response (Fig. 5.18a). There were detectors responding towards the end of the second cycle when the weather was getting cooler and water uptake was definitely decreasing. For the April/May cycle, it can be seen that the increment in irrigation quantities was not enough to initiate any detector response (Table 5.11 and Fig. 5.18a).

The CF and SWB treatments were under irrigated relative to the control (NP). Both treatments used the ET_o determined with the ET_o calculator of the SWB model. The cumulative ET_o for the April/May cycle was 108 mm (Table 5.12), which averages 3 mm day^{-1}. The ET_o may have been too low for autumn because the average ET_o value for a 5-year weather data set for Hatfield experimental station averaged 4.5 mm day^{-1} in autumn (Jovanovic, 2003). As a result, CF and SWB had to use water stored in the deeper soil layers (most notable with CF treatment), and that is the reason the two treatments produced statistically similar dry matter yields to the other treatments. Water content within the topsoil was steadily decreasing for CF, and declined even more pronounced for the subsoil, which is a typical resemblance of scenario 5, whereas scenario 3 would best suit SWB (Fig. 6.1).

6.2 CONCLUSIONS

The results obtained from this experiment revealed the great potential of using cheap and simple WFDs to manage irrigation, although we identified some important lessons to realise this potential. All treatments produced similar dry matter yields with varying amounts of irrigation water. However, each treatment used varying amounts of information to make that irrigation decision whereas the WFD (MACH in particular) used a *'Yes or No'* to make that decision. The MACH treatment received more irrigation than all treatments for all the cycles that it was evaluated, showing that there are several issues that need to be addressed for successful use of WFDs. Firstly, it is important that, when using the WFD, the user should choose an algorithm that increases irrigation amount when few shallow detectors respond to irrigation, and decrease irrigation amount or increase irrigation interval when more deep detectors are activated. The idea is to maintain adequate soil water content within the root zone or topsoil, and at the same time ensure minimum or no drainage to subsoil. This is helpful in the sense that WFDs can help the farmer not to consistently under or over-irrigate. The experience with FullStops shows that the MACH could be used more accurately when used in feedback mode, thus using the shallow detectors to control irrigation (increase or decrease amount or interval based on chosen algorithm) and deep detectors to decrease irrigation amount or lengthen interval. However, in this case, irrigation was controlled from deep detector response and most likely, due to weaker redistributing wetting fronts the deep detectors could not detect enough wetting fronts required by the algorithm to cut down irrigation quantities.

Hillel (1998) describes the existence of the wetting front as being due to lower hydraulic conductivity of the unwetted soil below and therefore water can only penetrate it when the gradient of the decrease in wetness is steep. So, it follows that the drier the soil is initially, the sharper must be the wetting front, and therefore in an initially wet soil the opposite can occur leading to weaker

wetting fronts. This aspect of weaker wetting fronts is being further investigated.

It has also been found that it is important to keep a proper record on irrigation history because if irrigation is to be applied based on detector response it is important to have knowledge of the last irrigation amount. This is noticeable with the April/May cycle, wherein wrong data about the irrigation and detector response was fed into the algorithm and ultimately contributed to over irrigation of the treatment. Potential errors were also made with other treatments e.g the full point was not determined accurately enough for the NP treatment and ET_o may have not been correctly estimated for the CF and SWB treatments.

The lesson learned with the FullStops is that it is good to control irrigation at 30 cm for the irrigation interval we choose. However, FullStops perform even better if there is a mechanism to check the depth of redistribution. This is because water continues to move downwards long after the control detector has stopped irrigation. Therefore, detector installed at the bottom of the root zone can effectively serve this feedback purpose. Thus, FS2 performed better than FS1 as the season progressed into the cooler times of the year because FS2 operated in a feedback mode.

A point here is not to say WFD technology is an ultimate solution to problems pertaining to irrigation management. However, given the nature of already available tools and technologies for scheduling irrigation, it can be envisaged that WFDs have potential for changing the way many farmers perceive irrigation management as being difficult and costly. Examples of our experience in this regard are briefly mentioned below.

In three case studies undertaken on farm level in the Western Cape, Mpumalanga and Limpopo provinces of South Africa, wetting front detectors were used. In the first case study, table grapes were grown under drip irrigation with the aim of reaching the early export market season. The farmer was introduced to WFD technology to evaluate his current practices. Three

electronic detectors were logged at a depth of 60 cm. This farmer over irrigated his crop, and he used to employ a consultant with a neutron probe, but felt the service was no longer required on a regular basis. They were surprised at the potential water saving they could make based on the wetting front detector record and decided to re-evaluate their current practice during times of low crop water use (Stirzaker et al., 2003).

In the second case study, grapes were grown under an open hydroponics system, in which drip irrigation was pulsed throughout the day. Detectors were buried at 30 and 50 cm. The aim was to ensure that the soil was regularly rewetted to 30 cm, but to minimize the drainage past 50 cm. Water was the central issue to this farmer. He used weather data and logged tensiometers to schedule irrigation and by changing irrigation infrastructure and management, he consistently cut back water applications. His feeling was that the detectors complemented his other scheduling methods, but that they could not be used on their own because his system was very fine-tuned and he needed, and had the skill to implement, detailed information. However, the detectors did show him that there were two reasonably long periods where he was under irrigating, and shorter periods when slight over irrigation occurred.

The third case study involved a small-scale farmer growing 2.5 ha of wheat under sprinkler irrigation. The major problem with this farmer was the risk of purchasing and applying fertilizer, both because of the financial risk and he was aware that leaching was a major problem on his very light soils. The farmer requested a pair of wetting front detectors, having seen them used on nearby food plots. He decided to apply nitrogen fertilizer and then followed the advice that "the shallow detector should respond regularly to irrigation and the deeper detector occasionally". At the end of the season, he harvested 5.4 t ha^{-1}, when the average yield for the scheme was 2.4 t ha^{-1}, and made a considerable profit. The farmer in this case did not have access to any scheduling method other than the WFDs. The most likely reason for this farmer's success is that he reduced N leaching by reducing drainage to deeper soil layers.

The above case studies show that irrigation-scheduling decisions for the farmer are different from the type of questions posed in this study. The study described here was about fine-tuning irrigation with different amounts of available information. For the farmers described in the case studies the detectors allowed them to evaluate the strengths and weaknesses of their irrigation strategy and reduced their risk with respect to giving "insurance" irrigations and applying fertiliser.

After all it is important to consider the fact that WFDs require a *'Yes or No'* to make irrigation adjustment whereas other well-known and widely accepted methods, like the neutron method require more detailed information to make an accurate irrigation decision. Moreover, the problems associated with adoption and use of irrigation scheduling aids is widespread (Leib *et al.*, 2002 and Tollefson, 1995), but it is mainly a function of a balance between costs, complexity and simplicity (Stirzaker *et al.*, 2003). These effects are even more pronounced in developing countries. Tollefson (1996) further contends that researchers need to develop economically viable technology that is readily adaptable to rural society, and that agricultural research must be directed to producer needs and results be made available to producers. Van der Westhuizen *et al* (1996) conclude that in South Africa the reason farmers do not schedule irrigation is that they do not perceive the net benefit to be positive.

The issues pertaining to irrigation scheduling still need to be addressed at *'grass roots level'* in some farming communities. An irrigation-scheduling tool like the WFD is simply meant to start an evaluation process wherein the farmer himself can use the tool to evaluate his current irrigation practices. It follows suite that in the case studies outlined, all the farmers were left with visible results as to what was happening with their irrigation practices. However, it is up to the farmers to make that decision of saving water and thereby cutting down the cost of irrigation. According to Walker (1995), a good preparation before on-farm trials when implementing a new technology is vital to successful adoption, and this lead to establishment of a good relationship of trust between researchers, extensions staff, and farmers. These linkages

created must be of mutual benefit to all parties, thus helping in capacity building and skills training in general agronomic practices that are important for sustainable irrigated agriculture.

This experiment revealed that WFDs could be used as an irrigation management tool, for monitoring current on-farm irrigation practices. For instance, when crop factors are used to schedule irrigation, WFDs can be used an indicator of over- or under-estimation of crop factors. This helps the farmer to avoid continual under or over-irrigation. In this way, WFDs serve as a learning tool that builds up information that can be used to rectify the mistakes made previously. When using the WFDs as an irrigation-scheduling tool, the farmer must choose an algorithm that controls irrigation from shallow detectors and use deep detectors for feedback. This helps to keep water content within the effective root zone at optimal levels, whilst minimizing drainage to subsoil.

Future work with WFDs should be done with a water sensitive crop that grows over one growing season, in this way, water use efficiency can be used to evaluate the efficiency of WFDs in irrigation scheduling.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ACRONYMS

a - Constant for neutron probe calibration equation that depends upon substances in the soil

ADL - Allowable depletion level

b - Slope of the neutron probe calibration equation

CF - Crop Factor

d_d - Depth of placement of the detector (m)

DOY - Day of the year

D_r - Drainage (mm)

E_{pan} - Evaporation from a class A pan (m)

E_s - Direct evaporation from the soil surface (m)

E_{sp} - Potential soil evaporation (kg m^{-2} s^{-1})

ET - Evapotranspiration (m)

ET_a - Actual evapotranspiration (m)

ET_m - Maximum crop evaporation (m)

ET_o - Reference evapotranspiration (m)

FC - Field capacity

FS1 - FullStop 1

FS2 - FullStop 2

K_c - Crop coefficient

K_{pan} - pan coefficient

MACH - Machingilana

N - Count ratio for the neutron probe

NP - Neutron probe

O - Overhead from a wetting front detector

P - Precipitation (mm)

PAW - Plant available water

PET - Potential evapotranspiration (mm)

PT - Potential transpiration (mm)

PWP - Permanent wilting point

R - Run-off from the soil surface (mm)

SWB - Soil Water Balance model

T - Transpiration (mm)

T_d - Daily transpiration (mm day^{-1})

TDR - Time Domain Reflectometry

Σ - The sum of

I - Neutron probe count rate

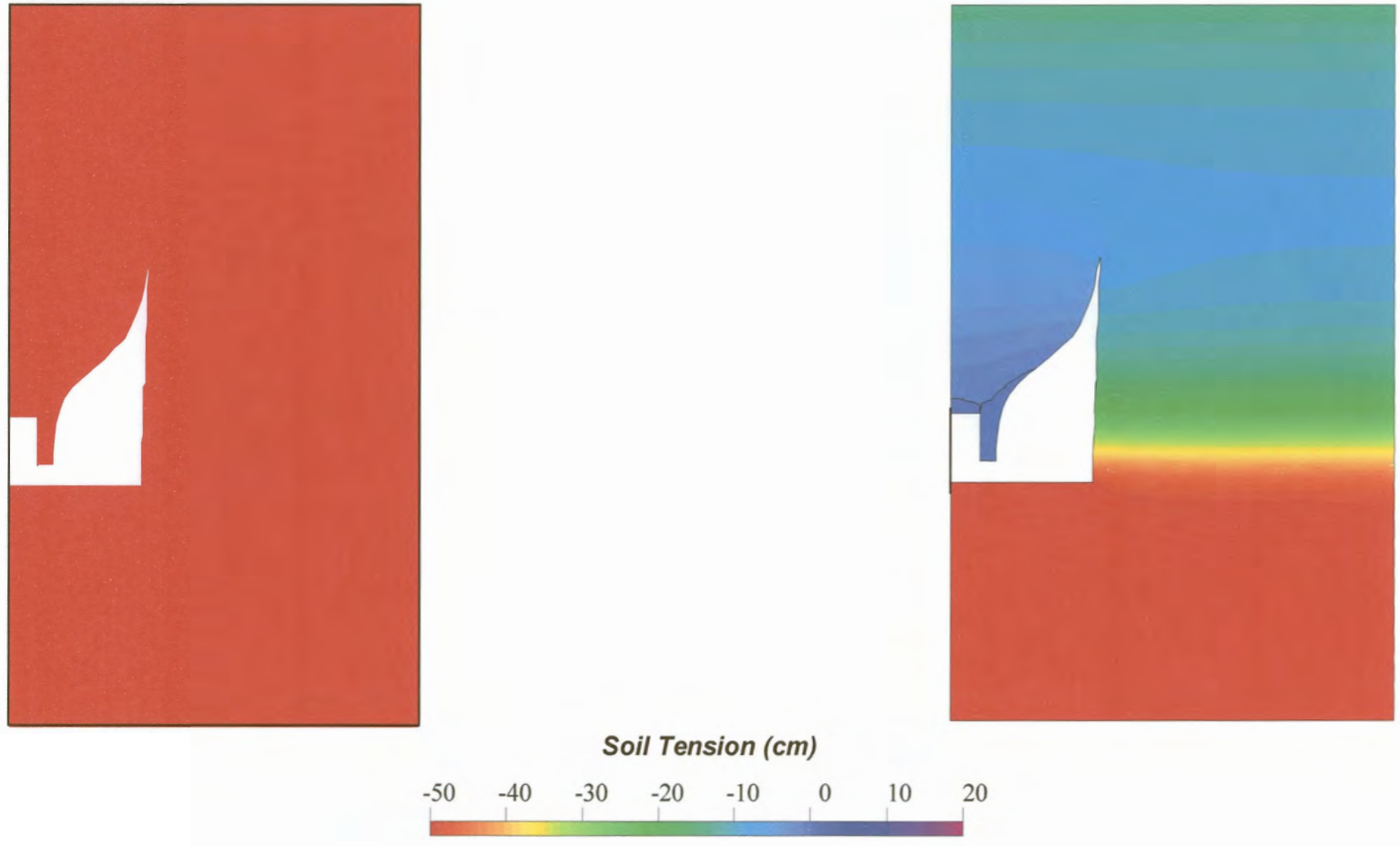
I_{std} - Neutron probe standard counts

θ	-	Volumetric soil water content (m m^{-1})
θ_{dul}	-	Volumetric water content at drained upper limit (m m^{-1})
θ_i	-	Initial water content in the soil
θ_{ll}	-	Volumetric water content at lower limit (m m^{-1})
θ_{rf}	-	Volumetric water content at refill point (m m^{-1})
θ_{wf}	-	Volumetric water content at the wetting front (m m^{-1})
ΔS	-	Change in soil water storage (mm)
®	-	Original trade name for product x
ℓ	-	litre
ψ_L	-	Leaf water potential (J kg^{-1})

APPENDIX A

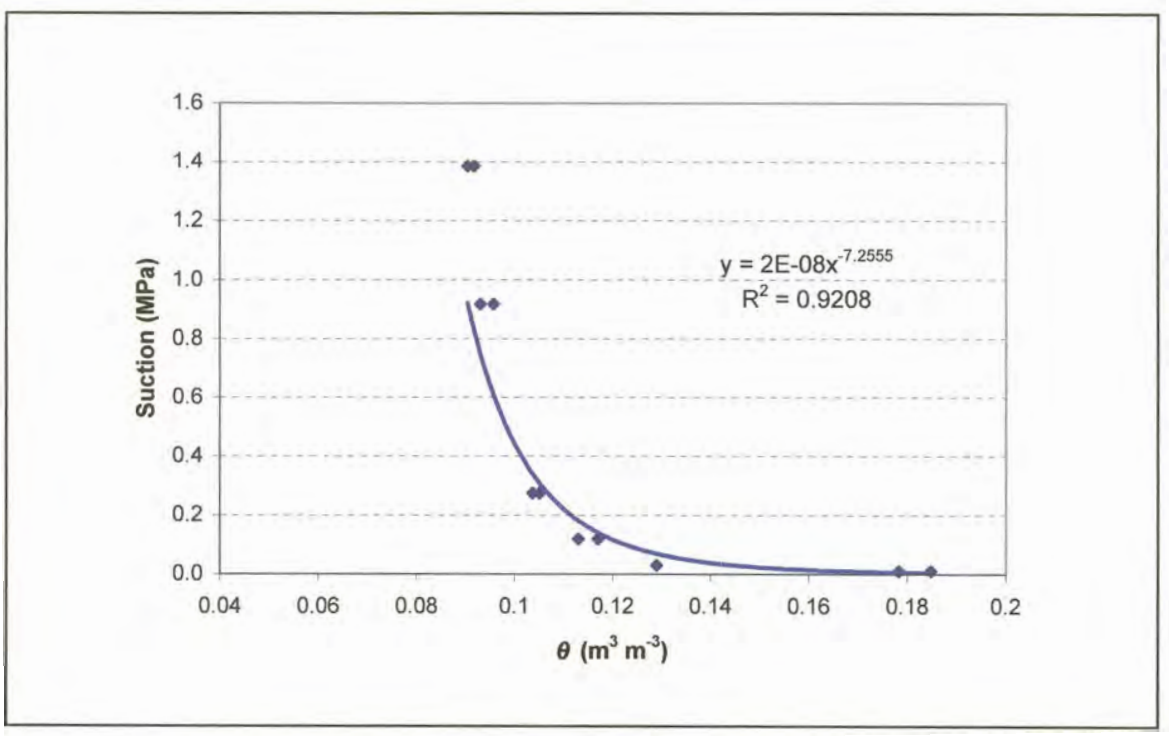
(I) A Hydrus simulation of how soil suction plays a critical role in the operation of the wetting front detector. In an initially dry soil, gravity and suction are the driving force for water movement, and therefore the build-up suction in the WFD will cause water to flow into the detector. (II) The position of the wetting front (and the soil tension above and below it) after detection by the WFD.

I. II.



APPENDIX B

Soil water characteristic curve for the WFD experiment, Hatfield experimental farm, determined according to the *'desorption'* method described by Hillel (1998); and Gardner (1986). The samples collected with a core sampler of a known volume were subject to different suction levels with a pressure plate until equilibrium was reached. The bulk density the soil sample was also determined.



APPENDIX C

Schematic layout of the WFD trial – Hatfield Experimental Farm showing only the treatment plots; border plots are excluded.

Rep1 SWB (21)	Rep1 FS1 (22)	Rep2 CF (23)	Rep2 MACH (24)	Rep3 FS1 (25)	Rep3 NP (26)	Rep4 SWB (27)	Rep4 NP (28)	Rep5 MACH (29)	Rep5 FS2 (30)
Rep1 MACH (20)	Rep1 NP (19)	Rep2 FS2 (18)	Rep2 FS1 (17)	Rep3 CF (16)	Rep3 MACH (15)	Rep4 FS1 (14)	Rep4 FS2 (13)	Rep5 SWB (12)	Rep5 CF (11)
Rep1 FS2 (1)	Rep1 CF (2)	Rep2 SWB (3)	Rep2 NP (4)	Rep3 SWB (5)	Rep3 FS2 (6)	Rep4 CF (7)	Rep4 MACH (8)	Rep5 FS1 (9)	Rep5 NP (10)

Legend

FS1 – FullStop 1
FS2 – FullStop 2
MACH – Machingilana
SWB – SWB model
NP – Neutron probe
CF – WFD generated crop factor

APPENDIX D

The irrigation controller configuration of WFD experiment at Hatfield experimental farm showing the flow rates as well the stations that controlled each solenoid valve.

Treatment	FS1 rep 1	FS1 rep 2	FS1 rep 3	FS1 rep 4	FS1 rep 5	FS2 rep1	FS2 rep 2	FS2 rep 3	FS2 rep 4	FS2 rep 5	NP	SWB	CF	Machingilana	Main meter
Solenoid valve	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Water meter number	1	1	1	1	1	6	6	6	6	6	2	3	5	4	7
Control station	1		2		3	8	9	10	11	12	4	5	6	7	
Number of plots	*8		*8		4	4	4	4	4	4	5	5	5	5	
Flow rate	*544		*544		272	272	272	272	272	272	340	340	340	340	

N:B * Indicates that the solenoid valves for this replicates where connected to a common control station although each one shuts-off irrigation separately.

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