# 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):

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

Where:

I = irrigation

P = precipitation

$E_S$ = soil evaporation

T = transpiration

R = run-off

$D_r$ = drainage below root zone

$\Delta S$ = change in soil water storage (with a negative value for $\Delta S$ 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 ($\Psi_L$) 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:

$$ET = I + P - R - D_r - \Delta S \qquad (2.2)$$

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):

$$ET_m = K_C \, ET_o \qquad (2.3)$$

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:

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

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).

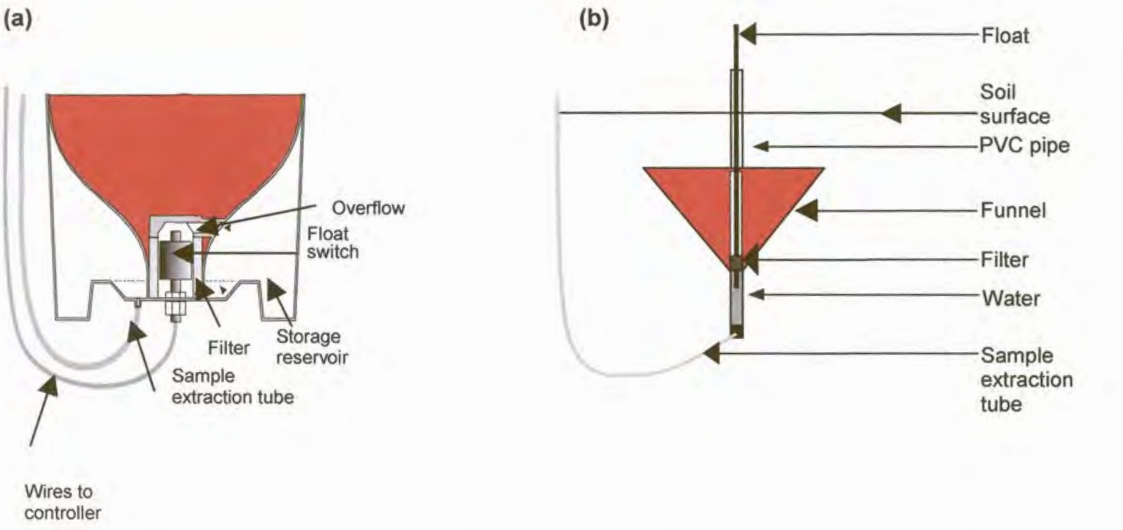

***Figure 3.1*** *(a) Electronic (FullStop), and (b) manual (Machingilana) version of the newly patented wetting front detector.*

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 $\theta_{wf}$, drained upper limit $\theta_{dul}$, refill point $\theta_{rf}$, and lower limit $\theta_{ll}$ 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 ($\theta_{wf}$) and refill point ($\theta_{rf}$) 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 ($\theta_{wf}$) | 0.21 |
| Drained upper limit ($\theta_{dul}$) | 0.18 |
| Refill point ($\theta_{rf}$) | 0.14 |
| Lower limit ($\theta_{ll}$) | 0.09 |

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

$$I = d_d (\theta_{wf} - \theta_i) \qquad (3.1)$$

where $\theta_i$ is the water content before irrigation.

Assume $\theta_i$ 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;

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

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;

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

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 $\ell$ 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 $\ell$ 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:

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

Where;

$ET = (E_s + T)$..........................................................................(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.*

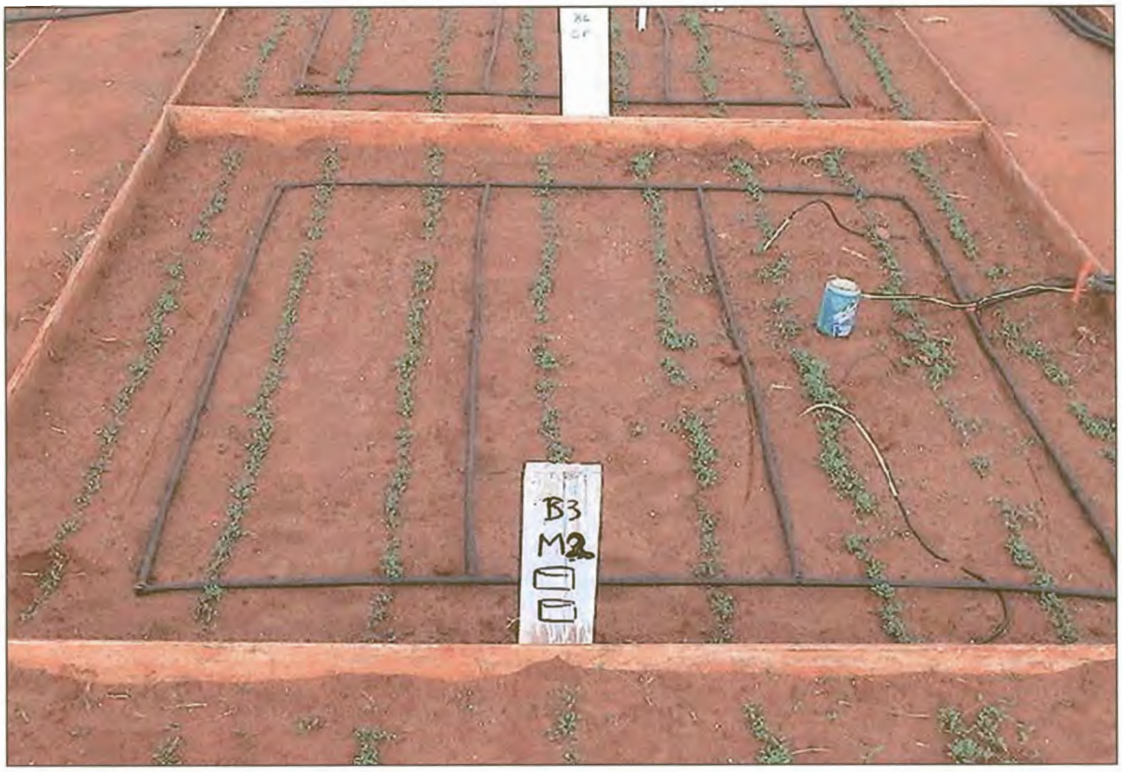

***Figure 4.3*** *An experimental plot with drip set-up. Each plot had four drip lines and three cross pieces at each end. Lucerne was planted in two rows between each dripper line.*

## 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 ($\theta$) (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):

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

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

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 $h^{-1}$).