FREQUENCY DOMAIN REFLECTOMETRY FOR IRRIGATION SCHEDULING OF COVER CROPS

by

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DECLARATION

I declare that the results contained in this thesis are from my own original work except where acknowledged.

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ABSTRACT

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A well-managed irrigation scheduling system needs a rapid, precise, simple, cost-effective and non-destructive soil water content sensor. The PR1 profile probe and Diviner 2000 were used to determine the timing and amount of irrigation of three cover crops (*Avena sativa* L., *Secale cereale* L. and *Lolium multiflorum* Lam.), which were planted at Cedara, KwaZulu-Natal. The PR1 profile probe was first calibrated in the field and also compared with the Diviner 2000. For the calibration of the PR1 profile probe the factory-supplied parameters (a_1 = 8.4 and a_0 = 1.6) showed good correlation compared to the soil-estimated parameters (a_1 = 11.04 and a_0 = 1.02). The factory-supplied parameters gave a linear regression coefficient (r^2) of 0.822 and root mean square error (RMSE) of 0.062. The soil-estimated parameter showed a linear regression coefficient of 0.820 with RMSE of 0.085. The comparison between the soil water content measured using the PR1 profile probe and Diviner 2000 showed a linear regression coefficient of 0.947 to 0.964 with a range of RMSE of 0.070 to 0.109 respectively for the first 100 to 300 mm soil depths. The deeper depths (400, 600 and 1000 mm) showed a linear regression coefficient of 0.716 to 0.810 with a range of 0.058 to 0.150 RMSE. These differences between the shallow and deeper depths could be due to soil variability or lack of good contact between the access tube and the surrounding soil.

To undertake irrigation scheduling using the PR1 profile probe and Diviner 2000, the soil water content limits were determined using field, laboratory and regression equations. The field method was done by measuring simultaneously the soil water content using the PR1 profile probe and soil water potential using a Watermark sensor and tensiometers at three depths (100, 300 and 600 mm) from a 1 m^2 bare plot, while the soil dries after being completely saturated. The retentivity function was developed from these measurements and the drained upper limit was estimated to be 0.355 m^3 m^{-3} when the drainage from the pre-wetted surface was negligible. The lower limit was calculated at -1500 kPa and it was estimated to be 0.316 m^3 m^{-3}. The available soil water content, which is the difference between the upper and lower limit, was equal to 0.039 m^3 m^{-3}. In the laboratory the soil water content and matric potential were measured from the undisturbed soil samples taken from the edge of the 1 m^2 bare plot before the sensors were installed. Undisturbed soil samples were taken using a core sampler from 100 to 1000 mm soil depth in three replications in 100 mm increments. These undisturbed soil samples were saturated and subjected to different matric potentials between -1 to -1500 kPa. In the laboratory, the pressure was increased after the cores attained equilibrium and weighed before being subjecting to the next matric potential. The retentivity function was then developed from these measurements. The laboratory method moved the drained upper limit to be 0.390 m^3 m^{-3} at -33 kPa and the lower limit be 0.312 m^3 m^{-3} at -1500 kPa. The regression equation, which uses the bulk density, clay and silt percentage to calculate the soil water content at a given soil water potential, estimated the drained upper limit to be 0.295 m^3 m^{-3} at -33 kPa and the lower limit 0.210 m^3 m^{-3} at -1500 kPa. Comparison was made between the three methods using the soil water content measured at the same soil water potential. The field-measured soil water content was not statistically the same with the laboratory and estimated soil water content. This was shown from the *paired-t test,* where the probability level (p) for the laboratory and estimated methods were 0.011 and 0.0005 respectively at 95 % level of significance. However, it showed a linear regression coefficient of 0.975 with RMSE of 0.064 when the field method was compared with the laboratory method. The field method showed a linear regression coefficient of 0.995 with RMSE of 0.035 when compared with the estimated method.

The timing and amount of irrigation was determined using the PR1 profile probe and Diviner 2000. The laboratory measured retentivity function was used to define the fill (0.39 m^3 m^{-3}) and high refill point (0.34 m^3 m^{-3}). The soil water content was measured using both sensors two to three times per week starting from May 29 (149 day of year, 2002) 50 days after planting until September 20 (263 day of year) 11 days before harvesting. There were five irrigations and twenty rainfall events. The next date of irrigation was predicted graphically using, the PR1 profile probe measurements, to be on 3 September (246 day of year) after the last rainfall event on 29 August (241 day of year) with 8 mm. When the Diviner 2000 was used, it predicted two days after the PR1 profile probe predicted date. This difference appeared since the Diviner 2000-measured soil water content at the rooting depth was slightly higher than the PR1 profile probe measurements. The amount of irrigation was estimated using two comparable methods (graphic and mathematical method). The amount of irrigation that should have been applied on 20, September (263 day of year) to bring the soil water content to field capacity was estimated to be 4.5 h and 23 mm graphically and 5.23 h and 20 mm mathematically. The difference between these two methods was caused due to the error encountered while plotting the correct line to represent the average variation in soil water content and cumulative irrigation as a function of time.

More research is needed to find the cause for the very low soil water content measurements of the PR1 profile probe at some depths. The research should be focused on the factors, which could affect the measurement of the PR1 profile probe and Diviner 2000 like salinity, temperature, bulk density and electrical conductivity. Further research is also needed to extend the non-linear relationship between the electrical resistance of the sensor and soil water potential up to -200 kPa. This non-linear equation of the Watermark is only applicable within the range of soil water potential between -10 and -100 kPa.

CHAPTER 1

INTRODUCTION

Irrigation plays a significant role in the agricultural production of drought prone arid and semi-arid regions. As Hillel (1990) points out, in these areas by cruel stroke of nature, the water requirement of crops exceed the rainfall supply. Under such conditions, even a slight improvement in water economy may spell the difference between marginal subsistence and profitable production. The existing traditional-bound irrigation schemes should be modernized to achieve higher levels of profitable and sustainable production. The new methods should be based on sound principles and techniques to attain greater control over the soil-crop-water regime and optimize irrigation in relation to other essential agricultural inputs.

In recent years development has taken place in the distribution and application of irrigation. This scientific development has been complemented by a series of technological innovations that monitor the soil-plant-atmosphere continuum which have made it possible to establish and maintain nearly optimal soil water content. Traditional methods of irrigation scheduling include sensors that monitor the soil (gravimetric method, tensiometer, neutron probe, electrical resistance blocks and thermal dissipation sensors), the crop (heat pulse method and pressure chamber) and the microclimate (evaporation pan, atmometers, lysimetry and reference evaporation methods). Other recent methods include infrared thermometry, time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR). Even more recent are soil profile sensors, designed for irrigation scheduling, such as the PR1 profile probe (Delta-T Devices, Cambridge, UK) and Diviner 2000 (Sentek Environmental Technologies, Stepney, Australia) soil water content sensors. These recently developed profile sensors use the high dielectric constant of water at high frequencies to estimate the soil water content down the soil profile. These techniques can provide precise, non-destructive, continual and unattended *in situ* measurement of soil water content under field conditions. These soil profile sensors can yield measurements of the soil water content by moving from access tube to access tube while recording the soil water content in a hand held logger, which can be downloaded to a computer.

To use these sensors for irrigation scheduling they need to be calibrated for the specific soil type in order to get accurate soil water content measurement. Like most soil water content and soil water potential sensors, these sensors do not measure directly the soil water content. Instead, they measure the dielectric property of the soil that could be related to soil water content by a calibration curve or equation. Usually the manufacturers of these sensors provide the calibration equation that converts the dielectric constant to voltage and further the voltage to volumetric soil water content. The calibration equations, which are provided by the manufacturer, are for general soils and to make the calibration equations site specific, these soil water content sensors need to be calibrated for the particular soil type.

Once the sensors are calibrated, the soil water content limits should be defined to undertake irrigation scheduling. The soil water content limits (lower limit and drained upper limit) can be measured in a field or laboratory or they can be estimated using empirical equations based on easily measured soil properties such as soil texture, bulk density and organic matter content. In the laboratory, the lower limit is estimated using a pressure chamber at a matric potential of -1500 kPa (Richards and Weaver, 1943). The water content at a matric potential of -33 kPa is used as an estimate of the drained upper limit for moderately coarse and fine-textured soils, whereas -10 kPa is used for coarse-textured soils (Colman, 1947; Jamison and Kroth, 1958). In the field, the lower limit is assumed to be the water content of the soil at which plants are practically dead or dormant as a result of the soil water deficit. The drained upper limit is the soil water content at which drainage from a pre-wetted soil has practically ceased or when the decrease in the soil water content is about 0.001 to 0.002 m^3 m^{-3} per day (Ratliff *et al.*, 1983).

Soil water monitoring to determine the time and amount of irrigation requires predetermined values of the drained upper limit, lower limit and refill point that is the potential below which crop production is measurably decreased (Campbell and Campbell, 1982). In addition, the actual soil water content must be measured with time to forecast the date of irrigation (Gear *et al.*, 1977). To determine the time of irrigation the refill point should also be defined based on optimum soil water potential provided on literatures. The depth-averaged soil water content measured using the profile sensors with time and the refill point indicated gives a means to forecast accurately the time of irrigation. The amount of irrigation can be determined using different methods. One method of determining the amount and duration of irrigation is by monitoring sub-hourly soil water content and the cumulative irrigation with time. The sub-hourly soil water content and the cumulative irrigation with appropriate calculations and graphical representation can be used to predicted the time and duration of irrigation which is required to bring the soil water content to field capacity.

The major objectives of this study were:

1) *To calibrate and compare the sensors used* (Chapter 6): (a) The PR1 profile probe was calibrated against mass soil water content and comparison was made between the PR1 profile probe and Diviner 2000; (b) Calibration and evaluation was made using tensiometers and Watermark sensors (and thermocouples for sensor temperature) which were used to define the soil water content limits under field conditions.

2) *To compare the methods used to define the soil water content limits* (Chapter 7): The drained upper and lower limits were determined in the field and in the laboratory and calculated using regression equations. Comparison and evaluation was made to determine which method is reliable to define the soil water content limits.

3) *To determine the timing and amount of irrigation that should be applied to the cover crops (oats, rye and ryegrass) using frequency domain reflectometry (FDR) sensors* (Chapter 8): Both the PR1 profile probe and Diviner 2000 were used to schedule irrigation of the cover crops and comparison was made between the time and amount of irrigation determined using both methods.

In this study, two frequency domain reflectometry profile sensors (PR1 profile probe and Diviner 2000) were used to determine the time and amount of irrigation. In the next two chapters the theoretical (Chapter 2) and practical (Chapter 3) aspects of irrigation scheduling were reviewed. The theoretical aspects of irrigation scheduling, dealt with the different approaches which were used to determine the time and amount of irrigation. The practical aspects of irrigation scheduling described the sensors, which monitor soil, plant and weather.

CHAPTER 2

THEORETICAL ASPECTS OF IRRIGATION SCHEDULING

2.1 INTRODUCTION

Irrigation scheduling is a process of determining when and how much water to irrigate. Water should be applied to the soil when the soil water content is still high enough that the soil can supply water adequately to meet the atmospheric demand without placing the plant under stress that reduces yield or quality of the harvested crop. Similarly, during irrigation, water should be supplied in quantities that will not cause excessive soil drainage, leaching, salinity problems, or produce undesirable growth as a result of excess water or restricted soil aeration. To address these two basic questions of irrigation scheduling, different methods of water management have been developed over several decades. In spite of this work, further research is still needed to make these water management methods farmer-friendly, simple and easy for farmers to adopt and practice.

At the farmers level, irrigation scheduling can offer the following advantages (Broner, 2002): i) it enables farmers to schedule water rotation among the various fields to minimize crop water stress and maximize yield; ii) it reduces the farmer's cost of water and labour through fewer irrigations thereby making maximum use of soil water storage; iii) it lowers fertilizer costs by keeping surface runoff and deep percolation to a minimum; iv) it increases net returns by increasing crop yields and crop quality; v) it minimizes water-logging problems by reducing the drainage requirements and vi) it assists in controlling root zone salinity problems through controlled leaching.

Several problems can also occur when adopting and practicing irrigation scheduling. Martin *et al.* (1990) has reviewed some of the practical problems that a farmer could face when practicing irrigation scheduling:

i) a common problem arises when rain occurs soon after or during irrigation. If the amount of rain is large enough to cause leaching in the area already irrigated but not in the area remaining to be irrigated, the soil water content will vary across the field. A similar problem occurs if rain is not uniformly distributed over the field. The lack of uniformity can become a systematic problem over the field;

ii) scheduling fields that contain varying soil type is complex because of different water holding capacities and therefore different allowable depletions. Similarly heterogeneity also occurs when multiple crops are planted in the same field;

iii) irrigation projects with a rigid delivery design obstruct the whole issue of irrigation scheduling. In such cases, the only choice that is left to the irrigator is to 'take it or leave it' but most irrigators obviously tend to irrigate as much as they can, even much beyond reasonable needs as an insurance against possible future disruptions of water delivery;

iv) the period of the season that is most limiting must be determined and then a management plan must be developed accordingly to accommodate the limitation. If this is not the case stress may develop later in the season when the system capacity becomes limiting.

2.2 METHODS TO DETERMINE THE TIME OF IRRIGATION

2.2.1 Refill point

One method of determining the time of irrigation is to monitor the soil water content. Gear *et al.* (1977) expressed irrigation scheduling using the refill point. Periodic soil water content measurements with soil water content sensors yield both the ambient soil water content and the rate of water used by the crop. A simple graph showing soil water content plotted versus time with the refill point indicated, will yield a visual means of forecasting accurately the time of irrigation (Lukangu *et al.*, 1999).

The refill point is the soil water potential below which crop production is measurably decreased or it can also be defined as the soil water potential at which the transpiration rate decreases by 10 % from its potential value. Practically the refill point (θ) is estimated on a volume basis using the following equation (Campbell and Campbell, 1982):

$$\theta = (\psi / a)^{-1/b} \qquad 2.1$$

where ψ is the optimum soil water potential (kPa) from Haise and Hagan (1967) or in Taylor and Ashcroft (1972), $a = -4 \times 10^{-2}$ kPa and b is calculated using the equation:

$$b = -7.82 / \ln \theta_l \qquad 2.2$$

where θ_l = 0.2 (% silt) + 0.6 (% clay) + 0.09 (Gupta and Larson, 1979) for mid-range bulk density and low organic matter soils.

2.2.2 Threshold soil water potential

Martin *et al.* (1990) and Taylor and Ashcroft (1972) showed that soil water potential can be used as a criterion to indicate the timing of irrigation. Soil water potential can be measured using tensiometers, gypsum blocks, Watermark sensors and thermal dissipation methods. Two matric potential values are required to apply the soil water potential for irrigation scheduling. One is the matric potential of the soil at the effective rooting depth and the second is the soil matric potential to be achieved by irrigation. Haise and Hagan (1967) and Taylor and Ashcroft (1972) tabulated the optimum soil water potential at which irrigation should be started to maintain maximum yield for many common crops. Using this method, irrigation commences when the soil sensors record the optimum soil water potential. For best results, the soil matric potential should be recorded with time, so that the plotted curve can be extrapolated ahead of time to anticipate when irrigation will be needed.

2.2.3 Allowable soil water depletion

Many researchers (Stegman, 1983; Heermann *et al.*, 1990; Martin *et al.*, 1990) demonstrated the use of allowable depletion as a criteria for irrigation scheduling. This method is by far the most widely used criteria for irrigation scheduling, particularly for water balance methods. These criteria express the portion or percentage of available water content at the root zone that can be safely depleted between irrigation for maintenance of a non-stress or low stress environment for crop growth. Available water content is defined as the difference between the soil water content at field capacity and permanent wilting point (Ratliff *et al.*, 1983; Savage *et al.*, 1996). Generally, a depletion criterion of 50 % from the available water content represents an average "safe" level for a wide array of crops and soils. The soil water content could be estimated from the water balance method or measured using soil water content sensors. The water balance method estimates the soil water content depletion using the following equation (Heermann *et al.*, 1990):

$$D_i = D_{i-1} + ET_i - P_i - IR_i \pm DR_i \qquad 2.3$$

where D_i the depletion on day i, D_{i-1} is the soil water depletion on day i-1, ET the estimate of total evaporation, P is the effective precipitation depth, IR is the net irrigation depth, and DR is the drainage loss from (+ sign) or upward flow to (- sign) the active root zone.

2.2.4 High-frequency irrigation

Hillel (1990) reviewed the application of high-frequency irrigation as a timing method. With this method, the definition of allowable soil water depletion or plant stress becomes relatively less important. This technique applies water more frequently using a highly mechanized system with high uniformity at a relatively light application rate. When irrigation rates are kept within the infiltration rate and the applied water is less than that required to replenish the soil profile, this timing method offers potential for greater precipitation effectiveness and reduced runoff or deep percolation loss. Irrigation at high frequency also satisfies the day-to-day evapotranspiration demand and maintains high soil water potential in the upper root zone. In turn, high soil water potentials minimize the diurnal depression of plant water potential. However, high-frequency irrigation increases evaporative loss from the soil as compared to low-frequency irrigation.

2.2.5 Threshold leaf water potential

The total leaf water potential can be measured using a scholander pressure chamber (Scholander *et al.*, 1965), thermocouple psychrometers (Savage, 1983; Savage and Cass, 1984) or hydraulic press (Heathcote *et al.*, 1979; Savage, 1983). Approximated threshold leaf water potential values for the application of irrigation scheduling are given for several crops by Stegman (1983) and Martin *et al.* (1990). However, this method has a major limitation on the application of irrigation scheduling since it is dependent on time of day when the measurement is taken. It is at its daily maximum near sunrise, and at its daily minimum in the midday to mid afternoon period. Thus, its application on irrigation scheduling is only limited to controlled environment and research sites. This method can be applied in irrigation scheduling by farmers, if the leaf water potential can be estimated from physically based or locally calibrated-empirical models.

2.2.6 Foliage-air temperature difference

Jackson (1982) reported the crop water stress index (CWSI) as an index to initiate irrigation. The use of foliage-air temperature differences as a timing method for irrigation is based on the concept that water stress will cause an increase in plant temperature as reduced transpiration dissipates less of the incoming solar irradiance. CWSI can be quantified using the upper and lower limits for crop-air temperature difference. The upper limit represents the temperature difference between the crop and air for severe stress when transpiration approaches zero. The lower limit represents the temperature difference between the crop and air when the crop is well irrigated. The CWSI varies from a value of zero for no water stress to a maximum value of one at a severe stress. For example, wheat is irrigated when the CWSI is between 0.3 and 0.5 (Jackson, 1982).

2.2.7 Allowable ET deficit

Due to limited water supply, high-energy cost or high system labour requirement, a farmer might choose to prolong the interval between irrigation until crop total evaporation (ET) decreases below the potential total evaporation (ET_m) rate. To implement this allowable ET deficit as a scheduling criteria, it requires a reliable method for estimating the ET decrease due to water stress. The following empirical equations were used to estimate the stress-induced reduction in ET from the ET_m:

$$ET / ET_m = 1 \qquad \text{if } AW \geq b \tag{2.4}$$

$$ET / ET_m = AW / b \qquad \text{if } AW < b \tag{2.5}$$

where AW is the percentage of available water remained in the root zone and b is the threshold percentage at which ET begins to fall below the ET_m rate. Many researchers reported the value of b ranges from a low value of 20 % to a high value near 50 % remaining available water (Stegman, 1983).

2.2.8 Models

Unlike the other methods of irrigation scheduling, models allow a great integration of complexities in the soil-plant-atmosphere system that impact the decisions of timing of irrigation (Martin *et al.*, 1990). For example, the crop growth model like the Decision Support System for Agrotechnology Transfer (DSSAT) model (Tsuji *et al.*, 1994) considers the soil water balance to determine the timing and amount of irrigation based on the soil inputs (lower limit of plant water availability, drained upper limit, field saturation, layer depth, root weighting factor and initial soil water content), precipitation, irrigation, transpiration, soil evaporation, runoff, and drainage from a profile (Ritchie, 1998). Similarly, the Cropping System Simulation model (CropSyst) (Stockle and Nelson, 1996) uses the water balance to determine the time and amount of irrigation. In automatic irrigation this model triggers irrigation when the calculated soil water content reaches the maximum allowable depletion.

2.3 METHODS TO DETERMINE WHEN TO STOP IRRIGATION

The accurate estimate of the amount of irrigation is a basic requirement for optimal irrigation management. Applying the correct amount of water is important for efficient water use and to prevent excessive soil water drainage, leaching, and salinity problems that could cause contamination of ground water. The amount of irrigation water that needs to be applied can be estimated either by monitoring the wetting front during irrigation or it can be calculated from the soil parameters.

2.3.1 Monitoring the wetting front

Zur *et al.* (1994) explained the control of water application in irrigation by monitoring the wetting front. The process of wetting a profile goes through two stages. At the end of the first process (infiltration stage) a certain soil depth (Z_L) is wetted in excess to a field water content that is a function of the application rate, and is constant with depth. During the second (redistribution stage) excess water from the initially wetted soil depth drains downward to wet an additional depth of soil. The resulting wetted soil profile down to the depth (Z_F) is characterized by the relatively stable soil water content of field capacity (θ_{FC}). Based on this principle, the arrival of the wetting front to a depth Z_L, which is called the critical depth, could be used as a signal to stop irrigation. The relationship between the planned depth (Z_F) and the critical depth (Z_L) depends on soil type, initial soil water content distribution and the application rate.

The critical depth (Z_L) can be estimated by multiplying the value of the planned depth (Z_F) by a reasonable coefficient in the range of 0.4 to 0.7 depending on the soil type. The correct value of the coefficient will then be determined by an iterative learning process within the specified range after repetitive irrigation and monitoring of the wetting front (Zur *et al.*, 1994). Alternatively, the value of the critical depth can also be computed using the Campbell and Campbell (1982) approach:

$$Z_L = Z_F\,(\theta_{FC} - \theta_i) / (\theta_{VS} - \theta_i) \qquad 2.6$$

where Z_L is the critical depth, Z_F is the depth that irrigated water will reach after the redistribution process (which must coincide with the effective rooting depth), θ_{FC} is the field capacity, θ_i is the initial soil water content before irrigation (and equal to the refill point) and θ_{VS} is the saturated soil water content.

The arrival of the wetting front at the critical depth (Z_L) could be detected using a wetting depth probe (Zur *et al.*, 1994). When the current flow across the sensor changes by more than 5% of the original reading, this indicates the arrival of the wetting front at the critical depth. The Fullstop controller (a funnel-shaped container, which is buried in the root zone) can also be used to detect the arrival of the wetting front at the critical depth. When the wetting front reaches the Fullstop, water collects at the base of the funnel. If it is automated, an electrical float switch is activated to stop the irrigation. In the non-automated model, the water collected and concentrated in the funnel, will lift the float as the water rises in a vertical tube (Drury, 2002).

2.3.2 Calculated value

The amount of irrigation applied will depend on crop, soil, weather and economic factors. If water is easily available and inexpensive, full irrigation is practiced but if water is limited, deficit irrigation may be practiced even at the expense of maximum yield (MacRobert and Savage, 1998). The amount of irrigation, assuming that full irrigation is being practiced is determined as follows (Singh *et al.*, 1995):

$$IRRIG = RD\ (FC - \Delta sc) / E_i \qquad 2.7$$

in which $IRRIG$ = calculated irrigation amount (mm); RD = rooting depth of plant according to its growth stage (mm); FC = field capacity in mm depth of water depending on the rooting depth (mm); Δsc = critical soil water content for the day in question (% volume); and E_i = irrigation efficiency (%). Alternatively, $IRRIG$ is simply calculated as follows:

$$IRRIG = FC - \Delta sc \qquad 2.8$$

The calculated value could be changed depending on whether full or deficit irrigation is being practiced, and on the delivery capacity and efficiency of the irrigation system. Also, in order to avoid over-irrigation in case of rain and leaching, the amount may also be reduced.

CHAPTER 3

PRACTICAL ASPECTS OF IRRIGATION SCHEDULING

3.1 INTRODUCTION

Irrigation scheduling usually deals with two basic questions: (1) when to start irrigation and (2) when to stop irrigation. These two basic questions can be approached in several ways. Generally, the different methods of irrigation scheduling can be broadly classified as methods that monitor soil, plant and weather. In the following topics the different methods of irrigation scheduling will be described with emphasis on description of the sensors, how the sensors work, application of the sensors in irrigation scheduling, and advantages and disadvantages of the sensors relative to each other.

3.2 MONITORING THE SOIL

According to Campbell and Campbell (1982), soil monitoring is the traditional method of determining when and how much irrigation to apply. The idea is to observe the water reserve of the root zone as it gradually diminishes following each irrigation, so as to know the time and amount of irrigation. The soil sensors can be broadly classified into two categories: sensors or methods that allow measurements of the soil water content (m^3 m^{-3}) – like gravimetric, neutron probe, time domain reflectometry (TDR), and frequency domain reflectometry (FDR) methods – and those that measure soil water potential (kPa) – tensiometers, gypsum blocks, Watermarks and thermal dissipation methods.

3.2.1 Gravimetric method

This is the standard method for calibration of all the other soil water determination techniques (Gardner, 1986). This method involves water content measurement by weighing the sample, removal of the water by oven drying, and reweighing the sample to determine the amount of water removed. Soil water content can then be expressed as either mass water content (g g^{-1}), or volumetric water content (m^3 m^{-3}) if the soil bulk density is known.

i) Volumetric soil water content is defined as

$$\theta_V = V_W / V_S \qquad 3.1$$

where θ_V is the volumetric water content ($m^3\ m^{-3}$), V_W is the volume of water contained in the sample and V_S is the total volume of the sample.

ii) Gravimetric water content is defined as

$$\theta_G = M_W / M_S \qquad 3.2$$

where θ_G is the gravimetric water content ($g\ g^{-1}$), M_W is the mass of water in the sample and M_S is the total mass of the dry sample.

To convert from volumetric to gravimetric water content the following equation is used:

$$\theta_G = \theta_V * (\rho_w / \rho_b) \qquad 3.3$$

where ρ_w is the density of water and ρ_b the bulk density of the sample (= M_S/V_S)

Gardner (1986) listed the apparatus required for gravimetric determination of water content as an auger, a suitable device to take a sample, a soil container with tight-fitting lids, an oven with means for controlling the temperature at 100 to 110 °C, a desiccator with active desiccant, and a balance for weighing the samples. In the field, if soil samples are taken under conditions where evaporation losses may be of sufficient magnitude to affect accurate measurement of the water content of the soil samples, special equipment for weighing the samples immediately or covering material must be used to reduce evaporative loss.

The main advantage of the gravimetric method, as Reynolds (1970) discussed, it requires relatively simple and inexpensive equipment. However, it requires a great deal of effort and time. Repeated sampling also disturbs the experimental area.

3.2.2 Neutron probe

Hillel (1980) described the neutron probe as a sensor which consists of two main components: (a) *a probe*, which is lowered into an access tube inserted vertically into the soil, and which contains a source of fast neutrons and a detector of slow neutrons; (b) a ratemeter (usually battery powered and portable) to monitor the flux of slow neutrons scattered by the soil.

The theory behind this method as explained by many researchers (Long and French, 1967; Visvalingam and Tandy, 1972; Gardner, 1986) is based on the following principle. Hydrogen, which has the same size and mass as a neutron, has a marked property for scattering and slowing neutrons (thermalizing effect). When a fast neutron source is placed in moist soil it immediately becomes surrounded by a cloud of thermal neutrons. Thermal neutron density is easily measured with a detector, insensitive to fast neutrons, which is placed in the vicinity of the fast neutron source. Then the thermal neutron density can be converted to volumetric water content using the calibration curve, which is usually linear over the range of interest.

Gear *et al.* (1977) pointed out that correct irrigation scheduling by use of neutron probe requires identification of the refill point at which irrigation should occur and periodic soil water content measurements by the neutron probe. Periodic soil water content measurement with the neutron probe will yield both the ambient soil water content and the rate of water use by the particular crop. The soil water content versus time, with the refill point indicated, will give a means to forecast accurately the time of the next irrigation.

The main advantage of the neutron probe method can be summarized as follows: i) it can measure water of any phase; ii) it is possible to obtain continuous profile water content measurement; iii) it can be automated; and iv) it has a minimum disturbance of adjacent soil. The disadvantages of this method are: i) it has inadequate depth resolution; ii) it cannot measure surface soil water content; iii) it has a radiation hazard; iv) calibration is affected by dry bulk density, soil texture, soil temperature, and neutron absorbing elements and v) it is expensive (Visvalingam and Tandy, 1972).

3.2.3 Time domain reflectometry (TDR)

In soil applications, TDR is used to measure the dielectric constant (a complex quantity and a measure of the polarity). Water, the component that governs the dielectric constant of the soil, has a dielectric constant of 80 as compared with values of 2 to 5 for soil solids. Thus, a measure of the dielectric constant of soil is a good measure of its water content (Topp and Davis, 1985). Although the dielectric constant is, in general, a complex property, there is, for soil a simple relationship between propagation velocity and dielectric constant. The dielectric constant can be calculated practically (Topp and Davis, 1985) if the velocity is given from knowledge of the length of the transmission line in the soil and the signal travel time in the soil is measured using the TDR:

$$\varepsilon = (c\, t / 2L)^{2} \qquad 3.4$$

where ε is the dielectric constant, c is the propagation velocity of an electromagnetic wave in free space (3×10^{8} m s^{-1}), t is the signal travel time (s), and L is the length of the transmission line (m).

It is also found that there is a strong dependence of the dielectric constant on volumetric water content (θ_V). Thus, the volumetric water content of a soil to schedule irrigation can be calculated from the empirical equation given by Topp *et al.* (1980).

$$\theta_V = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\, \varepsilon - 5.5 \times 10^{-4}\, \varepsilon^{2} + 4.3 \times 10^{-6}\, \varepsilon^{3} \qquad 3.5$$

Irrigation scheduling using TDR requires setting the refill point, the drained upper limit and periodic soil water measurement by the TDR sensor. The sensor should be installed where the water content in the field is lowest (the so called hot spot). This measurement will give both the current soil water content and the rate of water use by the plant. Soil water content measured by the TDR versus time, with both the refill and drained upper limit shown in the graph, will provide a visual means of predicting accurately the date of the next irrigation. If possible it can be automated to activate or control circuitry for irrigation equipment (Topp and Davis, 1985).

Dalton and Poss (1990) summarized that time-domain reflectometry can be utilized to make rapid measurements in the field, the ability to select an electrode length reduces insertion problems, and it is independent of soil texture, temperature and salt content. The main disadvantage of the sensor is the cost.

3.2.4 Frequency domain reflectometry (FDR)

These sensors include equipments such as the Thetaprobe (Delta-T Devices, 2001), PR1 profile probe (Delta-T Devices, 2002) and Diviner 2000 (Sentek Environmental Technologies, 2000). These sensors generate signals to detect the soil water content. As it is described in the PR1 profile probe users manual (Delta-T Devices, 2001), when power is applied to the sensor it generates a signal which is applied to pairs of stainless steel rings that further generate an electromagnetic field that extends to 100 mm into the soil. If the dielectric properties of the soil are different from the probe electronics, some of the signals are reflected. The reflected part of the signal combines with the applied signal to form a standing wave and this voltage of the standing wave acts as a simple, sensitive measure of the soil water content.

For the application of irrigation scheduling, periodic soil water content measurements with these sensors give both the ambient soil water content and the rate of water used by the crop. This simple method discussed by Gear *et al.* (1977), Lukangu *et al.* (1999) and Laboski *et al.* (2001) showing soil water content versus time will yield a diagrammatical means of predicting the next time of irrigation. The amount and duration of irrigation could also be determined using the sub-hourly measured soil water content and cumulative irrigation. The sub-hourly soil water content and cumulative irrigation were plotted in a graph with appropriate projection of lines to predict the amount and duration of irrigation (Lukangu *et al.*, 1999).

The advantage of these sensors is that, there are different design of sensors that include hand held devices, portable PR1 profile probes that are mechanically similar to the neutron probe (Roberson *et al.*, 1996), the sensors provide precise measurement of soil water content, has a lower power consumption, they are non-distractive, continuous and unattended *in situ* measurements of soil water content can be taken under field conditions using dataloggers (Veldkamp and O'Brien, 2000). The disadvantage of the sensors are that readings are influenced by soil texture, soil temperature and air gaps between the sensor and the soil, and systems operating at lower frequency are more susceptible to soil salinity (Delta-T Devices, 2001).

3.2.5 Tensiometers

Smajstrla and Harrison (1998) described the tensiometer as an instrument consisting of a porous cup connected through a rigid body tube, which is attached to a vacuum gauge. The cup and tube are filled with water. The porous cup is normally constructed of ceramic. Because of its structural make up porous cup is permeable to water. The tensiometer reading can be taken from a gauge, manometer or electronic pressure transducer.

As Cassel and Klute (1986) explained, when tensiometers are placed in the field with the ceramic cup firmly in contact with the soil, water starts to move through the cup to equilibrate with the soil water. A partial vacuum is then created as water moves from the sealed tensiometer tube. This vacuum causes a reading on the vacuum gauge, which is a measure of the energy per unit volume of water that would be needed by the plant to extract water from the soil (Smajstrla and Harrison, 1998).

Tensiometers are widely used to schedule the application of water for a large variety of trees and crops. Irrigation of container-grown plants and plants grown in greenhouse bed are also often scheduled using tensiometers. In the field, tensiometers should be installed at sites that are representative of the soil and of water application practices. It is also recommended that there should be two tensiometers per site, with the porous cup of one at a depth equal to one-fourth of the active rooting depth and the cup of the other just beneath the rooting zone. The upper tensiometer is used to schedule irrigation and the lower one is used as an indicator of drainage (Paramasivam *et al.*, 2000). A tensiometer, however, indicates only when irrigation should be scheduled and not how much water should be applied (Cassel and Klute, 1986).

Schmugge *et al.* (1980) summarized the advantages and disadvantages of this method as follows: i) tensiometers are easy to design and construct; ii) systems cost relatively little; iii) information can be obtained on soil water distributions under saturated and unsaturated conditions in real time; iv) tensiometers can usually be placed in soil easily and usually with minimum disturbance and v) the response time is very rapid. The disadvantages are: i) it provides direct measurement of soil water potential but only indirect measurement of soil water content; ii) it can be easily damaged during installation and iii) results can be determined only within the 0 to -80 kPa water potential range.

3.2.6 Electrical resistance blocks

3.2.6.1 Gypsum

An electrical resistance block generally contains a pair of electrodes embedded in gypsum. The embedded electrodes may be plates, screens, or wires in parallel or in a concentric arrangement. When these blocks are placed in a soil, they tend to equilibrate with the soil water (matric) potential (Hillel, 1980).

Many researchers (Pereira, 1951; Goltz *et al.*, 1981; Carlson and Salem, 1987) have explained the principles of the sensor as follows: the sensor is based on the electrical resistance of dry gypsum (essentially infinite resistance). When it is in equilibrium with the surrounding fluid, the electrical resistance of the block decreases with increasing water content. Gypsum blocks are porous and permit a small amount of calcium sulfate (a weak electrolyte) to move into solution with the permeating water, thereby creating a relatively stable conducting medium. A fixed voltage passes though the block and the potential difference across a wheatstone bridge is measured. This potential difference is a function of the electrical resistance. To convert the meter reading to resistance and further, the resistance into soil water content two calibration curves are required. The manufacturer provides the first calibration curve and the second should be determined for each specific soil type.

Carlson and Salem (1987) summarized the advantages and disadvantages of the sensor as follows: the advantages are i) it allows soil water content to be continuously and automatically recorded; ii) manual sampling is also easily performed; iii) measurement error is probably less than 10% of the actual volumetric soil water content; iv) response time is a few hours or less; v) the method can be implemented at as many levels and sites as needed; vi) the blocks are cheap, expendable and do not deteriorate greatly during the course of one growing season. The disadvantages are i) it deteriorates as the flow of water cracks the block; ii) certain types of highly porous soils do not equilibrate well with the blocks. In such situations the blocks may remain wet for a while as the surrounding soil dries and iii) gypsum blocks are subject to spurious temperature error.

3.2.6.2 Watermark

Armstrong *et al.* (1987) described the Watermark sensor as an instrument that is designed to offer the advantage of both tensiometers and gypsum blocks, while eliminating the major disadvantages of both. The electrodes are imbedded in a non-dissolvable matrix material, and the sensor incorporates an internal gypsum buffer to minimize the effect of salts experienced in irrigated landscapes. The matrix material is held in place by means of a porous membrane.

Shock *et al.* (1996) explained the use of the sensor in irrigation scheduling, and indicated that it has to be installed at the rooting depth of the plant. The sensor should be read daily and the soil water potential data plotted against time. The graph will then help the grower to decide when to irrigate the field and avoid the soil from drying below the optimum soil water potential.

Pogue (1990) summarized the advantages of the Watermark sensor relative to tensiometers and gypsum blocks. These sensors respond well to soil water potential between -10 to -200 kPa, which include the working range of both tensiometers (-10 to -80 kPa) and gypsum blocks (-80 kPa and below). The electrical resistance type sensors do not require the periodic servicing typically required by tensiometers. Their relatively low cost allows the use of a sufficient number in a given area to provide for adequate soil moisture sampling for scheduling and automatic control. Bausch and Bernard (1996) pointed out that as a limitation of Watermark sensors, they indicated a soil water potential of -9 kPa following irrigation whereas the tensiometer would essentially indicate zero soil water potential immediately after irrigation, Watermarks are less sensitive in coarse textured soils (Irmak and Haman, 2001), Watermarks are sensitive to salinity, soil temperature and the sensor's matrix characteristics changes with time (Spaans and Baker, 1992; Jovanovic and Annandale, 1997).

3.2.7 Thermal dissipation method

Phene *et al.* (1971) described the sensor as a matric potential sensor that measures heat dissipation to sense the water content of a porous block in equilibrium with the soil. It consists of a P-N junction diode that is surrounded by a heating coil (or rod) and embedded in a porous medium. The porous medium could be gypsum, castane mix, or ceramic. They recommended castane and ceramic materials with the ceramic offering the greatest stability. The sensor is independent of rapid temperature fluctuation in the environment. They also showed that the rate of heat dissipation in a porous medium of low heat conductivity is sensitive to water content. Because the specific heat capacity of water is different than that of soil, the amount of heat dissipation will vary with soil water content. Therefore, a consistent interval of heating will infer changes in matric potential as the soil water content changes.

Phene *et al.* (1971) described real-time *in-situ* measurements of soil matric potential logged to a small portable micrologger for real-time monitoring of soil matric potential and automatic scheduling of high-frequency irrigation systems.

Reece (1996) concluded that thermal dissipation sensors have a wide range of measurable matric potentials and they can easily be automated. However, the sensors are close to the accuracy of tensiometers and psychrometers.

3.3 MONITORING THE CROP

Hillel (1990) recommended monitoring the water status of a plant as a possible alternative to monitoring the soil. This can be done visually as well as instrumentally, to detect early signs of thirst (incipient stress) in time to irrigate and thus prevent significant reduction of yield. Numerous methods have been proposed over the years to monitor the state of water in the plant. These methods included techniques that estimate transpiration using excised leaves, observation of stomatal aperture, monitoring stem diameter, pressure-cell and psychrometric measurements (Savage and Cass, 1984) of leaf water potential, and more. These methods are difficult to carry out routinely. One method that may become practical is the monitoring of crop canopy temperature by remote sensing with an infrared radiation thermometer (Jackson, 1982).

3.3.1 Infrared thermometry

Jackson (1982) described infrared thermometry as a non-contact method for estimating the surface temperature of a target. The instrument measures the radiation emitted from the target, and relates this radiation to the surface temperature by the Stefan-Boltzmann law. The Stefan-Boltzmann law for a perfect radiator is expressed by:

$$E = \sigma T^4 \qquad 3.6$$

where E, the emittance, is the radiant energy emitted by the surface per unit area per unit time (W m^{-2}) at temperature T (K) and σ is the Stefan-Boltzmann constant (5.673 x 10^{-8} W m^{-2} K^{-4}).

The use of plant temperature to assess stress is based on the assumption that water, evaporating through the stomata of leaves, causes the leaves to be cooled below air temperature. As a plant becomes stressed due to inadequate soil water, transpiration will decrease and foliage temperature will rise. This change in foliage temperature, compared to air temperature, is the basis of the development of the crop water stress index (CWSI). Two approaches have been proposed to define this index, one theoretical (Jackson, 1982) and the second empirical approach (Idso *et al.*, 1981a, b):

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_l}{(T_c - T_a)_u - (T_c - T_a)_l} \qquad 3.7$$

where T_c is the crop temperature, T_a is the air temperature, $(T_c - T_a)_u$ represents the upper limit (the temperature difference occurring for severe stress when transpiration approaches zero), $(T_c - T_a)_l$ represents the lower limit (the temperature difference between the crop and the air when the crop is well watered). CWSI varies from a value of zero for no water stress to a maximum of value of one at severe stress:

$$CWSI = 1 - \frac{E_t}{E_{tp}} \qquad 3.8$$

where $\frac{E_t}{E_{tp}}$ = the ratio of actual to potential evapotranspiration rate.

Threshold CWSI values for irrigation timing are not well defined (Martin *et al.*, 1990). Idso *et al.* (1981b) reported wheat yield reductions when the mean CWSI during reproductive growth exceeded 0.2. Jackson (1982) suggested that irrigations should be applied when the CWSI for wheat is in the range 0.3 to 0.5. Further research is needed to define optimum CWSI values for irrigation scheduling.

3.3.2 Stem steady state heat energy balance

Savage *et al.* (1993) explained in detail the early heat pulse method and the revised technique, which is referred to as a steady state heat balance method (SSS). Here the new method SSS will be discussed.

The sensor for the SSS method consists of a heater surrounding the plant stem embedded in a thin sheet of cork, with a pair of thermocouples placed above and a pair below the heater. In order to determine the radial heat flux density, thermocouples are used to measure the temperature difference between the inner and outer layers of the cork substrate mounted to surround the stem. The sensor is battery powered and connected to a datalogger.

To describe the theory behind the sensor Van Bavel (1993) indicated that, a strip heater within the gauge inputs energy to the stem at a constant rate (Q_{in}). The energy balance is the principle based on the conservation of energy principle that determines the partitioning of energy to the stem, the sap flow (Q_f) and the heat losses to the ambient:

$$Q_{in} = Q_f + Q_v + Q_r + Q_s \qquad 3.9$$

where Q_{in} is the constant heat applied in watts, Q_f is the heat flux energy convected by the sap flow, Q_v is the heat conducted up (Q_u) and down (Q_d) the stem axially, Q_r is the heat conducted through the insulation radially to the ambient, and Q_s is the heat stored in the stem test section. For most applications Q_s is assumed to be small and can be ignored for all but very low sap flow applications. By measuring Q_{in}, Q_u, Q_d, and Q_r, the remainder, Q_f can be calculated. Q_f is the heat convection carried by the sap. After dividing by the temperature increase and the specific heat capacity of sap, the heat flux is converted directly to mass flow rate.

This method as opposed to early heat pulse method does not require calibration and a quantitative measurement of transpiration can be made directly. The method has the following limitations: comparison cannot be made between plants because of differing LAI; also, under conditions of high sap flow rates, the increase in temperature of the sap is small resulting in abnormally high estimates of the sap flow rate; a fairly large increase in temperature occurs in the region of the heater that may cause irreversible physiological damage and different diameter gauges are required for different diameter plants (Savage *et al.*, 1993).

3.3.3 Pressure chamber method

To determine the leaf water potential, pressure is applied to a detached fresh leafy shoot inside a pressure chamber (Scholander *et al.*, 1965) until xylem sap appears on the cut end. Then, the reading on the pressure gauge that is applied to bring its water potential to zero is the leaf water potential (Phene *et al.*, 1971).

Martin *et al.* (1990) tabulated the work of many researchers that approximate the threshold leaf water potentials that limit transpiration, net photosynthesis and crop yield. These values can then be used to determine the time of irrigation to maintain the leaf water potential to its optimum level.

Shackel *et al.* (1997) used midday stem water potential (the water potential of an attached leaf that has been prevented from transpiring by enclosure in a darkened plastic bag) for irrigation scheduling. For many different fruit tree species the midday stem water potential under frequently irrigated conditions range from -0.5 to -1 MPa depending on midday vapor pressure deficit. This measurement could be used to reliably quantify stress and may serve as a useful guide for making irrigation decisions on a site-specific basis.

Garnier and Berger (1985) also used the difference between the leaf water potential and stem water potential as a measure of leaf transpiration in peach trees to schedule irrigation. From the result they concluded that extreme care must be taken in the interpretation and use of leaf water potential as a physiological indicator for irrigation. However, stem water potential was found to be a more sensitive indicator of water stress in peach trees. Similar conclusions has been made by Noar (2000) that midday stem water potential is a better plant water stress indicator than soil predawn and midday leaf water potentials, and it should be considered for irrigation scheduling in fruit trees.

The only limitation as Noar (2000) pointed out is the inconvenient means of measurement as compared with other water stress indicators. Therefore, there is a need for easier-to-use water stress indicators that are correlated with midday stem water potential.

3.4 MONITORING THE WEATHER

Hillel (1990) described the idea of monitoring the weather as a method to follow the meteorologically imposed total evaporation (evapotranspiration) demand as it varies over time and to set the quantity of irrigation accordingly. The time of irrigation can then be determined in reference to the soil's effective storage capacity, its soil water potential or in reference to the status of the crop.

The following methods can be used to schedule irrigation by following an accounting (bookkeeping) procedure. They measure either reference crop total evaporation (Penman-Monteith equation), rate of evaporation (evaporation pan and atmometers) or directly total evaporation (lysimeter). Then total evaporation will be calculated and subtracted from the soil water storage until a critical soil water depletion level is obtained. At that point, irrigation will be scheduled to replenish the water content. Also, if rainfall occurs, the amount must be measured and entered into the bookkeeping procedure to account for all water inputs to the soil.

3.4.1 Evaporation pans

Doorenbos and Pruitt (1977) described the class A evaporation pan as a circular pan with a diameter of 1.21 m and 0.25 m deep. It is made of galvanized iron (22 gauge) or monel metal (0.8 mm). The pan is mounted on a wooden open frame platform with its bottom 15 mm above ground level. The pan must be level. It is filled with water 50 mm below the rim, and water level should not drop to more than 75 mm below the rim. Water should be regularly renewed to eliminate extreme turbidity.

Doorenbos and Pruitt (1977) also explained that the class A pan provides a measurement of the integrated effect of solar irradiance, wind speed, air temperature and relative humidity on evaporation from a specific open water surface. In a similar fashion the plant responds to the same climatic variables. To calculate the rate of water use by the plant, the reference crop total evaporation (*ETo*) is first calculated by multiplying the rate of evaporation (*Epan*) by the pan coefficient (*Kp*). The crop total evaporation (*ETcrop*) is then calculated by multiplying the reference crop total evaporation (*ETo*) by the crop coefficient (*Kc*).

The evaporation pan from the microclimatological methods appears to be more practical to characterize the evaporative demand of the atmosphere. This method can provide a basis for assessing crop water requirements if it is used with locally calibrated crop coefficients. However, the performance is tightly controlled and affected by the consistency and care (or lack thereof) in pan operation and maintenance including the conditions (Jensen *et al.*, 1990).

3.4.2 Atmometers

An atmometer is a device that measures the amount of water evaporated to the atmosphere from a wet, porous surface. The older version of atmometers consisted of a flat, circular evaporating surface of porous porcelain covering the top of a glazed porcelain funnel (Carder, 1960). Water is conducted to the funnel from a burette, which acts as a reservoir and measuring device. In its usual assembly, a mercury and wool valve is placed in the conducting tube from the reservoir to the funnel. This prevents water from backing up into the reservoir when rain falls or dew forms on the porous plate.

The new version of the atmometer called a "modified atmometer" was developed recently as a field instrument to measure alfalfa reference total evaporation (*ET*) (Altenhofen, 1985; Broner and Law, 1991). Simulation of the plant's transpiration is achieved by covering the evaporating surface with a rough green canvas. Covering the Bellani cup with the green canvas has two purposes. First, it simulates the crop reflection coefficient so that solar irradiance absorption by the atmometer will be similar to the solar irradiance absorption of the plants. Second, it simulates the leaf diffusion resistance to the flow of water vapour from inside the leaf to the atmosphere (Broner and Law, 1991).

The advantages of the atmometer are that it is small, easy to take readings, easily transported, and its parts are inexpensive and commercially available (Robertson and Holmes, 1959). Further modification of the atmometer to measure evaporation electronically also provides the potential for performing these tasks automatically (Parchomchuk *et al.*, 1996). However, the instrument is susceptible to frost damage, it is difficult to prime the sensor and the precision of daily data obtained by visual reading has limitations. In spite of the precision limitations, the instrument inaccuracies in daily readings tend to average out (Broner and Law, 1991).

3.4.3 Lysimetry

Aboukhaled *et al.* (1981) described a lysimeter as a large container filled with soil, located in the field, to represent the field environment, with a bare or vegetated surface for determining the evaporation of a growing crop, of a reference vegetative cover or evaporation from bare soils. The total evaporation can be determined in a simplest form by accounting for the incoming and outgoing water flux by a water balance equation:

$$P + I \pm R_o = ET + D \pm \Delta W \qquad 3.10$$

where P is precipitation, I is irrigation, R_o is surface runoff to or out of the lysimeter, ET is the total evaporation, D is deep percolation and ΔW is change of water content (W) of the isolated soil mass over a given time period.

Although this method is too expensive to be adopted commercially by farmers for irrigation scheduling, it is an excellent tool for research. One of the main advantages of lysimetry is that it measures total evaporation directly while other methods are developed to measure total evaporation indirectly. The disadvantage is that it is too expensive to apply for routine irrigation scheduling.

3.4.4 Reference evaporation method

The FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference total evaporation (Allen *et al.*, 1998).

The adjusted definition of reference total evaporation is the rate of total evaporation from a hypothetical reference crop with an assumed crop height 120 mm, a fixed crop surface resistance 70 s m^{-1} and reflection coefficient of 0.23, which is considered to closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The reference total evaporation (ET_o) can be estimated using the FAO Penman-Monteith method:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma \dfrac{900}{T+273} U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad 3.11$$

where ET_o is the reference crop total evaporation (mm day $^{-1}$), R_n net irradiance at the crop surface (MJ m $^{-2}$), G soil heat flux (MJ m $^{-2}$), T average air temperature (°C), U_2 wind speed measured at 2 m height (m s $^{-1}$), e_s saturated vapour pressure (kPa), e_a actual vapour pressure (kPa), ($e_s - e_a$) water vapour pressure deficit (kPa), Δ the slope of the vapour pressure curve (kPa °C $^{-1}$), γ psychrometric constant (kPa °C $^{-1}$), 900 is the conversion factor from hourly to daily measurement and if 37 is used instead of 900 it gives hourly ET_o calculation.

This method can also estimate limited or missing data. Wind speed can be approximated by an average value of 260 km day^{-1} or 3 m s $^{-1}$ and, for low wind conditions, values of 90 km day $^{-1}$ or 1 m s^{-1} can be taken. Actual vapour pressure (e_a) can be estimated from the minimum daily temperature (T_{min}) using the following formula (Allen *et al.*, 1998):

$$e_a = 0.6108 \exp\left(\frac{17.27\,T_{\min}}{T_{\min} + 273.3}\right) \qquad 3.12$$

Radiation can be approximated for inland stations from incoming extraterrestrial radiation (R_a) and the temperature deficit ($T_{max} - T_{min}$), using the following formula (Eq. 3.13), which was reviewed by Allen *et al.* (1998):

$$R_s = 0.17\,\frac{P}{P_o}\,(T_{max} - T_{min})^{0.5}\,\mathrm{R_a} \qquad 3.13$$

Smith *et al.* (1996) concluded that the procedure that has been established to estimate missing climatic data allow the FAO Penman-Monteith method to be used under all conditions. Further, the change of the ET_o definition to a hypothetical crop with fixed parameters eliminated problems related to the previous requirements in measuring a living reference ET_o and facilitate the calibration of crop coefficients for estimation of crop water use.

In this study the PR1 profile probe and Diviner 2000 were used to determine the time and amount of irrigation. The site, crop and the sensors, which were used in this study, were described in materials and methods (Chapter 4). The soil and soil water characteristics of the site were dealt in detail in Chapter 5. Chapter 6 showed the calibration and comparison of the sensors. The soil water content limits for the application of irrigation scheduling were determined using the field, laboratory and estimated methods (Chapter 7). The time and amount of irrigation, which were determined using the PR1 profile probe and Diviner 2000 were compared in Chapter 8. Finally in Chapter 9 general conclusions and recommendations were made for future research.

CHAPTER 4

GENERAL MATERIALS AND METHODS

4.1 SITE DESCRIPTION

The research was conducted at Cedara College of Agriculture which is located at a latitude of 29° 32' S, longitude 30° 17' E and altitude of 1076 m above sea level in the Midlands of KwaZulu-Natal province, South Africa. The field has a slope of 6 % in the N-S direction and it was totally surrounded by agronomic experimental plots and the area is classified as a mist belt zone (Schmidt and Schulze, 1989). In winter (April to August), the site has a minimum air temperature of -1.8 °C and maximum air temperature of 29 °C (Appendix 3). In summer (September to March), it has a minimum and maximum air temperature of 3 and 33 °C respectively. In this area the mean annual rainfall ranges between 725 and 925 mm with many rainfall occurrences during summer and very little amount of rainfall in winter. Irrigation is commonly used as a supplementary source of water during the winter period but in summer agriculture depends mainly on the rainfall. The climatic data, which were collected from 1975 to 2001 at Cedara meteorological station, is summarized in Figure 4.1.

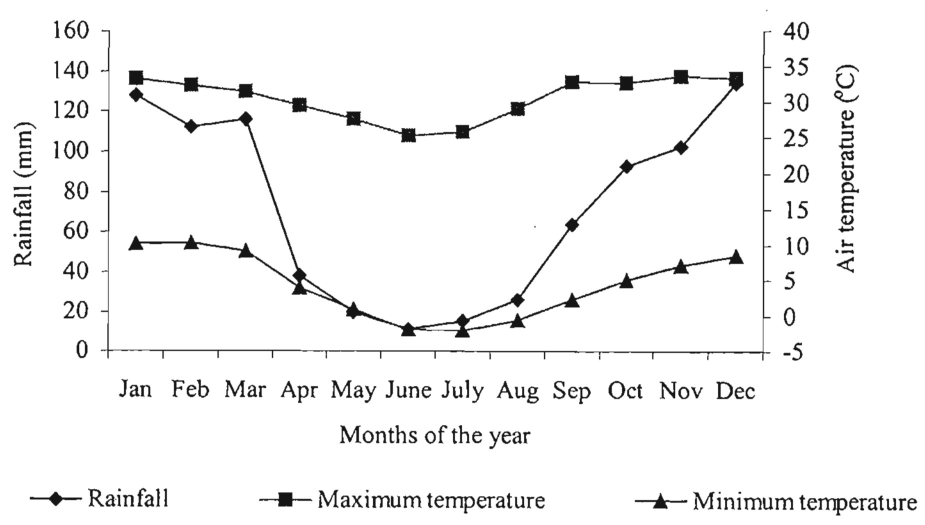


Fig. 4.1 Climatic data for the year of 1975 to 2001 (Agricultural Research Council, Institute of Soil, Climate and Water, Pretoria)

4.2 CROP DESCRIPTION

The cultivars *Drakensberg* for oats (Photo 4.1), *Macblue* for rye and *Midmar* for ryegrass were planted on April 09, 2002 in rows with a spacing of 0.15 m between rows and with different planting densities. Rye was planted at a density of 123 kg ha^{-1}, ryegrass at 30 kg ha^{-1} and oat at 90 kg ha^{-1} in a plot of 18 m by 6 m plots in three blocks. Weeding and fertilization were not used as a management practice within the cover crop plots. Irrigation was applied using a dragline sprinkler system and irrigation scheduling was practiced based on the irrigator's judgment by referring to the Diviner 2000 soil water content measurements.

4.2.1 Oats

The botanical name for oats is *Avena sativa* L. Generally, oats is an erect annual grass with a maximum height of 1.05 to 1.13 m and with a fibrous root system, which extends to a depth of 0.84 to 1.95 m. The root development of oats is dependent on the availability of oxygen in the profile. Root extension ceases when the flux density of oxygen is zero (Sorrells and Simmons, 1992). Oat varieties usually have a lower ability to produce tillers and show moderate to heavy density with a succulent growth type.

Photo 4.1 Portion of the experimental plots covered with oats at its maturation stage (Photo taken by MJ Savage, 2002)

Oats can grow in many soil types ranging from loam to heavy soil types and can tolerate wet soil, soil pH as low as 4.5. Oats is moderately resistant to cold air and soil temperature, but less tolerant to salinity. Generally, oat thrives in cool, moist climates and is particularly sensitive to hot and dry weather from head emergence to physiological maturity (Marshall and Sorrells, 1992).

Oats can be used as grain even though its consumption in most countries tends to be relatively low (Marshall and Sorrells, 1992). As a cover crop, oats can provide erosion control, enhance soil life, suppress weeds, and add organic matter.

4.2.2 Rye

The botanical name for rye is *Secale cereale* L. Rye can be described as an erect annual grass with flat blades and dense spikes, its habit resembles that of wheat, but is usually taller, with longer and more slender spikes. On average, the height of the plant reaches 1.47 m with 12 mm broad blades and 0.07 to 0.15 m long spikes. Rye has the best-developed root system among annual cereal crops. It has an extensive root system with no defined taproot, which enables it to be a drought-tolerant cereal crop. Because of the extreme hardiness of the rye plant and its ability to grow in sandy soils of low fertility, rye can be grown in areas that are generally not suitable for growing other cereal grains (Bushuk, 1976).

Rye is grown in cool temperature zones or at high altitudes. It is the most winter hardy of all small cereal grains enduring all but the most severe climates. The minimum air temperature for germination ranges between 3 ^{o}C and 5 ^{o}C and for vegetative growth to occur, a minimum air temperature of 4 ^{o}C is required. Once well established, the plant can withstand air temperatures as low as -35 ^{o}C. It grows best on well-drained loam or clay loam soils. Even heavy clays, light sand, and infertile or poorly drained soils are also feasible for growth. In general, it is tolerant to different soil types.

Rye can be used as grain, hay, pasture, cover crop and green manure. It is a good pioneer crop for sterile soils. When used as a cover crop, it is grown for erosion control, to add organic matter, to enhance soil life, and for weed suppression. It may also stabilize and prevent leaching of excess soil or manure nitrogen (Bushuk, 1976).

4.2.3 Annual ryegrass (Italian ryegrass)

The botanical name for ryegrass is *Lolium multiflorum* Lam. Ryegrass can be described as a winter-annual grass with an upright growth habit and can attain a maximum height of 1.2 m in the most favorable environment. Like most grasses, annual ryegrass has a fibrous root system, which can be extensive and reaches to a depth of 0.86 to 1.35 m.

Annual ryegrass can germinate in cooler soils than most other cover crop and pasture seeds. It can also adapt to many soil types but does best on loam or sand loam soils. It is generally adaptable to a wide range of soil types, with a pH varying between 5.5 and 7.0 (Field-Dodgson, 1974). Annual ryegrass can be grown under dry land conditions provided that the rainfall is 900 mm or more during the growing season. Otherwise, it must be irrigated (Donaldson, 2001).

Annual ryegrass can be used as (1) pasture, hay, wild life habitat; (2) temporary cover for lawns, critical areas, and burned areas; (3) winter green manure and cover crops for orchards and crop lands. It is a good choice for obtaining fast temporary cover for an exposed area with minimum seedbed preparation.

4.3 SENSOR DESCRIPTION

4.3.1 Profile probe (Type PR 1)

The PR1 profile probe (Delta-T Devices, 2001) is a frequency domain reflectometry (FDR) that measures soil water content at six different depths (100, 200, 300, 400, 600 and 1000 mm) within the soil profile (Photo 4.2). The sensor consists of a sealed composite rod, 25 mm in diameter, with an electronic sensor in the form of stainless steel rings arranged at fixed intervals along its length (Delta-T Devices, 2001). When readings are taken the probe is inserted into an access tube, 28 mm in diameter. The output (voltage or volumetric soil water content) can be taken by a hand held Moisture Meter (type HH2) from different access tubes. Unattended and continuous readings from one access tube can be obtained using dataloggers.

In this study the sensor was used for three purposes: i) to monitor the soil water content and the soil water potential (measured using other sensors) to develop the retentivity curve in the field (Appendix 1, Table 2) using a time interval of 3 h;

Photo 4.2 Profile probe (type PR1) with its access tube and hand held Moisture Meter (type HH2) (Photo taken by MJ Savage, 2002)

ii) to progressively monitor the wetting front (using a time interval of 2 min) along the profile during irrigation to determine the time to stop irrigation (Appendix 1, Table 1) and iii) to monitor the soil water content from different access tubes using the hand held Moisture Meter (type HH2) to determine the time to start irrigation.

When the sensor was used for the first two purposes, it was connected to a Campbell CR10X datalogger with the pair of connecting wires, corresponding to each depth, connected differentially as opposed to single-endedly (Appendix 1 contains details of the wire connection). The sensor was powered with a 12 V supply from the datalogger 12 V-switch. This was controlled by the program instruction P20 (Appendix 1, table 1 or 2, third program instruction) and warm up for 2 second using the Ex-Del-Diff instruction, P8 (Appendix 1, table 1 or 2, fourth program instruction). Power consumed by a single sensor with the 2 second warm up time was typically 20 mA x 2 s $\approx$ 0.01 mA h^{-1}. The measured voltage (V) was converted to volumetric soil water content (m^3 m^{-3}) using the manufacturer-supplied polynomial for mineral soils (Eq. 4.1) with instruction P55 (Appendix 1, table 1 or 2, fifth program instruction). The output was recorded every three hours when the PR1 profile probe was used together with the soil water potential sensors and every two minutes when the sensor was used to monitor the wetting front to determine the time to stop irrigation.

$$\theta_{min} = -0.113 + 1.62\,V - 3.56\,V^2 + 8.63\,V^3 \qquad 4.1$$

where θ_{min} is the volumetric soil water content ($m^3\ m^{-3}$) for a mineral soil and V the measured voltage (V)

The access tubes of the PR1 profile probe were installed using gouge and spiral augers. First, the gouge auger (22-mm diameter) was pushed into the soil up to the depth of the blade and the auger was fully rotated to excavate the soil, and then withdrawn while continuing to be rotated. When the desired depth was reached the hole was shaped with the spiral auger (25-mm diameter). The access tube was then pushed into the slightly narrow hole to secure a tight fit that prevented the creation of air gaps between the access tube and the soil.

4.3.2 Diviner 2000

The Diviner 2000 (Sentek Environmental Technologies, 2000) is a frequency domain reflectometry that comprises a data display unit and a portable probe (Photo 4.3). The probe measures soil water content at regular intervals of 100 mm in the soil profile to a depth of 1 m. The probe consists of a metal rod with a probe cap and a sensor at the bottom. The probe contains a connection cable that transfers data from the sensor to the Diviner 2000 display unit that is used as a data storage, display and conversion tool.

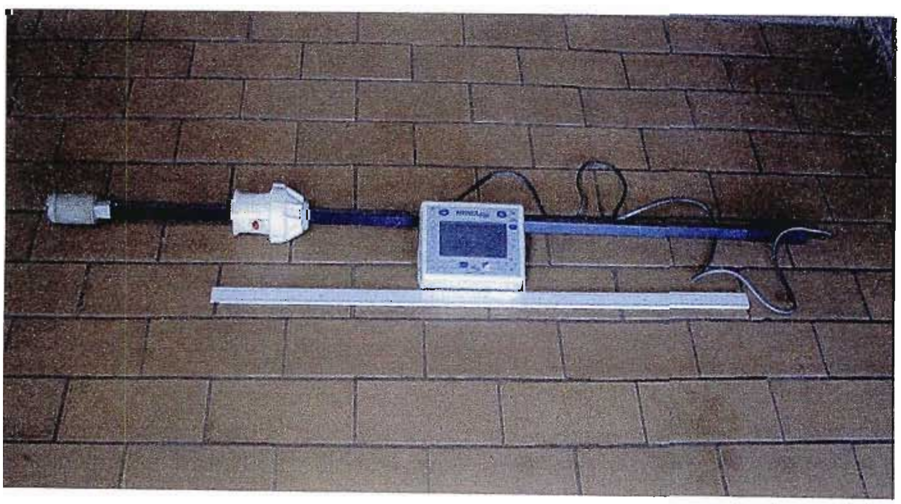


Photo 4.3 Diviner 2000 probe and its display unit. The one-meter ruler indicates the scale

As was the case for the PR1 profile probe, measurements were taken by inserting the probe in different access tubes, 50-mm diameter, that were installed at each plot to monitor the soil water content, in order to determine the time of irrigation. Each measurement was a snapshot of the soil water content at the specific depth in the soil profile. If more frequent measurements are taken soil water content data becomes more complete (Sentek Environmental Technologies, 2000).

The advantage of this sensor as it is described in the Diviner 2000 manual is that (i) the sensor gives accurate and consistent readings; (ii) the sensor is fast responding; (iii) the sensor is waterproof and it gives an alarm if there is water ingresses into the access tube; (iv) output can be in numerical or graphic in form to make instant decisions in the field. However, unattended measurements cannot be taken using the data display unit from one access tube.

4.3.3 Watermark (Model 257)

The Watermark sensor (Irrometer, Riverside CA, USA) consists of two concentric electrodes embedded in a reference matrix material, which is surrounded by a synthetic membrane for protection against deterioration (Photo 4.4). An internal gypsum tablet is also used to buffer against the salinity levels found in irrigated soils. With the sensor cable there is a capacitor circuit which blocks galvanic action due to the differences in potential between the datalogger earth ground and the electrodes in the block. Such current flow would cause rapid block deterioration (Campbell Scientific, 1996).

The sensors are connected to single-ended analog channels and instruction 5, the AC half bridge instruction, is used to excite and measure the output (Appendix 2, table 1, the fourth, fifth and sixth program instructions). Instruction 59, a bridge transformation, was used to give sensor resistance by taking the AC half bridge output (Appendix 2, table 1, seventh program instruction). Finally, the datalogger calculated the soil water potential (kPa) from the sensor resistance and soil temperature measured by type T-thermocouples using the following non-linear equation.

$$SWP = \frac{-R_s}{0.01306[1.062(34.21 - T_s + 0.01060 * T_s^2) - R_s]} \quad 4.2$$

where SWP is the soil water potential (kPa), R_s the measured resistance (kΩ) and T_s is the soil temperature measured using a type T thermocouple (^{o}C) (Armstrong *et al.*, 1987).

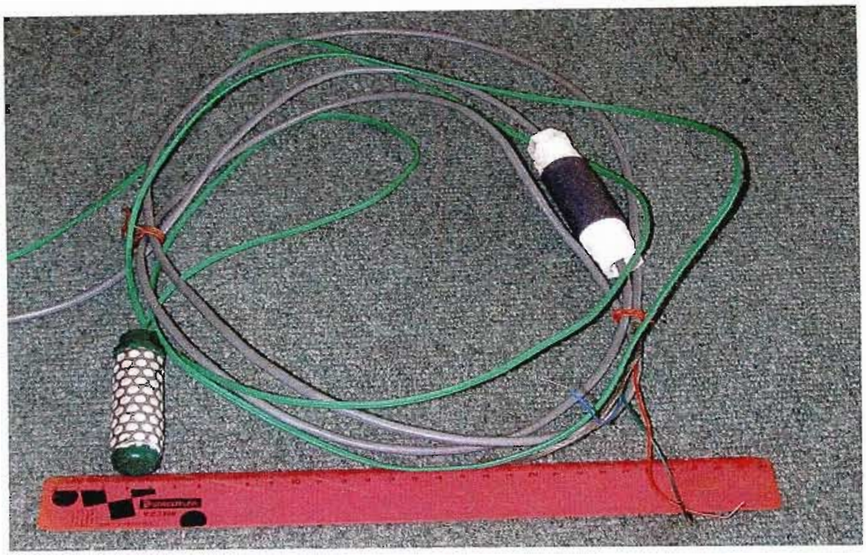


Photo 4.4 Watermark sensor (left) with an attached capacitor shield (right). The 300-mm ruler indicated the scale

Prior to the installation, the sensors were soaked in water for two days and installed in the field while they were wet. In the field, 25-mm diameter holes were made using a gouge auger to the desired depth and filled with slurry made from the excavated soil to get a snug fit in the soil. The sensors were then pushed with the PVC pipe, which was fitted tightly over the sensor collar until it reached the ultimate depth. The holes were then carefully backfilled and trampled down to prevent air pockets which could allow water to channel down to the sensors.

4.3.4 Tensiometer

The tensiometer (Photo 4.5) consists of a differential pressure transducer that provides an analog output signal proportional to the applied pressure, a porous ceramic cup that is permeable to water flow, hydraulic tubing (6 mm external diameter) filled with de-aired water and PVC conduit. Using this tensiometer soil water potential can be measured between 0 and -80 kPa with ± 2.5 % maximum error over the 0 to 85 ^{o}C temperature change (Thornton-Dibb and Lorentz, 2001).

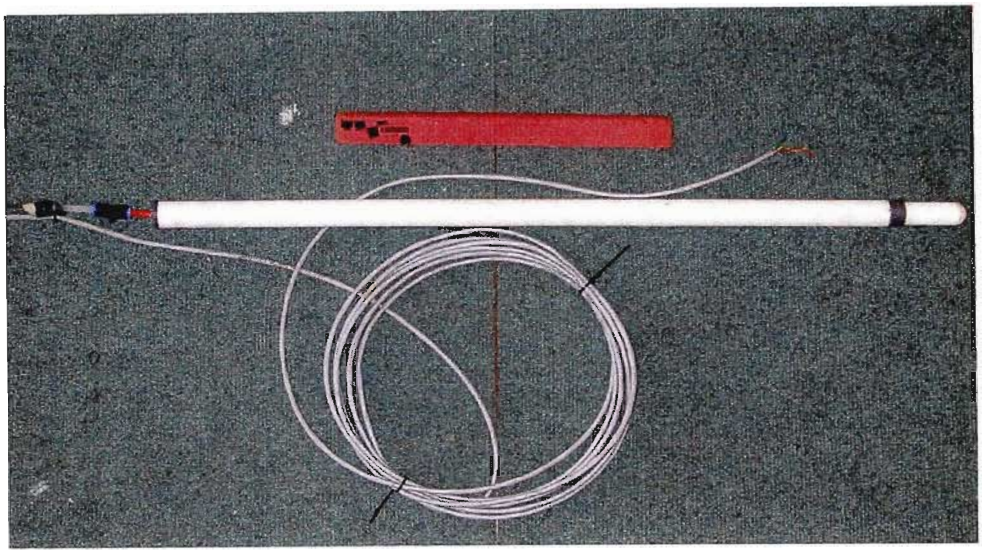


Photo 4.5 Tensiometer with its differential pressure transducer and the wire, which can be connected to a datalogger. The 300-mm ruler indicated the scale

Six tensiometers were connected to single-ended analog channels to measure soil water potential at three different depths (100, 300 and 600 mm) and each sensor was supplied with 5 V from a control port of the datalogger (Appendix 2, table 2, the second, sixth, tenth, fourteenth, eighteenth and twenty second program instructions). The same control port could not be used for all sensors due to a power limitation. A sensor warm-up time of 8 seconds was used, the voltage output of the sensors were measured and converted to soil water potential (kPa) using the calibration constants calculated from the calibration curve of the tensiometer transducer.

Before installation, the ceramic tips of the tensiometers were saturated for 24 h in water. In the field 22-mm diameter holes were made using the gouge auger and slurry was poured into the holes, which was made from the excavated soil to form a tight fit. The tensiometers were pushed carefully so that they reached the desired depth. The holes were then backfilled and trampled to prevent seepage of water to the sensor depth.

Once the tensiometers were installed, each of them required replenishment with de-aired water. With a squeeze bottle, de-aired water was squeezed to the tensiometer while pushing the thin tubing down into the bottom of the tensiometer. When air was totally removed from the tensiometer, the thin tubing was removed while constantly applying water. Similarly, air bubbles were removed from the pressure transducer by injecting a short burst of water into pressure transducer with a syringe. When both the tensiometers and pressure transducers were free from air bubbles, beads of water were made at both ends of the tensiometer and the pressure transducer. The tensiometer and the transducer were then immediately connected with tubing. The system was checked again for the presence of air bubbles in the transparent tube. If there were any visible bubbles then the replenishment process would be repeated. These processes were also done periodically after four to five days when air bubbles occurred in the transparent tube.

4.3.5 Dataloggers

The Campbell Scientific CR23X and CR10X dataloggers (Photo 4.6) were used to collect continuous and unattended readings from the PR1 profile probe, tensiometers, 257 Watermark sensors, thermocouples and rain gauge. The CR23X datalogger has 24 single-ended analog input channels (12 differential), 4 pulse count channels, 8 digital I/O ports, 2 continuous analog output channels, 4 precision voltage switched excitation channels, and has switched 12 V. It can display 24-characters in two lines. The CR10X datalogger has 12 single-ended analog input channels (6 differential), 2 pulses count channels, 8 digital I/O ports, no continuous analog output channels, 3 precision voltage switched excitation channels, it has switched 12 V and it uses a portable keyboard display (Campbell Scientific, 1998b). These two dataloggers were used together since the number of channels of each datalogger was insufficient for all the sensors used. The CR10X was used for the soil water content measurement from the PR1 profile probe and the amount of rainfall or irrigation from the rain gauge. The CR23X was solely used for measurements from the tensiometers, Watermarks sensors and the soil temperature from the thermocouples. Each datalogger was powered with two external 12 V external batteries connected in parallel and they had also internal cells, which can be recharged if connected to a solar panel or AC charger. The internal batteries were used to keep the program and the collected data in the memory of the datalogger in case the external source of power was disconnected.

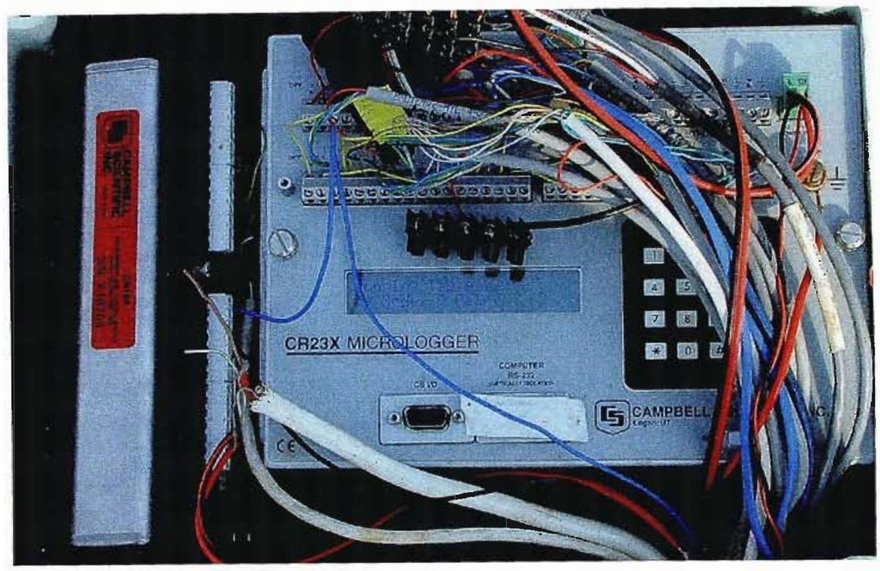


Photo 4.6 CR10X (left) and CR23X (right) dataloggers while they were taking field measurements (Photo taken by MJ Savage, 2002)

The programs (Appendices 1 and 2) for the dataloggers were written and compiled in PC208W. The program was downloaded to a storage module (SM716) directly from a computer using SC532 interface and transferred to the dataloggers. After the dataloggers recorded data for the specified period (usually one week) the data was dumped from each datalogger to the storage module for transfer to a computer for further analysis.

In the field the following precautions were taken for the safety of the dataloggers: i) the dataloggers were grounded using a thick copper wire to prevent lightning damage; ii) they were raised above ground by 0.2 m to prevent damage by water; iii) they were protected from direct sunlight, rain and theft in a secured box; iv) inside the box silica gel was used to keep the humidity inside the box low. The silica gel was changed periodically when it started to change its color to pink.

4.3.6 Thermocouple

Copper-constantan thermocouples were used to measure the soil temperature at three depths (100, 300, and 600 mm). The sensors were connected to differential analog channels and the temperature of the soil measured using instruction P14 (Appendix 2, Table 1, eighth, ninth and tenth instructions) where it used the panel temperature of the logger as the reference temperature to calculate the actual soil temperature. These measurements were then used to correct the soil water potential measured by the Watermark sensor (Eq. 4.2).

The sensors were buried in the field by making a hole using the gouge auger to the desired depth, and the sensors were pushed to the required depth. The hole was then backfilled by the excavated soil and trampled.

4.3.7 Automatic rain gauge

A tipping spoon automatic rain gauge (Rain-O-matic, Silkeborg, Denmark) was used to measure the amount of rainfall and applied irrigation. The sensor has the following parts: a rectangular funnel with a dimension of 50 mm x 100 mm, a tipping spoon attached with a magnet, and a dual reed switch, which allows counting the number of tips as a pulse. The sensor relies on the spoon being automatically tipped and emptied when the pre-adjusted water weight has been reached (Pronamic, 2002). One tip is equivalent to 1 mm of water. Thus, the number of tips counted as a pulse in the datalogger (Appendix 1, Table 1 or 2, seventh instruction) is equal to the amount of rainfall or applied irrigation.

4.4 ACCESSORIES

Three kinds of augers (gouge, spiral and Jarret) and one core sampler (Photo 4.7) were used to make different sized holes and to take disturbed and undisturbed soil samples. The gouge auger (22-mm diameter) is made up of tapered stainless steel, half-tube and smooth with a T-shaped handle. Holes for the access tubes were made by pushing the auger vertically into the soil without rotating to the depth of the blade. Once the blade was totally inserted, the auger was fully rotated to excavate the soil. After enough soil was excavated the auger was slowly withdrawn while rotating. In moist, soft and clay soils a very clean and straight hole is made without much effort. In resistant soils, a small section was dug at a time until the required depth was reached. The holes for the access tube of the PR1 profile probe, tensiometers, and Watermark sensors were prepared using this auger.

Photo 4.7 Accessories used to make holes and take disturbed and undisturbed soil samples. From top to bottom: core sampler, spiral auger, Jarret auger and gouge auger. The one-meter ruler indicates the scale

The spiral auger (25-mm diameter) has a spiral-shaped blade made up of a stainless steel soldered to a T-shaped metal handle. It was used to drill holes in wet, hard and compacted soils and to shape the holes for the access tubes of the PR1 profile probe which need to be 25 mm in diameter to have a tight fit. The Jarret auger has a core-shaped head with sharp and curved blades at the tip of the head and it has a T-shaped iron handle. It was used to make wider holes or to take disturbed soil samples at different depths.

The core sampler has three parts made up of stainless steel. The *handle* with a round flat head that was driven to the soil by a hammer; the *head* cylindrical shape with sharp edge and it can be fitted to the handle when undisturbed soil samples were taken and the *Sleeve,* which was inserted inside the head before sampling. Using the core sampler undisturbed soil samples can be taken from the surface up to a soil depth of one meter. Undisturbed soil samples were taken from the field for the development of the retentivity curve in the laboratory, to determine the volumetric water content of the soil at wet and dry range for the calibration of the PR1 profile probe and for the determination of the bulk density of the soil at different depths.

4.5 STATISTICAL TOOLS

Regression analysis was done to analyze the relationship between two similar sensors (PR1 profile probe and Diviner 2000) or methods (field and laboratory methods). Paired t-test was also done in some paired data. In the regression analyses the statistical parameters - the regression coefficient (r^2), root mean square error (RMSE), confidence limits of slope and intercept - were calculated to determine the relationship between the sensors or the methods used. To calculate these statistical parameters and plot the graph the following statistical tools were used: i) Genstat 6th edition; ii) a spreadsheet developed by Savage (1998); iii) PlotIT version 3.2 and iv) Microsoft Excel 2000.

i) *Regression coefficient (r^2)* the value of the regression coefficient ranges between 0 and 1. If it is zero, there is no linear relationship between the two variables. If it is 1, it implies that 100 % of the variation in the dependent variable is attributed to the linear regression relationship of the dependent variable with the independent variable (Savage, 2001).

$$r^2 = \left(\sum_{i=1}^{n} x_i\, y_i\right)^2 / \left[\left(\sum_{i=1}^{n} x_i^2\right)\left(\sum_{i=1}^{n} y_i^2\right)\right] \qquad 4.3$$

where $x = X - \overline{X}$ (independent variable) and $y = Y - \overline{Y}$ (dependent variable)

ii) *Root mean square error (RMSE)* mean square error tells the sum of the error due to the deviation from the regression line (unsystematic error) and the deviation from the 1:1 line (systematic error). This statistical parameter tells the actual size of the error and the *RMSE* is also easy to interpret since it has the same metric as the variables (Willmott, 1981).

$$RMSE = \left[N^{-1}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{0.5} \qquad 4.4$$

where N is the number of observations, P_i the predicted or the dependent variable for the i^{th} observation and O_i is the observed or independent variable for the i^{th} observation.

iii) *Confidence limits of slope and intercept.* If two sensors or methods are statistically the same, they will have a scatter plot with all points falling on a line with a slope of 1 and intercept 0, or the confidence limits of the slope and intercept encompasses the ideal slope of 1 and intercept 0 (Willmott, 1981).

$$\text{Confidence limit of a slope} = b \pm t_{n-2} s_b \qquad 4.5$$

$$\text{Confidence limit of an intercept} = a \pm t_{n-2} s_a \qquad 4.6$$

where b is the slope, a is the intercept, s_b is the standard error of the slope, s_a is the standard error of the intercept and t_{n-2} is the tables t value with n-2 degree of freedom.

CHAPTER 5

SOIL AND SOIL WATER CHARACTERISTICS

5.1 SOIL CHARACTERISTICS

The following soil characteristics were determined from soil samples, which were taken from two representative sites located at the higher and lower positions of the field. From each site, six samples were taken at six depths (100, 200, 300, 400, 600, and 1000 mm). Prior to the analysis the soil samples were air-dried, ground and passed through a 2-mm sieve. The samples were analyzed to determine particle size, particle density, bulk density, organic mater content, salinity status, pH, and extractable iron content.

5.1.1 Particle size analysis

Particle size analysis (PSA) is a measurement of the size distribution of individual particles in a soil sample. The major features of PSA are the destruction or dispersion of soil aggregates into discrete units by chemical, mechanical, or ultrasonic means and separation of particles according to size limits by sieving and sedimentation (Gee and Bauder, 1986).

This analysis was done to determine the particle size distribution of the soil samples by the pipette method (Johnston, 2000). A 20-g soil sample was dispersed chemically by calgon solution (sodium hexametaphosphate and sodium carbonate dissolved in de-ionized water) and mechanically by ultrasound at maximum output for three minutes. The suspension was then passed through a 0.053 mm sieve to a 1-liter measuring cylinder and filled with distilled water. When the temperature of the suspension reached room temperature, the suspension was agitated properly and a 20-ml sample was taken immediately by pipette to determine the amount of coarse silt. The second sample was taken from 100-mm depth at a pre-calculated time based on Stoke's law to determine silt and clay. To represent the clay content a 20-ml sample was taken at 75 mm below the surface based on the same principle. Each sample was then oven dried for 24 h at 105 °C to determine the mass of the soil particles. Finally, the sand fraction was determined from the soil sample that was left over after sieving by 0.053 mm sieve. After oven drying the soil was sieved through a nest of sieves consisting 0.500 mm for coarse, 0.250 mm for medium, 0.0106 mm for fine and very fine sand using a sieve shaker for five minutes.

Particle-size analysis data can be presented and used in several ways (Gee and Bauder, 1986). Here the United States Department of Agriculture (USDA) classification system (Fig. 5.1) was used to determine the textural class of the soil (Fig. 5.2). The relationship among the USDA, South Africa Binomial Soil Classification System (MacVicar *et al.*, 1977) and other classification systems were shown in Fig 5.1. In general from the data obtained (Table 5.1), the soil textural class in the shallow depths, 100 to 300 mm, was found to be clay loam. For the deeper depths the soil was predominantly a clay soil.

5.1.2 Soil particle density

Particle density of a soil refers to the density of the soil particles collectively. It is expressed as the ratio of the total mass of the solid particles to their total volume, excluding pore spaces between particles (Blake and Hartge, 1986b).

To determine the particle density, a 50 g soil sample was added to a pre-weighed 100 ml volumetric flask (*Wa*) and weighed again with the soil sample (*Ws*). To remove the entrapped air the flask was boiled for several minutes with frequent but gentle agitation on a hotplate and then allowed to cool. After it was cooled to room temperature the flask was filled with boiled, cooled, distilled water and weighed (*Wsw*). Finally, the soil was removed and the flask was weighed by filling with boiled, cooled and distilled water (*Wa*). The particle density was then calculated using the following formula (Johnston, 2000).

$$\rho_p = \rho_w (Ws - Wa) / [(Ws - Wa) - (Wsw - Ww)] \qquad 5.1$$

where ρ_w is the density of water in kg m^{-3} at temperature observed, *Ws* is weight of pycnometer plus soil sample corrected to oven-dry water content, *Wa* is weight of pycnometer filled with air, *Wsw* is weight of pycnometer filled with soil and water, and *Ww* is weight of pycnometer filled with water at the temperature observed.

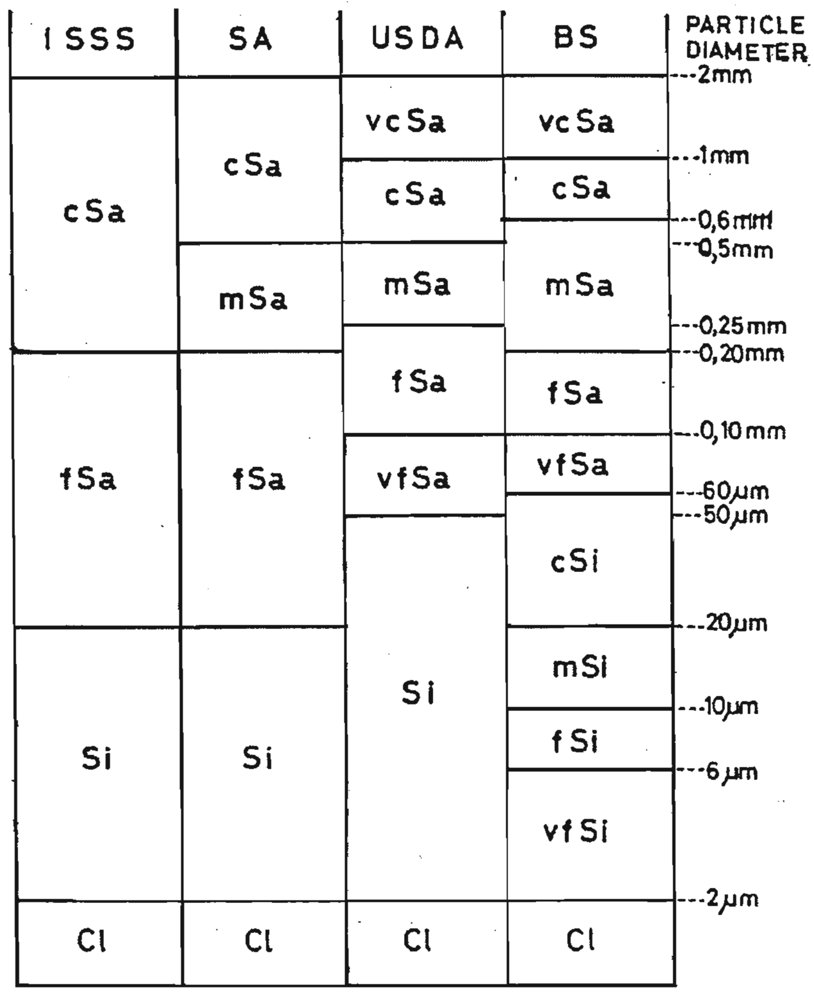


Fig. 5.1 Particle size classification systems according to the International Society of Soil Science (ISSS), South Africa (SA), United States Department of Agriculture (USDA) and British Standards (BS) (Hutson, 1983)

Cl	Clay	vc	Very coarse
Si	Silt	c	Coarse
Sa	Sand	m	Medium
f	Fine	vf	Very fine

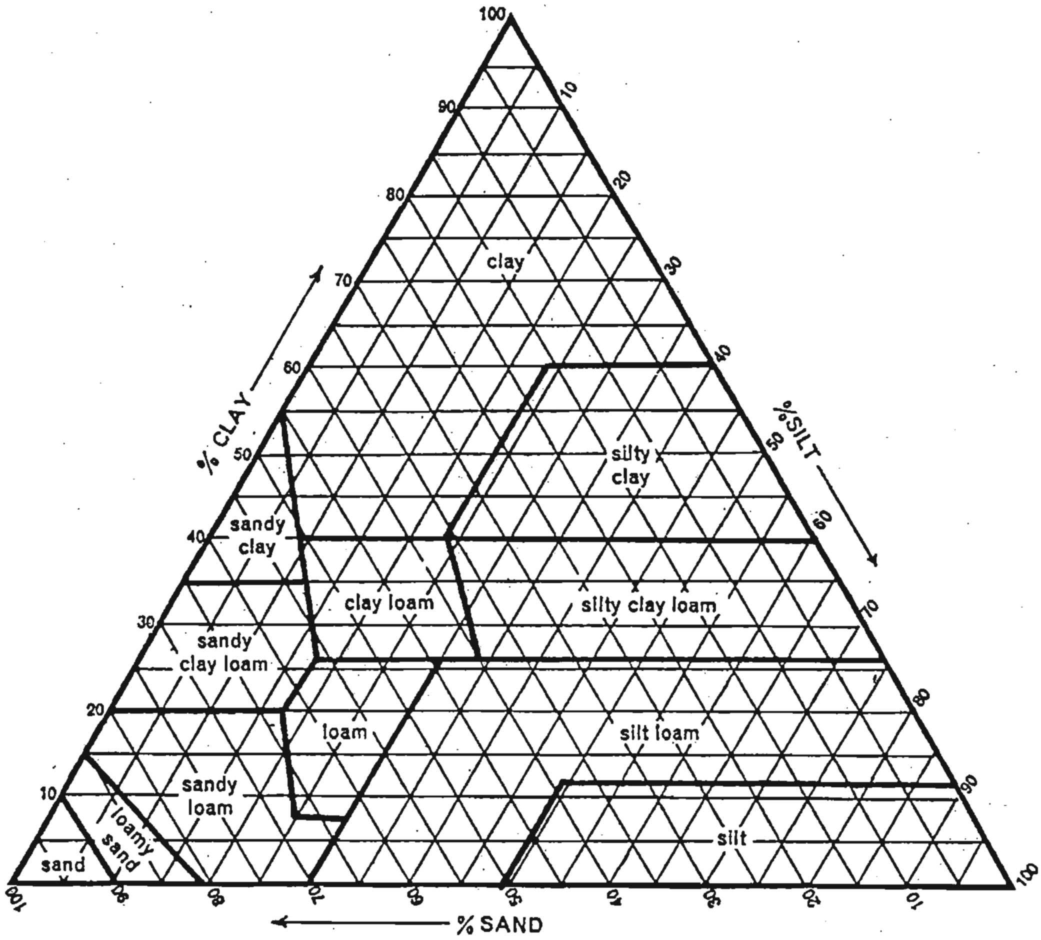


Fig. 5.2 Textural triangle for determining textural class from proportions of sand, silt and clay (Hutson, 1983)

Table 5.1 Summary of the soil characteristics

Location	Soil depth	Clay	Silt	Sand	Texture	Particle density	Bulk density	OC	Ca	Mg	Na	K	Fe	SAR	CEC	pH	EC
	(mm)	(%)	(%)	(%)	--	(kg m^{-3})	(kg m^{-3})	(%)	mol m^{-3}	mol m^{-3}	mol m^{-3}	mol m^{-3}	mol m^{-3}	_	mol m^{-3}	(KCl)	(mS m^{-1})
Upper slope	100	25.80	44.55	29.65	Loam	2520	1294	3.1	0.83	0.60	1.01	0.07	0.14	0.85	2.51	4.49	43.6
	200	30.04	40.06	29.90	Clay loam	2512	1300	2.8	0.58	0.40	0.50	0.06	0.12	0.51	1.55	4.45	26.4
	300	29.30	41.50	29.20	Clay loam	2544	1393	2.8	0.60	0.31	0.57	0.04	0.07	0.59	1.51	4.50	25.8
	400	45.57	28.48	25.95	Clay	2575	1370	1.9	0.52	0.23	0.48	0.06	0.11	0.55	1.30	4.47	21.6
	600	46.71	20.44	32.85	Clay	2599	1315	-	0.49	0.25	0.64	0.03	0.02	0.74	1.41	4.76	23.5
	1000	48.35	21.15	30.50	Clay	2641	1210	-	0.38	0.36	0.86	0.03	0.01	1.00	1.63	4.65	26.2
Lower slope	100	32.20	32.20	35.60	Clay loam	2513	1433	2.3	1.49	1.09	1.48	0.19	0.03	0.92	4.26	4.93	75.8
	200	34.97	34.98	30.05	Clay loam	2593	1391	2.6	0.90	0.61	1.02	0.09	0.11	0.83	2.62	4.56	45.1
	300	34.55	34.55	30.90	Clay loam	2590	1313	1.9	0.82	0.44	0.48	0.08	0.04	0.42	1.82	4.8	33.8
	400	40.68	25.42	33.90	Clay	2498	1411	1.2	0.70	0.34	0.60	0.03	0.03	0.59	1.67	5.32	29.7
	600	38.03	30.42	31.55	Clay loam	2696	1369	-	0.21	0.13	0.45	0.02	0.03	0.77	0.81	5.04	12.4
	1000	47.51	27.94	24.55	Clay	2789	1420	-	0.10	0.13	0.67	0.03	0.03	1.41	0.93	4.40	12.3

NB - organic carbon (OC) at the 600 and 1000 mm soil depths were not measured

As Millar *et al.* (1958) explained, the particle density of any soil is constant and does not vary with the amount of space between the particles unless there is considerable variation in content of organic matter or mineralogical composition. For many mineral soils the average particle density is about 2650 kg m^{-3}. This value agreed with the analyzed particle density of the soil (Table 5.1), which ranged between 2500 and 2790 kg m^{-3} for all of the soil samples.

5.1.3 Bulk density

Soil bulk density is the ratio of the mass of dry soil to the bulk volume of the soil (Blake and Hartge, 1986a). The bulk density of the soil was determined using a core method. Six undisturbed soil samples were taken from six different depths (100, 200, 300, 400, 600 and 1000 mm) from two different sites to represent the variability of the soil. The mass of the dry soil was determined after it was oven dried at 105 °C for 24 hours. The volume of the soil was assumed to be equal to the volume of the core sampler, since the soil was trimmed to the edge of the core at both ends. The internal diameter (D) and height (H) of the core were measured using a vernier caliper scale to calculate the volume of the core, $V = \pi (D/2)^2 H$, and the bulk density of the soil was calculated using the following equation:

$$\rho_b = M_{ds} / V \qquad 5.2$$

where ρ_b is the bulk density of the soil (kg m^{-3}), M_{ds} mass of dry soil (kg) and V the volume of the core sampler (m^3).

Bulk density is a widely used value and it is needed for converting gravimetric water content to volumetric water content, and for calculating porosity and void ratio when the particle density is known (Blake and Hartge, 1986b). For fine-textured soils the bulk density ranges between 1100 and 1600 kg m^{-3} (Millar *et al.*, 1958), which coincided with the calculated bulk density of the soil (1210 to 1438 kg m^{-3}) for all of the soil samples at the different depths (Table 5.1).

The total porosity of the soil was calculated using Eq.5.3, which considered only the soil bulk density (ρ_b) and particle density (ρ_s) of the soil. This value can also be used as an estimate of the soil water content at saturation.

$$P = 1 - \rho_b / \rho_s \qquad 5.3$$

where P is the total porosity of the soil (%), ρ_b is the soil bulk density (kg m^{-3}) and ρ_s is the soil particle density (kg m^{-3}) (Danielson and Sutherland, 1986).

5.1.4 Organic matter content

Organic matter content (OM) was determined by the Walkley-Black oxidation procedure (Walkley, 1947; Hughes *et al.*, 2000) using a soil sample that was air-dried and sieved to pass a 0.5 mm sieve. About 0.5 g of the soil sample was added to a 500-ml Erlenmeyer flask. Then 10 ml of the potassium dichromate solution 1N ($K_2Cr_2O_7$) and 20 ml H_2SO_4 were added carefully and the solution was left to stand for 20 minutes. After 20 minutes, 170 ml deionized water, 10 ml of 85% H_3PO_4, 0.2 g NaF and 5 drops of ferroin indicator were added. The same procedure was also followed for a blank sample.

The blank sample flask was titrated first to standardize ferrous ammonium sulphate and to recognize the titration end-point more easily when the solution was titrated. The titre volume for which the blank sample gradually turned from golden brown to dark green then to bright green finally to brownish black was noted and used to estimate the concentration of the ferrous ammonium sulphate used. The titre volume for which the soil sample solution turned to a dark brownish black was also noted and used to calculate the amount of potassium dichromate which was not oxidized by the organic carbon:

$$Y\,(ml) = \frac{V_{FAS} * C_{FAS}}{\left[K_2Cr_2O_7\right]} \qquad 5.4$$

where Y is the amount of Potassium dichromate that is not oxidized by organic carbon, V_{FAS} volume of ferrous ammonium sulphate of known charge concentration (C_{FAS}) used for titration and [$K_2Cr_2O_7$] is known concentration of potassium dichromate (1 N).

Thus, the volume of potassium dichromate (X) used by the organic matter was calculated as $X = (10 - Y)$. Finally the % of organic carbon in the soil was calculated using the following equation:

$$\% \text{ Organic carbon } = [X * 3 * 1.33 * (100 / \text{mass of soil})] \quad 5.5$$

The two samples from 600-mm and 1000-mm depths were excluded from the analysis because they were taken from deeper depths where organic matter was expected to be negligible.

The percentage of organic matter content of a soil determines whether a soil can be classified as either an organic or mineral soil. Mineral soils generally contain organic matter between 1 and 20 %, while organic soils contain above 20 % of organic matter. Fertile and loamy topsoil has an average organic matter content of about 5 % (Radojevic and Bashkin, 1999). Thus, from the analysis of organic matter content (Table 5.1) the soil was categorized as a mineral soil, with organic matter content in the range of 1.2 to 3.1 %.

5.1.5 Salinity status

The salinity status of soil can be represented by the amount of soluble salts in a given mass of dry soil or indirectly by the electrical conductivity (*EC*) of the saturation extract. For the electrical conductivity measurement, the extract was taken from saturated soil, which was prepared by adding gradually a soil sample in 50 ml of water. The soil was added until the soil paste showed a glistening surface and flowed slightly when the container was tipped, and slipped clearly off a spatula. These criteria were re-checked after the samples were left covered by a watch glass for one hour. When the paste fulfilled these criteria it was transferred to the Buchner funnel with a Whatman No. 42 filter paper in place where suction was applied with a vacuum pump. Using the soil extract the electrical conductivity was measured and the concentration of Na, Ca, and Mg determined using a flame method with an atomic absorption spectrophotometry (Johnston, 2000).

From the measured electrical conductivity (*EC*) and calculated value of *SAR* the soil salinity and sodicity can be determined respectively. A saline soil has an $EC > 400$ mS m^{-1} and non-saline soil has an $EC < 200$ mS m^{-1}. The soil sodicity is expressed in terms of exchangeable sodium percentage (*ESP*) which is > 15 in a Sodic soil and < 5 in a non-sodic soil. The *ESP* is numerically very similar to SAR, which is much easier to measure accurately.

$$SAR = \{Na\} / \left(\left(\{Ca\} + \{Mg\} \right) / 2 \right)^{0.5}$$

where, ionic concentration is expressed in mmol m^{-3}

Therefore, from the results obtained (Table 5.1), it can be concluded that the soil was non-saline and non-sodic with *EC* ranged between 12.3 and 75.8 mS m^{-1} and with an approximated *ESP* range (~*SAR*) between 0.42 and 1.41.

5.1.6 Soil pH

A soil sample of 10 g was weighed in 50 ml beaker and 25 ml of 1 mol kg^{-1} KCl was added. The sample was then allowed to stand for 30 minutes with occasional stirring using glass rod. The pH of the supernatant liquid was measured and recorded with a glass electrode pH meter (Hughes *et al.*, 2000).

Soil pH is used as a means of measuring acidity of a soil. The acidity is based on the concentration of the dissociated H ions, that is, on the active acidity. A soil with pH value between 3 to 4 is graded as excessively acid, 4 to 5 strongly acid, 5 to 6 acid, 6 to 7 weakly acid, 7 neutral and above 8 alkaline (Millar*et al.*, 1958).

The measured soil pH ranged between 4.4 and 5.3 at the six depths (Table 5.1). Thus, the soil is categorized as strongly acidic soil. For such soils application of lime is recommended to correct and bring chemical, physical, and biological changes in the soil to a range, which is beneficial to plant growth (Millar *et al.*, 1958).

5.1.7 Extractable iron content

The Ambic method (The Non-Affiliated Soil Analysis Work Committee, 1990) was used to determine the extractable iron content of the soil. This method requires Ambic-2 extraction solution which was prepared by dissolving 19.7 g ammonium bicarbonate, 3.72 g di-sodium EDTA and 0.37 g ammonium fluoride in about 500 ml de-ionized water and 10 ml superfloc was added. It was mixed well and made up to 1 liter with de-ionized water and allowed to stand over night, then adjusted to pH 8 with concentrated ammonium solution.

To prepare the extraction, 2.5 g soil was weighed in sample cup and 25 ml extraction solution was added. The solution was stirred for 10 minutes at 400 rpm and filter extracted in to a clean sample cup, using Whatman no. 1 filter paper. Then, the concentration of the extractable iron content of the soil was determined directly on the undiluted extract with an atomic absorption spectrophotometer.

5.2 SOIL WATER CHARACTERISTICS

5.2.1 Mass water content

This method involves water content measurement by weighing the wet sample, oven drying at 105 °C for 24 h, and reweighing the sample to determine the amount of water removed. Water content can then be expressed either as a ratio of mass of water to mass of dry soil (mass water content) or by multiplying the ratio by bulk density. The result may be expressed on a volumetric water content (Gardner, 1986):

$$\theta = \frac{W_w Y_d}{W_d Y_w} \qquad 5.7$$

where θ volumetric water content ($m^3\ m^{-3}$), W_w weight of water (kg), W_d dry weight of soil (kg), Y_d oven-dry bulk density (kg m^{-3}) and Y_w density of water (kg m^{-3}).

5.2.2 Soil water retentivity characteristics

The soil water retentivity characteristics represent the relationship between soil water content (θ_m or θ_v) and matric potential (Ψ_m). The water retention property of the soil is primarily dependent on the texture (particle size distribution of the soil), the structure (or arrangement of the particles), organic matter and degree of compaction of the soil (Klute, 1986).

The main aim of this analysis was to derive the pore size distribution, describe the degree of compactness or looseness of the soil (the bulk density) and to derive the constants for the determination of the 'refill point'.

To characterize the soil, six undisturbed soil samples were taken from six different depths (100, 200, 300, 400, 600, and 1000 mm) in three replications from representative sites in the field. Before the cores were placed on the tension table, they were trimmed carefully level with the edge of the sleeve. Then they were placed in a water bath and saturated by capillary action from the bottom up. When the soil was saturated, each core was weighed while water was dripping to obtain the saturated water content, they were then transferred to the tension table. A hanging water column was used for the low matric potential range (-1 to –10 kPa), a pressure pot was used for matric potentials between -50 and -100 kPa and a pressure chamber was used for the -1500 kPa. In each method the pressure was changed after the attainment of equilibrium and weighed before subjecting them to a different suction. Finally the cores were oven dried at 105 °C for four days to totally remove the water from the cores and reweighed to determine the water content on dry mass basis. Bulk density was also determined to convert the gravimetric soil water content (g g^{-1}) to volumetric water content ($m^3 m^{-3}$).

From the results obtained (Table 5.2 and 5.3), the retentivity curve (Fig. 5.3) showed high water retention and a gradual decrease in water content with the increasing matric potential. The soil had a mean water content of 48.6 % at saturation (Table 5.3), which agreed with the calculated porosity, 49 % (Eq. 5.3). The soil water content gradually decreased by 11 % at matric potential of -10 kPa. This high soil water content at any corresponding matric potential can be attributed to the high clay content (Table 5.1). As Hillel (1971) discussed, the retentivity curve is strongly affected by soil texture. In general, the greater the clay content the greater the water retention and the more gradual the slope of the curve.

The calculated air filled porosity (P_a) at -10 kPa is 5.43 % (Eq. 5.8), which further substantiates the above result. Air filled porosity is also dependent on soil texture; in soils with high clay content the soil tends to retain most of the water. Air filled porosity of 10 % is regarded as an index for a good aerated and non-compact soil which is non-limiting to root respiration and hence to plant growth (Hillel, 1980). An analysis of pore size distribution (Table 5.3) which was calculated using the capillary equation (Eq. 5.9) also revealed that the micropores (< 0.01 mm) are dominant, causing the soil to have high soil water content at the field capacity (-33 kPa) and at permanent wilting point (-1500 kPa).

$$P_a = P - \theta_{FC} \qquad 5.8$$

where P_a is air filled porosity (%), P is total porosity (%) and θ_{FC} soil water content at field capacity (%) on a volume basis.

$$\Psi = 2\,\gamma\, \cos\theta \,/\, r \qquad 5.9$$

where Ψ is the matric potential of soil water (kPa), γ is the surface tension of water which is 0.073 N m^{-1} at 20 °C and r is the radius of the pores (μm). The contact angle (θ) is assumed to be zero.

Table 5.2 Volumetric water contents ($m^3\ m^{-3}$) at different matric potentials for soil samples taken from the lower location at the site

Depth (mm)	ψ_μ (-kPa)	MWSC (g)	MDSC (g)	MC (g)	MS (g)	MW (g)	θ_γ ($g\ g^{-1}$)	Bulk density ($kg\ m^{-3}$)	θ_v (%)
	Saturation	299.36	251.44	121.77	129.67	47.92	36.97	1294.08	47.83
	1	296.26	251.44	121.77	129.67	44.82	34.58	1294.08	44.73
	2	295.82	251.44	121.77	129.67	44.38	34.24	1294.08	44.29
	3	295.53	251.44	121.77	129.67	44.09	34.02	1294.08	44.01
	4	295.26	251.44	121.77	129.67	43.82	33.81	1294.08	43.73
100	6	294.48	251.44	121.77	129.67	43.04	33.21	1294.08	42.95
	8	292.92	251.44	121.77	129.67	41.48	32	1294.08	41.39
	10	291.94	251.44	121.77	129.67	40.5	31.25	1294.08	40.42
	50	285.66	251.44	121.77	129.67	34.22	26.38	1294.08	34.15
	100	282.28	251.44	121.77	129.67	30.84	23.8	1294.08	30.78
	1500	-	-	-	-	-	-	-	26.48
	Saturation	303.13	253.64	123.36	130.28	49.49	37.99	1300.17	49.39
	1	300.43	253.64	123.36	130.28	46.79	35.91	1300.17	46.7
	2	300.19	253.64	123.36	130.28	46.55	35.73	1300.17	46.46
	3	300.1	253.64	123.36	130.28	46.46	35.66	1300.17	46.37
	4	300.08	253.64	123.36	130.28	46.44	35.65	1300.17	46.35
300	6	299.96	253.64	123.36	130.28	46.32	35.55	1300.17	46.23
	8	299.75	253.64	123.36	130.28	46.11	35.39	1300.17	46.02
	10	299.67	253.64	123.36	130.28	46.03	35.33	1300.17	45.93
	50	295.91	253.64	123.36	130.28	42.27	32.44	1300.17	42.18
	100	294.3	253.64	123.36	130.28	40.66	31.21	1300.17	40.58
	1500	-	-	-	-	-	-	-	35.89

where

ψ_m: Matric potential
MWSC: Mass of wet soil sample + core
MDSC: Mass of oven dry soil sample + core
MC: Mass of core including mass of lid, cloth and plastic band
MS: Mass of soil (MDSC – MC)
MW: Mass of water (MWSC – MDSC)
θ_g: Mass water content (MW / MS)
θ_V: Volumetric water content (θ_g * ρ_b / ρ_{water})

Table 5.3 Depicting the pore size distribution of the soil sample

ψ_m (-kPa)	Pore size (μm)	Pore diameter (μm)	Pore radius limits (μm)	Average water content (%)	% Pore space occupied by that size range
Saturation (0 kPa)	-	-	-	48.61	
1	146	292	>146	45.72	2.89
2	73	146	146 to 73	45.38	0.34
3	48.7	97	73 to 48.7	45.19	0.19
4	36.5	73	48.7 to 36.5	45.04	0.15
6	24.3	49	36.5 to 24.3	44.59	0.45
8	18.3	37	24.3 to 18.3	43.71	0.88
10	14.6	29	18.3 to 14.6	43.18	0.53
50	2.9	6	14.6 to 2.9	38.17	5.01
100	1.5	3	2.9 to 1.5	35.68	2.49
1500	0.097	0.19	<1.5	31.18	35.68

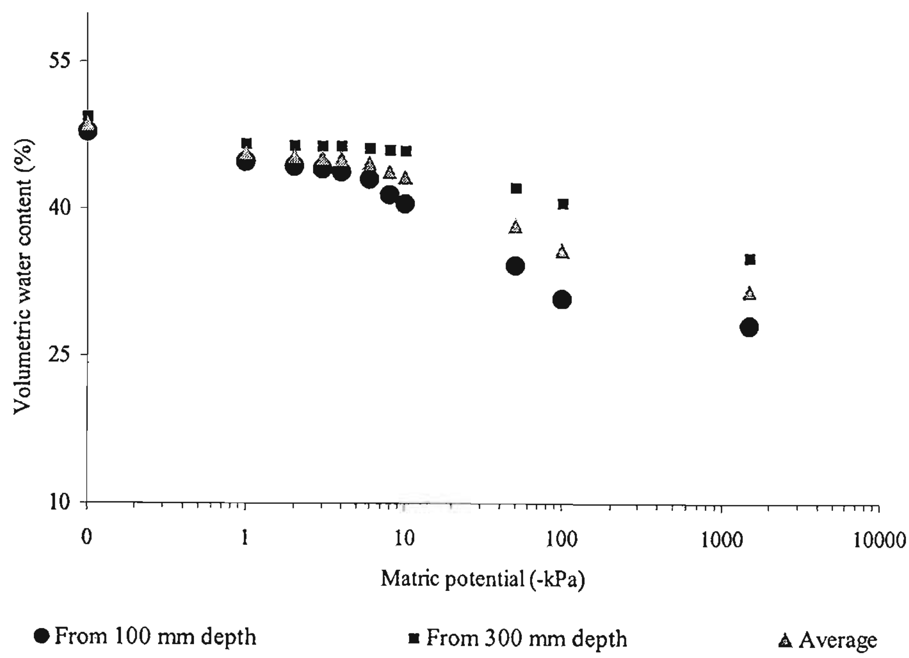


Fig. 5.3 Measured and average volumetric soil water content (%) *vs* matric potential (kPa)

5.3 CONCLUSIONS

Generally the selected soil physical characteristics of the two sites could be described as follows. The soil textural class in the shallow depth (100 to 300 mm) was clay loam. For the deeper depths the soil was predominantly a clay soil. For all the depths the particle density ranged between 2500 and 2790 Kg m^{-3}, bulk density between 1210 and 1438 Kg m^{-3}, organic matter between 1.2 and 3.1%, soil pH between 4.4 and 5.3 and electrical conductivity 12 and 758 mS^{-1} m^{-1}. The soil water content at saturation (0 kPa) was 0.486 m^3 m^{-3}, at -10kPa 0.43 m^3 m^{-3} and at-1500 kPa 0.31 m^3 m^{-3}.

Once the soil physical and soil water characteristics were determined, the sensors that were used to measure the soil water content (PR1 profile probe and Diviner 2000) and soil water potential (tensiometer and Watermark sensors) need to be calibrated for this specific soil to increase the accuracy of the measurement. The calibration curves or equations of these sensors are mostly developed for general soils and to make these calibration curves or equations site specific, these soil water content and soil water potential sensors need to be calibrated for this particular soil type.

CHAPTER 6

CALIBRATION AND COMPARISON OF SENSORS

6.1 INTRODUCTION

Most of the soil water content and soil water potential sensors do not measure soil water content and soil water potential directly. Instead, they measure a property that could be related to soil water content or soil water potential by a calibration curve. For example, the PR1 profile probe and the Diviner 2000, which are frequency domain reflectometry sensors, measure soil water content by generating an electromagnetic field to the soil. Since the dielectric properties of the soil are different from the probe electronics, some of the signals are reflected. The reflected signal combined with the applied signal forms a standing wave and the voltage of the standing wave acts as a simple, sensitive measure of the soil water content (Delta-T Devices, 2001). Usually manufacturers of the sensors provide a calibration curve that converts the measured voltage to volumetric ($m^3\ m^{-3}$) or mass soil water content ($kg\ kg^{-1}$). The calibration curve or equations are usually developed for general soils and to make the calibration curve site specific, the soil water content and soil water potential sensors need to be calibrated for the particular soil type.

The sensors, which were used in this study, were calibrated by comparing them with their respective standard methods or with a calibrated sensor. The PR1 profile probe was calibrated against water content determined by the gravimetric method within a dry and wet range. Tensiometers were calibrated in the laboratory by applying a known amount of suction using a vacuum pump and calibration constants were developed between the applied pressure and the output (voltage) of the sensor. Thermocouples were also calibrated by comparing the temperature measured by the thermocouple with mercury thermometer measured temperature. The spoon type tipping rain gauge was calibrated by comparing the number of counts with a known amount of applied water at a constant flow rate. Diviner 2000 was compared with the PR1 profile probe measurements. The calibration equation developed by Thomson and Armstrong (1987) was used to determine the sensitivity of the Watermark sensor to changes in resistance at different soil temperatures. The sensitivity of the sensor to diurnal soil temperature changes were also investigated.

6.2 PR1 PROFILE PROBE

For the calibration of the PR1 profile probe both the sensor (probe) and the hand held HH2 Moisture Meter were calibrated separately. The sensor was calibrated against the gravimetric method, and the HH2 Moisture Meter was calibrated against corresponding voltage measurements using a CR10X datalogger, which was tested for its accuracy using a standard voltage source.

6.2.1 The probe

The probe was calibrated using a two-point calibration method (Delta-T Devices, 2002). This method requires a comparison between PR1 profile probe readings and the corresponding gravimetric analysis in both moist and dry soils. Initially, readings (V_d, V_w) were taken from the PR1 profile probe in the soil when it was both dry and moist. Then soil samples were taken from the same depth close to the access tube to determine their water content (θ_d, θ_w) by gravimetric analysis. The values for $\sqrt{\varepsilon_d}$ and $\sqrt{\varepsilon_w}$ were then calculated by inserting V_d and V_w in the following equation (Delta-T Devices, 2001):

$$\sqrt{\varepsilon_w} = 0.65 + 13.6V_w - 29.9\, V_w^{\,2} + 72.5\, V_w^{\,3} \qquad 6.1$$

in which $\sqrt{\varepsilon_w}$ the square root of dielectric constant of the soil when it was moist and V_w is the voltage (V) measured using the PR1 profile probe in the moist soil. Similarly, the square root of dielectric constant of the soil for the dry range $\sqrt{\varepsilon_d}$ is calculated using voltage output of the dry soil (V_d).

The calibration constants a_1 and a_0 were then calculated using Eqs. 6.2 and 6.3 respectively (Delta-T Devices, 2002):

$$a_1 = (\sqrt{\varepsilon_w} - \sqrt{\varepsilon_d}\,) / (\theta_w - \theta_d) \qquad 6.2$$

$$a_0 = \sqrt{\varepsilon_w} - a_1 * \theta_w \qquad 6.3$$

From the results a_1 and a_o were calculated to be 11.04 and 1.02 respectively. The dielectric constant of the dry soil was 3.14 at volumetric soil water content of 0.192 $m^3 m^{-3}$ using the gravimetric method and the profile reading was 0.184 $m^3 m^{-3}$. The dielectric constant of the soil when it was moist was calculated to be 5.66. The volumetric soil water content of the moist soil was 0.42 $m^3 m^{-3}$ using the gravimetric method and the corresponding PR1 profile probe reading was 0.483 $m^3 m^{-3}$. Lukangu *et al.* (1999) found similar results for the calibration of the Thetaprobe (ML1) that the values of a_1 and a_o were 11.09 and 1.411 respectively. Comparison was made between the values of a_1 and a_o of PR1 profile probe and ML1 Thetaprobe because the values are the same for both sensors (Delta-T Devices, 2001). The factory-supplied parameters for calibrating mineral soil are a_1 = 8.4 and a_o = 1.6 (Delta-T Devices, 2001).

The soil-estimated and the factory-supplied parameters to estimate the volumetric water content were compared with the volumetric soil water content measured by gravimetric method (Fig. 6.1). The linear regression statistics for these comparisons are shown in Table 6.1. The regression coefficient for both factory-supplied (r^2 = 0 .822) and soil-estimated (r^2 = 0 .820) parameters were low. These could be due to soil variability (Schmitz and Sourell, 2000) and errors encountered while sampling and analyzing of the samples in the field and laboratory. However, the factory-supplied parameter showed good correlation when compared with the mass soil water content. The factory-supplied parameter resulted in slope and intercept confidence limits that encompass the ideal slope of one and intercept of zero. The soil-estimated parameter resulted in an intercept, which was statistically zero but the slope was statistically different from one. On average, the volumetric soil water content could be estimated within 0.046 $m^3 m^{-3}$ when using the soil-estimated parameters and 0.012 $m^3 m^{-3}$ when using the factory-supplied parameters. Both the soil and factory calibration gave smaller errors compared to the maximum error of 0.05 $m^3 m^{-3}$ specified by the manufacturer. Lukangu *et al.* (1999) found a value of 0.024 $m^3 m^{-3}$ when using soil-estimated parameters and 0.020 $m^3 m^{-3}$ when using the factory-supplied parameters. Similarly, the standard deviations for volumetric water content of 0.039 $m^3 m^{-3}$ (factory-parameters) and 0.029 $m^3 m^{-3}$ (soil-estimated) were comparable with the results obtained by Lukangu *et al.* (1999). They were 0.021 $m^3 m^{-3}$ for the factory-calibration and 0.013 $m^3 m^{-3}$ for the soil calibration. From the results obtained it looks reasonable to use the factory-parameters as calibration constants to estimate the volumetric soil water content using the PR1 profile probe.

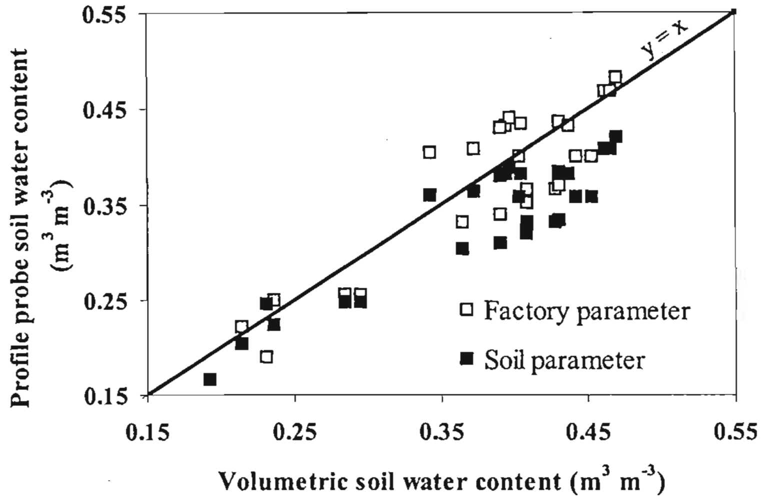


Fig. 6.1 Volumetric soil water content (m^3 m^{-3}) *vs* PR1 profile probe soil water content (m^3 m^{-3}) measurements using factory-supplied and soil-estimated parameters

Table 6.1 Regression analyses between the volumetric soil water content (X) versus the soil water content calculated using the field-estimated or factory-supplied parameters (Y).

Statistical parameters	Soil parameter	Factory parameter	Differences
N	27	27	-
r^2	0.820	0.822	-0.002
RMSE	0.085	0.062	0.023
T	10.677	10.761	-0.084
Slope (m^3 m^{-3}/ m^3 m^{-3})	0.755	1.015	-0.260
Intercept (m^3 m^{-3})	0.046	-0.018	0.064
Sy.x	0.029	0.039	-0.010
SUM X^2	14.319	14.319	0.000
SEslope	0.071	0.094	-0.023
Slope upper confidence limit 99%	0.558, 0.952	0.752, 1.278	-
Slope upper confidence limit 95%	0.609, 0.901	0.821, 1.209	-
SEintercept	0.051	0.069	-0.018
Intercept upper confidence limit 99%	-0.097, 0.190	-0.209, 0.174	-
Intercept upper confidence limit 95%	-0.060, 0.152	-0.159, 0.124	-

6.2.2 HH2 Moisture Meter

The HH2 Moisture Meter (Delta-T Devices, Cambridge, UK) was calibrated against the readings from the CR10X datalogger (Campbell Scientific, Logan, USA). The accuracy of the CR10X datalogger was first tested by applying a certain voltage using a voltage source (Botany Industrial Estate, Tonbridge, England). Since the datalogger gave the same reading as the supplied voltage, the CR10X datalogger was considered as an accurate device to calibrate the HH2 Moisture Meter. The soil water content was measured with the PR1 profile probe using the HH2 Moisture Meter and CR10X datalogger at the same time while the field was irrigated. Soil water content values between 0.2 and 0.5 m^3 m^{-3} were collected at six different depths over time for the calibration of the HH2 Moisture Meter.

From the statistical analysis (Table 6.2) there was a highly significant linear relationship ($r^2 = 0.99$) between the soil water content measured with the HH2 Moisture Meter and the CR10X datalogger. The measurement of the soil water content with the HH2 Moisture Meter was statistically different from the soil water content measured by the CR10X datalogger. This was shown from the statistical analysis of the *paired-t test,* where the probability level ($P<0.001$) was lower than the critical alpha value ($\alpha = 0.05$). The soil water content measured with the HH2 Moisture Meter was usually smaller than the soil water content measured with the CR10X. For example the minimum and maximum soil water content values measured with HH2 Moisture Meter were 0.065 and 0.414 m^3 m^{-3} respectively. These values were measured as 0.110 and 0.499 m^3 m^{-3} when the CR10X datalogger was used to measure the soil water content. On average, the HH2 Moisture Meter underestimated the soil water content by 0.049 m^3 m^{-3} compared with the CR10X measured soil water content. When a comparison was made between the soil water content measured with the HH2 Moisture Meter and CR10X, the regression line (Fig. 6.2) showed a bias from the 1:1 line with a percentage of systematic error of 95.9 % and a RMSE value of 0.064. The intercept of the regression line was statistically zero since the confidence limit encompassed the ideal intercept of zero at the 99 % level of significance. The slope of the regression line was, however, statistically different from one, as the confidence limit at both 95 and 99 % level of significance did not encompass the ideal slope of one. Thus, for the calibration of the soil water content measured with the HH2 Moisture Meter the slope of the regression line was used as a multiplier to correct the soil water content.

Table 6.2 Regression analyses between the soil water content measured using the CR10X (X) versus the soil water content measured using the HH2 Moisture Meter (Y).

Statistical parameter	HH2 Moisture Meter
n	27
r^2	0.991
RMSE	0.064
P (T<=t) two-tail (95 %)	<0.001
t	53.29
Slope ($m^3\ m^{-3}$/ $m^3\ m^{-3}$)	0.8752
Intercept ($m^3\ m^{-3}$)	-0.0233
Sy.x	0.0108
SUM (X^2)	14.1339
SEslope	0.0164
Slope confidence limit 99%	0.8294, 0.9209
Slope confidence limit 95%	0.8414, 0.9090
SEintercept	0.0119
Intercept confidence limit 99%	-0.0564, 0.0099
Intercept confidence limit 95%	-0.0477, 0.0012

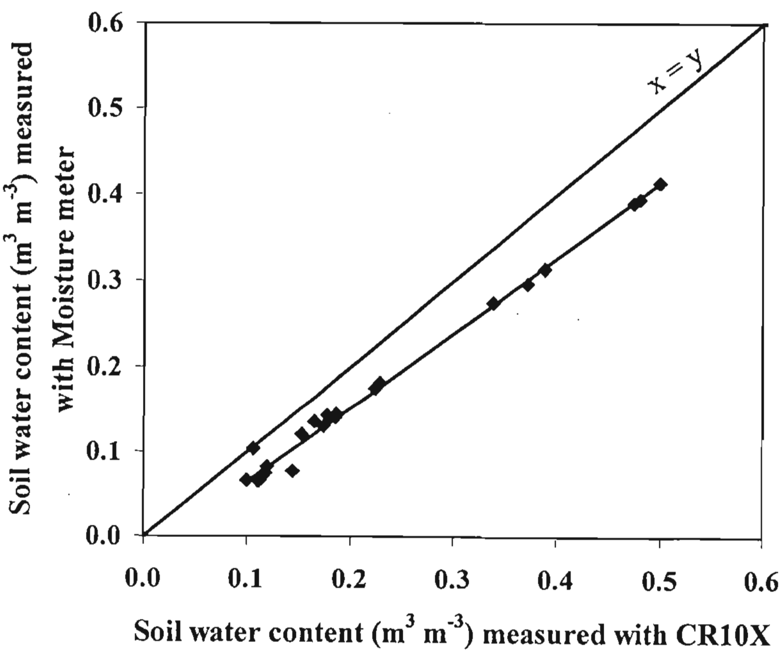


Fig. 6.2. Soil water content ($m^3\ m^{-3}$) measured using HH2 Moisture Meter *vs* CR10X measured soil water content ($m^3\ m^{-3}$)

6.3 DIVINER 2000

A comparison was made between the soil water content measured with the Diviner 2000 and the calibrated PR1 profile probe. Both sensors are frequency domain reflectometry (FDR) sensors and they measure the soil water content by generating an electromagnetic field to the soil where the soil acts as a dielectric media of the circuit. These sensors rely on the fact that water has a much higher dielectric constant than air or dry soil. Hence, changes in the soil water content are reflected by the changes of the dielectric constant of the soil (Delta-T Devices, 2001). The soil water content measurements were taken from the access tubes of each sensor, which were installed 300 mm apart from each other and the soil water content measurements were recorded manually using the HH2 Moisture Meter for the PR1 profile probe and Diviner 2000 display unit for the Diviner 2000.

From the statistical analysis there was highly significant linear relationship between the soil water content measured with the Diviner 2000 and the PR1 profile probe (Fig. 6.3). The regression coefficients for the first three depths ranged between 0.94 and 0.96 (Table 6.3). The regression coefficients for the deeper depths ranged between 0.72 and 0.81. These low regression coefficients at the deeper depths could be due to soil variability and loose contact of the access tubes with the soil. Good contact between the soil and access tube is crucial and loose access tube installation could yield to errors of within 0.1 $m^3\ m^{-3}$ (Delta-T Devices, 2001). The minimum and maximum soil water content measurements of the PR1 profile probe ranged between 0.126 and 0.283 $m^3\ m^{-3}$ at 100 mm. Similarly, the Diviner 2000 measured these values as the minimum soil water content 0.163 $m^3\ m^{-3}$ and the maximum soil water content 0.332 $m^3\ m^{-3}$ at the same depth. The statistical analysis of the 95 % confidence limit for both the slope and intercept showed that there was significant difference between the soil water content measured at some of the depths. The intercepts of the regression line for all the depths were zero except for 200 mm depth. Some of the confidence limits at 99 % level of significance encompass the ideal slope of one (Table 6.3). From the statistical analysis it can be concluded that the soil water content measurement of both sensors were not exactly the same at all the depths, but there was a good correlation at most of the depths.

If a comparison was made between the two sensors, both of them have the following common properties: i) both are FDR sensors; ii) both sensors measure soil water content up to one meter depth; iii) both sensors have 100 mm radius sphere of influence; and iv) both sensors use an access tube to measure the soil water content. However, each sensor has its own separate advantages and disadvantages. Advantages of the PR1 profile probe are that: i) continuous and unattended reading can be taken from one access tube by connecting to a datalogger; ii) the access tube for the PR1 profile probe is 28 mm in diameter and it is relatively easy to install than the 50 mm diameter access tube of the Diviner 2000; and iii) the PR1 profile probe and its HH2 Moisture Meter are relatively light and easy to handle. Advantages of the Diviner 2000 are: i) with one swipe of the sensor to the access tube, the sensor records the soil water content for all depths with 360 degree around the access tube. But for the PR1 profile probe to get the full 360 degree reading around the access tube the probe should be inserted to the access tube three times at 120 degree at a time; ii) the Diviner 2000 gives an alarm if there is water inside the access tube; and iii) in addition to the depths, which were measured by the PR1 profile probe, the Diviner 2000 measures the soil water content at 500, 700, 800 and 900 mm (Sentek Environmental Technologies, 2000).

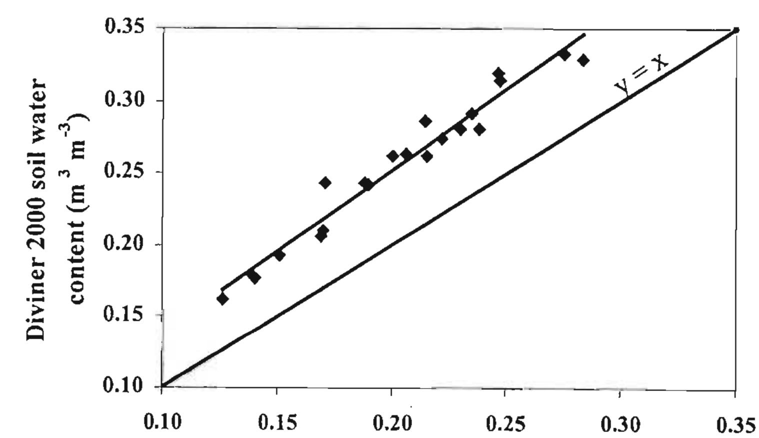


Fig. 6.3 Diviner 2000 soil water content (m^3 m^{-3}) *vs* PR1 profile probe soil water content (m^3 m^{-3}) at 100 mm soil depth

Table 6.3 Regression analyses between the PR1 profile probe measured soil water content (m^3 m^{-3}) and the Diviner 2000 measured soil water content (m^3 m^{-3}) for 21 measurement pairs

Statistical parameters	100 mm	200 mm	300 mm	400 mm	600 mm	1000 mm
r^2	0.957	0.964	0.947	0.810	0.746	0.716
RMSE	0.070	0.076	0.109	0.069	0.058	0.150
t	20.620	22.403	18.424	9.003	7.474	6.915
Slope	1.126	0.552	0.778	0.923	0.797	0.865
Intercept	0.027	0.086	-0.011	-0.022	0.040	-0.078
Sy.x	0.011	0.007	0.007	0.010	0.005	0.009
SUM (X^2)	10.092	10.161	10.205	10.184	10.180	10.283
SEslope	0.055	0.025	0.042	0.103	0.107	0.125
Slope confidence limit 99%	0.970, 1.283	0.481, 0.622	0.657, 0.899	0.630, 1.217	0.492, 1.102	0.507, 1.223
Slope confidence limit 95%	1.012, 1.241	0.500, 0.603	0.689, 0.866	0.709, 1.138	0.574, 1.020	0.603, 1.127
SEintercept	0.038	0.017	0.029	0.071	0.074	0.088
Intercept confidence limit 99%	-0.082, 0.135	0.037, 0.135	-0.095, 0.073	-0.226, 0.187	-0.172, 0.252	-0.320, 0.173
Intercept confidence limit 95%	-0.053, 0.106	0.050, 0.122	-0.073, 0.050	-0.171, 0.128	-0.115, 0.195	-0.261, 0.106

6.4 TENSIOMETERS

The tensiometer transducers were calibrated in the laboratory by applying a known suction using a vacuum pump. The reading for the applied suction was taken from a mercury manometer (mm) and the reading for the tensiometer transducers (kPa) was taken from a datalogger, which was programmed to measure soil water potential. From the reading of the datalogger, the voltage output of the transducers was calculated using Eq. 6.4. The tension (kPa) was calculated from the manometer reading (m) using the formula [Tension (kPa) = ρ_{Hg} * g * height of mercury] and *a* and *b* were assumed to be -0.0232 and 8 respectively which were calculated from the manufacturer supplied curve (Thornton-Dibb and Lorentz, 2001).

Transducer output (Volts) = [Tension (kPa) – b] / a 6.4

There was a highly significant linear relationship (Fig. 6.4) between the applied pressure and transducer-measured voltage. All the regression coefficients were greater than 0.999 and all the tensiometers have statistically the same slope (0.0299), which encompassed within the confidence limit of individual tensiometer (Table 6.4). The intercepts of the six tensiometers were not significantly different. Therefore, all the data were pooled and one regression line (Fig. 6.4) was used. The slope (a = 0.0299) and intercept (b = 0.1351) for the pooled data were used as offset and multiplier respectively to convert the transducer-measured voltage (V) to soil water potential (kPa).

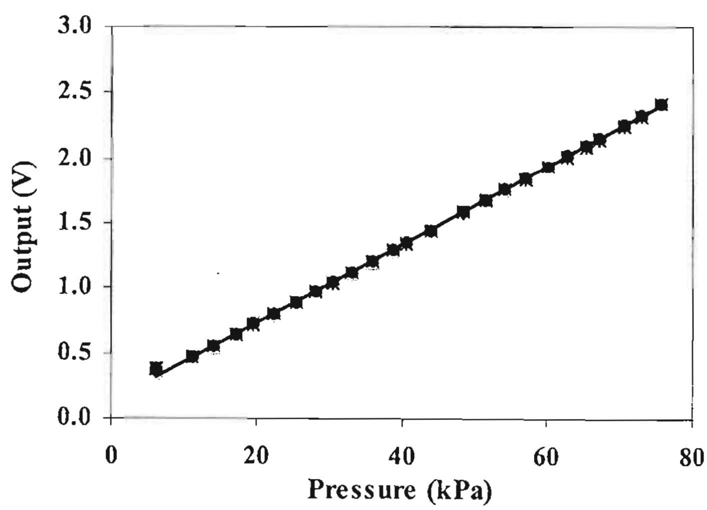


Fig. 6.4 Applied pressure (kPa) *vs* the output of the tensiometer transducer (V)

Table 6.4 Regression analyses between the applied pressure (kPa) and the transducer voltage reading (V) for 25 measurement pairs and 150 for the pooled data set

Statistical parameters	Tensiometer 1	Tensiometer 2	Tensiometer 3	Tensiometer 4	Tensiometer 5	Tensiometer 6	Pooled values
r^2	0.9995	0.9995	0.9996	0.9997	0.9997	0.9997	0.9996
t	215.9768	225.0914	227.4837	289.7975	256.9864	295.6469	595.5640
Slope	0.0298	0.0299	0.0299	0.0299	0.0299	0.0299	0.0299
Intercept	0.1326	0.1328	0.1329	0.1379	0.1364	0.1381	0.1351
Sy.x	0.0142	0.0137	0.0135	0.0106	0.0120	0.0104	0.0127
SUM (X^2)	51.6305	51.6305	51.6305	51.6305	51.6305	51.6305	134.3019
SEslope	0.00014	0.00013	0.00013	0.00010	0.00012	0.00010	0.00005
Slope confidence limit 99%	0.0294, 0.0302	0.0295, 0.0302	0.0295, 0.0302	0.0296, 0.0302	0.0295, 0.0302	0.0296, 0.0302	0.0297, 0.0300
Slope confidence limit 95%	0.0295, 0.0301	0.0296, 0.0301	0.0296, 0.0301	0.0297, 0.0301	0.0296, 0.0301	0.0297, 0.0301	0.0298, 0.0300
SEintercept	0.00020	0.00019	0.00019	0.00015	0.00017	0.00015	0.00005
Intercept confidence limit 99%	0.1321, 0.1332	0.1323, 0.1334	0.1324, 0.1334	0.1375, 0.1383	0.1359, 0.1368	0.1377, 0.1385	0.1350, 0.1352
Intercept confidence limit 95%	0.1322, 0.1330	0.1324, 0.1332	0.1325, 0.1333	0.1376, 0.1382	0.1360, 0.1367	0.1378, 0.1384	0.1350, 0.1352

6.5 WATERMARKS

The mathematical model that was developed by Thomson and Armstrong (1987) was used to relate the electrical resistance of the Watermark to soil water potential and soil temperature. They did the calibration for a matric potential of -10 to -100 kPa in a laboratory by placing the Watermark sensors inside an extractor and completely covered by soil. A thermocouple was also placed in the soil. The pressure was adjusted to a certain value corresponding to the first desired tension reading. Temperature and voltage were then measured for a range of temperature and soil water potential values. After data were obtained for a temperature cycle between 4 and 38 °C at temperature increments of 6 °C, the pressure was increased to the next value and the temperature cycle was repeated.

The generalized observational model (Eq. 6.5) developed by Thomson and Armstrong (1987) was used to estimate the constants, which were then use in the calibration equation (Eq. 6.6) for a range of soil water potential between -10 and -100 kPa:

$$R_i = \left[\alpha - \frac{\beta}{1-\gamma\Psi_i}\right]\left(\delta - T_i + \lambda T_i^2\right) \qquad 6.5$$

where, R_i is the sensor resistance for observation i, α, β, γ, δ, λ are unknown parameters to be experimentally determined, Ψ_i is soil water potential for observation i, and T_i soil temperature for observation i:

$$\Psi = \frac{-R}{0.01306[1.062(34.21-T+0.01060T^2)-R]} \qquad 6.6$$

Equation 6.6 was used to generate soil water potential values (Savage, 2002a) at different values of resistance (2 to 12 kΩ) and temperature (0.5 to 35 °C). These data were used to determine the response of the Watermark sensor to different resistance (indirectly soil water content) and temperature. The sensor is less sensitive to a change of resistance at the lower values as compared to the change of resistance in the higher values (Fig. 6.5). For example, a change of resistance from 2 to 3 kΩ at 20 °C caused a change of soil water potential from -8.7 to -13.8 kPa whereas a change of resistance from 8 to 9 kΩ at 20 °C caused a change of soil water potential from -52.8 to -65.1 kPa, a decrease of -12.3 kPa. The sensor is also sensitive to diurnal soil temperature change.

To determine the sensitivity of the sensor to temperature change, the mathematical model (Eq. 6.6) was differentiated as a function of temperature (Savage, 2002a) and it yields the following equation:

$$\frac{\delta\psi}{\delta T} = 81.316998\, R_S [1.062(34.21 - T_S + 0.01060 T_S^2) - R_S]^{-2} (-1 + 0.0212 T_S) \qquad 6.7$$

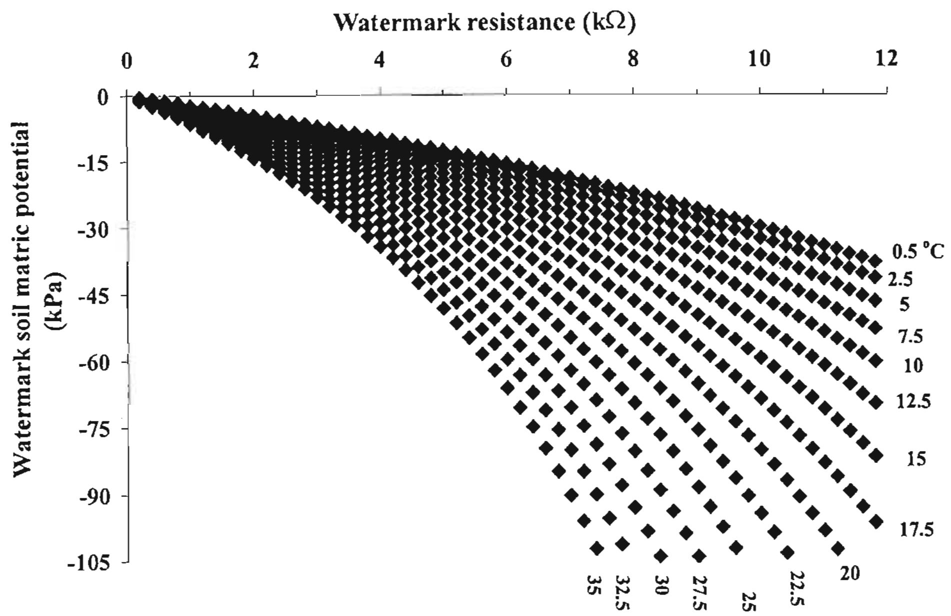


Fig. 6.5 Watermark soil matric potential (kPa) *vs* Watermark resistance (kΩ) at different soil temperatures

The sensitivity of the sensor to diurnal soil temperature change was made from the diurnal change of soil temperature at 100 and 600 mm soil depth (Fig. 6.6). The diurnal change of soil temperature at 600 mm soil depth was narrow as compared to the soil temperature change at 100 mm and there was a lag to reach both the minimum and maximum temperature (Fig. 6.6). For example at 290 day of year (2002) the minimum soil temperature at 100 mm soil depth was 21 °C at 09h00 and the maximum temperature was 29 °C at 18h00. At 600 mm soil depth at the same day of year the minimum soil temperature was 22 °C at noon and the maximum temperature was 26 °C at midnight. At 290 day of year (2002) the maximum air temperature was 34 °C at 10h00 and the minimum air temperature was 16 °C at 5h00 in the morning. If the above diurnal change of soil temperature at 100 mm was considered, it caused a change of soil water potential from -55.7 to -87.5 kPa at a fixed resistance (8 kΩ). At 600 mm soil depth the soil water potential changed from -58.6 to -73.5 kPa due to the diurnal soil temperature change (Fig. 6.7).

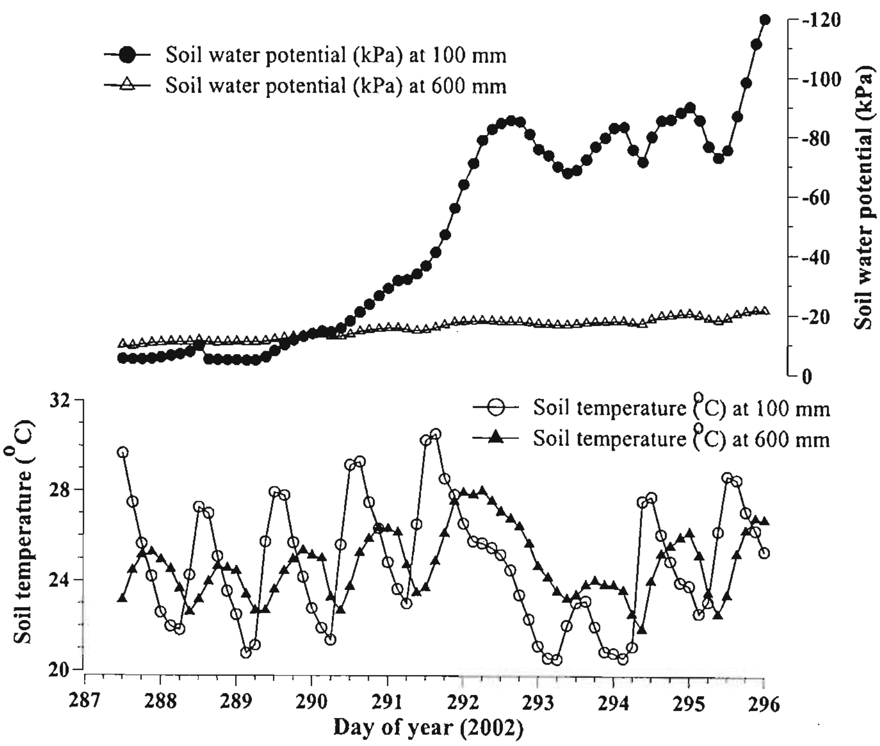


Fig. 6.6 Soil temperature (°C) at two depths and Watermark measured soil water potential (kPa) *vs* day of year (2002)

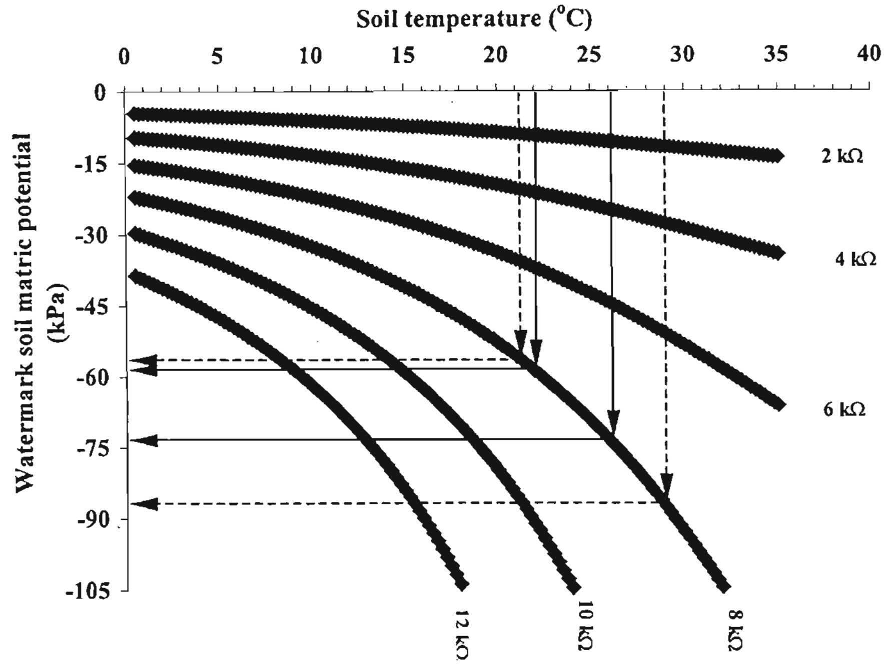


Fig. 6.7 Watermark soil matric potential (kPa) against soil temperature (°C) at different Watermark resistances (kΩ)

6.6 THERMOCOUPLES

The thermocouples were calibrated using the following materials: temperature controlling heater stirrer, one mercury thermometer, 4 L beaker, masking tape and a datalogger (Savage, 2002b). The thermocouples were first taped to a mercury thermometer and inserted into the beaker full of cold water. Using the temperature controlling heater stirrer the temperature of the water was increased gradually and readings were taken from the mercury thermometer and the datalogger at the same time after the water was uniformly stirred. Several readings were taken using the same procedure between 2 and 40 °C, which was assumed to represent the temperature range of the soil in the field.

To determine the calibration constant the temperature readings of each thermocouple were compared with the mercury thermometer temperature. Values of temperature obtained with the thermocouples were plotted against the mercury thermometer temperature (Fig. 6.8) and analyzed statistically (Table 6.5). From the statistical analysis all the thermocouples showed a coefficient of linear regression (r^2) greater than 0.999. The three thermocouples have statistically the same slope but they have different intercepts. Thus, the data were not pooled to be represented by one regression line. Thermocouple three resulted in a slope, which is statistically one but the rest of the thermocouples resulted in slope and intercept confidence limits that did not encompass the ideal slope of 1 and intercept of 0. Therefore, all the intercept and slope values (except slope of thermocouple three) were used for their respective thermocouples as a calibration constant to correct the soil temperature measured.

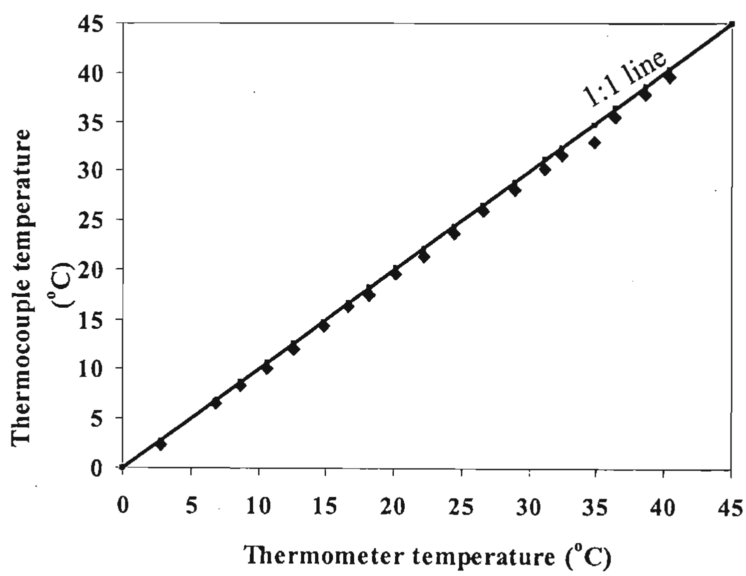


Fig. 6.8 Temperature (°C) measured using mercury thermometer *vs* temperature of type-T thermocouple

Table 6.5 Regression analyses between the mercury thermometer measured temperature (X) and the temperature of the thermocouples (Y)

Statistical parameters	Thermocouple 1	Thermocouple 2	Thermocouple 3
n	19	19	19
r^2	0.999	1.000	0.999
RMSE	0.362	0.141	0.488
t	166.122	191.273	171.648
Slope	0.981	0.979	0.987
Intercept	-0.286	0.111	0.476
Sy.x	0.286	0.248	0.278
SUM (X^2)	16.661	16.661	16.661
SEslope	0.006	0.005	0.006
Slope confidence limit 99%	0.964, 0.998	0.964, 0.993	0.971, 1.004
Slope confidence limit 95%	0.969, 0.994	0.968, 0.989	0.975, 1.000
SEintercept	0.006	0.005	0.005
Intercept confidence limit 99%	-0.302, -0.270	0.097, 0.125	0.460, 0.491
Intercept confidence limit 95%	-0.298, -0.275	0.101, 0.121	0.464, 0.487

6.7 RAIN GAUGE

The tipping spoon automatic rain gauge (Rain-O-matic, Silkeborg, Denmark) was calibrated by applying a known amount of water using a burette of 50 ml. The flow rate was fixed at approximately 85 mm h^{-1}, since it has an influence on the calibration curve (Campbell Scientific, 1998a). Readings were taken for every 10 ml while the water was flowing from the burette. The number of tips and time were recorded for every 10 ml and the applied water was expressed as a depth of water (mm) by dividing by the area of the orifice (50 cm^3).

The cumulative number of tips was plotted against the cumulative applied water (mm) to determine the slope and intercept for the calibration curve (Fig. 6.9). The slope and intercept were equal to 1 and 0 respectively and these values were used to convert the number of tips to amount of rainfall or irrigation in depth (mm).

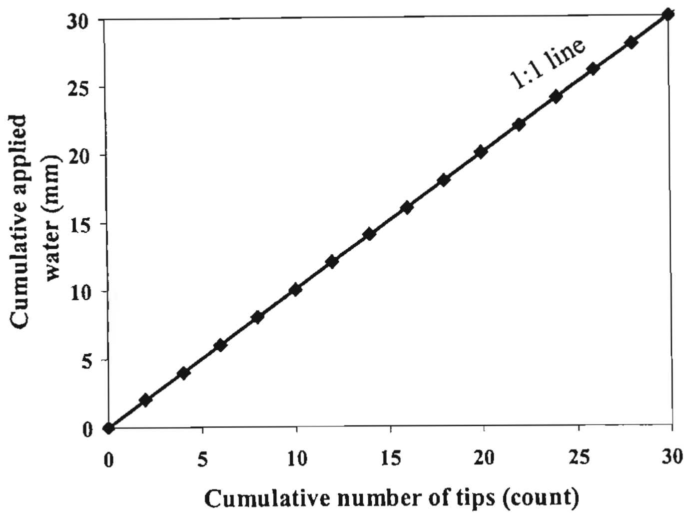


Fig. 6.9 Cumulative number of tips (count) *vs* cumulative applied water (mm) for a fixed flow rate of 85 mm h^{-1}

6.8 CONCLUSIONS

To increase the accuracy of the measurements all the sensors were calibrated by comparing them with their respective standard methods or with a calibrated sensor. For the PR1 profile probe the factory-parameters were chosen as a calibration constants to estimate the volumetric water content. The Diviner 2000 was compared with the measurement of the PR1 profile probe and it showed a regression coefficient between 0.71 and 0.957 for all the depths. For the tensiometers the slope and intercept of the pooled data were used as calibration constants. The mathematical model developed by Thomson and Armstrong (1987) was used to relate the electrical resistance of the Watermark to soil water potential and soil temperature. For the thermocouples the intercept and slope values of each sensor were used as calibration constants to correct the soil temperature measurement. The tipping spoon automatic rain gauge used the value one as multiplier to convert the number of tips to amount of rainfall or irrigation in depth (mm).

After all the sensors were calibrated or compared with a related sensor, they were installed in the field to develop the retentivity characteristics of the soil to estimate soil water content limits for application in irrigation scheduling.

CHAPTER 7

FIELD, LABORATORY AND ESTIMATED SOIL WATER CONTENT LIMITS

7.1 INTRODUCTION

Accurate measurement of the lower limit and the drained upper limit is required to estimate the available water reserve of a soil. Both the lower limit and drained upper limits can be measured in the field or laboratory or it can be estimated using empirical equations based on easily measured soil properties such as soil texture, bulk density and organic matter. The field-measured lower limit was assumed as the water content of the soil at which plants were practically dead or dormant as a result of the soil water deficit (Ratliff *et al.*, 1983). The lower limit could also be measured using *in situ* soil psychrometers at -1500 kPa (Savage *et al.*, 1996). The drained upper limit was taken as the soil water content at which drainage from a pre-wetted soil had practically ceased or when the soil water content decrease was about 0.001 to 0.002 $m^3 m^{-3}$ per day (Ratliff *et al.*, 1983).

In the laboratory, the most common procedure for estimating the drained upper limit and lower limit is to extract water from a disturbed or undisturbed soil sample using the soil water extraction apparatus (Richards and Weaver, 1943). The lower limit is estimated using the pressure chamber at a soil matric potential of -1500 kPa (Richards and Weaver, 1943). The water content at a matric potential of -33 kPa is used as an estimate of the drained upper limit for moderately coarse and fine-textured soils, whereas -10 kPa is used for coarse-textured soils (Colman, 1947; Jamison and Kroth, 1958).

Field or laboratory measurement of the relationships between soil water potential and soil water content is expensive, difficult, and often impractical (Saxton *et al.*, 1986). Thus, for many purposes, general estimation is often based on more readily available information such as texture, bulk density and organic matter, thereby reducing the time and cost of laboratory and field measurements. Many researchers (Brooks and Corey, 1964; Gupta and Larson, 1979; Mottram *et al.*, 1981; Rawls and Brakensiek, 1982; Cosby *el al.*, 1984; Schulze *et al.*, 1985; Hutson, 1986; Saxton *et al.*, 1986;

Ritchie *et al.*, 1999) have developed mathematical equations to estimate the water potential and water content relationships from texture, bulk density and organic matter. Mottram *et al.* (1981) developed a regression equation for top and subsoil of *Mkuzi* soil (Natal, South Africa) based on the soil texture (clay and silt), organic matter and bulk density. The lower limit was estimated at a matric potential of -1500 kPa and the upper limit of plant available water was defined at a matric potential of -5 kPa as opposed to the normally accepted -10 or -33 kPa. This choice was supported by the findings of MacLean and Yager (1972) in Zambia.

Ratliff *et al.* (1983) commented from the comparison made between field and laboratory measurements of lower limit and drained upper limit, that laboratory estimates of drained upper limit obtained at -33 kPa water contents were significantly less than field-measured drained upper limit for sands, sandy-loams, and sandy clay loams and significantly more than field measurements for silt loams, silty clay loams, and silty clays. Laboratory estimates of lower limit obtained at -1500 kPa water content measurements were significantly less than field lower limit measurements for sands, silt loams and sandy clay loams and significantly more than field observations for loams, silty clays, and clays. Ratliff *et al.* (1983) also suggested that, if accuracy is necessary in soil water balance calculations, laboratory-estimated soil water limits should be used with caution and field-measured limits are preferred.

Salter and Haworth (1961) also found that the direct method in the field involving soil sampling after irrigation and drainage had almost ceased, gave more accurate and consistent results than the suction-plate method (laboratory). From their results they concluded that for rough estimation of soil water content limits, the laboratory method using undisturbed cores of soil can give satisfactory results, but for more critical work, the use of the direct sampling (field method) is essential.

In this study, the three methods of defining the lower and drained upper limit were tested and the measurements compared. Field, laboratory and estimated values of soil water potential and soil water content values were measured to determine the soil water content limits.

7.2 MATERIALS AND METHODS

In the field, the soil water retention measurements were developed (Vaz *et al.*, 2002) using the soil water content measurements of the PR1 profile probe (Delta-T Devices, Cambridge, UK) and the soil water potential measurements of the tensiometers and Watermark sensors (Irrometer, Riverside CA, USA). In the laboratory, the soil water content and soil water potential were measured at the same time to develop the retentivity curve. A known amount of pressure was applied using a tension table creating a matric potential between -1 and -10 kPa, pressure pot (-50 and -100 kPa) and pressure chamber at -1500 kPa and the soil water content was measured after equilibrium was reached. The empirical equations developed by Hutson (1986) were used to estimate the soil water content limits. These equations needed the clay, silt, fine sand and bulk density as an input to calculate the soil water content at the corresponding matric potential.

For each method the soil water content and soil water potential was related using the retentivity function developed by Gardner *et al.* (1970). In the retentivity function, the soil water potential was treated as the independent variable and the soil water content the dependent variable. The retentivity function was then expressed in the following form (Gardener *et al.*, 1970):

$$\theta = (\psi / a)^{\frac{-1}{b}} \qquad 7.1$$

where θ is the volumetric soil water content (m^3 m^{-3}), Ψ is the soil water potential (-kPa), a and b are empirical constants, which can be developed from the regression line of $ln\ \theta$ vs $ln\ \Psi$:

$$a = exp\ (a_r * b) \qquad 7.2$$

$$b = -1/b_r \qquad 7.3$$

where a_r and b_r are the intercept and slope of the regression line respectively for the $ln\ \theta$ vs $ln\ \Psi$ graph fitted by a straight line.

7.2.1 Field measurements

In the field, inside a 1 m^2 bare plot (Photo 7.1), one PR1 profile probe, six tensiometers and six Watermark sensors were installed at 100, 300 and 600 mm soil depths in two replications. The depths were chosen to represent the root zones within the cultivated soil and immediately below the depth of cultivation. The tensiometers and the Watermark sensors were installed around the PR1 profile probe at a radius of 200 mm and 150 mm apart from each other. After all the sensors were installed the plot was flooded and covered for two days with black plastic to prevent evaporation and allow redistribution of the water down the profile. All the soil water potential sensors were attached to a CR23X datalogger (Campbell Scientific, Logan, USA) and the PR1 profile probe was connected to a CR10X (Campbell Scientific, Logan, USA) datalogger programmed to measure the soil water content and the soil water potential every 3 h. The water content and soil water potential relationship were determined from the simultaneous measurement of the PR1 profile probe and the soil water potential sensors (tensiometer and Watermark) while the soil was drying. The drained upper limit was assumed to be the water content when the soil water content decrease was negligible (Ratliff *et al.*, 1983). The lower limit was also calculated using the retentivity function at -1500 kPa, which corresponds closely to the field lower limit of soil water availability (Savage *et al.*, 1996).

Photo 7.1 A PR1 profile probe is shown at the center of a 1 m^2 bare plot. Tensiometers and Watermark sensors surround the PR1 profile probe. A Pronamic rain gauge is shown at the bottom right (Photo taken by MJ Savage, 2002)

7.2.2 Laboratory measurements

To determine the retentivity curve, six undisturbed soil samples were taken using the core sampler from 100, 200, 300, 400, 600, and 1000 mm soil depths in three replications on the edge of the 1 m^2 bare plot prior to the installation of the sensors. Before the cores were subjected to suction, they were trimmed carefully to the edge of the sleeve and saturated in a water bath by capillary action. After the cores were totally saturated, they were weighed while water was dripping to get the saturation weight and transferred to a tension table where a hanging water column was used to create a matric potential between -1 and -10 kPa, a pressure pot was used for matric potentials between -50 and -100 kPa and a pressure chamber for a matric potential at -1500 kPa. In each method, the pressure was changed after the cores attained equilibrium and weighed before subjecting them to the next matric potential. The time to equilibrate varied from 48 h at the higher tension (-1 to -10 kPa) to 10 days at the lower tension (-1500 kPa). Finally, the cores were oven dried at 105 °C for four days and reweighed to determine the water content on dry mass basis. Bulk density was also determined to convert the mass soil water content (g g^{-1}) to volumetric water content (m^3 m^{-3}).

7.2.3 Estimated values of soil water content limits

The regression equations (Eqs 7.4 to 7.10) that were developed by Hutson (1986) were used to estimate the soil water content at -1, -3, -10, -30, -100, -500 and -1500 kPa:

$$\theta_{-1} = 0.686 + 0.000794\ (Cl + Si) - 0.229\rho_b \qquad 7.4$$

$$\theta_{-3} = 0.349 + 0.00211\ (Cl + Si) - 0.096\rho_b \qquad 7.5$$

$$\theta_{-10} = 0.112 + 0.00380\ (Cl + Si) \qquad 7.6$$

$$\theta_{-30} = 0.065 + 0.00396\ (Cl + Si) \qquad 7.7$$

$$\theta_{-100} = 0.038 + 0.00372\ (Cl + Si) \qquad 7.8$$

$$\theta_{-500} = 0.0185 + 0.00366\ (Cl + Si) \qquad 7.9$$

$$\theta_{-1500} = 0.0187 + 0.00337\ (Cl + Si) \qquad 7.10$$

where θ is the volumetric water content in m^3 m^{-3}, $(Cl + Si)$ is the sum of clay and silt content of the soil in percentage and ρ_b is the bulk density of the soil in Mg m^{-3}.

These equations were developed based on 409 South African soil samples. To calculate the soil water content at the corresponding matric potential the percentage of clay, silt, fine sand, and bulk density in Mg m^{-3} were determined. These equations use the particle size classification of South Africa Binomial Soil Classification System (MacVicar *et al.*, 1977). According to this classification the average values between 100 and 300 mm soil depth equals: clay 40 %; silt 17 %; fine sand 43 % and bulk density 1354 kg m^{-3}.

The drained upper limit was calculated using the retentivity function (Eq. 7.11) at a matric potential of -33 kPa (Colman, 1947; Jamison and Kroth, 1958) and the lower limit was calculated using the regression equation at a soil matric potential of -1500 kPa (Richards and Weaver, 1943). The plant available water (PAW) was then calculated from the difference between the drained upper and lower limits.

$$\theta = (\Psi / 1.38 \times 10^{-4} \text{ kPa})^{-0.0987} \qquad 7.11$$

where θ is the volumetric soil water content (m^3 m^{-3}), Ψ is the soil water potential (-kPa), and the constants for the retentivity function $a = 1.38 \times 10^{-4}$ kPa and $b = -10.13$.

7.3 RESULTS AND DISCUSSION

7.3.1 Field measurements

The field-measured PR1 profile probe soil water content and Watermark soil water potential at 100, 300 and 600-mm soil depths are shown in Fig. 7.1. The soil water content varied between 0.23 and 0.30 m^3 m^{-3} for the first 100 mm soil depth with the corresponding soil water potential of -4 to -119 kPa. At 300 mm the soil water content varied between 0.47 and 0.50 m^3 m^{-3}, and the soil water potential decreased from -5 to -81 kPa. This small change in soil water content could be due to the high clay content of the soil (Table 5.1). In clay soils, since the pore-size distribution is more uniform, more of the water is adsorbed, so that increasing the matric potential cause a more gradual decrease in soil water content (Hillel, 1971). The soil at the 600-mm soil depth has low soil water content as compared to the shallow depths and the soil water content was almost constant at around 0.21 m^3 m^{-3} at the soil potential of -8 to -30 kPa.

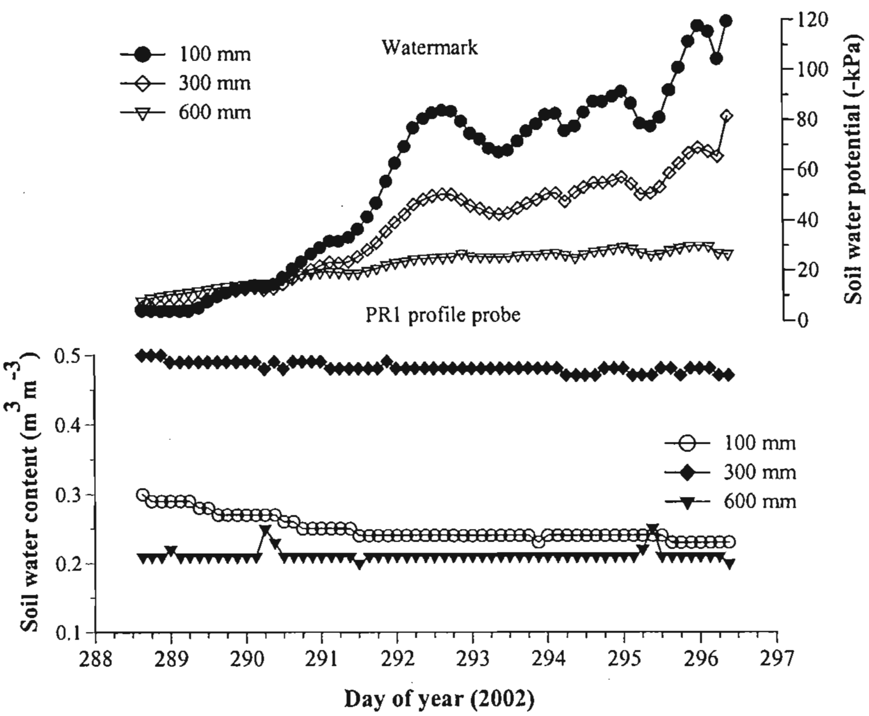


Fig. 7.1 Field-measured soil water content (m^3 m^{-3}) using the PR1 profile probe (lowest set of three curves) and soil water potential (-kPa) using Watermark sensors at three depths (upper set of three curves)

The field-measured soil water content and soil water potential were compared with the results obtained by Schmidt and Schulze (1989) for the Cedara Catchments. They calculated the plant available water (PAW) in the laboratory from the difference in the soil water content at -33 and -1500 kPa matric potentials. They obtained different ranges of soil water content at -33 and -1500 kPa. The lowest soil water content varied between 0.26 and 0.23 m^3 m^{-3} at -33 and -1500 kPa matric potentials respectively. The largest soil water content ranged between 0.43 and 0.24 m^3 m^{-3} at -33 and -1500 kPa matric potentials respectively. Considering that these measurements were made in the laboratory at a wider range of soil water potential (-33 to -1500 kPa), the field measured soil water content using the PR1 profile probe and soil water potential with Watermark looked reasonable when compared with the results of Schmidt and Schulze (1989).

The values of PR1 profile probe soil water content and Watermark soil water potential at 100 and 300 mm were averaged to determine the drained upper limit and lower limit of the soil at the rooting depth of the plant. The drained upper limit was 0.355 $m^3\ m^{-3}$ for the 300 mm soil depth. This value was taken as the soil water content when the decrease in soil water content at this depth was negligible (Fig. 7.2). The lower limit was calculated at a matric potential of -1500 kPa (Table 7.1) using the retentivity function:

$$\theta = (\Psi / 5.4 \times 10^{-11}\ \text{kPa})^{-0.0372} \qquad 7.12$$

where θ is the volumetric soil water content ($m^3\ m^{-3}$), Ψ is the soil water potential (-kPa), the constants for the retentivity function a = 5.4 x 10^{-11} kPa and b = -26.88 were calculated from the graph of *ln* θ *vs* *ln* Ψ.

The plant available water (PAW), which is the difference between the drained upper limit and lower limit of the soil, was then equal to 0.039 $m^3\ m^{-3}$ or 3.9 %. Schmidt and Schulze (1989) calculated the PAW for Cedara Catchments to be between 2.67 and 19.8 %.

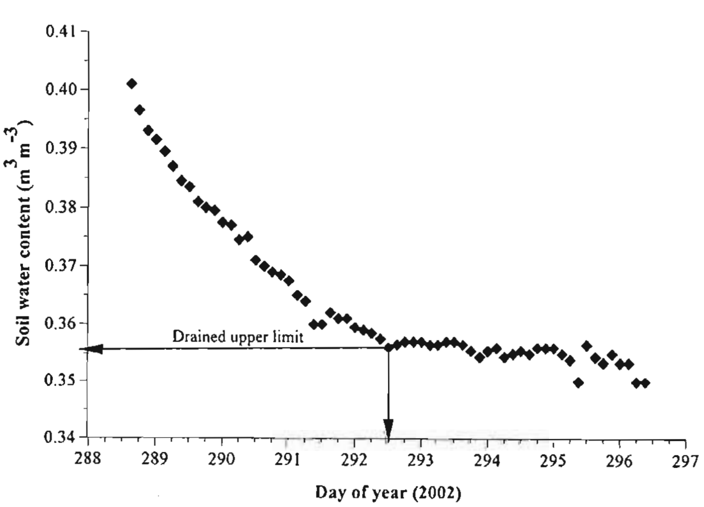


Fig. 7.2 PR1 profile probe soil water content *vs* day of year after flooding the plot to determine the drained upper limit of the soil between 100 and 300 mm soil depth

Table 7.1 Retentivity function calculated soil water content at certain points of soil water potential

Soil water potential (-kPa)	Field-measured θ ($m^3\ m^{-3}$)
1	0.415
5	0.391
10	0.381
33	0.365
50	0.359
100	0.350
500	0.329
1000	0.321
1500	0.316

The drained upper limit (0.355 $m^3\ m^{-3}$) determined in the field (Fig. 7.2), when the soil water content decrease was negligible, was close enough with the drained upper limit (0.365 $m^3\ m^{-3}$), which was estimated using the retentivity function at soil water potential of -33 kPa. This result agreed with the estimation of the drained upper limit at a soil water potential of -33 kPa, which was proposed by Colman (1947) and Jamison and Kroth (1958). Other workers have also proposed different matric potentials with satisfactory results. For example Hanks *et al.* (1954) used -20 kPa, Haise *et al.* (1955) used -10 kPa and Russel and Balcerek (1944), Mottram *et al.* (1981), MacLean and Yager (1972) used -5 kPa to estimate the drained upper limit. These variations in matric potential depend on soil texture. For example, sandy soils reach the drained upper limit at -6 kPa, loamy sand at -10 kPa, silt loams at -30 kPa and clay soils at -60 kPa (Water Resource Publications, 1964).

7.3.2 Laboratory measurements

The average soil water content (θ) and soil water potentials (Ψ) at the rooting depth (100 to 300 mm) were considered to estimate the drained upper limit and lower limits of the soil. From the laboratory result the drained upper limit was 0.39 $m^3\ m^{-3}$ at -33 kPa and the lower limit was 0.31 $m^3\ m^{-3}$ at -1500 kPa. The PAW was then calculated to be 0.08 $m^3\ m^{-3}$ (or 8 %).

The statistical analysis (Table 7.2) showed that the laboratory measurement of soil water content was statistically different from the corresponding field measured soil water content at a given soil water potential. This was found from the result of the *paired t-test* that the probability level ($P = 0.011$) was lower than the critical alpha value ($\alpha = 0.05$), which indicated that there were significant differences between the two means at 95 % level of significance. The slope and intercept of the regression line were also statistically different from one and zero respectively (Table 7.2), which demonstrated that the soil water content measurement in the laboratory was not a perfect estimation of the field measurement. The laboratory-measured soil water content showed a bias (Fig. 7.3) with systematic error of 94.6 %. When the laboratory-estimated drained upper limit was compared with the field-measured drained upper limit, the laboratory measurement over-estimated the drained upper limit by 0.045 $m^3\ m^{-3}$ (4.5 %). This result agreed with the conclusion made by Ratliff *et al.* (1983), that the laboratory estimates of the drained upper limit obtained at -33 kPa water contents were significantly higher than the field-measured drained upper limit. However, the laboratory estimate of the lower limit (0.312 $m^3\ m^{-3}$) obtained at -1500 kPa matric water potential was almost equal to the field-measured lower limit (0.316 $m^3\ m^{-3}$). This result agreed with the experimental result of Savage *et al.* (1996) - they found that the choice of the -1500 kPa soil water potential was appropriate and corresponded closely to the field lower limit of soil water availability.

The retentivity function for the laboratory measurement (Eq. 7.13) was developed to estimate values of soil water content at a given matric potential. The constants *a* and *b* were calculated from the slope and intercept of the graph $ln\ \theta$ *vs* $ln\ \Psi$ (Fig. 7.4) using Eqs 7.2 and 7.3:

$$\theta = (\Psi / 3.94 \times 10^{-6}\ \text{kPa})^{-0.0588} \qquad 7.13$$

where θ is the volumetric soil water content ($m^3\ m^{-3}$), Ψ is the soil water potential (-kPa), the constants for the retentivity function $a = 3.94 \times 10^{-6}$ kPa and $b = -17.01$.

Table 7.2 Comparison of field-measured (X) soil water content (m^3 m^{-3}) against the laboratory (Y_1) and estimated (Y_2) soil water content (m^3 m^{-3})

Statistical parameters	Laboratory-measured (Y_1)	Estimated values (Y_2)
n	9	9
r^2	0.975	0.995
RMSE	0.064	0.035
P (T<=t) two-tail (95 %)	0.011	0.0005
Slope	1.563	2.118
Intercept	-0.179	-0.472
Sy.x	0.009	0.006
SUM (X^2)	3.632	3.632
SE slope	0.094	0.059
Slope confidence limit 99 %	1.234, 1.892	1.912, 2.324
Slope confidence limit 95 %	1.341, 1.785	1.978, 2.257
SE intercept	0.060	0.037
Intercept confidence limit 99 %	-0.2979, -0.061	-0.603, -0.341
Intercept confidence limit 95 %	-0.2595, -0.099	-0.561, -0.384

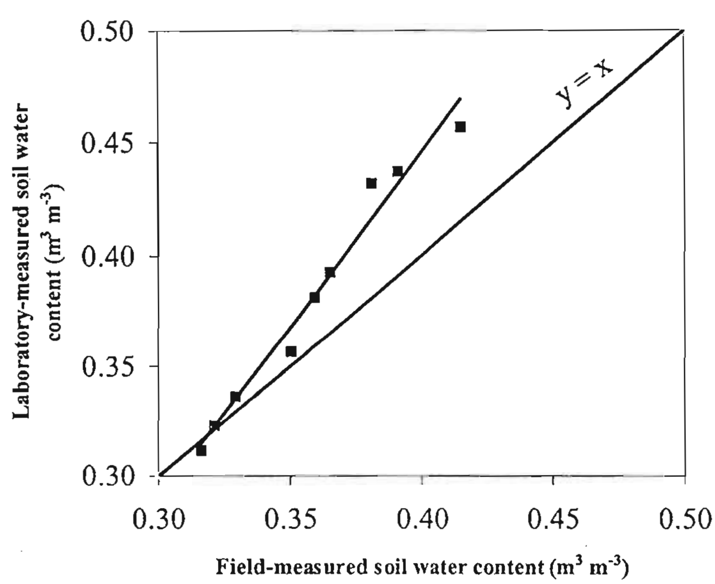


Fig. 7.3 Laboratory-measured soil water content (m^3 m^{-3}) *vs* field-measured soil water content (m^3 m^{-3}) at the same soil water potential (kPa)

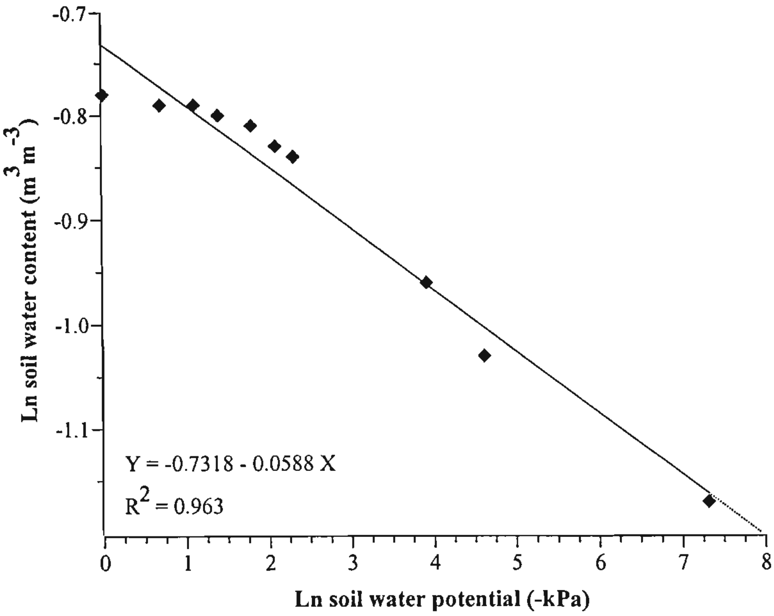


Fig. 7.4 Field-measured soil water content (*lnθ*) *vs* field-measured soil water potential (*ln Ψ*)

7.3.3 Estimated values of soil water content limits

The soil water content was estimated for the respective soil water potentials based on the Hutson (1986) regression equations and a comparison was made between the soil water content limits of field-measured and laboratory-measured values. Using the regression equations the drained upper limit was 0.295 m^3 m^{-3} at -33 kPa and the lower limit was 0.210 m^3 m^{-3} at -1500 kPa. The plant available water (PAW) was then 0.085 m^3 m^{-3}. The drained upper limit was under-estimated by 0.06 m^3 m^{-3} and 0.095 m^3 m^{-3} from the field-measured and laboratory value respectively. The lower limit was also under-estimated by 0.11 m^3 m^{-3} and 0.099 m^3 m^{-3} from the field and laboratory measurements respectively.

From the statistical analysis (Table 7.2) the estimated soil water content measurements were statistically different ($P < \alpha$) and biased (systematic error = 97%) from the corresponding field-measured soil water content at a given soil water potential

(Fig. 7.5). The slope and intercept were also statistically different from one and zero respectively. However, it showed a regression coefficient of 0.995 and if the slope and intercept were used as multiplier and offset to adjust the equation it adequately estimates the soil water content at the corresponding soil water potentials.

The retentivity function for the estimated values (Eq. 7.11) was developed to estimate values of soil water content at a given matric potential. The constants *a* and *b* were calculated using the graph lnθ *vs* ln Ψ (Fig. 7.6).

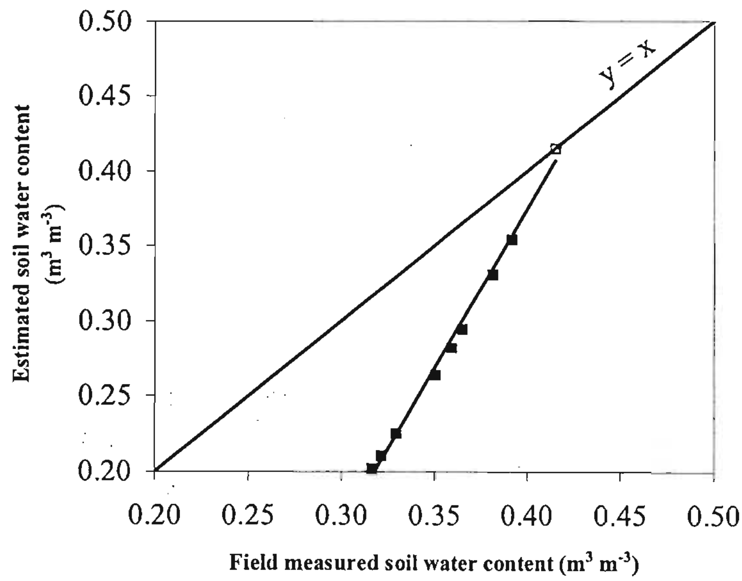


Fig. 7.5 Estimated soil water content *vs* field-measured soil water content at the same soil water potential

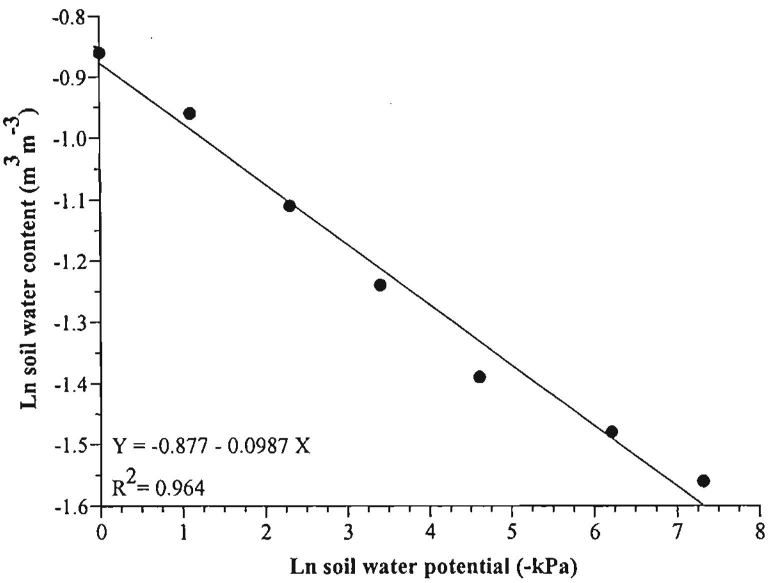


Fig. 7.6 Estimated soil water content (*lnθ*) *vs* the known soil water potential (*ln Ψ*) fitted to develop the linear regression

7.4 CONCLUSIONS

The result obtained using laboratory and estimated soil water content values were statistically different from the soil water content measured in the field confirmed work by Salter and Haworth (1961), Ritchie (1981), Ratliff *et al.* (1983). The variation in soil water content was mainly due to the difference of the methods, but in part the difference in soil water content could be due to soil variability and the treatment of the soil sample between the time when the samples were taken from the field and laboratory measurement (Savage *et al.*, 1996). With great care, laboratory measurements could yield a good estimation of soil water content limits, if the errors that could be encountered in field, and laboratory were minimized. The use of regression equations, which estimate the soil water content using some easily measurable soil parameters, could be useful to estimate the soil water content limits when the time, cost and labour needed to undertake the field and laboratory measurements is considered. The regression equations that were developed by Hutson (1986) showed a regression coefficient of 0.995 with systematic error of 97%. If the equation was calibrated against the mass soil water content at the corresponding soil water potential, it could yield a good estimate of soil water content.

In this study, the drained upper limit and lower limit were defined using the laboratory-measured values of soil water content at -33 and -1500 kPa. However, many workers (Salter and Haworth 1961; Ritchie 1981; Ratliff *et al.*, 1983) did not recommend the laboratory method, if direct measurement in the field is possible. The laboratory-measured values were taken, since the soil water content was measured within the whole range of matric potential starting from saturation until -1500 kPa. In the field, measurements were made from -4 to -119 kPa at 100 mm, -5 to -81 at 300-mm and -8 to -30 kPa at 600-mm soil depth. The plant available water (PAW) was then calculated from the difference of the drained upper limit (0.39 m^3 m^{-3}) and the lower limit (0.31 m^3 m^{-3}), which was equal to 0.08 m^3 m^{-3}. These values were then used in monitoring the soil water content using the PR1 profile probe and Diviner 2000 to determine the time and amount of irrigation.

CHAPTER 8

DETERMINATION OF THE TIMING AND AMOUNT OF IRRIGATION

8.1 INTRODUCTION

The timing and amount of irrigation can be determined by monitoring the soil, plant and the atmosphere system. Soil water monitoring to determine the timing and amount of irrigation represents the traditional method of irrigation scheduling. This method requires predetermined values of the field capacity, wilting point and refill point of the soil water potential or soil water content. In addition, the actual soil water content must be monitored with time to forecast the date of irrigation (Gear *et al.*, 1977).

The effective monitoring of soil water status requires frequent and accurate measurements; the technique should be rapid, precise, simple, cost effective and non-destructive. Chapter 3 discussed a variety of methods to monitor the soil water content such as gravimetric, neutron probe, time domain reflectometry and frequency domain reflectometry and soil water potential sensors like tensiometers, gypsum blocks, Watermark and thermal dissipation method. All these methods do not fully satisfy the above requirements. The gravimetric method fails to satisfy these requirements since it requires a great deal of effort, time and repeated sampling disturbs the soil. The soil water content measurement based on neutron scattering has been a valuable tool for the past 40 years because it possesses many of the above mentioned qualities. However, licensing, training of users and safety regulation pertaining to the radioactive source in these devices make their use expensive and restrictive in some situations such as unattended monitoring (Evett and Steiner, 1995). Tensiometers and heat dissipation sensors can meet the above requirements. But, some of these techniques cover a limited range of soil water potential. For example, the tensiometer has a lower limit of approximately -80 kPa due to the entry of air into the system for suction below this value. From the resistance sensors the Watermark sensor fairly satisfies the above requirements since the sensor is relatively cheap, non-destructive, it can be automated to control irrigation and it has a wide working range (-10 to -200 kPa) relative to tensiometers and gypsum blocks. However, the sensor is less sensitive to soil water potential between 0 and -9 kPa (Bausch and Bernard, 1996) and is also temperature sensitive (Thomson and Armstrong, 1987).

In recent years, the high dielectric constant property of water at high frequencies has been used as the basis to estimate the soil water content. The two major techniques that make use of this property are time domain reflectometry (TDR) and frequency domain reflectometry (FDR). These techniques can provide precise, non-destructive, continual and unattended *in situ* measurement of soil water content under field conditions. But to improve the calibration equation of the dielectric sensors, the equation may need to include linear terms of dry bulk density, organic matter, and clay content (Jacobsen and Schjonning, 1993). Time domain reflectometry (TDR) measures the propagation of an electromagnetic pulse along two parallel transmission lines (wave guides). The apparent dielectric constant of the soil can be estimated by measuring the travel time and the velocity. The frequency domain reflectometry (FDR) makes use of radio frequencies for determining the dielectric constant and thus the soil water content. Significant progress has been made in this approach, with the ability to carry out profile measurements being a recent improvement. The PR1 profile probe and Diviner 2000 are recently developed sensors that can measure soil water content at different depths along the soil profile.

In this project, these sensors (PR1 profile probe and Diviner 2000) were used to monitor the volumetric soil water content at different depths for a period of 120 days so as to determine the timing and amount of irrigation. To determine the time of irrigation the refill point was first defined based on the Haise and Hagan (1967) method of optimum soil water potential. The soil water content was then monitored using the PR1 profile probe and Diviner 2000 at different depths of the soil. A plot of the average soil water content at the effective rooting depth versus time with the refill point indicated, yields a visual means of forecasting accurately the time of irrigation. The amount of irrigation, which brings the soil water content in the effective rooting depth to field capacity was determined using two different methods. The first method monitors the wetting front and irrigation is stopped when the wetting front reaches a certain pre-calculated depth (critical depth). After irrigation the excess soil water within the critical depth will then be redistributed and bring the effective rooting depth to field capacity. The second method monitors sub-hourly soil water content graphically or in a spreadsheet with the field capacity indicated. The sub-hourly soil water content and cumulative irrigation were plotted in a graph with appropriate projection of lines to predict ahead the duration and amount of irrigation.

8.2 MATERIALS AND METHODS

The time and amount of irrigation were determined using both the PR1 profile probe and the Diviner 2000. The access tubes of each sensor were installed within each plot of the cover crop at a distance of 300 mm from each other, since the horizontal sphere of influence of both sensors is 100 mm (Photo 8.1). The PR1 profile probe measures soil water content at a fixed depth and to measure the soil water content spatially the sensor was moved from access tube to access tube with the data being recorded in the hand held HH2 Moisture Meter or manually in a spreadsheet and later downloaded to a computer. The Diviner 2000 employs a single sensor, which moves up and down manually in the access tube. The sensor records the soil water content at 100-mm depth increments utilizing an automatic depth recorder. The device was moved around the field from access tube to access tube to record the soil water content in the Diviner 2000 displaying unit and later downloaded to a computer.

To determine the time of irrigation, the fill and refill points of the soil were determined for the field at a representative site. The fill point was assumed to be the field capacity of the soil at -33 kPa as taken from the laboratory measurement. The high and low refill points were calculated based on the table of optimum soil water potential listed (Taylor and Ashcroft, 1972) and the percentage of upper limit of available soil water depletion recommended by Haise and Hagan (1967). After the high and low refill points were determined, the soil water content was monitored periodically (two to three times per week) using the PR1 profile probe and Diviner 2000. The soil water content at the maximum root activity (effective rooting depth) was averaged and plotted as a function of time on a graph with the high and low refill points indicated. From this graph the time of irrigation could accurately be forecasted.

The duration and amount of irrigation was determined using two different methods, which employ the monitoring of the wetting front, cumulative irrigation and the sub-hourly soil water content at the rooting depth. The first method monitors the wetting front at pre-calculated depth and the arrival of the wetting front at this depth indicated the time to stop irrigation. This critical depth (L) was calculated using the following equation:

$$L = L_f\,(\theta_{FC} - \theta_i)\,/\,(\theta_{VS} - \theta_i) \qquad 8.1$$

where L_f is the depth that irrigated water will reach after the redistribution process (which must coincide with the rooting depth), θ_{FC} is the field capacity, θ_i is the initial soil water content before irrigation (which is the refill point) and θ_{VS} is the saturated soil water content (Campbell and Campbell, 1982). It is assumed that there is no plant water uptake during redistribution and that the soil profile is uniform.

The second method monitors the sub-hourly soil water content at the rooting depth of the plants. The depth-averaged sub-hourly soil water content and the cumulative irrigation were plotted versus time in a graph (similarly it could be done in a spreadsheet) to predict ahead the duration and amount of irrigation that could bring the soil water content at the rooting depth to field capacity.

Photo 8.1 Access tubes of the PR1 profile probe (left) and the Diviner 2000 (right) after they were installed 300 mm apart from each other

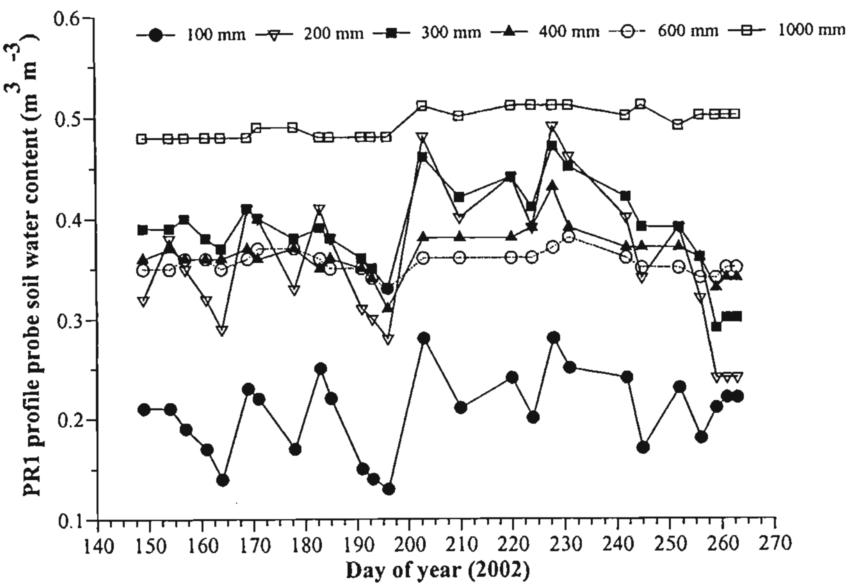
8.3 RESULTS AND DISCUSSION

8.3.1 Daily measurement of soil water content

Soil water content was measured using a PR1 profile probe (Fig. 8.1a) and Diviner 2000 (Fig. 8.1b) 2 to 3 times per week starting from May 29 (149 day of year, 2002) 50 days after planting (99 day of year, 2002) until September 20 (263 day of year, 2002) 11 days before harvesting (274 day of year, 2002). From the graph of the soil water content it can be seen that the variation of soil water content at the shallow depths (100, 200, and 300 mm) were much higher than the deeper depths (400, 600 and 1000 mm). There was also a rapid decrease of soil water content after irrigation or rainfall at the shallow depths. For example, on 29 July after three consecutive rainfall events on 19, 20 and 21 July with 51, 32 and 10 mm respectively, there was an abrupt decrease in the depth-averaged soil water content between 100 and 300 mm from 0.407 to 0.343 $m^3 m^{-3}$ but there was only a decrease from 0.417 to 0.413 $m^3 m^{-3}$ soil water content at the deeper depths (Fig. 8.2a). This rapid decrease of soil water content at the shallow depths can be attributed to root extraction of water (Phene *et al.*, 1989). To determine the root distribution of the cover crops a soil column of 100 mm in depth was taken using the gauge auger next to the plants at 100 mm increment up to 1000 mm soil depth. The soil samples were washed in a sieve to separate the root of the plants from the soil. The oven dry weight of the root was then taken to determine the distribution of the roots with depth. The results showed that 85 % of the roots were within at the first 100 to 300 mm soil depth (Appendix 1).

The soil water content measured with both the PR1 profile probe and Diviner 2000 followed the same pattern (Fig. 8.2a and b) and there was small variation between the soil water content measured with the PR1 profile probe and Diviner 2000. The soil water content at 100 mm varied within the range of 0.13 to 0.28 $m^3 m^{-3}$ and 0.16 to 0.33 $m^3 m^{-3}$ for the PR1 profile probe and Diviner 2000 soil water content measurements respectively. At this depth there was also high fluctuation of soil water content, due to the higher plant root density (57 to 64 %) and evaporation from the soil surface. At the deeper depths the range between the maximum and minimum soil water content narrowed and there was also low fluctuation of soil water content. For example, at the 1000 mm soil depth the PR1 profile probe measured a maximum of 0.51 $m^3 m^{-3}$ and minimum of 0.48 m^3 m^{-3} soil water content throughout the growing season. These measurements were recorded as 0.45 and 0.41 m^3 m^{-3} when the Diviner 2000 was used.

a



b

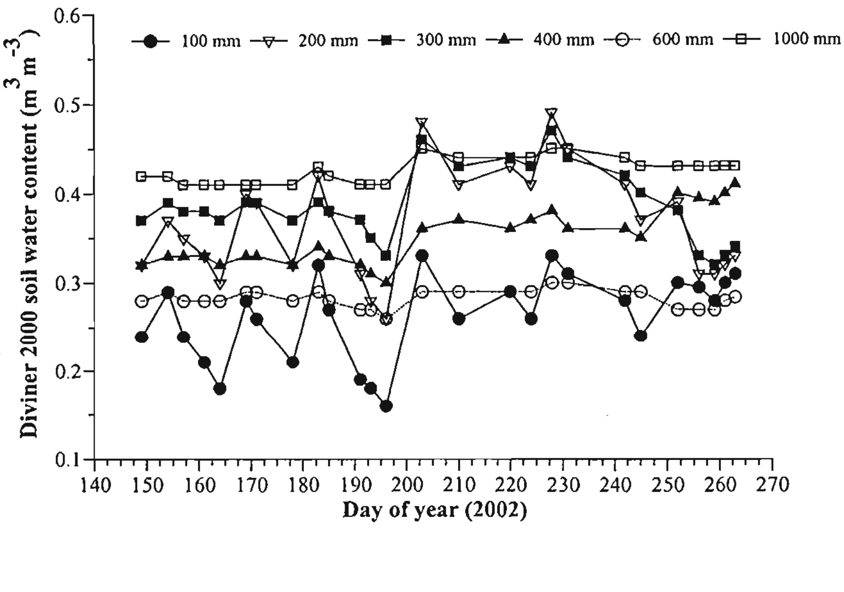


Fig. 8.1 Daily measured soil water content using (a) PR1 profile probe and (b) Diviner 2000 at different soil depths between 149 and 263 day of year (2002)

8.3.2 Time of irrigation

In order to schedule irrigation using soil water measurements, the fill and refill points of the soil were first determined. The fill point is the field capacity of the soil at -33 kPa, which is equal to 0.39 $m^3 m^{-3}$. The refill point was calculated based on the optimum soil water potential values given by Taylor and Ashcroft (1972). The soil water potential (kPa) was then converted to soil water content ($m^3 m^{-3}$) using the retentivity function (Eq. 7.12) developed from the laboratory measurements. The optimum soil water potential for small grains (wheat, oats, barely and rye) is -40 to -50 kPa (0.387 $m^3 m^{-3}$ to 0.382 $m^3 m^{-3}$) at vegetative period and -800 to -1200 kPa (0.325 $m^3 m^{-3}$ to 0.317 $m^3 m^{-3}$) during ripening. According to Haise and Hagan (1967) for small grains 65 to 75 % upper limit of available soil water depletion (0.340 $m^3 m^{-3}$ to 0.332 $m^3 m^{-3}$) was recommended until the grain is well formed and 80 to 90 % of the available soil water content (0.328 $m^3 m^{-3}$ to 0.320 $m^3 m^{-3}$) was recommended near maturity. In this research, 0.34 $m^3 m^{-3}$ as the high refill point and 0.33 $m^3 m^{-3}$ as the low refill point were used to represent the high and low evaporative demand respectively.

The cover crops were irrigated on 29 May, 2 July, 2 August, 18 September and 20 September corresponding to 50, 84, 115, 162 and 164 days after planting with 10, 19, 15, 8 and 8 mm water respectively. There were also 20 rainfall events between 29 May and 20 September. The first three days of irrigation were recorded manually using a rain gauge but for the last two days the irrigation was measured using a tipping spoon automatic rain gauge. All the rainfall events were taken from the nearby automatic weather station. The soil water content measured with PR1 profile probe and Diviner 2000 at different depths, the refill point, and the soil water content at field capacity are shown (Fig. 8.2a and b) together with the irrigation and rainfall events. Irrigation must commence when the soil water content is equal to or slightly below the refill point (Singh *et al.*, 1995). The average soil water content at the effective rooting depth was below the refill point starting from 29 May (day of year 149) until 15 July (day of year 196). This would suggest that the cover crops were stressed within this period until the three consecutive rainfalls during 19, 20 and 21 July (day of year 200, 201, and 203 respectively) brought the soil water content slightly higher than field capacity. The soil water content was within the optimum range during the periods of 22 July (day of year 203) and 9 September (day of year 252) with two events slightly above field capacity (Fig. 8.2a and b).

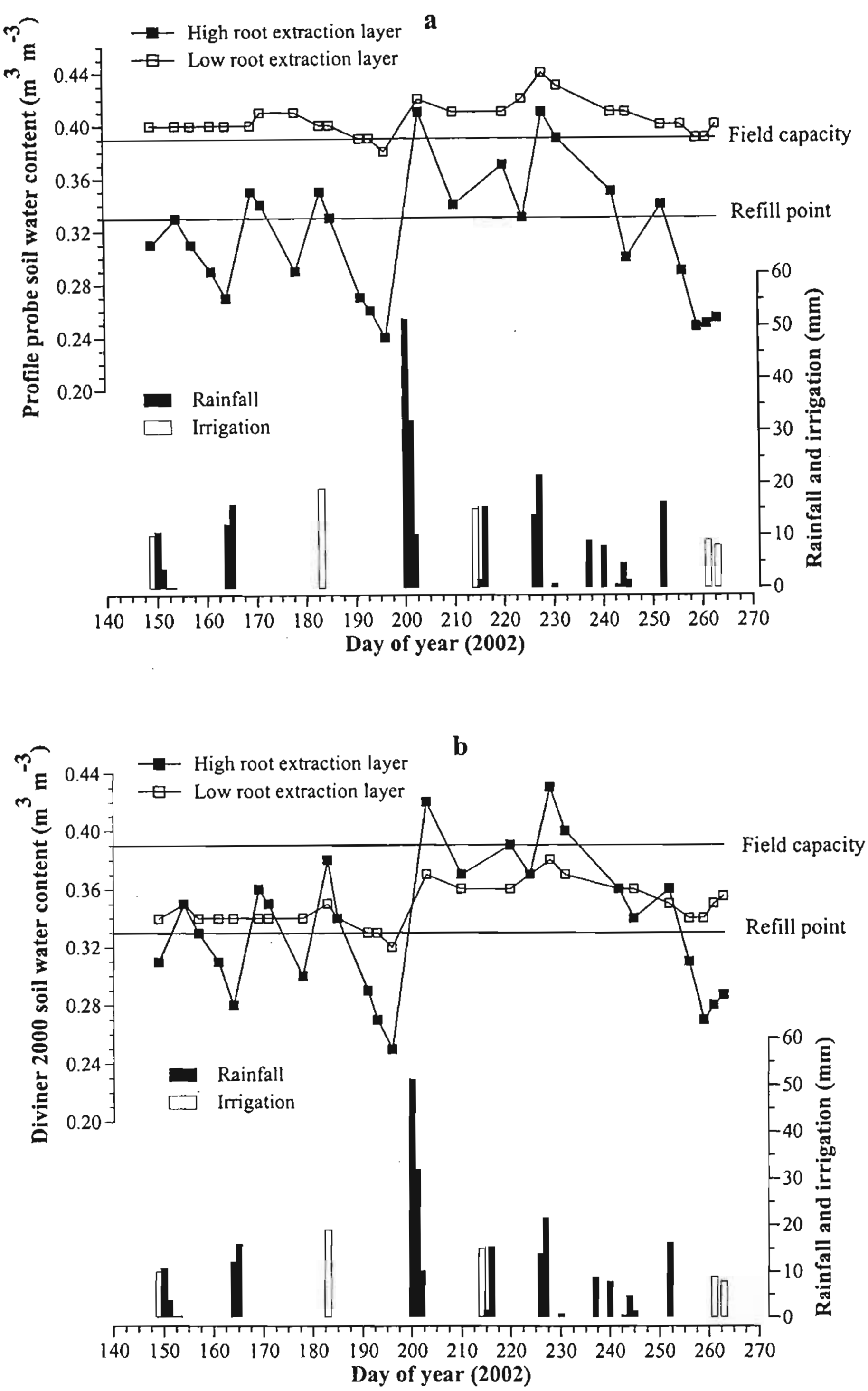


Fig. 8.2 The depth-averaged soil water content for the high (100 to 300 mm) and low (400 to 1000 mm) root extraction layers, which were measured using (a) PR1 profile probe and (b) Diviner 2000 with the recorded rainfall, irrigation, field capacity and refill point

The average soil water content below the rooting depth (400, 600, and 1000 mm) was almost constant and it showed a slight change regardless of the irrigation and rainfall. The PR1 profile probe measured soil water content below the root zone, which ranged between 0.37 and 0.44 m^3 m^{-3}. Similarly, the Diviner 2000 measured soil water content below the root zone varied between 0.32 and 0.38 m^3 m^{-3} (Fig. 8.3a and b). The recording of the soil water content below the root zone shows whether the end points are correctly set and whether monitoring in the root zone is adequate. An increase in water content of soil below the root zone indicates leaching (Campbell and Campbell, 1982). This narrow range in soil water content at these depths could be due to low root density (15 %) and insufficient rainfall and irrigation that could reach at these depths to increase the soil water content. The soil water content within the rooting depth for both sensors followed the same pattern with the Diviner 2000-measured soil water content being slightly greater than the profile measured soil water content (Fig. 8.3a). Ideally, the depth-averaged soil water content within the rooting depth should be within the range of the field capacity and the refill point to maintain the optimum soil water content needed by the cover crop. If it goes above the fill point, leaching will occur. If it goes below the refill point, production will be reduced (Campbell and Campbell, 1982).

Between 22 July and 9 September the depth-averaged soil water content in the rooting depth fluctuated between field capacity and the refill point, except for the rainfall events during 22 July and 16 August, which increased the soil water content above the field capacity of the soil. At these two periods the soil water content at the rooting depth reached its highest soil water content value (Fig. 8.3a and b). Starting from 9 September the soil water content decreased gradually and went below the refill point on 13 September. Even though irrigation was applied twice on 18 and 20 September, it was not sufficient to increase the soil water content above the refill point. To maintain the average soil water content at the rooting depth within the field capacity and refill point, irrigation should have been applied on 3 September and 5 September if the high refill point was considered for the PR1 profile probe and Diviner 2000 respectively (Fig. 8.3b). The high refill point is used when evaporative demand is high and the lower value is used when the evaporative demand is low; intermediate values can also be used if the atmospheric demand for evaporation is intermediate (Taylor and Ashcroft, 1972).

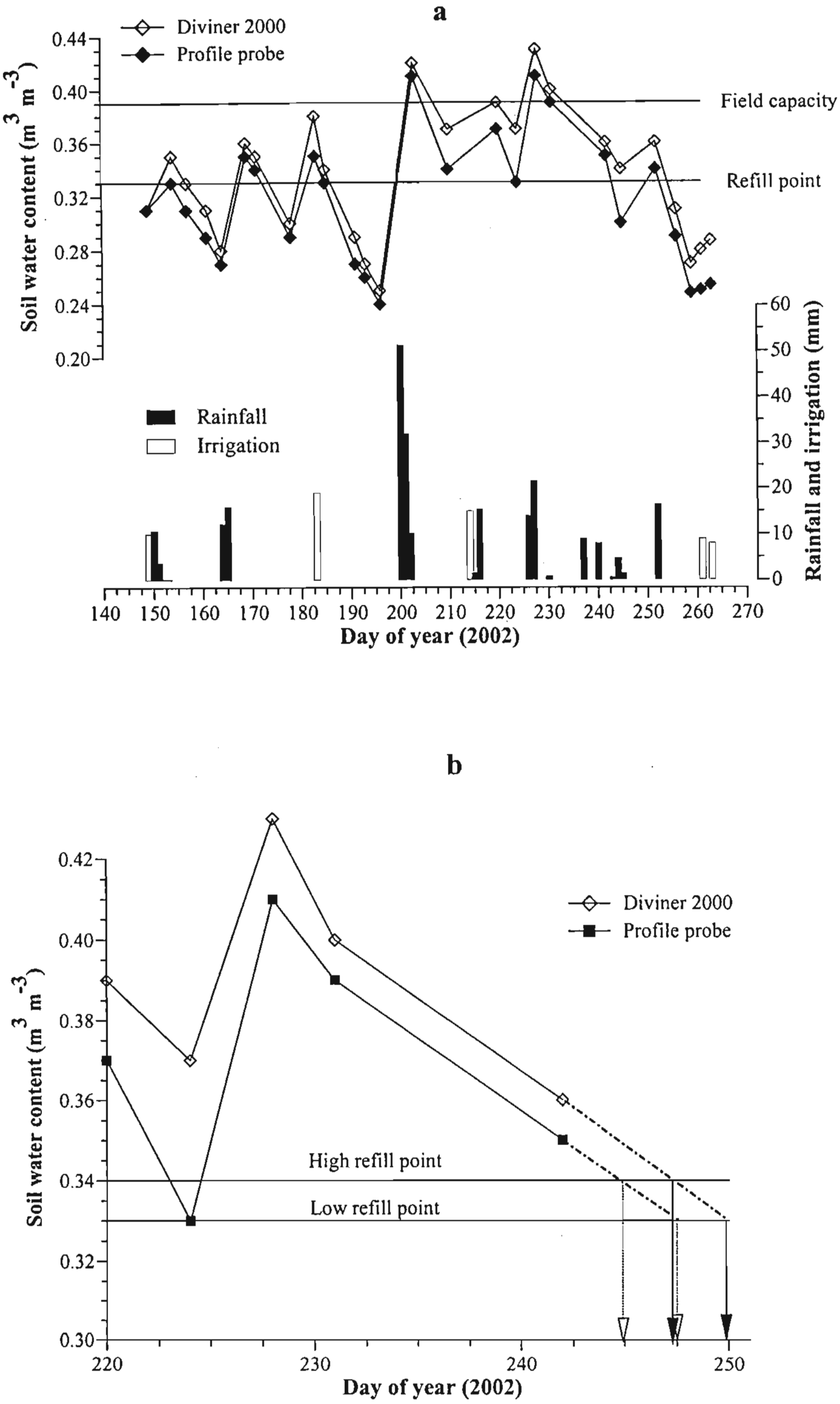


Fig. 8.3 (a) The depth-averaged soil water content for the rooting depth; (b) the daily depth-averaged soil water content for both PR1 profile probe and Diviner 2000 measurements versus number of days after the last irrigation together with the high and low refill points. This graph projects to the day for the next irrigation

8.3.3 Amount of irrigation

Irrigation was applied using a dragline sprinkler system, and irrigation scheduling was practiced based on the irrigator's judgment by referring to the Diviner 2000 soil water content measurements. Between 29 May and 20 September there were five irrigation and twenty rainfall events. For the last two irrigations on 18 and 20 September the applied water and the sub-hourly soil water content were measured using the tipping spoon automatic rain gauge and PR1 profile probe respectively. The amount of irrigation that could bring the average soil water content to field capacity was estimated using the following two methods.

Method 1

Based on the Campbell and Campbell (1982) equation (Eq. 8.1) the critical depth was calculated to be 180 mm. However, due to the difficulty of the PR1 profile probe to measure at this depth, a depth of 200 mm was used as the critical depth instead. When the wetting front reached this depth irrigation should have been stopped to avoid excess water and subsequent deep percolation. An irrigation of 8 mm was applied 164 days after planting on 20 September for two hours when the depth-averaged soil water content was 0.254 m^3 m^{-3}. The wetting front reached the 100-mm depth after one hour of irrigation. Irrigation was then terminated before the wetting front had reached the 200 mm depth. The depth-averaged soil water content (0.272 m^3 m^{-3}) after irrigation was less than the soil water content at field capacity.

Method 2

The following method from Lukangu *et al.* (1999) was used to predict the duration and amount of irrigation that should have been applied to bring the soil water content to field capacity (Fig. 8.4). This method uses sub-hourly soil water content measurements and it avoids excess and insufficient application of irrigation. The sub-hourly increase in depth-averaged soil water content during irrigation was linearly projected to the field capacity soil water content line (1). At the intersection of the two lines, a vertical line was traced to the *x*-axis (2) to indicate the time that the applied irrigation water would increase soil water content to field capacity. The sub-hourly cumulative irrigation was linearly projected to the vertical line (3). At the intersection of the vertical line (2) and the oblique line (3), a horizontal line was traced to intersect with the *y*-axis for cumulative irrigation (4) to indicate the irrigation amount required to increase soil water content to the field capacity.

Based on this method, irrigation should have continued for more than 2.5 h if the graphic solution was used (Fig. 8.4) and 3.23 h if the mathematical solution was used (Table 8.1). In terms of applied water 15 mm (graphic) and 12.9 (mathematical) of additional water should have been applied to increase the depth-averaged soil water content to field capacity. The estimated values using graphical and mathematical methods were comparable. As Lukangu *et al.* (1999) pointed out that the small difference observed between graphical and mathematical methods was caused by error in plotting the correct line to represent the average variation in soil water content and cumulative irrigation as a function of time.

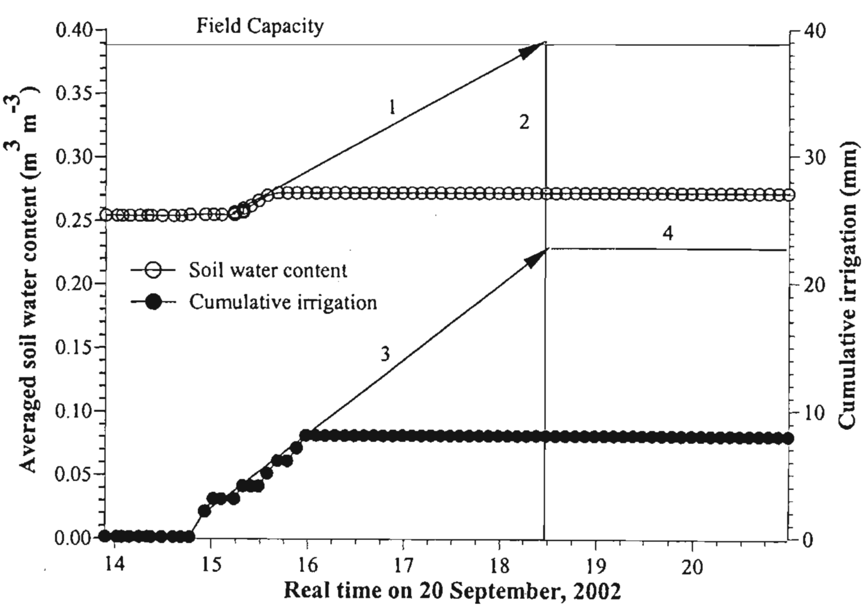


Fig. 8.4 The sub-hourly soil water content (left y-axis), cumulative applied irrigation (right y-axis) and day time at Cedara expressed in 24 h (x-axis). Projected lines used to determine the time when soil water content would reach the field capacity (vectors 1 and 2), and the amount of cumulative irrigation that would be applied (vectors 3 and 4)

Table 8.1 The amount of irrigation and the duration of application estimated using graphical and mathematical approaches from sub-hourly measurement of the soil water content (m^3 m^{-3}) and the applied irrigation (mm)

Date	Irrigation amount	Irrigation rate	θ_V after irrigation	θ_V rate	Duration of irrigation	Estimated time to take θ_V to FC = 0.39 m^3 m^{-3}		Time difference between actual and estimated		Estimated irrigation to take WC to FC		Irrigation difference between the actual and the estimated	
	mm	mm h^{-1}	m^3 m^{-3}	m^3 m^{-3} h^{-1}	h	Graph h	Calculation h	Graph h	Calculation h	Graph mm	Calculation mm	Graph mm	Calculation mm
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14
20 Sep, 2002	8	4	0.272	0.026	2	4.50	5.23	-2.5	-3.23	23	20.92	-15	-12.92

Irrigation rate (mm) = Irrigation amount / Duration of irrigation *i.e.* Column 3 = Column 2 / Column 6

θ_V rate (m^3 m^{-3}) = (θ_V after irrigation - θ_{Vi}) / Duration of irrigation *i.e.* Column 5 = (Column 4 - θ_{Vi}) / Column 6

Estimated time to take θ_V to FC = (FC - θ_{Vi}) / θ_V rate *i.e.* Column 8 = (0.39 - θ_{Vi}) / Column 5

Time difference between actual and estimated for the graph = Duration of irrigation – Estimated time

i.e. Column 9 = Column 6 - Column 7

Time difference between actual and estimated for the calculation = Duration of irrigation – Estimated time

i.e. Column 10 = Column 6 - Column 8

Estimated irrigation to take θ_V to FC = Estimated time * Irrigation rate

i.e. Column 12 = Column 8 * Column 3

Irrigation difference between actual and estimated for the graph= Irrigation amount – Estimated irrigation

i.e. Column 13 = Column 2 - Column 11

Irrigation difference between actual and estimated for the calculation = Irrigation amount – Estimated irrigation

i.e. Column 14 = Column 2 - Column 12

8.4 CONCLUSIONS

The PR1 profile probe and Diviner 2000 soil water contents can be used for irrigation scheduling. If these sensors are calibrated for the specific soil, they can give a comparable soil water content measurement. These newly improved soil profile sensors have the advantage of measuring soil water content at different depths. Soil water content can be measured from different access tubes using one probe, by moving from access tube to access tube while recording the soil water content measurements using a hand held HH2 Moisture Meter for PR1 profile probe, and a Diviner 2000 display unit which act as a data storage, display and conversion tool. The PR1 profile probe has one major advantage that it can measure continuous and unattended soil water content by connecting with a datalogger.

To use these sensors for irrigation scheduling the field capacity and refill point of the soil need to be determined first in the field or laboratory or the values could be calculated using a regression equation. In this study, the field capacity was determined from the laboratory measurement of soil water content at -33 kPa. The refill point was defined based on the recommended optimum soil water potential from the literature and a percentage of the upper limit of available soil water depletion. Once these points were defined the soil water content was monitored at different depths using the PR1 profile probe and Diviner 2000. To determine the time of irrigation the soil water content at the rooting depth was averaged and plotted in a graph, which indicated the field capacity and refill point. The time of irrigation was then predicted when the depth-averaged soil water content in the rooting depth reached the refill point. The time of irrigation, which was predicted using the PR1 profile probe, was two days earlier than the Diviner 2000 when the high refill point was considered. This difference occurred since the Diviner 2000 measured soil water content at the rooting depth slightly over estimated the soil water content measured by the PR1 profile probe. Similarly, the duration and amount of irrigation, which should have been irrigated to bring the soil water content to field capacity was estimated using the sub-hourly monitored soil water content at the rooting depth. The depth-averaged sub-hourly soil water content at the rooting depth and the cumulative irrigation were plotted in a graph and spreadsheet to determine the duration and amount of irrigation. Both the graphical and mathematical approaches showed similar results with the estimated time of irrigation 4.5 and 5.23 h and amount of irrigation 23 and 20.9 mm respectively.

CHAPTER 9

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

9.1 INTRODUCTION

To undertake successful irrigation schemes the existing traditional-bound irrigation system should be modernized to control the amount and time of irrigation. Irrigation scheduling could be done by monitoring the soil, plant and the atmosphere. Over the years, different methods have been developed to monitor the soil-plant-atmosphere continuum. These methods include sensors that monitor the soil (gravimetric method, tensiometer, neutron probe, electrical resistance blocks and thermal dissipation sensors; the crop (heat pulse method and pressure chamber) and the microclimate (evaporation pan, atmometers, lysimetry and reference evaporation methods). Other recent methods include infrared thermometry, time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR). Nowadays there are more recent soil profile sensors like the PR1 profile probe and Diviner 2000, which can provide precise, non-destructive, continual and unattended *in situ* measurements of soil water content. In this study, the PR1 profile probe and Diviner 2000 were applied in irrigation scheduling. These sensors were first calibrated and compared under field conditions. The soil water content limits were also determined in the field and laboratory and calculated using regression equations, to determine the time and amount of irrigation.

9.2 CALIBRATION AND COMPARISON OF THE SENSORS

The PR1 profile probe was calibrated in the field and the soil-estimated parameter was compared with the factory-supplied parameter. There was good correlation between the PR1 profile probe soil water content determined using factory-supplied parameter and the soil-estimated soil water content. The factory-supplied parameter to estimate the volumetric soil water content gave a regression coefficient (r^2) of 0.822 and RMSE 0.062, while the soil-estimated volumetric soil water content gave a regression coefficient (r^2) of 0.820 and RMSE 0.085. On average, the volumetric soil water content could be estimated within 0.012 $m^3\ m^{-3}$ when using the factory-supplied parameter and 0.046 $m^3\ m^{-3}$ when using the soil-estimated parameter. Soil water content determination using the factory-supplied parameters was used for irrigation scheduling and also for comparison of the PR1 profile probe and the Diviner 2000-measured soil water content.

Comparison between the PR1 profile probe and Diviner 2000-measured soil water content was made in the field. The volumetric soil water content measured using both sensors showed a highly significant linear relationship. The regression coefficient (r^2) for the first three depths (100 to 300 mm) ranged between 0.947 to 0.964 and the RMSE ranged between 0.070 and 0.109. The regression coefficient for the deeper depths (600 to 1000 mm) ranged between 0.716 and 0.810 and the RMSE ranged between 0.058 and 0.150. These low regression coefficients at the deeper depths could be due to soil variability or loose contact between the access tube and the soil. When technical comparison was made between the two sensors, the PR1 profile probe has one major advantage over the Diviner 2000, that it can measure continuous and unattended soil water content using a datalogger. The Diviner 2000 only measures soil water content in all depths by moving from access tube to access tube while recording the soil water content in the logger.

The tensiometers, Watermark sensors and thermocouples, which were used to define the soil water content limits in the field, were also calibrated and evaluated using generated data. The tensiometers were calibrated in the laboratory and they showed highly significant linear relationship between the applied pressure and the transducer-measured voltage. All the tensiometers have statistically the same slope and intercept, so the data were pooled and represented by one regression line, which has a regression coefficient of 0.999. The slope and intercept of the pooled data were used as multiplier and offset respectively to convert the transducer-measured voltage into soil water potential. The mathematical model by Thomson and Armstrong (1987) was used to evaluate the Watermark sensitivity to resistance and temperature change. From the generated data it was shown that the sensor is more sensitive to a change of resistance at the higher resistance values: For example, a change of resistance from 2 to 3 kΩ at 20 °C caused a decrease in soil water potential by 5.1 kPa, while a change of resistance from 8 to 9 kΩ at 20 °C caused a decrease of 12.3 kPa. Similarly, the diurnal change of soil temperature from 21 °C to 29 °C at 100 mm soil depth caused a change of soil water potential from -55.7 to -87.5 kPa at a fixed resistance (8 kΩ). The calibration of the thermocouples against the mercury thermometer temperature showed a highly significant linear regression coefficient of 0.999 and RMSE of 0.141. The slope and intercept for the thermocouples were not statistically one (except for one thermocouple) and zero respectively. Thus, the slope and intercept of each sensor were used as a multiplier and offset respectively to correct the thermocouple-measured temperature.

9.3 FIELD, LABORATORY AND ESTIMATED SOIL WATER CONTENT LIMITS

The soil water content limits were determined in the field, laboratory, and regression equations, which were developed by Hutson (1986). From the field measurement the drained upper limit and lower limit were found to be 0.355 and 0.316 $m^3\ m^{-3}$ respectively. In the laboratory these values were 0.390 and 0.312 $m^3\ m^{-3}$ respectively. From the regression equation the drained upper limit and lower limit were calculated to be 0.295 and 0.210 $m^3\ m^{-3}$ respectively. The soil water contents of the three methods, which were measured at the same matric potential from saturation until -1500 kPa, were analyzed statistically. From the *paired-t test* the laboratory-measured and estimated soil water content were statistically different from the field-measured soil water content at the same matric potential. However, they showed a linear relationship with a regression coefficient of 0.975 and a RMSE of 0.064 between the laboratory and field-measured soil water content. Similarly, the soil water content estimated and field-measured soil water content at the same matric potential showed a linear relationship with regression coefficient of 0.995 and RMSE of 0.035. The laboratory-measured soil water content and retentivity function were used to calculate the refill point and fill point (field capacity).

9.4 IRRIGATION SCHEDULING USING THE FDR SENSORS

9.4.1 Daily soil water content

Soil water content was measured every two to three days per week using both the PR1 profile probe and Diviner 2000. The soil water content measured using both sensors, followed the same pattern, although the Diviner 2000 soil water content measurement were slightly higher than the PR1 profile probe measured soil water content at the rooting depth. It was also observed that the soil water content at the shallow depth (100 to 300 mm) rapidly declined after rainfall or irrigation as compared to the deeper depths

(400 to 1000 mm). This is due to the high root density (85 %) of the cover crops at the shallow depth and redistribution in the soil profile. The soil water content at the deeper depths fluctuated within a narrow range. For example, the PR1 profile probe-measured soil water content at the deeper depth ranged between 0.37 and 0.44 $m^3 m^{-3}$. Similarly, the Diviner 2000-measured soil water content varied between 0.32 and 0.38 $m^3 m^{-3}$.

9.4.2 Time of irrigation

The depth-averaged soil water content measured using the PR1 profile probe and Diviner 2000 at the rooting depth were used to determine the time of irrigation. Ideally, the depth-averaged soil water content within the rooting depth should range between field capacity and the refill point to maintain the optimum soil water content need of the cover crops. The next date of irrigation (after the last rainfall event on 29 August with an amount of 8 mm) was predicted graphically (Fig. 8.3b) using the soil water content of both sensors. Using the high refill point and the PR1 profile probe measured soil water content, the next irrigation should have been on 3 September. The Diviner 2000-measured soil water content at the high refill point predicted two days after the PR1 profile probe predicted date. This difference occurred since the Diviner 2000 measured soil water content at the rooting depth was slightly higher than the PR1 profile probe measured soil water content.

9.4.3 Amount of irrigation

The amount and duration of irrigation that should have been applied on 20 September (day of year 263) to bring the soil water content to field capacity was estimated using two compatible techniques (graphical and mathematical methods). The depth-averaged initial soil water content was 0.254 $m^3 m^{-3}$ and 8 mm of water was applied on 20 September, which was not enough to increase the soil water content to field capacity. The duration and amount of irrigation that should have been applied to bring the soil water content to field capacity were estimated graphically to be 4.50 h and 23 mm respectively. Similarly, the duration and amount of irrigation were estimated mathematically as 5.23 h and 20.92 mm. The difference between these two methods was caused due to the error encountered while plotting the correct line to represent the average variation in soil water content and cumulative irrigation as a function of time.

9.5 RECOMMENDATIONS FOR FUTURE RESEARCH

There is a need to conduct research on the factors that affect the measurement of the PR1 profile probe and Diviner 2000 like salinity, temperature, bulk density and electrical conductivity. The motivation for this research originated from the measurement of the soil water content at two depths (400 and 600 mm) from two different access tubes. The soil water content measured using the PR1 profile probe was for example unrealistic low value (0.026 m^3 m^{-3}) on 03 June (day of year 154), which was much more smaller than the Diviner 2000-measured soil water content (0.35 m^3 m^{-3}) at the same depth. The measurements of soil water content above and below these depths were normal and the PR1 profile probe and Diviner 2000-measured soil water content were also comparable. There are different possibilities, which could cause these measurements to differ such as air gaps between the access tube and soil or any soil parameter, which could affect the dielectric property of the soil. Preliminary soil analyses were done using soil samples from these depths but it did not show any peculiar result with regard to the factors, which could affect the dielectric constant of the soil.

There are two equations (linear and non-linear relationships) to convert the resistance of the Watermark to soil water potential. The linear relationship is applicable to calculate the soil water potential in the range of 0 to -200 kPa. The non-linear relationship by Thomson and Armstrong (1987) is only applicable within the range of soil water potential between -10 and -100 kPa. This non-linear equation was used to relate the electrical resistance of the Watermark to soil water potential and soil temperature. The calibration for a matric potential within this range was done in a laboratory by placing the sensors inside an extractor full of soil where the temperature of the soil was measured using a thermocouple. The relationship between the matric potential, electrical resistance and temperature were developed for a soil temperature range of 4 to 38 °C and for the above mentioned matric potential range. Therefore, there is a need to perform more research to extend the non-linear relationship including temperature up to -200 kPa soil water potential.

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Appendix 1 Program for PR1 profile probe and rain gauge to measure the soil water content and amount of rainfall/irrigation using CR10X datalogger

```
; {CR10X}
; Record of wetting front and normal water content
; monitoring using the PR1 profile probe
; Select to have table 1 or table 2 on
; Table 1: 10 s interval for monitoring wetting front
; Switch off table 1 by pressing *1 A 0 A *0
;
; Table 2: 3600 s interval for normal monitoring
; Switch off table 2 by pressing *2 A 0 A *0

; PR1 profile probe
; Yellow 1H, Green 1L
; Black 2H, Green 2L
; Brown 3H, Green 3L
; White 4H, Green 4L
; Turquoise 5H, Green 5L
; Pink 6H, Green 5L
; Red goes to Switched 12 V
; Blue goes to G (power 0 V)
; Connect a wire between Switched 12 V Control and C8

*Table 1 Program
 01: 10       Execution Interval (seconds)

1: Batt Voltage (P10)
 1: 1       Loc [ Vbattery ]

2: If time is (P92)
 1: 0       Minutes (Seconds --) into a
 2: 2       Interval (same units as above)
 3: 30      Then Do

3: Set Port(s) (P20)
 1: 1000    C8..C5 = high/low/low/low
 2: 0000    C4,C3,C2,C1 Options

4: Ex-Del-Diff (P8)
 1: 6       Reps
 2: 15      2500 mV Fast Range
 3: 1       DIFF Channel
 4: 1       Excite all reps w/Exchan 1
 5: 200     Delay (units 0.01 sec)
 6: 0000    mV Excitation
 7: 2       Loc [ Voltage_1 ]
 8: 0.001   Mult
 9: 0.0     Offset

5: Polynomial (P55)
 1: 6       Reps
 2: 2       X Loc [ Voltage_1 ]
 3: 8       F(X) Loc [ WC_1    ]
 4: -.084   C0
 5: 1.77    C1
 6: -3.88   C2
 7: 9.42    C3
 8: 0.0     C4
 9: 0.0     C5

6: Set Port(s) (P20)
 1: 0000    C8..C5 = low/low/low/low
 2: 0000    C4,C3,C2,C1 Options

7: Pulse (P3)
 1: 1       Reps
 2: 1       Pulse Channel 1
 3: 2       Switch Closure, All Counts
 4: 14      Loc [ Irrig    ]
 5: 1.0     Mult
 6: 0.0     Offset

8: Do (P86)
 1: 10      Set Output Flag High (Flag 0)

9: Set Active Storage Area (P80)
 1: 1       Final Storage Area 1
 2: 100     Array ID

10: Real Time (P77)
 1: 1220    Year,Day,Hour/Minute (midnight = 2400)

11: Minimum (P74)
 1: 1       Reps
 2: 00      Time Option
 3: 1       Loc [ Vbattery ]

12: Sample (P70)
 1: 12      Reps
 2: 2       Loc [ Voltage_1 ]

13: Totalize (P72)
 1: 1       Reps
 2: 14      Loc [ Irrig    ]

14: End (P95)

*Table 2 Program
 02: 3600     Execution Interval (seconds)

1: Batt Voltage (P10)
 1: 1       Loc [ Vbattery ]

2: If time is (P92)
 1: 0       Minutes (Seconds --) into a
 2: 180     Interval (same units as above)
 3: 30      Then Do

3: Set Port(s) (P20)
 1: 1000    C8..C5 = high/low/low/low
 2: 0000    C4,C3,C2,C1 Options

4: Ex-Del-Diff (P8)
 1: 6       Reps
 2: 15      2500 mV Fast Range
 3: 1       DIFF Channel
 4: 1       Excite all reps w/Exchan 1
 5: 200     Delay (units 0.01 sec)
 6: 0000    mV Excitation
 7: 2       Loc [ Voltage_1 ]
 8: 0.001   Mult
 9: 0.0     Offset

5: Polynomial (P55)
 1: 6       Reps
 2: 2       X Loc [ Voltage_1 ]
 3: 8       F(X) Loc [ WC_1    ]
 4: -.084   C0
 5: 1.77    C1
 6: -3.88   C2
 7: 9.42    C3
 8: 0.0     C4
 9: 0.0     C5

6: Set Port(s) (P20)
 1: 0000    C8..C5 = low/low/low/low
 2: 0000    C4,C3,C2,C1 Options

7: Pulse (P3)
 1: 1       Reps
 2: 1       Pulse Channel 1
 3: 2       Switch Closure, All Counts
 4: 14      Loc [ Irrig    ]
 5: 1.0     Mult
 6: 0.0     Offset

8: Do (P86)
 1: 10      Set Output Flag High (Flag 0)

9: Set Active Storage Area (P80)
 1: 1       Final Storage Area 1
 2: 200     Array ID

10: Real Time (P77)
 1: 1220    Year,Day,Hour/Minute (midnight = 2400)

11: Minimum (P74)
 1: 1       Reps
 2: 00      Time Option
 3: 1       Loc [ Vbattery ]

12: Sample (P70)
 1: 12      Reps
 2: 2       Loc [ Voltage_1 ]

13: Totalize (P72)
 1: 1       Reps
 2: 14      Loc [ Irrig    ]

14: End (P95)

*Table 3 Subroutines

End Program
```

-Input Locations-
1 Vbattery 1 2 2
2 Voltage_1 5 4 2
3 Voltage_2 9 4 2
4 Voltage_3 9 4 2
5 Voltage_4 9 4 2
6 Voltage_5 9 4 2
7 Voltage_6 17 4 2
8 WC_1 5 2 2
9 WC_2 9 2 2
10 WC_3 9 2 2
11 WC_4 9 2 2
12 WC_5 9 2 2
13 WC_6 17 2 2
14 Irrig 1 2 2

-Program Security-
0000
-Mode 4-
-Final Storage Area 2-0
-CR10X ID-0
-CR10X Power Up-3

Final Storage Label File for: CR10X.CSI
Date: 3/3/2003
Time: 09:21:01

100 Output_Table 10.00 Sec
1 100 L
2 Year_RTM L
3 Day_RTM L
4 Hour_Minute_RTM L
5 Vbattery_MIN L
6 Voltage_1 L
7 Voltage_2 L
8 Voltage_3 L
9 Voltage_4 L
10 Voltage_5 L
11 Voltage_6 L
12 WC_1 L
13 WC_2 L
14 WC_3 L
15 WC_4 L
16 WC_5 L
17 WC_6 L
18 Irrig_TOT L

200 Output_Table 3600.00 Sec
1 200 L
2 Year_RTM L
3 Day_RTM L
4 Hour_Minute_RTM L
5 Vbattery_MIN L
6 Voltage_1 L
7 Voltage_2 L
8 Voltage_3 L
9 Voltage_4 L
10 Voltage_5 L
11 Voltage_6 L
12 WC_1 L
13 WC_2 L
14 WC_3 L
15 WC_4 L
16 WC_5 L
17 WC_6 L
18 Irrig_TOT L

Estimated Total Final Storage Locations used per day 155952.0

Program Trace Information File for: CR10X.CSI
Date: 3/3/2003
Time: 09:21:01

T = Program Table Number
N = Sequential Program Instruction Location Number
Instruction = Instruction Number and Name

Inst ExTm = Individual Instruction Execution Time
Block ExTm = Cumulative Execution Time for program block,
i.e., subroutine
Prog ExTm = Cumulative Total Program Execution Time

				Output Flag High		
	Inst ExTm	Block ExTm	Prog ExTm	Inst ExTm	Block ExTm	Prog ExTm
T|N|Instruction	(msec)	(msec)	(msec)	(msec)	(msec)	(msec)
1|1|10 Batt Voltage	8.3	8.3	8.3	8.3	8.3	8.3
1|2|92 If time is	0.7	9.0	9.0	0.7	9.0	9.0
1|3|20 Set Port(s)	11.3	20.3	20.3	11.3	20.3	20.3
1|4|8 Ex-Del-Diff	24034.5	24054.8	24054.8	24034.5	24054.8	24054.8
1|5|55 Polynomial	20.4	24075.2	24075.2	20.4	24075.2	24075.2
1|6|20 Set Port(s)	11.3	24086.5	24086.5	11.3	24086.5	24086.5
1|7|3 Pulse	2.2	24088.7	24088.7	2.2	24088.7	24088.7
1|8|86 Do	0.3	24089.0	24089.0	0.3	24089.0	24089.0
Output Flag Set @ 18 for Array 100						
1|9|80 Set Active Storage Area	0.3	24089.3	24089.3	0.3	24089.3	24089.3
1|10|77 Real Time	0.2	24089.5	24089.5	3.8	24093.1	24093.1
Output Data 3 Values						
1|11|74 Minimum	2.0	24091.5	24091.5	8.0	24101.1	24101.1
Output Data 1 Values						
1|12|70 Sample	0.2	24091.7	24091.7	5.3	24106.4	24106.4
Output Data 12 Values						
1|13|72 Totalize	1.6	24093.3	24093.3	2.7	24109.1	24109.1
Output Data 1 Values						
1|14|95 End	0.2	24093.5	24093.5	0.2	24109.3	24109.3

Program Table 1 Execution Interval 10.000 Seconds

Table 1 Estimated Total Program Execution Time in msec 24093.5 w/Output 24109.3

Table 1 Estimated Total Final Storage Locations used per day 155520.0

-------------- Table 2 --------------

2|1|10 Batt Voltage	8.3	8.3	8.3	8.3	8.3	8.3
2|2|92 If time is	0.7	9.0	9.0	0.7	9.0	9.0
2|3|20 Set Port(s)	11.3	20.3	20.3	11.3	20.3	20.3
2|4|8 Ex-Del-Diff	24034.5	24054.8	24054.8	24034.5	24054.8	24054.8
2|5|55 Polynomial	20.4	24075.2	24075.2	20.4	24075.2	24075.2
2|6|20 Set Port(s)	11.3	24086.5	24086.5	11.3	24086.5	24086.5
2|7|3 Pulse	2.2	24088.7	24088.7	2.2	24088.7	24088.7
2|8|86 Do	0.3	24089.0	24089.0	0.3	24089.0	24089.0
Output Flag Set @ 28 for Array 200						
2|9|80 Set Active Storage Area	0.3	24089.3	24089.3	0.3	24089.3	24089.3
2|10|77 Real Time	0.2	24089.5	24089.5	3.8	24093.1	24093.1
Output Data 3 Values						
2|11|74 Minimum	2.0	24091.5	24091.5	8.0	24101.1	24101.1
Output Data 1 Values						
2|12|70 Sample	0.2	24091.7	24091.7	5.3	24106.4	24106.4
Output Data 12 Values						
2|13|72 Totalize	1.6	24093.3	24093.3	2.7	24109.1	24109.1
Output Data 1 Values						
2|14|95 End	0.2	24093.5	24093.5	0.2	24109.3	24109.3

Program Table 2 Execution Interval 3600.000 Seconds

Table 2 Estimated Total Program Execution Time in msec 24093.5 w/Output 24109.3

Table 2 Estimated Total Final Storage Locations used per day 432.0

Estimated Total Final Storage Locations used per day 155952.0

Appendix 2 Program for soil water potential sensors (tensiometers and Watermark sensors) connected to the CR23X datalogger

```
; {CR23X}
; Watermark sensors
; Wiring for each blue (UNP) or black (CSI) wire connects to
; individual EX channel
; All reds go to their respective SE channel
; Green (UNP) or white (CSI) connect to ground
; Tensiometers
; All reds go to their respective EX channel
; All Yellow go to their respective SE channel
; Green, blue and clear go to ground
; Thermocouple
; Blue goes to high
; Red or white connect to low
; {CR23X}
;
*Table 1 Program
 01: 3600      Execution Interval (seconds)

1: If time is (P92)
 1: 0      Minutes (Seconds --) into a
 2: 180    Interval (same units as above)
 3: 30     Then Do

2: Batt Voltage (P10)
 1: 1      Loc [ Vbattery ]

3: Panel Temperature (P17)
 1: 2      Loc [ Tpanel   ]

;Six Watermark sensors
4: AC Half Bridge (P5)
 1: 2      Reps
 2: 14     1000 mV, Fast Range
 3: 1      SE Channel
 4: 1      Excite all reps w/Exchan 1
 5: 500    mV Excitation
 6: 3      Loc [ KOhms_1 ]
 7: 1.0    Mult
 8: 0.0    Offset
5: AC Half Bridge (P5)
 1: 2      Reps
 2: 14     1000 mV, Fast Range
 3: 3      SE Channel
 4: 2      Excite all reps w/Exchan 2
 5: 500    mV Excitation
 6: 5      Loc [ KOhms_3 ]
 7: 1.0    Mult
 8: 0.0    Offset

6: AC Half Bridge (P5)
 1: 2      Reps
 2: 14     1000 mV, Fast Range
 3: 5      SE Channel
 4: 3      Excite all reps w/Exchan 3
 5: 500    mV Excitation
 6: 7      Loc [ KOhms_5 ]
 7: 1.0    Mult
 8: 0.0    Offset

7: BR Transform Rf[X/(1-X)] (P59)
 1: 6      Reps
 2: 3      Loc [ KOhms_1 ]
 3: 1.0    Multiplier (Rf)

8: Thermocouple Temp (DIFF) (P14)
 1: 1      Reps
 2: 21     10 mV, 60 Hz Reject, Slow Range
 3: 4      DIFF Channel
 4: 1      Type T (Copper-Constantan)
 5: 2      Ref Temp (Deg. C) Loc [ Tpanel   ]
 6: 9      Loc [ Tsoil_1 ]
 7: 1.0    Mult
 8: 0.0    Offset

9: Thermocouple Temp (DIFF) (P14)
 1: 1      Reps
 2: 21     10 mV, 60 Hz Reject, Slow Range
 3: 5      DIFF Channel
 4: 1      Type T (Copper-Constantan)
 5: 2      Ref Temp (Deg. C) Loc [ Tpanel   ]
 6: 11     Loc [ Tsoil_3 ]
 7: 1.0    Mult
 8: 0.0    Offset

10: Thermocouple Temp (DIFF) (P14)
 1: 1      Reps
 2: 21     10 mV, 60 Hz Reject, Slow Range
 3: 6      DIFF Channel
 4: 1      Type T (Copper-Constantan)
 5: 2      Ref Temp (Deg. C) Loc [ Tpanel   ]
 6: 13     Loc [ Tsoil_5 ]
 7: 1.0    Mult
 8: 0.0    Offset

11: Z=X (P31)
 1: 9      X Loc [ Tsoil_1 ]
 2: 10     Z Loc [ Tsoil_2 ]

12: Z=X (P31)
 1: 11     X Loc [ Tsoil_3 ]
 2: 12     Z Loc [ Tsoil_4 ]

13: Z=X (P31)
 1: 13     X Loc [ Tsoil_5 ]
 2: 14     Z Loc [ Tsoil_6 ]

14: Beginning of Loop (P87)
 1: 0      Delay
 2: 6      Loop Count

15: Z=X*Y (P36)
 1: 9    -- X Loc [ Tsoil_1 ]
 2: 9    -- Y Loc [ Tsoil_1 ]
 3: 15   -- Z Loc [ WP_kPa_1 ]

16: Z=X*F (P37)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: .0106  F
 3: 15   -- Z Loc [ WP_kPa_1 ]

17: Z=F (P30)
 1: 34.21  F
 2: 0      Exponent of 10
 3: 21   -- Z Loc [ Tscor_1 ]

18: Z=X-Y (P35)
 1: 21   -- X Loc [ Tscor_1 ]
 2: 9    -- Y Loc [ Tsoil_1 ]
 3: 21   -- Z Loc [ Tscor_1 ]

19: Z=X+Y (P33)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: 21   -- Y Loc [ Tscor_1 ]
 3: 15   -- Z Loc [ WP_kPa_1 ]

20: Z=X*F (P37)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: 1.062  F
 3: 15   -- Z Loc [ WP_kPa_1 ]

21: Z=X-Y (P35)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: 3    -- Y Loc [ KOhms_1 ]
 3: 15   -- Z Loc [ WP_kPa_1 ]

22: Z=X*F (P37)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: .01306  F
 3: 15   -- Z Loc [ WP_kPa_1 ]

23: Z=X/Y (P38)
 1: 3    -- X Loc [ KOhms_1 ]
 2: 15   -- Y Loc [ WP_kPa_1 ]
 3: 15   -- Z Loc [ WP_kPa_1 ]

;Make the water potentials negative

24: Z=X*F (P37)
 1: 15   -- X Loc [ WP_kPa_1 ]
 2: -1     F
 3: 15   -- Z Loc [ WP_kPa_1 ]

25: End (P95)

26: Do (P86)
 1: 10     Set Output Flag High (Flag 0)
```

```
27: Set Active Storage Area (P80)
 1: 1      Final Storage Area 1
 2: 100    Array ID

28: Real Time (P77)
 1: 220    Day,Hour/Minute (midnight = 2400)

29: Resolution (P78)
 1: 0      Low Resolution

30: Sample (P70)
 1: 6      Reps
 2: 3      Loc [ KOhms_1  ]

31: Sample (P70)
 1: 6      Reps
 2: 9      Loc [ Tsoil_1  ]

32: Sample (P70)
 1: 6      Reps
 2: 15     Loc [ WP_kPa_1 ]

33: End (P95)

34: Serial Out (P96)
 1: 71     Destination Output

*Table 2 Program
 02: 3600     Execution Interval (seconds)

1: If time is (P92)
 1: 0      Minutes (Seconds --) into a
 2: 180    Interval (same units as above)
 3: 30     Then Do

;Six tensiometers
2: Set Port(s) (P20)
 1: 0      C8..C5 = low/low/low/low
 2: 0001   C4..C1 = low/low/low/high

3: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

4: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 22     SE Channel
 4: 27     Loc [ SP_1    ]
 5: -.0232 Mult
 6: 8      Offset

5: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

6: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0010   C4..C1 = low/low/high/low

7: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

8: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 23     SE Channel
 4: 28     Loc [ SP_2    ]
 5: -.0232 Mult
 6: 8      Offset

9: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

10: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0100   C4..C1 = low/high/low/low

11: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

12: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 24     SE Channel
 4: 29     Loc [ SP_3    ]
 5: -.0232 Mult
 6: 8      Offset

13: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

14: Set Port(s) (P20)
 1: 0      C8..C5 = low/low/low/low
 2: 1000   C4..C1 = high/low/low/low

15: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

16: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 13     SE Channel
 4: 30     Loc [ SP_4    ]
 5: -.0232 Mult
 6: 8      Offset

17: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

18: Set Port(s) (P20)
 1: 0001   C8..C5 = low/low/low/high
 2: 0000   C4..C1 = low/low/low/low

19: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

20: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 14     SE Channel
 4: 31     Loc [ SP_5    ]
 5: -.0232 Mult
 6: 8      Offset

21: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

22: Set Port(s) (P20)
 1: 0010   C8..C5 = low/low/high/low
 2: 0000   C4..C1 = low/low/low/low

23: Delay w/Opt Excitation (P22)
 1: 1      Ex Channel
 2: 0      Delay W/Ex (units = 0.01 sec)
 3: 800    Delay After Ex (units = 0.01 sec)
 4: 0      mV Excitation

24: Volt (SE) (P1)
 1: 1      Reps
 2: 30     Auto, 50 Hz Reject, Slow Range (OS>1.06)
 3: 15     SE Channel
 4: 32     Loc [ SP_6    ]
 5: -.0232 Mult
 6: 8      Offset

25: Set Port(s) (P20)
 1: 0000   C8..C5 = low/low/low/low
 2: 0000   C4..C1 = low/low/low/low

26: Do (P86)
 1: 10     Set Output Flag High (Flag 0)

27: Set Active Storage Area (P80)
 1: 2      Final Storage Area 2
 2: 200    Array ID

28: Real Time (P77)
 1: 220    Day,Hour/Minute (midnight = 2400)

29: Minimum (P74)
 1: 1      Reps
 2: 1      Value with Seconds
 3: 1      Loc [ Vbattery ]

30: Sample (P70)
 1: 6      Reps
 2: 27     Loc [ SP_1    ]
```

31: End (P95)

32: Serial Out (P96)
1: 71 Destination Output

*Table 3 Subroutines

End Program

-Input Locations-
1 Vbattery 5 1 1
2 Tpanel 1 3 1
3 KOhms_1 5 4 2
4 KOhms_2 25 2 2
5 KOhms_3 13 2 2
6 KOhms_4 25 2 2
7 KOhms_5 13 2 2
8 KOhms_6 17 2 2
9 Tsoil_1 5 5 1
10 Tsoil_2 1 1 1
11 Tsoil_3 5 2 1
12 Tsoil_4 1 1 1
13 Tsoil_5 5 2 1
14 Tsoil_6 1 1 1
15 WP_kPa_1 1 8 8
16 WP_kPa_2 1 1 0
17 WP_kPa_3 1 1 0
18 WP_kPa_4 1 1 0
19 WP_kPa_5 1 1 0
20 WP_kPa_6 1 1 0
21 Tscor_1 1 2 2
22 Tscor_2 1 0 0
23 Tscor_3 1 0 0
24 Tscor_4 1 0 0
25 Tscor_5 1 0 0
26 Tscor_6 1 0 0
27 SP_1 1 1 1
28 SP_2 1 1 1
29 SP_3 1 1 1
30 SP_4 1 1 1
31 SP_5 1 1 1
32 SP_6 1 1 1
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
5000

Program Trace Information File for: WMTEPP_J.CSI
Date: 10/11/2002
Time: 16:42:15

T = Program Table Number
N = Sequential Program Instruction Location Number
Instruction = Instruction Number and Name

Inst ExTm = Individual Instruction Execution Time
Block ExTm = Cumulative Execution Time for program block, i.e., subroutine
Prog ExTm = Cumulative Total Program Execution Time

T	N	Instruction	Inst ExTm (msec)	Block ExTm (msec)	Prog ExTm (msec)	Output Flag High Inst ExTm (msec)	Output Flag High Block ExTm (msec)	Output Flag High Prog ExTm (msec)
1	1	92 If time is	0.4	0.4	0.4	0.4	0.4	0.4
1	2	10 Batt Voltage	2.5	2.9	2.9	2.5	2.9	2.9
1	3	17 Panel Temperature	2.8	5.7	5.7	2.8	5.7	5.7
1	4	5 AC Half Bridge	8.8	14.5	14.5	8.8	14.5	14.5
1	5	5 AC Half Bridge	8.8	23.3	23.3	8.8	23.3	23.3
1	6	5 AC Half Bridge	8.8	32.1	32.1	8.8	32.1	32.1
1	7	59 BR Transform Rf[X/(1-X)]	8.5	40.6	40.6	8.5	40.6	40.6
1	8	14 Thermocouple Temp (DIFF)	39.5	80.1	80.1	39.5	80.1	80.1
1	9	14 Thermocouple Temp (DIFF)	39.5	119.6	119.6	39.5	119.6	119.6
1	10	14 Thermocouple Temp (DIFF)	39.5	159.1	159.1	39.5	159.1	159.1
1	11	31 Z=X	0.4	159.5	159.5	0.4	159.5	159.5
1	12	31 Z=X	0.4	159.9	159.9	0.4	159.9	159.9
1	13	31 Z=X	0.4	160.3	160.3	0.4	160.3	160.3
1	14	87 Beginning of Loop	0.2	160.5	160.5	0.2	160.5	160.5
Execution times in the loop are calculated for one pass only.								
1	15	36 Z=X*Y	0.7	161.2	161.2	0.7	161.2	161.2
1	16	37 Z=X*F	0.7	161.9	161.9	0.7	161.9	161.9
1	17	30 Z=F	0.5	162.4	162.4	0.5	162.4	162.4
1	18	35 Z=X-Y	0.7	163.1	163.1	0.7	163.1	163.1
1	19	33 Z=X+Y	0.7	163.8	163.8	0.7	163.8	163.8
1	20	37 Z=X*F	0.7	164.5	164.5	0.7	164.5	164.5
1	21	35 Z=X-Y	0.7	165.2	165.2	0.7	165.2	165.2
1	22	37 Z=X*F	0.7	165.9	165.9	0.7	165.9	165.9
1	23	38 Z=X/Y	1.5	167.4	167.4	1.5	167.4	167.4

-CR10X ID-
0
-CR10X Power Up-
3
-CR10X Compile Setting-
3
-CR10X RS-232 Setting-
-1
Final Storage Label File for: WMTEPP_J.CSI
Date: 10/11/2002
Time: 16:42:15

100 Output_Table 3600.00 Sec
1 100 L
2 Day_RTM L
3 Hour_Minute_RTM L
4 KOhms_1 L
5 KOhms_2 L
6 KOhms_3 L
7 KOhms_4 L
8 KOhms_5 L
9 KOhms_6 L
10 Tsoil_1 L
11 Tsoil_2 L
12 Tsoil_3 L
13 Tsoil_4 L
14 Tsoil_5 L
15 Tsoil_6 L
16 WP_kPa_1 L
17 WP_kPa_2 L
18 WP_kPa_3 L
19 WP_kPa_4 L
20 WP_kPa_5 L
21 WP_kPa_6 L

200 Output_Table 3600.00 Sec
1 200 L
2 Day_RTM L
3 Hour_Minute_RTM L
4 Vbattery_MIN L
5 Vbattery_Sec_MIN L
6 SP_1 L
7 SP_2 L
8 SP_3 L
9 SP_4 L
10 SP_5 L
11 SP_6 L

Estimated Total Final Storage Locations used per day 768.0

```
1|24|37 Z=X*F                 0.7  168.1  168.1    0.7  168.1  168.1
1|25|95 End                   0.2  168.3  168.3    0.2  168.3  168.3
1|26|86 Do                    0.2  168.5  168.5    0.2  168.5  168.5
 Output Flag Set @ 126 for Array 100
1|27|80 Set Active Storage Area   0.2  168.7  168.7    0.2  168.7  168.7
1|28|77 Real Time             0.1  168.8  168.8    2.2  170.9  170.9
 Output Data 2 Values
1|29|78 Resolution            0.4  169.2  169.2    0.4  171.3  171.3
1|30|70 Sample                0.1  169.3  169.3    1.7  173.0  173.0
 Output Data 6 Values
1|31|70 Sample                0.1  169.4  169.4    1.7  174.7  174.7
 Output Data 6 Values
1|32|70 Sample                0.1  169.5  169.5    1.7  176.4  176.4
 Output Data 6 Values
1|33|95 End                   0.2  169.7  169.7    0.2  176.6  176.6
1|34|96 Serial Out              *  169.7  169.7      *  176.6  176.6

Program Table 1 Execution Interval 3600.000 Seconds

Table 1 Estimated Total Program Execution Time in msec 169.7 w/Output 176.6

Table 1 Estimated Total Final Storage Locations used per day 504.0


--------------- Table 2 ---------------
2|1|92 If time is             0.4   0.4   0.4    0.4   0.4   0.4
2|2|20 Set Port(s)            6.6   7.0   7.0    6.6   7.0   7.0
2|3|22 Delay w/Opt Excitation   8000.5 8007.5 8007.5  8000.5 8007.5 8007.5
2|4|1 Volt (SE)               131.7 8139.2 8139.2  131.7 8139.2 8139.2
2|5|20 Set Port(s)            6.6 8145.8 8145.8   6.6 8145.8 8145.8
2|6|20 Set Port(s)            6.6 8152.4 8152.4   6.6 8152.4 8152.4
2|7|22 Delay w/Opt Excitation   8000.5 16152.9 16152.9  8000.5 16152.9 16152.9
2|8|1 Volt (SE)               131.7 16284.6 16284.6  131.7 16284.6 16284.6
2|9|20 Set Port(s)            6.6 16291.2 16291.2   6.6 16291.2 16291.2
2|10|20 Set Port(s)           6.6 16297.8 16297.8   6.6 16297.8 16297.8
2|11|22 Delay w/Opt Excitation  8000.5 24298.3 24298.3  8000.5 24298.3 24298.3
2|12|1 Volt (SE)              131.7 24430.0 24430.0  131.7 24430.0 24430.0
2|13|20 Set Port(s)           6.6 24436.6 24436.6   6.6 24436.6 24436.6
2|14|20 Set Port(s)           6.6 24443.2 24443.2   6.6 24443.2 24443.2
2|15|22 Delay w/Opt Excitation  8000.5 32443.7 32443.7  8000.5 32443.7 32443.7
2|16|1 Volt (SE)              131.7 32575.4 32575.4  131.7 32575.4 32575.4
2|17|20 Set Port(s)           6.6 32582.0 32582.0   6.6 32582.0 32582.0
2|18|20 Set Port(s)           6.6 32588.6 32588.6   6.6 32588.6 32588.6
2|19|22 Delay w/Opt Excitation  8000.5 40589.1 40589.1  8000.5 40589.1 40589.1
2|20|1 Volt (SE)              131.7 40720.8 40720.8  131.7 40720.8 40720.8
2|21|20 Set Port(s)           6.6 40727.4 40727.4   6.6 40727.4 40727.4
2|22|20 Set Port(s)           6.6 40734.0 40734.0   6.6 40734.0 40734.0
2|23|22 Delay w/Opt Excitation  8000.5 48734.5 48734.5  8000.5 48734.5 48734.5
2|24|1 Volt (SE)              131.7 48866.2 48866.2  131.7 48866.2 48866.2
2|25|20 Set Port(s)           6.6 48872.8 48872.8   6.6 48872.8 48872.8
2|26|86 Do                    0.2 48873.0 48873.0   0.2 48873.0 48873.0
 Output Flag Set @ 226 for Array 200
2|27|80 Set Active Storage Area   0.2 48873.2 48873.2   0.2 48873.2 48873.2
2|28|77 Real Time             0.1 48873.3 48873.3   2.2 48875.4 48875.4
 Output Data 2 Values
2|29|74 Minimum               1.1 48874.4 48874.4   4.4 48879.8 48879.8
 Output Data 2 Values
2|30|70 Sample                0.1 48874.5 48874.5   1.7 48881.5 48881.5
 Output Data 6 Values
2|31|95 End                   0.2 48874.7 48874.7   0.2 48881.7 48881.7
2|32|96 Serial Out              * 48874.7 48874.7     * 48881.7 48881.7

Program Table 2 Execution Interval 3600.000 Seconds

Table 2 Estimated Total Program Execution Time in msec 48874.7 w/Output 48881.7

Table 2 Estimated Total Final Storage Locations used per day 264.0


Estimated Total Final Storage Locations used per day 768.0

*Execution time is unknown.
```

Appendix 3 A summarized climatic data for Cedara meteorological station for the year of 1974 to 2001

Months	Rainfall (mm)	T_max (^{O}C)	T_min (^{O}C)	RH_max (%)	RH_min (%)
January	132.3	33.1	10.4	96.6	24.7
February	111.8	32.6	10.6	96.7	23.9
March	109.4	31.7	9.3	96.8	21.8
April	44.8	29.3	4.3	97.4	19.9
May	20.5	27.5	1.2	97.4	16.8
June	12.0	25.4	-1.8	97.4	14.5
July	14.0	25.8	-1.9	97.2	13.1
August	24.3	29.0	-0.2	96.6	12.3
September	60.6	32.9	2.9	96.4	12.5
October	91.7	33.0	5.6	96.4	16.4
November	110.2	33.7	7.4	97.3	18.5
December	142.6	33.2	8.9	97.0	22.6

T_max is the maximum air temperature (^{O}C)

T_min is the minimum air temperature (^{O}C)

RH_max is the maximum relative humidity (%)

RH_max is the minimum relative humidity (%)

(Source of data from Agricultural Research Council, Institute of Soil, Climate and Water, Pretoria)

Appendix 4 Root distribution of the cover crops with depth

Depth (mm)	Cumulative Weight (g)			Cumulative Weight (%)		
	Oats	Rye	Rye grass	Oats	Rye	Rye grass
100	0.19	0.19	0.19	57	62	64
200	0.27	0.23	0.24	79	75	80
300	0.29	0.26	0.25	85	85	85
400	0.29	0.27	0.26	85	89	88
500	0.31	0.28	0.27	93	92	92
600	0.33	0.29	0.28	99	93	95
700	0.34	0.29	0.28	100	95	95
800	0.34	0.29	0.28	100	95	95
900	0.34	0.30	0.29	100	98	98
1000	0.34	0.31	0.30	100	100	100