EVALUATION OF SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING OF STRAWBERRIES

by

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ABSTRACT

Horticultural producers are in need of efficient and timely techniques for determining crop water requirements. The question of when and how much to irrigate, termed irrigation scheduling, is particularly important for high-value crops such as strawberries (*Fragaria ananassa*). During the growing season, irrigation scheduling decisions are influenced by climatic variables such as rainfall, temperature and humidity, which directly impact soil moisture levels. A field study was therefore conducted to evaluate two soil moisture sensors for irrigation scheduling of commercial strawberries on a farm in Simcoe, Southern Ontario. Strawberries were grown on raised beds with plastic mulch under two management practices – open field and plastic high tunnels. For each practice, two soil moisture sensors based on time domain reflectometry (TDR) were evaluated. The sensors, Campbell Scientific’s water content reflectometer (WCR) and ESI’s Gro-point (GP) monitored soil moisture continuously over the growing season (May to October 2007). Soil samples were collected to obtain volumetric water content as a unit of reference for the purpose of comparison and evaluation of the two sensors. Equivalent water depths (EWD) were calculated for an effective strawberry rooting depth of 0.3 m. The calculated EWDs were compared with the grower’s irrigation scheduling practices. The study found that the WCR and GP reliably recorded continuous trends in soil moisture throughout the growing season. For the WCR sensor, gravimetric analyses of soil samples showed excellent correlation, resulting in $R^2$ of 0.94 and 0.97 for the open field and plastic high tunnel, respectively. The $R^2$ for the GP sensor was good at 0.88 for the open field but poor for the plastic high tunnels, due to a malfunctioning sensor. The EWDs for the two plots were calculated to be 699 mm for the open field and 711 mm for the plastic high tunnels. A significant finding of the study is the importance of selection of the location of the sensors with respect to the irrigation dripper, and depth of installation depending on crop type. Gravimetric samples must be taken in close proximity to the sensor. Moreover, site-specific calibration can improve performance of the sensors.
RÉSUMÉ

Les horticulteurs ont besoin de déterminer avec précision les besoins en eau d’irrigation des cultures. En effet, la bonne gestion de la production et l’obtention d’un meilleur rendement des fraises (*Fragaria ananassa*) nécessitent la planification de la quantité d’eau à apporter et le jour de l’irrigation. Le climat, la pluviométrie et la variation de la température durant le stade de croissance des plantes sont des variables importantes qui compliquent la tâche de la planification de l’irrigation. La problématique de cette étude s’inscrit dans l’optique d’évaluer l’apport de deux capteurs d'humidité du sol de type TDR (*Time Domain Reflectometry*) à la planification de l’irrigation des fraises à Simcoe, au sud d’Ontario. Il convient de noter que les fraises ont été cultivées avec la technique du paillis de plastique, en plein champ, ainsi qu’avec la technique du tunnel en plastique. Pour atteindre les objectifs assignés à cette étude, l’utilisation de deux capteurs de type WRC (*Campbell Scientific water content reflectometer*) et GP (*ESI’s Gro-point*) a permis de suivre d’une manière continue l'humidité du sol pendant le stade de croissance (mai à octobre 2007). Aussi, des échantillons du sol ont été collectés afin d'obtenir la teneur volumique en eau. Cette dernière a été utilisée comme référence et a permis ainsi de comparer et d'évaluer les résultats obtenus à l’aide des différents capteurs. Également, nous avons calculé l’équivalent d’eau en profondeur (EEP) pour une zone racinaire des fraises de 30 cm. Ce procédé nous a permis de comparer l’EEP calculé pour les différentes pratiques d’irrigation adoptées par les producteurs. Les résultats obtenus ont démontré que le WCR et GP représentent la variabilité de l'humidité du sol pendant le stade de la croissance. Pour le capteur WCR, nous avons pu établir une corrélation très intéressante avec l'analyse gravimétrique des échantillons du sol. En effet, le $R^2$ est de l’ordre de 0,94 et 0,97 pour les conditions du plein champ et du paillis de plastique respectivement. Quant au capteur GP, la corrélation est plus intéressante dans les conditions du plein champ avec un $R^2$ de l’ordre de 0,88, mais faible dans les conditions du tunnel en plastique, dû au mal fonctionnement du capteur. L’EEP a été calculé pour les deux parcelles, il est de l’ordre de 699 mm pour le champ libre et de 711 mm pour le tunnel en plastique.

À la lumière des résultats obtenus, nous avons montré l’importance du choix de l'emplacement des capteurs à l’égard du gouteur d'irrigation et que la profondeur de son
installation dépend du type de la culture. Également, le prélèvement des échantillons gravimétrique doit être effectué à proximité du capteur afin d’assurer une meilleure performance.
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AW</td>
<td>Available Water</td>
</tr>
<tr>
<td>BM</td>
<td>Benchmark</td>
</tr>
<tr>
<td>COWSEP</td>
<td>Canada Ontario Water Supply Expansion Program</td>
</tr>
<tr>
<td>CR205</td>
<td>Datalogger model</td>
</tr>
<tr>
<td>CS625</td>
<td>Water content reflectometer model</td>
</tr>
<tr>
<td>$d_b$</td>
<td>Soil bulk density</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Soil particle density</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>ET&lt;sub&gt;C&lt;/sub&gt;</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>EWD</td>
<td>Equivalent Water Depth</td>
</tr>
<tr>
<td>FC</td>
<td>Field Capacity</td>
</tr>
<tr>
<td>FDR</td>
<td>Frequency Domain Reflectometry</td>
</tr>
<tr>
<td>GP</td>
<td>Gro-Point Sensor</td>
</tr>
<tr>
<td>GPS</td>
<td>Geographical Positioning System</td>
</tr>
<tr>
<td>GS</td>
<td>Gravimetric Sample</td>
</tr>
<tr>
<td>$K_a$</td>
<td>Dielectric constant</td>
</tr>
<tr>
<td>MAD</td>
<td>Management Allowable Depletion</td>
</tr>
<tr>
<td>ME</td>
<td>Main Equipment (Sensor) Location</td>
</tr>
<tr>
<td>NMM</td>
<td>Neutron Moisture Meter</td>
</tr>
<tr>
<td>OMAFRA</td>
<td>Ontario Ministry of Agriculture Food and Rural Affairs</td>
</tr>
<tr>
<td>PFRA</td>
<td>Prairie Farm Rehabilitation Administration</td>
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<tr>
<td>PVC</td>
<td>Poly Vinyl Chloride</td>
</tr>
<tr>
<td>PWP</td>
<td>Permanent Wilting Point</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of regression</td>
</tr>
<tr>
<td>SIS</td>
<td>Scientific Irrigation Scheduling</td>
</tr>
<tr>
<td>SPSS</td>
<td>A commercial statistical software</td>
</tr>
<tr>
<td>TDR</td>
<td>Time Domain Reflectometry</td>
</tr>
<tr>
<td>VWC</td>
<td>Volumetric Water Content</td>
</tr>
<tr>
<td>WCR</td>
<td>Water Content Reflectometer</td>
</tr>
<tr>
<td>WIN</td>
<td>Weather Innovations Network</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Dielectric permittivity</td>
</tr>
<tr>
<td>$\rho_{soil}$</td>
<td>Bulk density of soil</td>
</tr>
<tr>
<td>$\rho_{water}$</td>
<td>Density of water</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Soil moisture content</td>
</tr>
<tr>
<td>$\theta_{fc}$</td>
<td>Soil moisture at field capacity</td>
</tr>
<tr>
<td>$\theta_{g}$</td>
<td>Gravimetric soil moisture content</td>
</tr>
<tr>
<td>$\theta_{pwp}$</td>
<td>Soil moisture at permanent wilting point</td>
</tr>
<tr>
<td>$\theta_v$</td>
<td>Volumetric soil moisture content</td>
</tr>
<tr>
<td>$\psi_m$</td>
<td>Soil matric potential</td>
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CHAPTER 1

1. INTRODUCTION

1.1. Background

Canada's available water resources were long considered abundant, and various users exploited them somewhat indiscriminately; however, more recently, competition has arisen between different economic sectors for access to this resource. This particularly holds true in regions such as South-western Ontario (Figure 1.1), where the need for timely, sufficient and affordable good quality water for crops and animals has led agricultural producers to become increasingly sensitive and responsive to water issues. In Southern Ontario, agricultural water management practices vary according to land topology, climatic conditions, system operation costs and local water availability.

In some regions, excessive moisture or water logging can have detrimental effects on agricultural production. In other parts of Canada, rainfall is just sufficient to meet crop water requirements. Continuing shifts in the spatio-temporal variability of precipitation and surface runoff patterns over recent and coming decades, partly due to a changing climate, will have uncertain impacts on water availability for agricultural production. The quantity and quality of regional water resources are affected by human activities. In irrigated agriculture, application of adequate and timely water, depending upon the soil-water-plant environment is crucial in crop production. With the advent of improved soil water technologies, irrigation can be scheduled through advanced soil moisture monitoring devices. In Canada, the challenge of effective farm water management can be addressed through the use of advanced technologies such as soil moisture monitoring sensors. Various organizations have implemented numerous innovative
initiatives to determine crop water needs and develop models of irrigation scheduling, which balance economic returns against future ecological vulnerability (Charlesworth et al; 2005).

**Figure 1.1. Map of Southern Ontario**

The study presented in this thesis represents a portion of an applied and collaborative research project entitled “Determining Irrigation Needs by Monitoring On-Farm Soil Moisture” initiated by the Brace Centre for Water Resources Management, McGill University, Canada. The federal and provincial governments through the Prairie Farm Rehabilitation Association (PFRA) of Agriculture and Agri-Food Canada and the Ontario Ministry of Agriculture Food and Rural
Affairs (OMAFRA), respectively provided the financial support and technical expertise under the Canada Ontario Water Supply and Expansion Program (COWSEP). One of the project’s objectives was to look into several cost- and time-efficient computer-based real-time soil moisture monitoring technologies which could be used by crop growers.

The COWSEP research project was designed and successfully implemented on commercial farms by various partners, to assess different soil moisture sensor technologies, in four different cropping zones. A wide range of field sites, varying in soil type and local climate, were selected in Southern Ontario. During the project implementation, greater attention was given to in situ monitoring of soil moisture, ensuring data quality, grower capacity building and feedback regarding the soil moisture sensors evaluated. The results of the project were disseminated to the stakeholders, including federal and provincial government officials, agribusinesses, and other crop growers.

On-farm field sites, selected at four locations in Ontario (Leamington, Dresden, Simcoe, and Niagara-on-the-Lake), were equipped with several types of permanent soil moisture sensors. An additional 15 nearby farm sites were used for measuring soil moisture content gravimetrically, as well as with a portable time domain reflectometer (TDR). In each region, six widely-adopted soil moisture sensors were installed viz., TDRs, water content reflectometers, tensiometers, electrical resistance blocks and capacitance probes. Growers were consulted as to the best location to install monitoring equipment on their farms, their field management practices, design of their irrigation systems, their operational management practices, and benchmark locations for assessing soil moisture variability within a zone. Data from the sensors were collected during the entire 2007 growing season.
This thesis research was specifically targeted towards one site (Simcoe) and one crop (strawberry, *Fragaria ananassa, Duchesne*) and the evaluation of TDR readings in relation to agricultural water management of two different strawberry cropping systems (*i.e.* open field with plastic mulch *vs.* plastic high tunnel with plastic mulch).

### 1.2. Objectives

The prime objective of this thesis research was to undertake on-farm comparison and evaluation of soil moisture sensors to determine the amount and timing of irrigation needed for commercial strawberry production in Southern Ontario under two different management practices.

The study was carried out with the following specific objectives:

1. To monitor soil moisture, using gravimetric sampling and *in situ* evaluation of a Campbell Scientific Water Content Reflectometer (WCR) and Environmental Sensors Inc Gro-point (GP), sensor technologies as tools for irrigation scheduling.
2. To correlate soil moisture sensor data with gravimetric soil moisture measurements from the two study plots, namely strawberries grown in open field and under plastic high tunnels.
3. To compare irrigation applications and water use for open field and plastic high tunnel strawberries using flow meter data, grower’s irrigation records and soil moisture sensor data.

### 1.3. Scope and limitations

The study was conducted within certain limitations: time and budget constraints restricted the study to a single growing season, and of several products in the market, only two soil moisture sensor technologies for irrigation management were evaluated here. Since the sensors
were evaluated for a specific soil, specific crop type under two crop management conditions, the results should not be generalized or extrapolated for other conditions.
CHAPTER 2

2. LITERATURE REVIEW

2.1. Background

Sensors for soil moisture monitoring have been used in various natural resource management practices, such as research on crop yield, watershed management, environmental monitoring, precision agriculture and irrigation scheduling. One such application, which forms the focus of this research, is the role of electrical sensors in irrigation scheduling in commercial strawberry production. By knowing the soil moisture content ($\theta$), agricultural producers can make timely decisions of when to start and when to stop water application, so as to optimize water use and produce a good quality crop (Hanson et al., 2000). Furthermore, scheduling irrigation is important for environmental quality by reducing chemical percolation and nutrient loss in the soil, and in achieving crop-specific water requirements, which would help the irrigators (Leib et al., 2002).

In advanced agriculture, many instruments and methods have been used to monitor and measure soil moisture. Tensiometers, resistance blocks, gravimetric methods, and granular matrix sensors have been commonly used for many decades and will continue to be widely applied in irrigation scheduling (Gardner, 1986; Seyfried, 1993; Leib, 1998; Leib, et al., 2002). These irrigation management techniques and instruments vary with respect to their accuracy, labour intensity, cost and simplicity of use. Previously, many studies have been conducted, to evaluate soil water devices both qualitatively and quantitatively in respect to setup requirements, maintenance, initial cost, accuracy and data interpretation (Ley et al., 1994). At the same time, the sensor industry coupled with rapidly advancing computer technology has resulted in a variety...
of new sensors for irrigation scheduling. The newly-designed sensors monitor soil moisture content continuously and on a real-time basis.

In particular, the timing and amount of irrigation are important factors for efficient on-farm water management. Scientific irrigation scheduling (SIS) is distinct in using crop evaporation and transpiration data, as well as soil moisture-based sensor technologies to precisely calculate when and how much to irrigate. This technology, if incorporated into commercial farm practices would result in timely and efficient water management (Leib et al., 2002). For both field and high tunnel-grown strawberries, daily growing season irrigation decisions must consider several factors simultaneously: available soil moisture, weather, plant developmental stage and air/soil temperature. Given that these factors change with time, irrigation scheduling decisions require a regular assessment of soil moisture at different soil depths to complement a grower’s subsequent water applications to the field.

In today’s commercial agriculture, technology plays an important role in different sectors of farm management; in particular soil moisture sensor technologies have proven to be efficient in helping corporate growers manage irrigation. Here, TDR-based soil moisture sensors have been valuable in irrigation management, especially in the cultivation of crops with requirements for large and timely water applications (Jeffrey, 2004). Irrigation managers traditionally used simple rules-of-thumb for decision making, typically based on depletion of available soil water. Recently research has proven that in high value crops such as intensively-managed strawberries, rule-of-thumb is not a sufficiently accurate method for making irrigation decisions (Werner, 1993; Bierman, 2005). Parameters such as management allowable depletion (MAD), the percentage of available soil water that can be withdrawn from the soil before the crop is subjected to yield-affecting stress, has been used for development of recommendations based on
irrigation method, crop stages, and climatic variability (Brace Centre for Water Resources Management, 2008).

2.2. Methods of measuring soil moisture

Soil moisture is the fundamental measurable parameter for making irrigation management decisions. Different methods have been used to estimate soil moisture at particular soil depths in relation to the crop rooting depth (Charlesworth, 2005). These measurement methods can be classified into direct (gravimetric) and indirect (i.e. soil moisture sensor technologies). The installation of a sensor at a particular location is key in obtaining reliable soil moisture readings (Coelho, 1996). In addition to selection of an appropriate site in the field, placement of the sensors with respect to irrigation lines and crops is an important criterion to consider when using this technology.

2.2.1. Gravimetric methods

The most widely adopted and frequently used direct method of soil moisture measurement involves removing soil moisture by heating the soil sample at 105°C. The accuracy of this method depends on the accuracy of weighing; however, these errors are negligible in relation to soil variability in the field (Campbell and Mulla, 1990).

While this method is fairly accurate, there are practical issues which may prevent its use for scheduling irrigation. Besides being very time and labour-intensive, it requires repeated disturbance of the soil, equipment (soil auger, soil cylinders, oven, and scale) and at least 48 hours after sampling to obtain results. While gravimetric soil moisture content ($\theta_g$ — g water per 100 g soil) measurement only requires auger sampling, volumetric soil moisture content ($\theta_v$ — cm$^3$ water per 100 cm$^3$ soil) requires the use of sampling cylinders of known volume to calculate
soil bulk density (g cm\(^{-3}\)). Hence these methods more often serve as references rather than the means for irrigation scheduling.

2.2.2. **Indirect methods**

Indirect water content measurement requires the installation of instrumentation and soil moisture based sensors in the soil profile. These measurement methods can be broadly categorized according to the physical principles invoked: soil dielectric properties or soil suction pressure (i.e., soil matric potential, \(\psi_m\)) both of which vary with the wetness or dryness of the soil. The earliest soil moisture sensors were analog soil tensiometers, which displayed \(\psi_m\), or soil tension according to the soil's moisture content. Their ease of use and low cost led to their wide adoption by growers, and they remain among the most widely used soil moisture sensors (Campbell and Mulla, 1990).

2.2.2.1. **Soil dielectric properties**

One method for indirect measurement of soil moisture employs the soil's dielectric constant (\(K_a\)). For dry soil, \(K_a <10\); for air, \(K_a = 1.0\), while for water \(K_a \approx 80\) (Fares and Polyakov, 2006). This constant can be estimated by either TDR or frequency domain reflectometry (FDR). As soil moisture and hence the soil's \(K_a\) increases, the time for an electromagnetic wave pulse to travel from one electrode to another and reflect back through the soil increases. Thus, for a given electrode spacing, depth and orientation (usually parallel and roughly 0.05 m apart), measuring a pulse's travel time in a soil at different gravimetrically-measured moisture contents allows one to develop a linear or quadratic relationship between the travel time and \(\theta_g\) or \(\theta_v\) (Prichard et al., 2004). In the TDR method, the sensor consists of two or more parallel rods installed in the soil at a particular depth and in a particular orientation. A pulse
is emitted and the travel time is measured, which is then converted into soil moisture readings. In the FDR method, the capacitance or dielectric permittivity ($\varepsilon$) is measured using two electrodes that are separated by a dielectric material, (i.e., a material which is a poor conductor). This principle is used in capacitance probes, where an oscillator applies a set frequency in the range of 50 to 150 MHz to the electrodes. These electrodes then produce a resonating frequency, which is smaller as the soil is wetter (Prichard, 2004). Hence, the output of the FDR based sensor can be defined as “the frequency response of the soil’s capacitance due to the soil moisture level” (Fares and Polyakov, 2006).

2.2.2.2. Soil suction

A second popular method for measuring soil moisture is by monitoring $\psi_m$. The conventional tensiometer, consisting of a transparent tube with a ceramic tip, has been used for many decades. The tube is filled with water and is airtight, so as the water reaches equilibrium with the soil surrounding it, the suction pressure varies, and this indicates the wetness or dryness of the soil. The tensiometer can be replaced or can be reset by refilling the tube. During installation it is important for the soil to be thoroughly saturated before sealing the tube and placing it in the soil (Prichard et al., 2004). Another indirect way of measuring tension is by measuring the soil's electrical resistance. In this measurement procedure, inexpensive, easy to install and low-maintenance electrically resistant blocks are used, which have a wider working range (0 to 200 kPa) than conventional tensiometers (Thompson et al., 2006).
2.3. Soil moisture sensors

In this section, some specific soil moisture sensors based on the principles of dielectric properties and soil suction pressure are reviewed.

2.3.1. Time domain reflectometers

2.3.1.1. Campbell Scientific water content reflectometer

To measure $\theta_g$ or $\theta_v$, the water content reflectometer (WCR) employs the principles of time domain reflectometry to calculate the moisture within the soil (Campbell Scientific., 2006). One difference between TDR and WCR is that the measurement frequency of the WCR is generally between 15 and 45 MHz (Seyfried and Murdock, 2001), whereas for the TDR it can be as high as 1 GHz. Water content reflectometers (WCR) function along the principles of the TDR to calculate the soil's $\varepsilon$ (Czarnomski et al., 2005; Kelleners et al., 2005). Two rods (sensor probes) attached to the WCR, along which the electrical signal is propagated, allow, based on the capacitance of the soil in which they are installed, the determination of $\varepsilon$ and $K_a$. The calculations for determining the dielectric parameters are built-in to the device's circuitry, reducing the cost, and also alleviating the need for long cables between sensors and data loggers (Chandler et al., 2004). The probes used in this study (WCR CS625, Campbell Scientific Inc, Logan UT) were the latest model of this soil moisture sensor currently in widespread use. The WCR were permanently installed for the entire growing season, at a depth of 0-0.3 m. Soil temperature has a significant effect on WCR sensors, and this effect increases with the increase in the magnitude of $\theta_v$ (Seyfried and Murdock, 2001).

A scatter-plot of WCR measurements vs. gravimetric data showed close correspondence, even in sandy soils (< 10% clay). Studies have shown that the manufacturer's WCR sensor
calibrations can be used for measurements in sandy soils and in clay soils of low electrical conductivity (Seyfried and Murdock, 2001; Kelleners et al., 2005). Results from four years of studies on soils with < 10% clay, showed WCR readings to provide a precise and reliable range of soil moisture content (Chandler et al., 2004); however, WCR overestimated the $\theta_v$ in soils of high clay content. In such conditions, in-situ calibrations would improve the quality of results (Chandler et al., 2004). Similarly, when the EC is greater than 0.1 S m$^{-1}$, field calibration of the WCR is required. The CS 625 model was used with the standard calibration provided by the manufacturer (Seyfried and Murdock, 2001), which was stated to be accurate for soils having an EC < 0.5 dS m$^{-1}$, a bulk density < 1.55 Mg m$^{-3}$ and a clay content < 30% (Campbell Scientific, 2006). Variations in these parameters affect the soil's electrical conductivity and at low frequencies, also affect soils' electrical properties (Chandler et al., 2004).

2.3.1.2. Gro-Point

The Gro-Point (GP) moisture sensor also operates on TDR principles, but the voltage pulse is transient in nature and not reflected by the wire guides. Placement of the sensor requires a trench at a required depth, and proper hand packing to avoid any air pockets. A data logger is attached to the sensor, and proprietary software is used to interpret the data. The sensors are usually factory calibrated for particular soil types. The GP sensor is designed and manufactured by Environmental Sensors Inc. (http://www.esica.com).

2.3.1.3. Portable Field Scout TDR

Time domain reflectometer based-sensors have different designs, of which the Field Scout (TDR 300, Spectrum Technologies Inc., 2007) is portable. The TDR 300 calculates $\varepsilon$ based on the propagation time of electromagnetic wave, typically within ±0.1 ns. While for water $\varepsilon$ is 80
(depending on temperature), for other soil constituents, such as minerals $2 < \varepsilon < 5$. Therefore the bulk permittivity of the soil is directly related to the soil moisture content. This property makes the TDR 300 efficient for in situ determination of $\theta_v$. The attached probes function as wave guides, with the standard TDR signals being transformed into square wave output with a frequency equivalent to $\theta_v$ (Spectrum Technologies Inc, 2007).

2.3.2. **Frequency domain reflectometers**

2.3.2.1. C-Probe (EnviroScan)

EnviroScan systems may have several FDR sensors mounted on a probe, which is then inserted into a PVC access tube. Before installation all the sensors are normalized by taking readings in air and submerged in water. The installation requires a certified person to ensure good probe-soil contact and operation of all the mounted FDR sensors. A separate data logger is attached to download and store the data. Data transfer to a computer for interpretation requires proprietary software developed by EnviroScan. The device was designed and is produced in Australia by Sentek Environmental Technologies (Sentek, 1995) ([http://www.sentek.com.au](http://www.sentek.com.au)).

2.3.2.2. Echo probe

An Echo probe operates on the principle of capacitance, and it measures the dielectric constant of soil. It is made up of copper electrodes further sealed in epoxy-impregnated fiberglass (Fares and Polyakov, 2006). Manufactured by Decagon Devices, Inc., (Pullman, WA, USA), there are several lengths available. Typically echo probes are permanently installed throughout the growing season, and connected to either a data logger or telemetry system through which soil moisture content readings may be transmitted. The Echo probe measures soil $\varepsilon$ in volts, by measuring the charge time of a capacitor placed in the soil (Czarnomski *et al.*, 2007).
Although the Echo probe displays readings in volts, it is easiest to interpret these readings as a trend line for the purposes of scheduling irrigation.

2.3.2.3. Theta probe

The Theta probe is another capacitance-based instrument, but does not require an access tube for installation. It consists of steel pins that act as a transmission line; these pins work by monitoring soil moisture changes, using the properties of radio frequency energy when transmitted into and reflected by the soil. The probe head houses an internal circuitry and a sensor which can be used for point measurements or continuous monitoring. The output is in volts and can be converted to soil moisture based on a linear calibration equation (Charlesworth, 2005).

2.3.3. Tensiometers

This device used for measuring soil $\psi_m$ is comprised of a tube filled with water, attached to ceramic cup on one end and a vacuum gauge on the other. During installation, the ceramic tip or cup must make firm contact with the soil at the desired depth. To ensure good contact between the tensiometer and soil, water or soil slurry can be used during insertion into the soil. This includes pushing the device right to the bottom of the hole prepared for it. The maximum pressure range is from 0-75 kPa, and pressure readings are then converted to $\theta$, through the soil characteristic curve (http://www.irrometer.com). The same principle is used with Water Mark equipment data readings, expressed in centibars (McCann et al., 1992).

2.3.4. Electrical resistance sensors

An electrical resistance device is housed in a gypsum block or other granular matrix material. Usually an auger is used to place these sensors at multiple depths throughout the soil
profile, and slurry or water is used to ensure firm contact with surrounding soil. The moisture data is transmitted to and stored in a data logger. These sensors read in centibars of soil tension, ranging from 0-200 kPa, and then converted to $\theta_v$ (McCann et al., 1992; Spaans and Baker, 1992).

2.3.5. **Neutron probe**

Neutron probes or neutron moisture meters (NMM) are another way of measuring $\theta_v$. They are considered to be among the most robust and accurate methods of soil water content measurement (Charlesworth, 2005). The principle is that fast moving neutrons arising from a small radioactive source collide with hydrogen ions in the soil and are slowed down; the higher the water content, the higher the extent of collisions. (George, 1999) However, due to perceptions of radiation safety threat, its use has declined.

2.4. **Irrigation scheduling criteria**

In southern Ontario, the need for more efficient and timely management of water applications is increasing in commercial fruit production. However, decisions regarding irrigation and water conservation are still made by traditional techniques based on the growers’ past experience, (e.g., the hand-feel method). For improved accuracy and precision in irrigation scheduling, scientific irrigation systems (SIS) have proven more effective in water management, especially for large corporate farms. Such a scheduling system can be implemented by continuous soil moisture monitoring using soil moisture sensors in the field or indirectly by measuring climatic parameters, calculating evapotranspiration and using a water balance to predict moisture in the root zone (Leib et al., 2002). The first method constitutes the scope of this study. In strawberry production, certain information needs to be collected regarding the field and
soil moisture level, in order to schedule irrigation based upon soil moisture thresholds for triggering SIS irrigation.

2.4.1. Soil available water

The development of a proper rooting system and the uptake of the required amount of water from the soil are critical at every stage in plant growth. Too much or too little soil moisture can have direct effects on fruit production. When the soil moisture exceeds the field capacity ($\theta_{fc}$), it causes water logging in the soil and depresses oxidative processes in the root zone. Field capacity is the soil moisture status after a saturated soil has been drained by gravity (Hanson et al., 2004). On the other hand, if the soil moisture drops to a level below the permanent wilting point ($\theta_{pwp}$), then the rooting system cannot extract the moisture from the soil, because the soil is too dry. Hence, the available soil water (AW) is defined as: $\text{AW} = \theta_{fc} - \theta_{pwp}$ (Brouwer et al., 1985; Werner, 1993).

![Figure 2.1. Soil moisture profile for a typical soil (Werner, 1993)](image-url)
2.4.2. Management allowable depletion

The traditional rule of thumb for irrigation scheduling was to make simple on-off decisions in terms of water applications to the field. Studies have shown this approach to be inadequate and cause water stress under intensive irrigation for high value crops (Werner, 1993). The management allowable depletion (MAD) technique uses the percent of available water depleted (or remaining) in the soil profile, as the factor to minimize crop stress. Irrigation triggers are determined based on the crop rooting depth, to prevent soil moisture from reaching the permanent wilting point. As a crop's rooting depth varies, the recommended soil moisture depletion is directly tied to the crop grown. For deep-rooted crops, peaches [Prunus persica (L.) Batsch] will use a greater volume of the soil profile for withdrawing water than a shallow-rooted crop, such as peppers [Capsicum annum L.], and thus have access to more water in between irrigations (Thompson et al., 2006; Hanson and Orloff, 2007). During the critical plant growth stages, such as fruiting and ripening for strawberries, the management allowable depletion levels are smaller to meet the crop’s higher water use. For instance, in the cell division and pre-harvest stage for peaches, the recommended MAD is 40% whereas at other stages it can be upto 65% (Hanson et al., 2004).

2.4.3. Setting triggers for irrigation

Critical factors for determining the right irrigation triggers based on soil moisture levels are the type of irrigation system (i.e. drip, trickle, sprinkler, etc.) used; the crop being grown; the growth stage of the crop; and the soil characteristics. For drip irrigation, different studies have recommended different levels of soil moisture depletion (MAD) varying from 10% (Lebouef et al., 2007), 15% (Nyvall, 2005), 25% (Nyvall, 2002) and a range of 10-30% (Bierman, 2005). The corresponding range in studies with sprinkler systems was from 30-50%. Nyvall (2002)
suggested MAD levels of 50% for strawberries, while Hanson (2004) suggested 15% and Ley (1994) suggested a range of 50-65%.

Another governing factor for irrigation scheduling is soil texture, as the water holding capacity is different for different soils. Hanson (2004) provided generalized values for field capacity, permanent wilting point and available soil water, for a range of soil types from sand to clay. The soil texture of the field in this study was sandy loam. The literature values referenced for comparison with field results are given in Table 2.1.

Table 2.1. Volumetric soil moisture content at field capacity, permanent wilting point and available soil water (Hanson, 2004)

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Field Capacity (%)</th>
<th>Permanent Wilting Point (%)</th>
<th>Available Soil Water Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>10</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>16</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>21</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Loam</td>
<td>27</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Sandy Clay Loam</td>
<td>36</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>32</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>29</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>28</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Clay</td>
<td>40</td>
<td>22</td>
<td>18</td>
</tr>
</tbody>
</table>

2.5. **Crop response to irrigation scheduling**

Horticultural crops can be managed by different practices ranging from greenhouse to perennial field crop production. In both scenarios, water application is the element which most affects quality and yield (Blatt, 1984; Rolbiecki et al., 1997; Evenhuis et al. 2002; and Kirnak et al., 2003). In commercial fruit production, yield response to the water application shows substantial variation in relation to the natural climatic condition and their management *i.e.* cultivar used, cultivation practices, soil and variety selection. The timing and amount of water
must be adjusted according to the plant growth stage, with a view to maximizing marketable yield.

The introduction of drip irrigation systems has resulted in more efficient water use in field irrigation, compared to other types of irrigation systems (Rzekanovski, 1997; Rolbiecki et al., 2004). Researchers have investigated various methods for irrigation scheduling with reference to strawberry production. Some studies have given more importance to climatic models and consider it as the prime factor for better output (Krüger et al., 1999; Yuan et al., 2004). Other studies have indicated that the use of sensors for the soil moisture measurement have proven better in irrigation management and resulted in higher yield (Evenhuis et al., 2002; Kirschbaum et al., 2004).

When unexpected changes in the evaporative leaf surface area occur, climatic models have not shown a significant response (Evenhuis et al., 2002), which makes it difficult to estimate a crop coefficient for strawberry production (Trout et al., 2004). Irrigation water requirements of the strawberry crop vary with the cultivar used and the growth stage (Krüger et al., 1999). Furthermore, cultivation and management practices, defoliation and mulching also have certain effects on soil moisture and on soil structure (Marshall et al., 1996). Increases in irrigation water did not necessarily show positive effects on fruit size or fruit firmness, though some adverse effects were observed (Goulart et al., 1986). However in studies where drip irrigation was used under plastic greenhouse conditions, such a system was shown to efficiently provide adequate irrigation, increase yield and improve the economic returns of the strawberry crop. Strawberry production in Southern Ontario commonly uses raised beds, with plastic mulch covering the drip irrigation line to conserve water, control weeds with less use of herbicides, and keep the fruit clean. These practices also enhance fruit size, nutritive value, and give rise to early
maturity of the produce. Strawberry plants grown on raised beds under plastic mulch have uniform and deeper root growth and distribution as compared to flat beds (Dwyer et al., 1987; Albregts et al., 1996; Hochmuth et al., 1996; and Kruger et al., 1999).

Drip irrigation works best on horticultural row crops such as strawberries, both in terms of water use efficiency and yield. Excessive soil moisture has an adverse effect on strawberry yield and quality, by causing root rot and causing anaerobic conditions for plant tissue growth. Inadequate soil moisture can cause stress, affect fruit quality and reduce yields. The most favourable irrigation system can be defined as that by which a timely and sufficient water application is made, without simultaneously causing leaching of soil nutrients into deeper zones (Kruger et al., 1999). Management of a drip irrigation system on a high frequency application basis combined with plastic mulch provides sufficient soil moisture at the root zone while ensuring water savings.

TDR-based soil moisture sensors are commonly used to monitor soil moisture in intensive production of high-value crops (such as strawberries). Although TDR has a pivotal role in scheduling irrigation, certain types of sensors present challenges or limitations, which must be evaluated and overcome, and require proper installation and calibration. Different TDR devices employ different designs to estimate soil moisture by indirect measurement, resulting in differences in performance and mode of use. In this study the performance of the GP (Environmental Sensors Inc) and WCR (Campbell Scientific CS 625) are evaluated, installed at the depth of strawberry root front.

Strawberries have very low tolerance to water deficiency, dry soil and poor drainage, because of their shallow root zone (Kalle et al., 2007). In Southern Ontario this fruit has
enormous production potential at the commercial level. To ensure strawberry fruit quality and meet market demands, growers use or have adopted state-of-the-art technologies in their field management, particularly with respect to water resources for irrigation purposes. On the other hand, manufacturers have developed a variety of soil moisture sensors, providing growers a wide selection of appropriate sensors based on critical factors i.e. crop irrigation requirement, cost investment, labour requirement and suitability of the system to the crop (Blatt et al., 1984).

Strawberries can be cultivated on open field raised beds and as well under plastic high tunnels with plastic mulch. In both production practices polyethylene film or plastic sheets are used for a number of purposes: tunnel cover, plastic mulching, and irrigation drip tape (Yuan et al., 2004). There are certain differences in the climatic factors in field and tunnel strawberry cultivation. Strawberry production in the field is directly exposed to sunlight and other environmental and climatic changes occurring during the crop's growing season. In plastic high tunnel production systems, some climatic factors such as intense rainfall, high evapotranspiration, strong winds, and their effects on plants are mitigated due to the controlled environment (Kalle et al., 2007).

Irrigation scheduling in Southern Ontario requires real time management. In Ontario 20% of the total water is used by the agricultural sector (De Loë et al., 2001). Irrigation water needs are highly seasonal, with 54% of irrigation water being used in the summer (June, July, and August). While most corporate growers employ the same water conservation and irrigation strategies (Dolan et al., 2000), greater focus on efficient water use is needed to overcome future challenges in water supplies. Thus it is very important to ensure that growers use water in the most efficient possible way to obtain optimum yield and high quality product. But this can only be achieved by proper irrigation scheduling.
Crop yield analysis is an effective procedure for assessing economic benefits of any fruit production system in the greenhouse and the field. The objective of planting any fruit crops is to obtain the highest yield and the highest quality. To improve fruit yield and quality, an increasing number of fields have adopted high tunnels for strawberry production. 80% of these tunnels are made of plastic, and are usually used in a side opening condition (Haraguchi et al., 2000). Commonly, strawberries are cultivated in open field and inside the plastic high tunnels for berry production and plastic mulching is widely used in raised-bed culture of strawberry to save water, keep the fruits clean, increase the fruit size and yield and to enhance earliness and fruit quality. The black color plastic mulch is used to control weed and thus minimize the use of herbicides (Blatt, 1984; Baumann et al., 1993; Kasperbauer, 2000). Strawberries planted on raised beds develop deeper, strong and more uniform root distribution as compare to flat beds. This type of practice indicates that raised beds provide more favorable soil medium for root growth (Goulart and Funt, 1986; Dwyer et al., 1987; Albregts et al., 1991; Hochmuth et al., 1996).
CHAPTER 3

3. METHODOLOGY

3.1. Site description

This study was conducted at Strawberry Tyme Farm Inc, Simcoe, Ontario from May 1st to Oct 15th 2007. The site provided an opportunity to compare drip irrigation under two types of strawberry production practices (open field vs. plastic high tunnel) under plastic mulch. In this study, two types of time domain reflectometry (TDR) based sensors were evaluated for their ability to accurately estimate $\theta_i$ in a 0.30 m soil profile planted to strawberries.

3.1.1. Site layout

The experimental layout was identical for the two study plots (Table 3.1). Both systems had the same variety of strawberries planted in Fall 2006 in raised beds under plastic mulch. The plots chosen were 213 m long and 5.5 m wide. For the plastic high tunnels, this comprised one bay, with four beds in the bay. For both plots, each bed was 1 m wide with 4 rows of strawberries planted on the bed, at a spacing of 0.28 m.

Table 3.1. Plot specifications

<table>
<thead>
<tr>
<th>Crop: Strawberry</th>
<th>Irrigation: 2 drip tapes per bed</th>
<th>Planted: Fall 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open field</td>
<td>0.80</td>
<td>5</td>
</tr>
<tr>
<td>Tunnel</td>
<td>0.80</td>
<td>5</td>
</tr>
</tbody>
</table>
The drip irrigation system was the same inside the plastic high tunnels and in the open field (Table 3.2). The raised beds were surface drip irrigated, with 2 drip tapes on each bed. The emitter spacing was 0.3 m and the design flow rate was 0.91 L hr\(^{-1}\).

### Table 3.2. Drip irrigation system specifications

<table>
<thead>
<tr>
<th>System</th>
<th>Brand</th>
<th>No. of Emitters</th>
<th>Emitter spacing (m)</th>
<th>Pressure (kPa)</th>
<th>Emitter Flow rate (L hr(^{-1}))</th>
<th>System flow rate (L hr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Field</strong></td>
<td>Surface</td>
<td>56000</td>
<td>0.3</td>
<td>69</td>
<td>0.91</td>
<td>50870</td>
</tr>
<tr>
<td><strong>Plastic High Tunnel</strong></td>
<td>Surface</td>
<td>56000</td>
<td>0.3</td>
<td>69</td>
<td>0.91</td>
<td>50870</td>
</tr>
</tbody>
</table>

The factors that were constant for both plots were: crop variety, design of raised beds with plastic mulch, and the irrigation system. The main difference between the plastic high tunnels and open field is irrigation scheduling, which was influenced by the different climatic conditions such as rainfall, evapotranspiration rate, humidity and sunlight. All of these factors directly affect crop growth due to the number of heat units available to the plant between the open fields and the plastic high tunnels. The plastic high tunnels create a different microclimate for the strawberries compared to open fields. A second important difference is soil type, which is addressed in the following section. Both variables directly affect soil moisture.

3.1.2. **Benchmark sampling locations**

Some measures were taken to account for the variability in soil texture between the plots. In addition to the sensor locations, also known as main equipment zone (ME), four benchmark zones (BM) were identified for each plot in consultation with the grower. Through the growing season, soil samples were collected at the 2 ME and 8 BM locations with the objective of monitoring the spatial variability of soil moisture (Figure 3.1.). As water applications within a plot are constant, the BM demonstrates the influence of spatial variability in soil type and
topography. Soil samples were also collected at the beginning of the season at ME and BM locations and analyzed for textural class, organic matter, bulk density, field capacity and permanent wilting point. This is described in detail in section 3.4.

![Study plots - soil sampling and sensor locations](image)

**Figure 3.1. Study plots – soil sampling and sensor locations**

### 3.2. Soil moisture sensor descriptions

Both sensors types are TDR-based, provide $\theta_v$, and were permanently installed in the study area for the duration of the strawberry fruiting season, ending in mid October 2007. Both sensors have a similar operating mechanism and were connected by cables to data loggers. The data were periodically transferred from the data logger to a laptop computer. The two sensors are described in more detail in the following sections.

#### 3.2.1. Campbell Scientific water content reflectometer

Time domain reflectometry is based on estimating the dielectric permittivity ‘$\varepsilon$’ of the soil (Kelleners et al., 2005). The WCR (model CS625) is a device which operates on the principle of dielectric properties. The WCR CS625 measures $\varepsilon$ of surrounding materials, and changes its output value based on the property of the medium surrounding it. Since water is a medium of high $\varepsilon$ and is the only component inside the soil which changes significantly in the
concentrations, the WCR can effectively be used to determine $\theta_v$ at any particular location (Leib et al., 2003).

The principle of operation of the CS625 is based on the propagation of an electromagnetic pulse along the probe with different velocities depending on the $\varepsilon$ of the surrounding media. An increase in $\theta_v$ increases the polarization time and thus decreases the propagation velocity along the probing rods, which are installed at a depth of 0-0.3 m in the study plot. The probe rods’ receptiveness to dielectric permittivity can be used to determine the $\theta_v$. The output frequency or period is empirically related to the water content. In this study, the manufacturer’s calibration equation (Eq. 3.1) was used (CS625 Instruction Manual, 2006). Since this was a one crop growing season study, it was not possible to collect an adequate number of soil samples for site-specific calibration at the beginning of the season. Moreover, the analysis of water holding capacity was only completed mid-season. Therefore, to ensure consistency, the manufacturer’s calibration equation was used throughout the growing season:

$$\theta_v = -0.0663 - 0.0063 t + 0.0007 t^2$$

where,

\[ t \quad \text{is the period of time (\(\mu\text{sec}\)), and} \]

\[ \theta_v \quad \text{is the volumetric water content (cm}^3\text{ cm}^{-3}\text{).} \]

3.2.2. Environmental Sensors Inc. Gro-Point

The second TDR used in this study was the Gro-Point probe from ESICA (Environmental Sensors Inc, Sidney, BC). The operating system of the Gro-Point works on a principle similar to that of the WCR. The difference is that the voltage pulse is temporary and is not reflected by the wire guides. For installation, a trench is dug at the desired depth (0.20 m) using a shovel. The
Gro-Point sensors are then placed in the trench at the desired depths and soil hand packed around them to avoid air pockets.

3.3. **Sensor installation and monitoring**

The soil moisture sensors were installed along the drip tape and in between two plant rows to monitor the variability in soil moisture available to the plants. Due to the presence of the plastic mulch, it was not possible to ascertain the exact locations of the drip emitters before installation. This was verified at the end of the growing season. However, an attempt was made to be consistent in installing the sensors in both plots. In the open field, the WCR and GP were installed at a distance of 115 mm and 25 mm from the drip tape emitters, respectively. In the plastic high tunnels, the corresponding distances were 115 mm (WCR) and 230 mm (GP) (Figure 3.2.).

The protocols used for the installation of the sensors and the laboratory tests were drawn from the instrument manuals. Data was downloaded weekly from the field data logger and triplicate soil samples were taken twice a week, over the entire season, for gravimetric $\theta_v$ determination, which was also used as a standard for the sensor-produced data.
Figure 3.2. Sensor placement and layout on the raised beds.
The WCR CS625 sensors were connected to a Campbell Scientific CR205 datalogger. The sensors were installed at a depth of 0-0.3 m to monitor the mean soil moisture of the entire root zone of the strawberry crop. The 0.3 m probe rods were installed vertically in the soil profile to give an average measurement for the complete root zone. Data were downloaded to a laptop computer using the LoggerNet software. The GP sensor was installed vertically to a depth of 0.2 m, which is a limitation due to a shorter probe length. Data was continuously recorded on the Gro-Point datalogger and downloaded to a laptop computer or a data shuttle during field visits. All sensors were setup to run continuously, with the WCR and GP outputting mean soil moisture ($\theta_c$) every 4 hours and every 20 minutes, respectively, throughout the growing season.

*Table 3.3. Sensor installation specifications*

<table>
<thead>
<tr>
<th>Soil Moisture Sensor</th>
<th>Profile Depth</th>
<th>Orientation</th>
<th>Datalogger</th>
<th>Measurement frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content reflectometer</td>
<td>0-0.30 m</td>
<td>Vertical</td>
<td>Campbell Scientific CR205</td>
<td>4 hours</td>
</tr>
<tr>
<td>Gro-Point</td>
<td>0-0.20 m</td>
<td>Vertical</td>
<td>Gro-Point Data logger</td>
<td>20 minutes</td>
</tr>
</tbody>
</table>

As one of the objectives of the study was to compare water use as a consequence of the different irrigation schedules in the two study plots, records of number of hours irrigated in each plot were maintained by the grower. Moreover, a flow meter was installed to quantify the flow during the irrigation in the plastic high tunnels. Due to budget constraints, a flow meter was not installed for monitoring open field irrigation. However, the grower maintained a record of the number of hours irrigated in both the plastic high tunnels as well as the open field. These records were used to estimate the amount of irrigation based on design flow rate, which was then compared with the flow meter data.
3.4. Soil sampling and data collection

To obtain baseline data, the soil physical properties and AW were determined. Soil variability of the study plot was ascertained by collecting triplicate soil core samples from each benchmark. Four sets of triplicate samples were taken from both fields to a depth of 0.05 m from the surface. In addition, samples were also collected at the depth of 0.20-0.25 m at the sensor locations (ME), representing the effective root zone. All the soil cores collected were carefully packed in cheese cloth, placed in re-sealable plastic bags, and kept in a cooler while transported to the laboratory at the Macdonald Campus of McGill University, where they were subsequently stored in a refrigerator. The samples were analyzed for $\theta_{fc}$, $\theta_{pwp}$, bulk density ($\rho_{soil}$), organic matter content and textural classification.

Bulk density estimations were done using steel cores with dimensions of 0.05 m diameter and 0.025 m in length. The same soil samples were used for the particle size and organic matter analyses (loss on ignition method). For determining water holding capacity of the study area, further triplicate sampling was done and these samples were analyzed for water retention characteristics using a pressure plate apparatus (Delwyn and Rahardjo, 1993). The $\theta_{fc}$ and $\theta_{pwp}$ are important soil properties when using soil sensors in scheduling irrigation, since they are required to calculate AW and percent AW depletion. Furthermore, soil sampling for gravimetric analysis was carried out twice a week, using a hand-held auger. Three replicate soil samples were taken from each benchmark and samples were collected at two different depths: 0-0.1 m and 0.1-0.3 m.

Standard measurement procedures (Black, 1965) were followed to determine $\theta_g$ or $\theta_v$. A wet soil subsample (20 g) was weighed and dried in the oven at 105$^0$ C for 24 hours, the
difference between the dry and wet soil represented the moisture in the soil subsample. The weight balance error was assumed to be ±0.01 g.

The following equations were used to determine soil moisture content in a given sample of soil:

\[
\theta_s = \frac{(\text{wgt wet soil sample + tare}) - (\text{wgt of dry soil sample + tare})}{(\text{wgt of dry soil + tare}) - \text{tare}}
\]  

(3.2)

The soil volumetric water content was calculated as

\[
\theta_v = \theta_s \times \frac{\rho_{\text{soil}}}{\rho_{\text{water}}}
\]  

(3.3)

where, \(\rho_{\text{water}}\) is the density of water (g cm\(^{-3}\)), equal to 1.0, and the other parameters are as previously defined.

3.5. Setting triggers for irrigation

At the start of the growing season, irrigation scheduling decisions were left entirely to the grower, based on his experience of the field and cropping system. As this study constitutes a part of a larger project (COWSEP, 2007), there were logistical delays between obtaining baseline results for soil texture, field capacity and permanent wilting point. Hence, a certain degree of guesswork was unavoidable during the initial month. Once initial soil moisture trends were established and soil physical properties obtained, regular meetings were held with the grower to ascertain appropriate triggers for irrigation in the open field and plastic high tunnels. Based on a literature review (Lebouef et al., 2007; Nyvall, 2005; Nyvall, 2002; Bierman, 2005), these
triggers were in the range of 10-30% of soil moisture depletion (MAD) for strawberries. Hence for this study, the recommended soil moisture range was 65%-85% of field capacity, which approximately translates to a threshold of 35% soil moisture depletion for initiating irrigation.

3.6. Calculation of equivalent water depth

Irrigation water applications were converted into equivalent water depth (EWD) for the effective strawberry crop rooting depth of 0.3 m. The maximum soil water storage capacity (or saturation) can be calculated as follows:

\[
MSWS = \frac{\theta_{fc} \times ECRD}{100}
\]  

(3.4)

where MSWS is the maximum soil water storage in mm, \(\theta_{fc}\) is the volumetric field capacity (cm\(^3\) cm\(^{-3}\)) ECRD is the effective crop rooting depth in mm.

Similarly, EWD is calculated as follows:

\[
EWD = \frac{\theta_v \times ECRD}{100}
\]  

(3.5)

Where EWD is the equivalent water depth, \(\theta_v\) is the volumetric soil moisture content (cm\(^3\) cm\(^{-3}\)) and ECRD is the effective crop rooting depth.

The effective crop rooting depth for strawberries is 0.3m. For both the WCR and GP sensors, EWD was calculated for the depth of installation, i.e. 0-0.3m for the WCR and 0-0.2 m for the GP sensor. This was compared with the calculated EWD from gravimetric samples, also calculated to 0.3m using equation 3.5.

EWD calculations were performed for both the flow meter data as well as the grower’s irrigation records on the number of hours irrigated. The number of irrigation hours were converted to volume of
water applied using the irrigation system specifications (Table 3.2). The irrigation water use in mm is calculated as:

\[
\text{Irrigation water use} = \frac{\text{Emitter flow rate} \times \text{Operating time} \times 1000}{\text{Irrigated area}}
\]  

(3.6)

Where irrigation water use is in mm, emitter flow rate is in m\(^3\) hr\(^{-1}\), operating time is in hr and irrigated area is in m\(^2\).
CHAPTER 4

4. RESULTS AND DISCUSSION

4.1. Site rainfall

An automated weather station installed by the Weather Innovation Network (WIN), one of the project partners, provided the precipitation from May 17\(^{th}\) to Oct 16\(^{th}\) (Figure 4.1). The total growing season rainfall was 217.4 mm. The rainfall recorded at the site was compared with Environment Canada’s 30-year climate normals from nearby weather stations, for data recorded between 1971 and 2000. The two nearest stations were Nanticoke, Ontario which is at a distance of 25 km from Simcoe, and Waterford, Ontario which lies within 15 km of Simcoe. The normal cumulative rainfalls at these stations for the months of May to October were 449.1 mm and 505.9 mm, respectively (Table 4.1). This shows that the study year was an exceedingly dry year, as the
recorded rainfall at Simcoe was 52% and 57% below normal when compared to Nanticoke and Waterford, respectively.

*Table 4.1. Monthly cumulated rainfall at Simcoe study site and Foldens, and climate normals for nearby weather stations.*

<table>
<thead>
<tr>
<th>Precipitation data</th>
<th>Distance from site (km)</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-year (1971-2000) Normals, Nanticoke, Ont.</td>
<td>25</td>
<td>73.9</td>
<td>83.6</td>
<td>95.4</td>
<td>90.2</td>
<td>110.5</td>
<td>85.7</td>
<td>449.1</td>
</tr>
<tr>
<td>30-year (1971-2000) Normals, Waterford, Ont.</td>
<td>15</td>
<td>73.3</td>
<td>87.2</td>
<td>89.2</td>
<td>81.1</td>
<td>98.0</td>
<td>77.1</td>
<td>505.9</td>
</tr>
<tr>
<td>30-year (1971-2000) Normals, Foldens, Ont.</td>
<td>50</td>
<td>77.1</td>
<td>86.6</td>
<td>98.8</td>
<td>93.3</td>
<td>91.7</td>
<td>76.1</td>
<td>523.6</td>
</tr>
<tr>
<td>2007 Growing Season, Foldens, Ont.</td>
<td>50</td>
<td>48.8</td>
<td>11.6</td>
<td>53.4</td>
<td>87.0</td>
<td>48.1</td>
<td>41.7</td>
<td>290.6</td>
</tr>
<tr>
<td>2007 Growing season, study site in Simcoe, Ont.</td>
<td>0</td>
<td>-</td>
<td>20.2</td>
<td>36.8</td>
<td>58.4</td>
<td>74.2</td>
<td>27.8</td>
<td>217.4</td>
</tr>
</tbody>
</table>

As of this writing, rainfall data for the study year (2007) were not available online for the Waterford and Nanticoke weather stations. The closest station with recorded and available data was found to be Foldens, located some 50 km from Simcoe. Based on historical normals, Foldens receives around 25-75 mm more rainfall through the months of May-October than the two stations within a 25 km distance of the study site. In the study year, the total rainfall recorded at Foldens was 290.6 mm, which is consistent with the study site's weather station record of 217.4 mm (i.e. a difference of 73.2 mm). This is additional evidence that 2007 was a particularly dry growing season, with rainfalls being about 50% below normal in the region.
4.2. Soil characteristics

The soil physical properties were evaluated in the laboratory at McGill University, Macdonald Campus, to acquire baseline information regarding the study plots and for subsequent analysis pertaining to the irrigation scheduling and sensor evaluations. These soil results are presented in Table 4.2. There was significant difference in soil properties, such as soil texture, water holding capacity, and bulk density in the open field vs. plastic high tunnel field. Also, soil heterogeneity was found between the sampling benchmarks in both study plots, i.e. within open field and plastic high tunnel strawberries under the plastic mulch (Table 4.2). Volumetric soil moisture was expressed as cm$^3$ per 100 cm$^3$, but for ease in writing this is given as mL dL$^{-1}$.

In examining different soil parameters and comparing the results with literature values, inconsistencies were observed in some variables. The values for the $\theta_{pwp}$ were quite high compared to literature values for similar soils. Moreover, some of the samples for the benchmarks both in open field and plastic high tunnel were not analyzed for $\theta_{pwp}$ as the soil cores were disturbed in transit. Also, some samples gave erroneous $\theta_{pwp}$ values due to a faulty pressure plate apparatus. Hence, literature values have been used along with the measured $\theta_{fc}$ for calculating irrigation trigger points. The values of $\theta_{pwp}$ adopted were 7 mL dL$^{-1}$ for loamy sand and 9 mL dL$^{-1}$ for sandy loam, for both open field and plastic high tunnels (Hanson, 2004).

4.2.1. Sensor locations

Soil particle analysis for the topsoil at the sensor locations showed the soil of plastic high tunnels to be a loamy sand, comprised of 80.5% sand, 15.6% silt, and 3.9% clay, while that of the open field was a sandy loam with 57.2% sand, 39.6% silt, and 3.24% clay. However, at the rooting depth of 0.25 m, both plots were classified as sandy loams, with the sand-silt-clay percentages being 69.6-14.7-15.7 for the open field and 57.3-24.8-17.9 for the plastic high
tunnels. Bulk densities at the 0.25 m depth were higher than the topsoil, a sign of compaction caused by machinery and human traffic.

In the open field, $\theta_{fc}$ at 0.05m and 0.25m were 12.0 mL dL$^{-1}$ and 19.0 mL dL$^{-1}$, respectively. This greater water retention at the lower depth was despite the 12% greater sand content at 0.25 m than 0.05 m, probably because the lower depth contained 15.7% clay compared to 3.2% at 0.05 m. In comparison, for the plastic high tunnel, $\theta_{fc}$ at 0.05 m was 15.3 mL dL$^{-1}$ whereas at 0.25 m it was 18.3 mL dL$^{-1}$. This 3 mL dL$^{-1}$ difference in $\theta_{fc}$ may be attributed to the greater clay (17.9%) and lower sand content (23%) at 0.25 m vs. 0.05 m. The difference of 0.5 mL dL$^{-1}$ in $\theta_{fc}$ between open field and plastic high tunnel might also be attributable to the loamy topsoil and textural difference in percentage of silt and clay (Table 4.2).

### 4.2.2. Benchmark locations

Similar to the ME zone, soil samples were collected at the 8 BM locations across the two study plots. However, due to time and budget constraints, analyses could only be performed for the topsoil (0.05 m) at the BM locations.

#### 4.2.2.1. Open field benchmarks

Three of the four BM were characterized as a sandy loam soil, with the exception of BM1, which was loamy sand. The $\theta_{fc}$ at BM1 in the open field was the lowest of all four benchmarks, at 14.7 mL dL$^{-1}$, and may be attributed to it having the greatest percentage of sand (81%). The $\theta_{fc}$ at BM2 was the greatest at 21.5 mL dL$^{-1}$, which may be attributed to its lower sand content (24%) and highest clay content (9.2%) among the all the topsoil samples. The difference of 7 mL dL$^{-1}$ in $\theta_{fc}$ is thus accounted for by the variability in the textural analysis (Table 4.2).
4.2.2.2. Plastic high tunnel benchmarks

Textural analyses of the BM found two locations characterized as a loamy sand (BM1, BM4), and two as a sandy loam (BM2, BM3). This spatial variability is due to the proximity of each pair of locations, as compared to the other pair. BM1 and BM4 lie at the east end of the bed, whereas BM2 and BM3 are located at the west end, almost 180 m apart. This difference is reflected in the field capacity values. The $\theta_{fc}$ in the plastic high tunnel at BM1 and BM4 were similar at 11.2 mL dL$^{-1}$ with the same loamy sand soil, and the $\theta_{fc}$ at the BM2 and BM3 sites were also similar, with values of 17.2 mL dL$^{-1}$ and 18.0 mL dL$^{-1}$. Benchmarks BM2 and BM3 have the same bulk density, roughly the same sand content, with the only difference being in silt-clay content. The 7 mL dL$^{-1}$ difference in $\theta_{fc}$ between the benchmarks in plastic high tunnel is likely due to the higher percentage of sandy soil in these locations of the study plot.
Table 4.2. Soil physical properties of experimental plots

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Depth</th>
<th>$\theta_{fc}$</th>
<th>$\theta_{pwp}$</th>
<th>Bulk density</th>
<th>Porosity$^a$</th>
<th>Organic matter</th>
<th>Textural Analysis</th>
<th>Soil class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>mL dL$^{-1}$</td>
<td>mL dL$^{-1}$</td>
<td>g mL$^{-1}$</td>
<td>cg g$^{-1}$</td>
<td>cg g$^{-1}$</td>
<td>cg g$^{-1}$</td>
<td>% sand</td>
</tr>
<tr>
<td>Open field</td>
<td>0.05</td>
<td>12.0</td>
<td>11.1</td>
<td>1.44</td>
<td>0.46</td>
<td>2.6</td>
<td>57.2</td>
<td>39.6</td>
</tr>
<tr>
<td>Sensor location (ME zone)</td>
<td>0.25</td>
<td>19.0</td>
<td>18.3</td>
<td>1.55</td>
<td>0.42</td>
<td>1.4</td>
<td>69.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Open field – Benchmarks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM1</td>
<td>0.05</td>
<td>14.7</td>
<td>7.0 *</td>
<td>1.36</td>
<td>0.49</td>
<td>2.3</td>
<td>80.2</td>
<td>13.1</td>
</tr>
<tr>
<td>BM2</td>
<td>0.05</td>
<td>21.5</td>
<td>9.0 *</td>
<td>1.41</td>
<td>0.47</td>
<td>3.3</td>
<td>67.0</td>
<td>23.8</td>
</tr>
<tr>
<td>BM3</td>
<td>0.05</td>
<td>16.4</td>
<td>9.0 *</td>
<td>1.21</td>
<td>0.54</td>
<td>2.3</td>
<td>66.7</td>
<td>30.6</td>
</tr>
<tr>
<td>BM4</td>
<td>0.05</td>
<td>15.6</td>
<td>9.0 *</td>
<td>1.45</td>
<td>0.45</td>
<td>3.0</td>
<td>73.0</td>
<td>18.9</td>
</tr>
<tr>
<td>Plastic high tunnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor location (ME zone)</td>
<td>0.05</td>
<td>15.3</td>
<td>14.7</td>
<td>1.51</td>
<td>0.43</td>
<td>2.3</td>
<td>80.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Tunnel - Benchmarks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM1</td>
<td>0.05</td>
<td>11.2</td>
<td>7.0 *</td>
<td>1.44</td>
<td>0.46</td>
<td>2.2</td>
<td>81.5</td>
<td>10.1</td>
</tr>
<tr>
<td>BM2</td>
<td>0.05</td>
<td>17.2</td>
<td>9.0 *</td>
<td>1.35</td>
<td>0.49</td>
<td>3.1</td>
<td>66.2</td>
<td>32.1</td>
</tr>
<tr>
<td>BM3</td>
<td>0.05</td>
<td>18.1</td>
<td>9.0 *</td>
<td>1.35</td>
<td>0.49</td>
<td>3.0</td>
<td>65.4</td>
<td>25.8</td>
</tr>
<tr>
<td>BM4</td>
<td>0.05</td>
<td>11.2</td>
<td>7.0 *</td>
<td>1.38</td>
<td>0.48</td>
<td>1.9</td>
<td>76.8</td>
<td>19.8</td>
</tr>
</tbody>
</table>

* Estimated from Hanson (2004)

$^a$ Porosity is calculated assuming a soil particle density ($d_p$) of 2.65 Mg m$^{-3}$ for mineral soils. Porosity = 1 – $d_b$/d_p where $d_b$ is bulk density and $d_p$ is soil particle density.
4.3. **Open field**

4.3.1. **Gravimetric data**

To address the study's first objective, soil samples were analyzed by gravimetric methods and \( \theta_v \) calculated. All the \( \theta_v \) values acquired from gravimetric analysis are plotted in Figure 4.2 and Figure 4.3. Over the season, \( \theta_v \) in the topsoil (0-0.1 m) varied between 13.2 mL dL\(^{-1}\) and 38.5 mL dL\(^{-1}\) (Figure 4.2; Table 4.4). Moreover, the moisture at a depth of 0.1-0.3 m varied from a minimum of 10.9 mL dL\(^{-1}\) to a maximum of 34.4 mL dL\(^{-1}\) (Figure 4.3; Table 4.4). The \( \theta_v \) values found for both depths were quite high in reference to the calculated field capacity of 19 mL dL\(^{-1}\) and the literature estimate of 21 mL dL\(^{-1}\) (Hanson, 2004), indicating that the soil moisture was mostly over field capacity or near saturation levels.

**Table 4.3. Seasonal statistics for volumetric soil moisture (mL dL\(^{-1}\)) in the open field**

<table>
<thead>
<tr>
<th>Site</th>
<th>BM1</th>
<th>BM2</th>
<th>BM3</th>
<th>BM4</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Loamy sand</td>
<td>Sandy loam</td>
<td>Sandy loam</td>
<td>Sandy loam</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>0.0-0.1</td>
<td>0.1-0.3</td>
<td>0.0-0.1</td>
<td>0.1-0.3</td>
<td>0.0-0.1</td>
</tr>
<tr>
<td>Seasonal mean (mL dL(^{-1}))</td>
<td>23.1</td>
<td>25.7</td>
<td>28.8</td>
<td>30.2</td>
<td>18.7</td>
</tr>
<tr>
<td>Seasonal minimum (mL dL(^{-1}))</td>
<td>17.8</td>
<td>21.6</td>
<td>14.6</td>
<td>23.6</td>
<td>13.4</td>
</tr>
<tr>
<td>Seasonal maximum (mL dL(^{-1}))</td>
<td>32.4</td>
<td>30.6</td>
<td>38.5</td>
<td>34.4</td>
<td>25.5</td>
</tr>
<tr>
<td>Median (mL dL(^{-1}))</td>
<td>22.7</td>
<td>26.3</td>
<td>28.9</td>
<td>30.4</td>
<td>18.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.035</td>
<td>0.02</td>
<td>0.043</td>
<td>0.02</td>
<td>0.029</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.006</td>
<td>0.004</td>
<td>0.007</td>
<td>0.004</td>
<td>0.005</td>
</tr>
</tbody>
</table>

The difference in trends of \( \theta_v \) variability for the open field and plastic high tunnel are attributable to the difference in soil physical properties and precipitation depths. However, the \( \theta_v \) values in both scenarios (open field and plastic high tunnel) were above the \( \theta_fc \) most of the time.

The designated sampling benchmarks showed variation in soil moisture in regard to the soil
physical properties; however similar trends of soil moisture were found amongst the pairs of benchmarks located at the same end of the plots (i.e. BM1 and BM4, and BM2 and BM3), at the depths of 0-0.1 m and 0.1-0.3 m.

Using the main equipment zone’s \( \theta_i \) data as a standard for comparison to the other designated benchmarks explains some differences in \( \theta_i \) variation in the study plot. In the open field at the 0-0.1 m depth (top soil), BM2 showed a roughly 20% greater \( \theta_i \) (38.5 mL dL\(^{-1}\)), than at the main equipment site (31.9 mL dL\(^{-1}\)). The \( \theta_i \) values at the other benchmarks (BM1, BM3 and BM4) were more or less similar to that at the main equipment site (Table 4.4).

Seasonal mean data for the open field at the depths of 0-0.1 m and 0.1-0.3 m (Table 4.4) showed BM2 to have the higher seasonal mean \( \theta_i \) values (28.8 mL dL\(^{-1}\) and 30.2 mL dL\(^{-1}\), respectively), whereas BM3 showed the lowest values (18.8 mL dL\(^{-1}\) and 18.7 mL dL\(^{-1}\)); sites BM1 (23.1 mL dL\(^{-1}\) and 25.7 mL dL\(^{-1}\)) and BM4 (27.1 mL dL\(^{-1}\) and 27.6 mL dL\(^{-1}\)) have seasonal means value of \( \theta_i \) nearest to those at the ME site (20.5 mL dL\(^{-1}\) and 26.3 mL dL\(^{-1}\)). This is because they were located closer than the other two benchmarks (BM2 and BM3).

The higher \( \theta_i \) readings at certain benchmark points in the open field (strawberries with plastic mulch) could be due to heterogeneity in the soil amongst the benchmark locations, and different timing of auger sampling (gravimetric sample), i.e. before and after irrigation applications. Also, time and daylight being important factors in gravimetric soil moisture analyses, they might have influenced the high \( \theta_i \) in the months of August and in the last week of September amongst all benchmarks. This pattern of analysis was followed throughout the growing season in the open field and plastic high tunnel strawberries with plastic mulch.

In open field strawberries, irrigation occurred every fifth day. The distance from the irrigation tape emitter may also be a considerable factor in the variation of results during the
growing season. Due to the large number of gravimetric samples taken over the 6-month period it became necessary to sample progressively farther away (1 to 1.5 m) from the sensors to avoid duplicating sampling locations and prevent excessive soil disturbance. The $\theta_t$ at BM2 showed large variation and high trends for the 0-0.1 m depth, ranging from a minimum of 15 mL dL$^{-1}$ to a maximum 37 mL dL$^{-1}$ while at the depth of 0.1-0.3 m it varied from a minimum of 24 mL dL$^{-1}$ to a maximum of 34 mL dL$^{-1}$. In general, measured $\theta_t$ exceeded $\theta_c$ (19%) for a significant portion of the season, showing high $\theta_t$ in the study plots (Figures 4.2 and 4.3). Variations in $\theta_t$ clearly demonstrate this difference, $\theta_t$ being almost 13 mL dL$^{-1}$ over the $\theta_c$ at times. While BM1, BM4 and ME showed similar fluctuations in $\theta_t$ at both depths i.e. 13 mL dL$^{-1}$ to 33 mL dL$^{-1}$ at 0.0-0.10 m and 19 mL dL$^{-1}$ to 33 mL dL$^{-1}$ in general, the BM3 site showed the lowest $\theta_t$ levels: 12 mL dL$^{-1}$ to 25 mL dL$^{-1}$ in the top soil and 9 mL dL$^{-1}$ to 25 mL dL$^{-1}$ at the rooting depth (0.1-0.3 m). One may attribute the fluctuations in soil moisture to external climatic factors i.e. rainfall, dew, non-uniformity of drip irrigation, leakages from the irrigation tape, etc., in addition to the different soil physical properties at each benchmark in open field strawberries. By studying individual benchmarks in relation to calculated field capacity ($\theta_c = 19\%$) of the study site, some of the benchmarks show seemingly saturated soil moisture levels, which might have had a negative impact on growth, and upwardly influence seasonal $\theta_t$ averages of all four benchmarks.
Figure 4.2. Open field volumetric soil moisture data (0-0.1 m depth)

Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by volume)

Field Capacity (FC =19%)

Trigger point
Figure 4.3. Open field volumetric soil moisture data (0.1-0.3m depth)

- **Trigger point**
  - Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by volume)
- **Field capacity (FC = 19%)**
At each benchmark, different physical soil properties were found (Table 4.2), which further explain the high moisture level at certain benchmarks. Overall, BM2 and BM4 showed greater variation in $\theta_v$ and higher $\theta_v$ values: 15 mL dL$^{-1}$ to 37 mL dL$^{-1}$ at (0.0-0.1m) and 23 mL dL$^{-1}$ to 35 mL dL$^{-1}$ at (0.1-0.3m) as compared to BM1 and ME. Benchmarks BM1, BM3 and ME showed similar maximum $\theta_v$ values, i.e. 30-33 mL dL$^{-1}$ at both depths. However minimum $\theta_v$ values vary widely, from 9 to 23 mL dL$^{-1}$ across the two depths. The high $\theta_v$ levels might be related to the higher percentage of clay at BM2 (9.1%) and BM4 (8.1%), as shown in Table 4.2.
4.3.2. Sensor data

4.3.2.1. Water content reflectometer

The $\theta_v$ recorded from June to October (4 hour intervals) using the WCR TDR devices are presented in Figure 4.4. Early in June and twice in July, $\theta_v$ was in the irrigation trigger zone, but otherwise it remained above. During the season, $\theta_v$ varied from a minimum level of 12 mL dL\(^{-1}\) to a maximum of 24 mL dL\(^{-1}\). In the open field, the sensor was installed at 115 mm distance from the emitter. The values of $\theta_v$ recorded by the WCR were fairly balanced between values above and below the $\theta_v$ of 19 mL dL\(^{-1}\) (Table 4.2), but in relation to the irrigation trigger points (65% to 85% FC), $\theta_v$ was well above the upper trigger of 16 mL dL\(^{-1}\) for most of the growing season. The continuous spiking in the trend line (Figure 4.4) represents the irrigations made in study plot, and indicates over irrigation throughout the season.

![Figure 4.4. Campbell Scientific Water content reflectometer soil moisture data (0-0.3 m depth)](image_url)

*Figure 4.4. Campbell Scientific Water content reflectometer soil moisture data (0-0.3 m depth)*

| Trigger point | Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by vol.) | Field Capacity, FC = 19%.

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By keeping $\theta_i$ within the irrigation trigger zone \textit{i.e.}, 65\% to 85\% of the calculated field capacity, it would make it easy for the grower to know when to irrigate and how much to irrigate, resulting in a significant water savings.

4.3.2.2. Gro-Point

The Gro-Point sensor’s results (Figure 4.5) show $\theta_i$ in the open field to vary between a minimum of 8mL dL$^{-1}$ and a maximum of 16mL dL$^{-1}$, which is mostly in the required moisture level (65\% to 85\% of $\theta_{fc}$ - $\theta_{pwp}$ range), but at same time, GP-measured $\theta_i$ dropped to the $\theta_{pwp}$ at different stages of the strawberry growing season (first 3 weeks in June, 2$^{nd}$, 3$^{rd}$ weeks of July, and first three weeks of August 2007).

In open field strawberries, low moisture readings from the Gro-point sensor were observed throughout the season. The possible reasons were: poor contact between sensor probes and the soil, the sensor may have been installed too far from the drip emitter, or there may have been a calibration error by the manufacturer. It was found that the low values were despite the fact that the installation of the GP was very close to the emitter, at 25 mm, compared to the 115 mm distance for the WCR. By using the same manufacturer’s calibration for soil moisture monitoring, different results were observed inside the tunnel for the same crop and irrigation system. The reasons for the variation in the open field with different irrigation intervals may be attributed to the different sensitivity levels of WCR and GP sensors in measuring the soil moisture in the soil.

For the purpose of comparative analysis of gravimetric results with TDR sensor produced data, a daily average was taken. Regarding the difference in depths for comparative analysis, the GP installed at 0.0-0.2m was compared with gravimetric sample for 0.1-0.3 m. Similarly, the
WCR installed at 0.0-0.3m was also compared with gravimetric sample from 0.1-0.3 m depth of the soil. The reason for this is because of the high variability in the topsoil.

Figure 4.5. Gro-Point soil moisture data (0-0.2m depth).

<table>
<thead>
<tr>
<th>Trigger point</th>
<th>Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by vol.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field Capacity, FC = 19%</td>
</tr>
</tbody>
</table>

4.3.3. Irrigation records

The second objective of the research was to compare water use in the open field with the plastic high tunnels. To meet this objective, the grower maintained irrigation records for the open field indicating the number of hours of irrigation made in the growing season, as this was different for the open field and plastic high tunnel strawberries under similar plastic mulching. In general, the open field irrigations were made after every fifth day or once a week. Less irrigation was applied to the open field compared to the plastic high tunnel, as in field strawberries, adequate moisture was contributed by incident precipitation on several occasions. The total number of hours recorded by the grower was 121.5 hours. Irrigation records were translated into an equivalent depth of water applications, by considering the strawberry rooting depth of 0.3 m, and using equation 3.6 (Table 4.4).
Table 4.4. Weekly irrigation records and corresponding equivalent water depths (EWD) at 0-0.3m in the open field

<table>
<thead>
<tr>
<th>Week</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (hrs)</td>
<td>EWD (mm)</td>
<td>Rain (mm)</td>
<td>Time (hrs)</td>
<td>EWD (mm)</td>
<td>Rain (mm)</td>
</tr>
<tr>
<td>1</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>23.0</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>17.3</td>
<td>*</td>
<td>6</td>
<td>34.5</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>46.0</td>
<td>3.8</td>
<td>6</td>
<td>34.5</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>23.0</td>
<td>1.8</td>
<td>3</td>
<td>17.3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>11.5</td>
<td>0</td>
<td>1.5</td>
<td>8.7</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>17.0</td>
<td>97.9</td>
<td>5.6</td>
<td>20.5</td>
<td>118.1</td>
<td>20.2</td>
</tr>
</tbody>
</table>

*Not recorded
4.3.4. Equivalent water depth: gravimetric vs. sensor comparison

The equivalent water depth (EWD) was estimated using the $\theta_r$ values acquired from both sensor readings (WCR and GP) and gravimetric analysis at depth of 0.1-0.3m using equation 3.5. These values are plotted and the best fit regression lines were developed (Figure 4.6) for open field strawberries. The linear relationship of the EWD obtained from the WCR sensor (0-0.3m) and gravimetric $\theta_r$ readings for the 0.1-0.3m depth, showed an excellent fit ($R^2= 0.93$). Similarly, the linear relationship of the EWD obtained from the GP sensor (0-0.2m) and gravimetric $\theta_r$ readings for the 0.1-0.3 m depth, also showed an excellent fit ($R^2= 0.88$; Figure 4.6). Moreover, the regression-fitted lines showed few obvious outliers, and these were probably due to the presence of some aberrant sensor readings. These data points can be easily identified in the scatter diagram (Figure 4.6). Moreover, it was observed from the trend of data in the scattered diagram that the randomness is more pronounced during the beginning and last two months of the growing season. This may be due to sensor reading errors during their standardization in the beginning of the experiment. The sampling error could also be due to collection of soil samples at different times of the day and at different distances (1 m to 1.5 m) from the sensor points in the field. However, during the mid-season months (July, August) of the growing season i.e. at the plant maturity and fruit production stages, the EWD exhibited a better match with $\theta_r$. By dividing the growing season in different time parts in terms of plant growth stages and irrigation management, one can get good regression values for a given non-gravimetric method of measuring soil moisture.
Figure 4.6. Correlations between equivalent water depth measurements of soil moisture sensors and gravimetric soil samples
4.4. Plastic high tunnels

4.4.1. Gravimetric data

The same pattern of weekly sample collection and \( \theta_v \) determination was followed in the plastic high tunnel as in the field, as reflected in Figures 4.7 and 4.8. Inside the plastic high tunnel the same numbers of gravimetric samples were taken over the growing season as in the open field, with a gradual increase in the distance from 1 m to 1.5 m from the sensors to avoid re-sampling the same spot. Inadvertent gravimetric sample collection near the irrigation tape emitter may also have contributed to the variation in results, and may have impacted on the correlation between the sensors and the gravimetric samples.

For comparative analysis of gravimetric results with TDR sensor produced data, similar data collection days were selected for the regression analysis. Regarding the difference in depths and assuming disturbance of top soil (0-0.1 m), results at the depth of 0.1-0.3 m were taken for comparative analysis, i.e. GP at 0-0.2 m was compared with gravimetric \( \theta_v \) average for 0.1-0.3 m, whereas WCR at 0-0.3 m was compared with gravimetric average from 0.1-0.3 m. The results are explained for both depths separately below.

The results from the gravimetric method illustrated that throughout the growing season, the \( \theta_v \) was above the field capacity \( (\theta_{fc} = 19 \text{ mL dL}^{-1}) \) in the plastic high tunnel for the depths of 0-0.1 m and 0.1-0.3 m (Figures 4.7 and 4.8). The variability in \( \theta_v \) showed a minimum of 15.5 mL dL\(^{-1}\) to a maximum of 31.9 mL dL\(^{-1}\) for the 0-0.1 m depth, and of a minimum of 15.9 mL dL\(^{-1}\) to a maximum of 32.8 mL dL\(^{-1}\) for the 0.1-0.3m soil depth. In terms of \( \theta_v \) at both depths (0-0.1 m and 0.1-0.3 m), greater variation in \( \theta_v \) and higher \( \theta_v \) values were found for the benchmarks than the main equipment site. This same trend can be seen over the season (Figures 4.7 and 4.8). The data (Table 4.5) show clearly higher \( \theta_v \) readings at BM2 and BM3 than other locations: 21.2
mL dL\(^{-1}\) to 31.9 mL dL\(^{-1}\) at 0-0.1 m and 23.2 mL dL\(^{-1}\) to 30.3 mL dL\(^{-1}\) at 0.1-0.3 m, about 11 mL dL\(^{-1}\) above the calculated \(\theta_c\) of 19\%. Comparatively, the \(\theta_v\) at BM3 ranged from 17.0 mL dL\(^{-1}\) to 30.1 mL dL\(^{-1}\) at 0-0.1 m and 19.9 mL dL\(^{-1}\) to 32.8 mL dL\(^{-1}\) at 0.1-0.3 m, again about 11 mL dL\(^{-1}\) higher than \(\theta_c\). The BM1 and BM4 sites showed similar \(\theta_v\) values at both depth ranges: from 15.5 mL dL\(^{-1}\) to 29.4 mL dL\(^{-1}\) at 0-0.1 m and 15.9 mL dL\(^{-1}\) to 28.7 mL dL\(^{-1}\) at 0.1-0.3 m, about 10 mL dL\(^{-1}\) higher than \(\theta_c\). This unevenness in \(\theta_v\) inside the plastic high tunnel might be attributed to heterogeneity in the soils of the two locations and different timing of gravimetric sampling (e.g., before and after irrigation). Late August to last week of September showed the greatest range in \(\theta_v\) among benchmarks. This might have been the result of differences in soil physical properties amongst the benchmarks and as well the number of irrigation made inside the plastic high tunnel. In plastic high tunnel strawberries, irrigation was applied every other day while in open field strawberries irrigation was made after every fifth consecutive day (grower’s irrigation record). However, \(\theta_v\) in plastic high tunnel was above the \(\theta_c\) of 19\% most of the time.

### Table 4.5. Seasonal statistics for volumetric soil moisture (mL dL\(^{-1}\)) in the plastic high tunnel field

<table>
<thead>
<tr>
<th>Site</th>
<th>BM1</th>
<th>BM2</th>
<th>BM3</th>
<th>BM4</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Loamy sand</td>
<td>Sandy loam</td>
<td>Sandy loam</td>
<td>Loamy sand</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>0.0-0.1</td>
<td>0.1-0.3</td>
<td>0.0-0.1</td>
<td>0.1-0.3</td>
<td>0.0-0.1</td>
</tr>
<tr>
<td>Seasonal mean</td>
<td>22.1</td>
<td>22.9</td>
<td>25.4</td>
<td>27.4</td>
<td>23.5</td>
</tr>
<tr>
<td>Seasonal minimum</td>
<td>16.1</td>
<td>18.7</td>
<td>21.2</td>
<td>23.3</td>
<td>17.0</td>
</tr>
<tr>
<td>Seasonal maximum</td>
<td>29.2</td>
<td>28.5</td>
<td>31.9</td>
<td>30.3</td>
<td>30.1</td>
</tr>
<tr>
<td>Median</td>
<td>21.7</td>
<td>23.0</td>
<td>25.3</td>
<td>27.2</td>
<td>23.6</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.031</td>
<td>0.023</td>
<td>0.031</td>
<td>0.018</td>
<td>0.032</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.005</td>
<td>0.004</td>
<td>0.005</td>
<td>0.003</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Figure 4.7. Plastic high tunnel volumetric soil moisture data (0-0.1m depth)

Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by volume)

Field capacity (FC = 19%)
Figure 4.8. Plastic high tunnel volumetric soil moisture data (0.1-0.3m depth)

Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by volume)

Field Capacity (FC = 19%)
The $\theta_v$ at each benchmark in the plastic high tunnel treatment exceeded the $\theta_{fc}$ (19 mL dL$^{-1}$) at depths of 0-0.1 m and 0.1-0.3 m, and at certain benchmark points (Fig 4.7 and 4.8), $\theta_v$ varied widely (15 mL dL$^{-1}$ to 32 mL dL$^{-1}$) over the growing season. This variability in soil moisture can be attributed to the differences in soil sample collection time (i.e. morning, evening, before and after irrigation) and soil physical and chemical properties of each benchmark location. The soil physical analyses confirmed that differences in soil properties were found amongst the designated benchmarks in the open field and as well in the plastic high tunnel (Table 4.2).

Benchmarks BM2 and BM3 had the largest $\theta_v$ ranges at the 0.0-0.1 m depth, 21 mL dL$^{-1}$ to 32 mL dL$^{-1}$ and 16 mL dL$^{-1}$ to 30 mL dL$^{-1}$, respectively. Similarly at depth from 0.1-0.3 m, the ranges for BM2 and BM3 were 24 mL dL$^{-1}$ to 30 mL dL$^{-1}$ and 19 mL dL$^{-1}$ to 33 mL dL$^{-1}$, respectively. These maximum values of $\theta_v$ exceeded $\theta_{fc}$ by roughly 11 mL dL$^{-1}$. These high $\theta_v$ values might be due to a low percentage of sand and high silt content (Table 4.2).

For BM1, BM4 and ME the range of $\theta_v$ values at either depth were similar, about 15 mL dL$^{-1}$ to 30 mL dL$^{-1}$ at 0-0.1 m and 15 mL dL$^{-1}$ to 32 mL dL$^{-1}$ at 0.1-0.3 m. These maximum values of $\theta_v$ again clearly exceeded $\theta_{fc}$ by roughly 11 mL dL$^{-1}$. From these results it appears that the grower was over-irrigating during most of the season. By monitoring the soil moisture with different sensors one could easily make better water management decisions as to when to irrigate and how much to irrigate.
4.4.2. Sensor data

4.4.2.1. Water content reflectometer

Figure 4.9 shows the change in $\theta_i$ with time, as recorded from June to October (4 hours interval between each download). The WCR measurements inside the plastic high tunnel gave higher $\theta_i$ levels than in the field, ranging from a minimum of 27 mL dL$^{-1}$ to a maximum of 33% mL dL$^{-1}$, whereas in the open field there was a greater range, from a minimum of 14 mL dL$^{-1}$ to a maximum of 24 mL dL$^{-1}$, but values were lower overall. In the plastic high tunnel treatment, the sensor recorded consistently higher $\theta_i$ levels in the early season and these values gradually dropped. The WCR showed $\theta_i$ values 12 mL dL$^{-1}$ above $\theta_{fc}$, comparatively to the open field where the WCR-recorded $\theta_i$ was much closer to the calculated $\theta_{fc}$. Another discernable difference between WCR trends of the open field (Figure 4.3) and plastic high tunnels is that the latter data are more even. The absence of precipitation inside the plastic high tunnels makes it easier for the grower to follow a regular irrigation schedule and keep the soil moisture within a small range.

![Plastic High Tunnel-WCR (0-0.3 m depth)](image)

Figure 4.9. Campbell Scientific water content reflectometer moisture data (0-0.3m depth)

- **Trigger point**
- Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by vol.)
- **FC 19%**
The higher moisture level in the first two months (June and July, 2007) might be due to the standardization of the equipment or leakage of water from the irrigation tape. The grower may have tended to over-irrigate the field. The plastic high tunnel’s higher $\theta_v$ levels might have also been contributed by certain factors such as indirect sunlight and higher humidity, resulting in lower evapotranspiration in the controlled hooped environment. Although unlikely, the WCR probe’s sensitivity within the soil may also have been a factor that caused variable results between the plots (manufacturer’s calibration).

4.4.2.2. Gro-Point

The Gro-Point’s $\theta_v$ measurements (Figure 4.10) showed $\theta_v$ to be mostly between 23 mL dL$^{-1}$ and 33 mL dL$^{-1}$, with a minimum $\theta_v$ of 18 mL dL$^{-1}$ and peak $\theta_v$ of 36 mL dL$^{-1}$ in early June (Figure 4.10). With the exception of this period, the $\theta_v$ was well above the $\theta_{fc}$ for most of the growing season. Compared to the $\theta_{fc}$, the grower was irrigating almost 12 mL dL$^{-1}$ above the adequate level, which is a waste of water. The spikes (peaks) show the irrigation applications (Figure 4.10). However, the extremely sharp peaks are uncharacteristic and were not observed for the WCR sensor, indicating either improper installation location, malfunctioning sensor or faulty calibration. The GP was installed at much further from the emitter than the WCR, which should have resulted in a slower response to irrigations. However, the soil moisture trends contradict this, thereby ruling out installation location as a reason for the erroneous readings.

The irrigation trigger zone is highlighted (from 12 mL dL$^{-1}$ to 16 mL dL$^{-1}$) and compared to the results produced by WCR, about 17 mL dL$^{-1}$ extra water was applied to the study plot than necessary. Even by using manufacturer’s calibration for soil moisture monitoring, one can easily find adequate soil moisture inside the soil at crop rooting front. The higher $\theta_v$ in the tunnel is attributable to several factors such as, more frequent irrigation in the tunnel than in the field, no
direct sunlight, humidity, evapotranspiration and partially controlled environment. Again this shows that irrigation can effectively be managed to save water, by timing irrigation using TDR sensors.

**Figure 4.10. Gro-Point soil moisture data (0-0.2m depth).**

- **Trigger point** Irrigation target range (65% - 85% of FC at 0.25 m, i.e. 12-16% soil water content by vol.)
- **Field Capacity, FC = 19%**

4.4.3. **Irrigation records**

4.4.3.1. Flow meter data

In the plastic high tunnel one flow meter was installed at the main supply line to keep record of the irrigation (time, number of irrigations and quantity) for the strawberry growing season, at seven day intervals (Table 4.6). However, having had one flow meter operating for the plastic high tunnel strawberries, the results were compared with grower records for both open field and plastic high tunnel strawberries, mainly to validate the grower’s records. The results from the flow meter confirmed that more frequent irrigations were made inside the plastic high tunnel as compared to the open field strawberries (Table 4.6). The grower irrigated in the plastic high tunnel every other day.
In June and July, which is considered to be the strawberry fruiting stage, more irrigation is required for quality production. The data shows consistent irrigation as per plant requirements i.e. total of 168.8 mm in 27.6 hours with gradual increase to 172.6 mm in 33.4 hours. August and September showed a slight decrease in irrigation i.e. 24 hours with 124.1mm in August and 23.7 hours with 132.7 mm. The total irrigation time recorded by the flowmeter was 112.2 hours, from June to October. This data was converted into equivalent water depth (EWD) of applications in mm of water applied (equation 3.5), and was found to be 617 mm for the entire growing season. The high number of short interval irrigations, may be attributed to the controlled environment inside the plastic high tunnel, which has direct effects on the evapotranspiration rate ($ET_c$), sunlight, relative humidity and rainfall.

*Table 4.6. Flow meter data and corresponding equivalent water depths (EWD) at 0-0.3m in the plastic high tunnel field*

<table>
<thead>
<tr>
<th>Weeks</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (hrs)</td>
<td>EWD (mm)</td>
<td>Time (hrs)</td>
<td>EWD (mm)</td>
<td>Time (hrs)</td>
<td>EWD (mm)</td>
</tr>
<tr>
<td>1</td>
<td>*</td>
<td>*</td>
<td>9</td>
<td>46.7</td>
<td>7.8</td>
<td>46.6</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>15.6</td>
<td>8.6</td>
<td>44.4</td>
<td>4.8</td>
<td>24.4</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>77.9</td>
<td>4.8</td>
<td>21.5</td>
<td>2.5</td>
<td>13.9</td>
</tr>
<tr>
<td>4</td>
<td>8.7</td>
<td>58.8</td>
<td>9.1</td>
<td>48.5</td>
<td>7.1</td>
<td>31.9</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
<td>16.5</td>
<td>1.9</td>
<td>11.5</td>
<td>1.8</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27.6</strong></td>
<td><strong>168.8</strong></td>
<td><strong>33.4</strong></td>
<td><strong>172.6</strong></td>
<td><strong>24</strong></td>
<td><strong>124.1</strong></td>
</tr>
</tbody>
</table>

*Not recorded

4.4.3.2. Grower irrigation records

On average, inside the tunnels, irrigation was made every alternate day for 1-2 hours. Irrigation was based on weather conditions and critical plant growth stages, namely flowering and fruiting. Table 4.6 shows the weekly irrigation record and the corresponding equivalent
water depth, which is calculated for the effective root zone of 0-0.3 m for the strawberry crop (equation 3.6). The pattern of irrigation was altered during the growing season based on the installed soil moisture sensors. Previously, a fixed or timely schedule of irrigation was followed, while in 2007, the on/off decision was made based on the continuous $\theta_i$ data from the installed WCR, GP sensors and weekly gravimetric samples. According to the grower’s irrigation records, the total number of hours irrigated in the growing season was 121.5. For the months of June to September, when the flowmeter was operational, the number of hours recorded by the grower was 100.5, which compares with flowmeter data of 108.7 hours, a difference of 8.2 hrs. In terms of equivalent depth of water applied, this translates to 42.5 mm. When the number of irrigation hours is viewed on a monthly basis, it was observed that the grower tends to underestimate the amount of water applied. However, the difference on an average is only around 2 hours per month, with the total irrigation time ranging between 20-30 hours per month.

Table 4.7. Weekly irrigation records and corresponding equivalent water depths (EWD) at 0-0.3m in the plastic high tunnel field

<table>
<thead>
<tr>
<th>Weeks</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time hrs</td>
<td>EWD (mm)</td>
<td>Time hrs</td>
<td>EWD (mm)</td>
<td>Time hrs</td>
<td>EWD (mm)</td>
</tr>
<tr>
<td>1</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>23.4</td>
<td>8</td>
<td>46.8</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>17.5</td>
<td>6</td>
<td>35.1</td>
<td>6</td>
<td>35.1</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>46.8</td>
<td>6</td>
<td>35.1</td>
<td>6</td>
<td>35.1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>23.4</td>
<td>3</td>
<td>17.6</td>
<td>8</td>
<td>46.8</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>11.7</td>
<td>1.5</td>
<td>8.8</td>
<td>2</td>
<td>11.7</td>
</tr>
<tr>
<td>Total</td>
<td>17.0</td>
<td>99.3</td>
<td>20.5</td>
<td>120.0</td>
<td>30.0</td>
<td>175.5</td>
</tr>
</tbody>
</table>

*Not recorded
4.4.4. **Equivalent water depth: gravimetric vs. sensor comparison**

Using regression, the plastic high tunnel EWD gravimetric results were compared to the WCR and Gro-Point measurements (Figure 4.11). The linear relationship between the WCR (0.0-0.3 m) and gravimetric readings for the 0.1-0.3 m depth were observed to fit extremely well ($R^2= 0.97$). The linear relationship between gravimetric EWD and GP sensor at 0-0.2 m depth was poor ($R^2<0.0001$) (Figure 4.11). With this exception, EWD and sensor values showed a close linear relationship for both open field and plastic high tunnel strawberries. In the case of the Gro-point sensor some of the scattered points, easily identified in Figure 4.9, deviated significantly from the gravimetric results, but these did not seem to come from any particular part of the growing season.

![Figure 4.11. Correlations between equivalent water depth measurements of soil moisture sensors and gravimetric soil samples in the plastic high tunnel](image)
In this study, sensor’s field performance, sensor’s reliability and effectiveness in relation to the irrigation management were the focus; evaluation of sensors against one another was not carried out. Whereas, by comparing the results produced by TDR sensors against the gravimetric results individually, one can see the overall compatibility of sensor-generated results in regards to soil moisture inside the soil.

Considering the factors described in the previous section, such as installation locations, different depth of sensors, inherent variability and sensitivity to the local changes inside the soil prevent the two sensors from generating matching results. Visual monitoring of the sensor-produced data by graphical presentation gives a fair idea of each sensor’s outputs; a statistical comparison cannot be made between sensors. In addition, the sensors which are used in this research study were not calibrated with field data. Accordingly the manufacturer’s calibration was used for measuring the volumetric water content in the open field and plastic high tunnel strawberries.

Again, one must be careful while making such comparison in applied research, as the locations at which soil samples were taken may have had different soil moisture level as compare to the sensor’s installed locations. Also, the depths for gravimetric sampling were not always the same as sensor depths, so both these Campbell Scientific CS 625 (WCR) and Gro-Point ESI (GP) could not be precisely evaluated by this method. Hence the responses of the sensors were validated by the gravimetric soil samples. In general sensor’s performance, data trends and graphical presentation of the gravimetric data evidently verify that the overall performance of both the TDR sensors were acceptable, except for GP in the tunnels.
CHAPTER 5

5. SUMMARY AND CONCLUSIONS

The research carried out in this study had three objectives. The first objective was to monitor soil moisture through the principles of time domain reflectometry for scheduling irrigation under two strawberry cultivation practices, namely open field and plastic high tunnel. The second objective was to compare the water use under the two practices using flowmeter data and grower irrigation records. The third objective was to correlate soil moisture sensor and gravimetric data, and evaluate their performance in comparison to gravimetric soil moisture sampling. Volumetric water content was used as a unit of reference for the purpose of comparing sensors. Two types of TDR sensors (Campbell WCR and ESI Gro-point) were used for the field evaluation in a commercial strawberry crop. Furthermore, in order to quantitatively evaluate the performance of the various sensors tested with regard to the principle of operation, equivalent water depth (EWD) was estimated. For the statistical analysis, the coefficient of regression $R^2$ was used. The main findings of the study are listed below, organized according to the objectives.

5.1. Soil moisture monitoring

In general, the data trends and graphical presentation of the gravimetric data support the fact that the overall performance of both TDR sensors was accurate. The principle of time domain reflectometry was therefore used successfully for real-time in-situ monitoring of soil moisture for the irrigation scheduling of strawberry in sandy soils.

i. Soil moisture sensor readings provide a quick visual means of observing trends in soil moisture as influenced by rainfall and irrigation applications. However, a certain degree of training and experience is required to determine the right triggers for irrigation.
Both the WCR and the GP sensor showed similar trends. Based on the results of gravimetric sampling, it was found that the factory calibration was inadequate and that site-specific calibration might be required to better delineate the irrigation triggers. Although the uncalibrated sensors were sufficiently consistent to aid irrigation scheduling by setting levels at which irrigation should be turned on and off, the actual values measured were not always realistic, making interpretation of data somewhat difficult.

Sensor location is highly critical for soil moisture monitoring. Some factors to be considered are location with respect to the dripper, depth of installation, soil variability and topography. Gravimetric sampling at the benchmarks demonstrated the importance of site selection by highlighting the spatial variability in soil moisture, even within a single plot.

**5.2. Water use and irrigation scheduling**

Water use was compared between the two plots by referring to grower irrigation records. Additionally, a flowmeter was installed to measure irrigation in the plastic high tunnels. This was used to validate the grower’s records and provide a basis for comparing the two fields. In theory, the plastic high tunnels require more irrigation than the open field, as rainfall supplements irrigation in the open field. However, the study year was an exceedingly dry year with rainfall being only about 50% of normal seasonal values. As a result, differences in irrigation amounts between the two management practices are not highlighted as well as they would have been in a year with normal or excess rainfall.

In general, the open field was irrigated once every five days, for 3 to 4 hours. The frequency of irrigation was altered depending on rainfall and soil moisture status. A total of 699 mm of water was applied to the crop in the open field.
ii. The plastic high tunnels were irrigated every alternate day for 1 to 2 hours. This was almost consistently followed through the growing season as the influence of rainfall on soil moisture was negligible. Despite the different irrigation schedules, the total amount of water applied was 711 mm, which is marginally higher than the amount recorded for the open field.

iii. The flowmeter recorded 112.2 hours of irrigation, which converts to 617 mm of water applied. However, the flowmeter was not operational during the month of May. When a comparison was done for June-September, a difference of 42.5 mm was found between the flowmeter and grower irrigation records.

iv. This study was unable to conclusively suggest which of the two systems (open field or plastic high tunnels) is better for water conservation, higher quality crop yields and fruit quality. This was mainly because of two factors: consistent over-irrigation on both plots and low rainfall amounts during the growing season.

5.3. **Sensor performance**

Equivalent water depths were estimated using the volumetric water content values acquired for both the sensors (WCR and GP) and gravimetric analysis for different depths. The resultant values were plotted and best regression lines were developed in open field and plastic high tunnel strawberries under the plastic mulch, respectively.

i. The linear relationship of the EWD obtained from WCR (0-0.3 m) and gravimetric readings (0.1-0.3 m) were observed to be the best fit (coefficient of determination, $R^2 = 0.93$ and $R^2 = 0.97$) in open field and plastic high tunnel strawberries respectively. Hence, the WCR sensor was found to be a reliable and precise instrument for irrigation scheduling.
ii. Similarly, the linear relationship with $R^2 = 0.88$ in the open field can explain the variation in EWD of GP sensor at 0-0.2 m and gravimetric readings at 0.1-0.3 m depth.

iii. In three of four cases, the regression fitting parameters $R^2$ were high, the linear regression line explaining the relationship between the sensor and gravimetric readings in all the cases. However, the GP in the tunnel showed a poor regression between the sensor and gravimetric readings ($R^2 < 0.0001$); this was due to some sensor readings with significant deviations from the gravimetric readings. These data points can be easily identified in the scatter diagram (Figure 4.11). Moreover, it can clearly be observed, that there is more variation in the beginning and at the end of the season. This initial variability may be due to the standardization of the sensors at the time of installation. The gravimetric sampling error may be due to collection of soil samples at different times of the day and the distance of 0.1 m to 1.5 m from the sensor location in the plots.

iv. During the mid months (July, August) of the growing season i.e. at the plant maturity and fruit production stages, results from the EWD and $R^2$ show higher correlation with the linear regression equation. At the end of the season, regressions performed less well than in the mid-season. By dividing the growing season in different portions of time, one can get good regression values for management purposes, by using the same methods of analysis for soil moisture monitoring.

Finally, one must be careful while making sensor evaluations, as the locations at which soil samples were taken may have had different soil moisture level as compare to the sensor’s installed locations. Also, the depths for gravimetric sampling were not always the same as sensor depths, so both these Campbell Scientific CS625 (WCR) and Gro-Point ESI (GP) could not be
precisely evaluated by this method. It can be concluded that there is no one single soil moisture sensor which is considered to be best, as each sensor has its own positive aspects and limitations.
CHAPTER 6.

6. RECOMMENDATIONS

Based on the findings of the study, the following recommendations are made for future research:

i. This study demonstrated the importance of site selection and sensor installation for scheduling irrigation based on in situ soil moisture monitoring. However, further controlled experiments are required to ascertain the optimal location of installation of the sensors, with respect to the drip emitters and plant rows.

ii. Studies need to be conducted to determine the appropriate soil depth for monitoring soil moisture for irrigation scheduling purposes, based on crop type and growth stages, maybe by varying depth of monitoring with growth stage.

iii. Further investigation is required to evaluate the effectiveness of site-specific sensor calibration, and its potential to eliminate the uncertainty associated with identifying the right triggers for turning irrigation on and off.

iv. Irrigation schedules need to be monitored more closely to be able to compare water use between two management systems, i.e. open field and plastic high tunnels.

v. Growers need to be trained on how to interpret data for irrigation scheduling based on soil moisture triggers.
7. REFERENCES


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