IRRIGATION SCHEDULING STRATEGIES FOR TOMATO PRODUCTION IN SOUTHWESTERN ONTARIO

By

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Suggested Short Title

Irrigation scheduling of processing tomatoes

Abstract

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Doctor of Philosophy **Bioresource Engineering**

Precision irrigation scheduling is critical to improving irrigation efficiency. It is a combined technical and managerial tool that determines accurately when, how much and how often irrigation is applied to meet optimum crop response. This is particularly challenging in humid regions such as Southwestern Ontario, where soil moisture is often influenced by periodic rainfalls. The overarching goal of this three year research project was to investigate different irrigation scheduling strategies for tomato production in Leamingtion, Ontario.

There were four specific objectives. The first sought to develop an optimum irrigation schedule for intensive cultivation of processing tomatoes by examining different irrigation trigger levels. Moisture triggers were expressed as a fraction of field capacity and soil tension, which are also related to soil available water content (AWC). Triggers with moisture depletion levels of ≤ 40 % (AWC) produced the higher yields. However, the best yields were obtained from the tension treatment with an upper and lower moisture threshold of -10 kPa and -30 kPa, which represented 20 to 24% depletion in AWC.

The second objective sought to develop a robust protocol for implementing an irrigation scheduling. Three different types of soil moisture sensors were evaluated. The tension based senor emerged with the highest evaluation score. However, all three sensors could be used to effect irrigation scheduling. The sensor based irrigation data was subsequently compared with the Peman-Monteith model. It was found that the soil moisture treatments with a moisture depletion level of ≤ 40 % soil available water content (AWC) adequately met crop water requirements throughout the season.

The third objective examined the spatio-temporal variability of soil moisture under drip irrigation in a controlled greenhouse environment. The study indicated that soil moisture content was not uniformly distributed prior to or after an irrigation event. For double row

planting of tomatoes with a central drip line, a row spacing of 50 cm was adequate for planting of seedlings, due to the higher soil moisture contents within that zone. Further, due to the lack of uniform distribution of moisture in the soil profile, paired sensors (with one either side of the drip line) can provide a better estimate of soil moisture depletion for sensor based irrigation scheduling.

The fourth objective investigated the nutrient dynamics along the soil profile over the growing season. Soil nutrients (P and N) were monitored at three different levels of the profile (0 to 30, 30 to 50 and 50 to 70 cm) and at the pre-planting, mid-season and end of season stages. Statistical significance in Olsen P and NO_3-N was obtained both across the season and along the profile for each of the three years. The variability among treatments was not significant. The P and N concentrations at the 50 to 70 cm depths were found to be high, with the potential of being leached through the subsurface drainage system. A modification in the application of P and N can help reduce leaching of nutrients below the rooting zone. This would necessitate a split application of P and more frequent application of liquid N in smaller quantities.

Résumé

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La planification précise de l'irrigation est critique à l'amélioration de son rendement. C'est un outil technique et de gestion qui permet d'évaluer avec précision la quantité et la fréquence d'application de l'irrigation afin de répondre à la demande pour une croissance optimale des cultures. Cette planification est particulièrement difficile dans les régions humides, comme celles du sud-ouest ontarien, où l'humidité des sols est influencée par des pluies périodiques. Le but fondamental de ce projet de recherche de trois ans était d'étudier les différentes stratégies de planification de l'irrigation pour la production de tomates à Leamington, Ontario.

Il y a eu quatre objectifs spécifiques. Le premier a visé à développer une planification optimale de l'irrigation pour des conditions intensives de culture de la tomate destinée à la transformation en examinant différents facteurs déclencheurs pour l'irrigation. Le taux d'humidité, comme élément déclencheur, a été exprimé par une fraction de la capacité au champ et de la succion du sol, qui sont reliés à la réserve utile (RU) d'eau du sol. Le dispositif de déclenchement avec un appauvrissement en eau de ≤ 40% (RU) a produit les meilleurs rendements. Les meilleurs rendements ont été obtenus lors d'une tension entre les seuils critiques supérieur et inférieur d'humidité de -10 kPa et -30 kPa, ce qui représentait un appauvrissement de 20 à 24% de la RU.

Le second objectif a visé le développement d'un protocole robuste pour la mise en opération d'une planification du calendrier d'irrigation. Trois différents types de capteurs de l'humidité du sol ont été évalués. Le capteur basé sur la mesure de succion est sorti gagnant avec la plus haute note d'évaluation. Cependant, les trois capteurs peuvent être utilisés avec succès pour le contrôle du calendrier d'irrigation. Les données obtenues lors de l'irrigation contrôlée par les capteurs ont été comparées avec le modèle de Peman-Monteith. Il a été démontré que les niveaux d'humidité du sol qui ont assuré un

appauvrissement en eau de ≤ 40% de la réserve utile (RU) du sol en eau ont permis de remplir les besoins en eau des cultures tout au long de la saison.

Le troisième objectif a examiné la variabilité spatio-temporelle de l'humidité du sol lors de l'irrigation au goutte-à-goutte dans une serre à environnement contrôlé. L'étude a montré que l'humidité du sol n'était pas distribuée uniformément et ce avant, comme après l'irrigation. Dans le cas des tomates de champ avec une ligne centrale de goutte-à-goutte, un espacement de rangée double de 50 cm fut adéquat pour le semis des jeunes pousses, grâce au plus haut taux d'humidité du sol dans cette zone. De plus, avec le manque d'uniformité de la distribution de l'humidité dans le sol, des capteurs jumelés (placés de chaque côté de la ligne goutte-à-goutte) pourraient donner une meilleure estimation de l'appauvrissement en eau du sol pour une meilleure programmation de l'irrigation contrôlée par capteur.

Le quatrième objectif a étudié la cinétique des éléments nutritifs à travers le profil du sol tout au long de la saison de culture. Les éléments nutritifs du sol (P et N) ont été surveillés à différents niveaux du profil (0 à 30, 30 à 50 et 50 à 70 cm) et au moment précédant le semis, en mi-saison et en fin de saison. La signification statistique de P et N a été obtenue tout au long de la saison et selon le profil du sol et ce pour les trois années de l'étude. La variabilité entre les traitements n'a pas été significative. Les concentrations en P et N aux profondeurs de 50 et 70 cm se sont avérées élevées, avec un potentiel d'être emportées par le système de drainage souterrain. Une modification de l'application de P et N peut aider à réduire le lessivage du sol sous la zone racinaire.

Preface and contribution of Authors

All the manuscripts in this thesis (Chapters 3, 4, 5, 6, 7 and 8) have been authored by Felix Jaria and Dr. Chandra Madramootoo. Felix Jaria is the first author; he designed field experiments, installed instrumentation, carried out the field and laboratory work, data analysis and wrote the manuscripts. Professor Chandra Madramootoo, research supervisor, is the co-author; he provided supervisory guidance, funding and constructive comments in relation to the field experiments and reviewing of the manuscripts.

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Finally, greatest thanks go to the Mighty God of heaven, who saved me by His grace and daily sustains me by his power to preserve me to the end.

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Nomenclature

AAFC	- Agriculture and Agri-Food Canada
AAI	- Area Actually Irrigated
AEI	- Area Equipped with Irrigation Infrastructure
ABA	- Abscisic acid
AMITOM	-The Association Méditeranéenne Internationale de la Tomate
BMPs	- Best Management Practices
BNF	- Biological Nitrogen fixation
BR	- Bowen ration method
DI	- Drip Irrigation
e_a	- Actual vapour pressure (kPa)
EC	- Eddy covariance
e_s	- Saturation vapour pressure (kPa)
e_s-e_a	- Saturation vapour pressure deficit (kPa)
EM	- Electromagnetic
ETo	- Reference Evapotranspiration (mmday^{-1})
FAO	- Food and Agriculture Organization
FAOSTAT	-The Food and Agriculture Organization Statistical Database
G	- Soil heat flux density (MJm^{-2}day^{-1})
GDP	- Gross Domestic Product
IAH	- Irrigated Area Harvest
ICID	- International Commission on Irrigation and Drainage
IFPRI	- International Food Policy Research Institute
IPTRID	- International Programme for Technology and Research in Irrigation and Drainage
IWMI	- International Water Management Institute
LWRP	- The Low Water Response Program
OHCRSC	- Ontario Horticultural Crop Research and Service Committee
OMAFRA	- Ontario Ministry of Agriculture Food and Rural Affairs
OVPG	- Ontario Processing Vegetable Growers
OWRA	- Ontario Water Resources Act

PRD	- Partial root zone drying
PTTW	- Permit to Take Water Program
PVC	- Polyvinyl chloride
RDI	- Regulated deficit irrigation
SIS	- Scientific irrigation scheduling
SDI	- Subsurface drip irrigation
SOLAW	- State of the World's Land and Water Resources for Food and Agriculture
SSC	- Soluble solids concentration
T	- Mean daily air temperature at 2m height (°C)
U_2	- Wind speed at 2m height (ms^{-1})
θ_v	- Volumetric Water content
WPTC	- World Tomato Processing Council
WSNs	- Wireless Sensor Networks
WUE	- Water Use Efficiency
ε_a	- Apparent dielectric permittivity
Ψ_w	- Soils water potential
Ψ_m	- Matrix potential
Ψ_g	- Gravitational potential
Ψ_O	- Osmotic potential
Ψ_T	- Total potential
R_n	- Net radiation at the crop surface ($mMJm^{-2}day^{-1}$)
Δ	- Vapour pressure curve (kPa $°C^{-1}$)
γ	- Psychrometric constant (kPa$°C^{-}$

Chapter 1 -General Introduction

1.1 Irrigation and the global perspective

Irrigation has been practiced for millennia. Early archeological studies have proven the existence of irrigation systems in Euphrates-Tigris (Mesopotamia), the Nile, and China (Weiss et al., 1993). Shiklomanov (2000) estimated during the 1800's and 1900's, the global extent of irrigated lands was approximately 8 million and 47 million hectares respectively. Between 1900 and 2000, irrigated agriculture increased from approximately 50 million hectares to 275 million hectares (Gleick, 2000) (Fig. 1.1). Further, a study by De Wrachien (2003) estimated that global irrigated area increased by around 2% a year in the 1960s and 1970s, subsequently reduced to about 1.5% in the 1980's, and by <1% in the 1990s.

At the World Food Summit in 1996, the FAO estimated that 60% of the extra food required to meet future population growth must come from irrigated agriculture (FAO, 2003). Recent updates by the State of the World's Land and Water Resources for Food and Agriculture (SOLAW) estimates that by 2050, rising populations and incomes will require a 70% increase in global food production. In quantitative terms this will be equivalent to an additional annual production of one billion tonnes of cereals and 200 million tonnes of livestock products (FAO, 2011).

Presently, agriculture accounts for over 70% of the world's water withdrawal (Raskin et al., 1997). 40% of global crop production comes from the 18% of irrigated agricultural lands and employs about 30% of the global population in rural areas. In contrast, rain-fed agriculture accounts for 80% arable lands and produces 60% of the world's food (De Wrachien, 2003; Rockstrom & Falkenmark, 2000). Irrigation makes the most significant contribution to global food security in Asia, representing nearly two-thirds of the total global irrigated area. These lands account for as much as 80%, 70% and 50% of food production in Pakistan, China, and India and Indonesia respectively (Barker & Molle, 2004). Most agriculture in the Middle East countries relies on irrigated agriculture. Irrigated agriculture in Iraq, Saudi Arabia and Iran is expected to account for 92%, 84%

and 73% respectively of all agricultural production in these countries. It is expected that in the USA and Asia, 67% and 50% of agriculture will be under irrigation by the year 2025 (Calzadilla et al., 2010). In Spain, irrigated agriculture represents 60% of agricultural production, utilizing 19% of the cultivated area (3.6 million hectares) and consumes 80% of the total water supply (Berbel & Gómez-Limón, 2000)

Two hundred and eighty eight million ha (19%) of the world's 1600 million ha of arable land, is presently irrigated (FAO, 2007). Irrigated agriculture is under increasing pressure to manage water more efficiently. This is driven by increasingly limited water resources, quality requirements, economic factors, demands on labor and the need to minimize resource degradation and yield losses resulting from inefficient irrigation (water logging, salinization, deteriorated surface and ground water quality) (FAO, 2011).

Rattan et al.(2005) warned that the 21st Century requires a "Blue Revolution" to complement the "Green Revolution". This would facilitate the expansion of food production in order to meet the nutritional needs of the growing world population. In this new Blue Revolution, water-use productivity must be wedded to land-use productivity. Science and technology must lead the way.

1.2 Background

Ontario accounts for 10.8%, of Canada's lands, which translates to approximately 1,076,395 km^2, of which 917,741 km^2 (82.3%) and 158,654 km^2 (17.7%) represents land and water respectively. The province of Ontario with an irrigated area of 63,311ha, (ranks 4th in the Canada) representing 7.4% of the total irrigated lands in Canada (844 975 ha) (Statistics Canada, 2006a). Vegetable crops are an important component of Canada's agricultural industry with 45.4% of all irrigated lands under vegetable production (Statistics Canada, 2006c). The agricultural sector consumes 20% of the total water withdrawn in Ontario, of which 54% is consumed mainly during the summer months (de Loë et al., 2001)

As early as the 1970's, Ontario led as the major processing tomato producing province in Canada (Tiessen, 1979). The unique combination of climate and soils created a suitable environment for the production and processing of tomatoes (Madramootoo et al, 2007). In 1977, Canada produced 9,376 ha of processing tomatoes, producing an estimated 142,842 Mg (at 12.4 Mg ha^{-1}) valued at \$37.1 million dollars. About 93% of the total acreage was grown in the province of Ontario, with the remaining 7% shared between Quebec and British Colombia (Tiessen, 1979). By 1998, there was approximately 11,500 ha under production with yields averaging 44.7 Mg ha^{-1}. Over time acreages of tomato gradually decreased due to improvement in yields. In 2005, processing tomatoes were grown on 6,635 ha producing 641,404 Mg at an average yield of 89.2 Mg ha^{-1}, generating \$59.5 million (Table 2.6). An additional 1,012 ha were grown for the fresh market with a farm value of \$18.2 million (OHCRSC, 2006). In 2008, Ontario's farm cash receipt from vegetables in Ontario was \$932 million. Southern Ontario produces an estimated 73% of major vegetables in the province; 30% of these vegetables were produced under irrigation (Statistics Canada, 2006a).

It is estimated that approximately 40 to 50% of the processing tomato acreage was irrigated in 2007. Today, Ontario produces more than 98% of all processing tomatoes in Canada. 90% of production is concentrated in the counties of Essex and Kent in the southwest of the province (LeBoeuf, 2007). Approximately 80% of all field tomatoes are processed and 20% used for fresh-market consumption.

The production of processing tomatoes in Leamington is a very important industry in Southwestern Ontario because of the climate, soil type, availability of lands, good quality water resources and close proximity to a ready market. However, Canada's tomato processing industry produces less than 10% of production in the United States (Table 2.6). The success of the Canadian industry is contingent on the ability to compete at the international level. This competitive edge is achieved through a number of cohesive factors, one of which is proper irrigation management. The provision of irrigation to meet crop water requirement is therefore a prerequisite and important factor of production. Proper irrigation management is facilitated through scientific irrigation scheduling which determines the critical timing of irrigation events and the correct application volumes to be provided to the crop throughout the growing season.

1.3 Problem definition

Expanding populations and the associated growth in industrial and agricultural water demands have led to increased competition over limited water resources. Local and national demands for limited resources result in heightened competition among the many users. The domino effect of providing the resource for one user inevitably results in depriving other users. Kulkarni (2011) calculated that irrigation is the largest user of freshwater globally, accounting for about 70% of all withdrawals. An assessment by Smith et al. (1996) estimated that only 40 to 60% of the water is effectively used by crop. The challenge facing irrigated agriculture is to utilize the limited water resources more sustainably.

Under conditions of unlimited water resources, maintaining soil moisture within the crop's rooting zone at close to field capacity throughout the growing season would be ideal for maximum production. However, ideal conditions are far from ideal in the humid region of Southwestern Ontario, with limited water resources and periodic rains. Further, there are limited water resources to be shared amongst many users, and irrigation scheduling has to be managed to maximize the use of potential rainfall. 71% of the water withdrawn for agriculture is consumed and is the greatest water consumer (Harker et al., 2008). With increasing pressure on water resources for irrigated agriculture, the challenge facing the agrarian community in Ontario is the understanding of crop response to different irrigation trigger levels or deficit irrigation levels. Deficit irrigation increases WUE of a crop by reducing irrigation during non-critical crop growth stages (particularly during crop vegetative stage) without negatively impacting crop yields.

1.4 Research objectives

The overarching goal of this study was to increase the economic productivity of large scale field processing tomatoes in Leamington, by more effectively utilizing limited water resources. This study should assist Ontario farmers to accurately meet schedule irrigation in terms of timing and quantity, and render irrigation water management more environmentally sustainable. The research was undertaken with the following objectives:

- To develop an optimum irrigation schedule for intensive cultivation of processing tomatoes by examining different irrigation trigger levels;
- To develop and test a protocol for a real-time soil moisture monitoring system for scheduling irrigation and its comparison with an empirical crop water requirement model;
- To determine the impact of spatio-temporal variability of soil moisture under drip irrigation for tomato cultivation; and
- To determine the nutrient dynamics in the soil profile over the growing season of the crop.

1.5 Scope

This three year research project was conducted on a private farm in Leamington, Southwestern Ontario during the months of May to September from 2008 to 2010. The research project involved the irrigation scheduling of field processing tomatoes under buried and surface drip irrigation. The study plots were equipped with continuously monitoring volumetric or tensiometric soil moisture sensors, which informed the irrigation scheduling process. The farm consisted of primarily a two-layered soil with a loamy sand extending to approximately 30 cm below the surface, followed by a sandy layer. This soil type was representative of the general farm area.

Experiments were located in different areas of the same farm each year in order to facilitate annual crop rotation. Data was collected on soil moisture, irrigation duration and volumes, crop yields and fruit quality. A weather station was installed to measure climatic parameter for further analysis. A total of 14 different parameters were monitored to evaluate and inform the four main research objectives.

1.6 Thesis organization

This thesis has been developed as a series of manuscripts, each contributing to the objectives stated in section 1.4. This thesis is presented in 9 chapters:

Chapter 1 General Introduction; background; problem definition and objectives.

Chapter 2 Literature review of irrigated agriculture in Canada, with special focus on Ontario and field tomato processing. A review of the irrigation scheduling methods and strategies presently used were discussed. The current types of soil moisture monitoring technology in relation to precision irrigation scheduling were also discussed. Also reviewed was the subject of water use efficiency, water and solute dynamics under drip irrigation.

Chapter 3 Determination of the threshold for irrigation management of processing tomatoes using continuous soil moisture monitoring sensors under drip irrigation in south-western Ontario. This chapter address objectives one and part of objective two in relation to the development of the irrigation scheduling protocol.

Chapter 4 In situ calibration of volumetric moisture sensors in a drip irrigated loamy sand. The proper calibration of soil moisture sensors is an important prerequisite in sensor based precision irrigation scheduling. This chapter therefore addresses an important component of objective two.

Chapter 5 Determination of irrigation water requirements of processing tomato (*Lycopersicon esculentum* L.) using soil moisture sensor and weather data. This chapter focuses on the second aspect of objective two.

Chapter 6 Using real time soil moisture measurements to better schedule irrigation water application. This chapter deals with objective two.

Chapter 7 Determination of spatio-temporal variability of soil moisture under surface drip irrigation using soil moisture sensors. This chapter addresses objective three.

Chapter 8 To determine the nutrient dynamics in the soil profile over the growing season of the crop. This chapter addresses objective four.

Chapter 9 Contains summary and conclusions from this research. It also highlights recommendations for follow-up research and the contribution to knowledge.

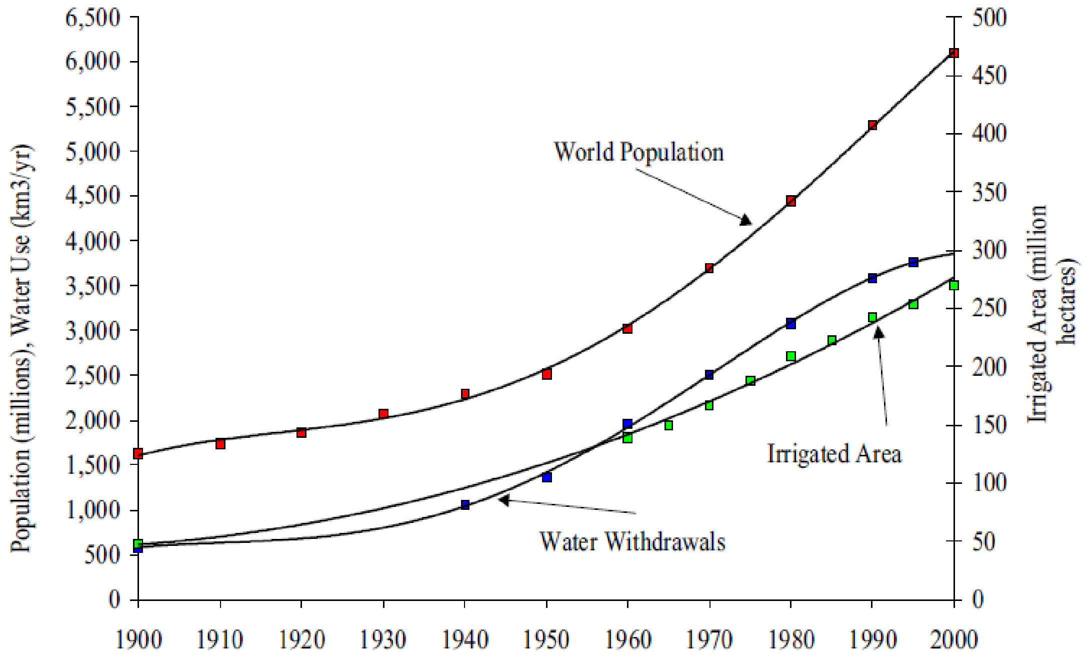

Figure 1.1-World population, water use and irrigated area from 1900 to 2000

Chapter 2 – Literature Review

2.1 Irrigated Agriculture in Canada

Canada has the fourth largest supply of freshwater in the world behind Russia, China and Brazil. Approximately 9% of Canada's total area is covered by freshwater although the country has less than 1% of the world's population. Canada has more lake area than any other country in the world with an estimated 2 million lakes, covering approximately 7.6% of the land area (Statistics Canada, 2011b). The Great Lakes are an important fresh water source, having roughly 1% of its waters renewed each year by snowmelt and rainfall. The Great Lakes contain approximately 20% of the world's fresh water resources (Environment Canada, 1996). Table 2.1 provides a matrix of the distribution of water amongst the various provinces in Canada. Despite these impressive statistics, Canada has its own unique agriculture-related water issues. About 60% of Canada's freshwater drains to the north, while 90% of the Canadian population lives in the south. Issues of surface and ground pollution and escalating demand amongst other users (agriculture, domestic, industry, tourism and recreation), are imposing increasing pressure on freshwater resources in the South (Environment Canada, 1987).

Approximately 7% of the nation's land surface is cultivated and is concentrated in the southern portion of the country. The Canadian Prairies represent 82% of the total lands under cultivation. Southern Ontario and Quebec contribute 13%. The current farming area is 67.8 million hectares and has remained constant since World War II, (Statistics Canada, 2006c).

In 2001, approximately 80% of all cultivated land was characterized as cropland (land used primarily for the production of row crops, close-growing crops, fruit and nut crops). An increase in 45% (25.2 million ha to 36.4 million ha) in (crop land) was realized during the period of 1951 to 2001 (Hofmann et al., 2005). In 2006, agriculture and the agri-food system contributed $87.9 billion to Canada's Gross Domestic Product (GDP) representing 8% of the Canadian economy and employed 2.1 million persons. (AAFC, 2008).

Due to harsher climatic conditions further north, almost all of Canada's cultivated land lies within 500 km of its southern border with the United States. Canada's agricultural production consists of primarily four categories of farming; grain farms (wheat, oats, flax, and rapeseed); livestock farms (cattle, poultry and eggs, pork, and lamb); specialized farms (potatoes, tree fruits, tobacco, or vegetables); and mixed farms (the combination of livestock and grain production). Due to the varied agro-climatic zones, cropping system differ among the various regions of Canada (Encyclopædia Britannica, 2011).

2.1.1 Irrigation in Canada

In British Columbia, Alberta and Saskatchewan, irrigation started in the late 1800s and early 1900s (Chinn, 1999). The origin of irrigation development in Canada emanated from Western Canada (Tollefson et al., 2002). Of the 65.9 million hectares of agricultural lands, approximately 0.86 million hectares of irrigated land exist, of which 7.7% is found in the province of Ontario, 2.8% in Manitoba, 11.4% in Saskatchewan, 13.4% in British Columbia and 60.2% in Alberta. The total irrigated lands in Canada represent only 2.5% of the total agricultural lands for 2006 (Table 2.2). Although Alberta had the most lands under irrigation in 2006 (0.5 million ha), this represented only 5.4% of the cropped lands while British Columbia irrigated 20.4% of its cropped lands (Statistics Canada, 2006c).

About 75% of all agricultural water withdrawals in Canada take place on the Prairies, mainly for irrigation (Harker et al., 2008). Holm (2008) indicated that Alberta's irrigated lands represent 65% of Canada irrigated lands. These irrigated lands are fed by 8,000 km of conveyance network and 50 water storage reservoirs; they support 40 different crops grown on 625,000 ha. Irrigation is provided to 13 irrigation districts occupying 525,000 ha and a further 1000 ha of private farms. Irrigated agriculture in Alberta contributes directly and indirectly to 13% of the regional gross domestic production, 19% of regional production and 30% of regional employment. Almost one-third of the province's gross domestic product in processing industries is directly related to irrigation.

Saskatchewan and Alberta are climatically similar which have influenced the widespread irrigation plans. Large portions of farmlands are under irrigation in southern Alberta (0.5

million ha) while Quebec has a very small portion of the arable land under irrigation (0.03 million ha). The drier parts of Canada, which includes the southern regions of Alberta, British Columbia, and Saskatchewan require irrigation and accounts for 89.0% of all irrigation in Canada for 2006 (Statistics Canada, 2006). Most irrigation in Alberta and Saskatchewan regions utilize center-pivots, side wheel role systems or flood irrigation for grains, oilseeds, forage crops and sugar beets. Recently, irrigation system efficiencies have increased by 40% in Alberta due to the conversion from flood irrigation to more efficient center-pivot systems (IWMS, 2002).

CANICID (1999) highlighted that in British Columbia, micro-irrigation systems and permanent-set standing sprinklers are mostly used for fruit/vegetable and hay production. In the four provinces of Alberta, British Columbia, Manitoba and Saskatchewan, water resources for irrigation are diverted from rivers and streams due to limited good quality groundwater. However Manitoba is not exclusively dependent on surface water resources as some good quality groundwater can be harvested (Chinn, 1999).

Tollefson (2002) identified that in British Columbia, irrigation is used primarily in the semi-arid interior valleys for forage, fruit and higher valued crop production. As a result, the need for high quality products for the potato processing industry has been the catalyst for irrigation development in Manitoba. Further, the use of centre-pivot irrigation for potatoes is becoming increasingly important for the province. Chinn (1999) noted that the intensive fruit growing industry in British Columbia is contingent on irrigation for the constant supply of good quality fruit. In some areas, irrigation is used for frost protection. Harker et al.'s (2008) study of British Columbia found that increased optimization of water use for crop production has been realized due to the use of micro-irrigation systems (trickle or drip irrigation). Further, these irrigation systems have increased optimization of water use for crop production, and could eliminate surface loss and restrict subsurface losses. Chinn (1999) found that much of the irrigated grain and forage in Alberta is grown for the livestock industry. Irrigation in Manitoba and Alberta and to a lesser degree Saskatchewan, facilitate the production of quality potatoes for seed potato, French fries and chip processing industries.

Compared to the western provinces, irrigation water demand is relatively small for eastern Canada. This can be attributed to the smaller irrigated land base (approximately 100,000 ha) and the region's high annual precipitation rates (700-900 mm) which exceed evapotranspiration (500-600mm) (OMAFRA, 2004). Irrigation is mainly used for high value horticultural crops in the fruit and vegetable industries including potatoes. The rainfall distribution does not always synchronize with crop water needs and hence supplemental irrigation is required during the months of June, July and August, to meet crop water demands. The main methods of irrigation in (eastern) Canada are sprinkler and drip systems (Harker et al., 2008).

Harker et al., (2008) revealed that improved irrigation effectiveness gained national focus through higher efficiency irrigation systems; improved water resources management; irrigation scheduling; minimizing evaporation losses and, production of higher value crops. The shift to efficient irrigation systems does not necessarily translate into water savings, unless these systems are managed correctly.

2.1.2 Ontario water resources

Ontario is Canada's second-largest province after Quebec and covers approximately 1 million km^2 (Baldwin et al., 2000) supporting the largest population (13 million). The province is bordered to the west by Manitoba (95° 09' W longitude), Hudson Bay to the north (56° 51' N Latitude), Quebec to the east and Middle Island in Lake Erie to the south (41° 40′ N Latitude.). Additionally, the southern boundary is bordered by three states of the United States; Minnesota, Michigan, and New York (Government of Ontario, 2010).

Ontario's strategic location provides access to a large supply of fresh water; which includes 250,000 lakes covering a total surface area of 181,153 sq. km. This fresh water represents 17% of the province's total area, along with countless rivers and streams, and groundwater sources. The Great Lakes contains 20% of the world's fresh surface water supply (Ministry of Natural Resources, 2011). Four of the five lakes form part of the Canada-United States border. It is noteworthy that Gabriel and Kreutzwiser (1993) suggested that only 1% of the Great Lakes water is actually renewable.

The province of Ontario consists of three primary watersheds; the Great Lakes which drain into the St. Lawrence River, the Hudson Bay draining north into the Hudson Bay and Nelson River draining west to Manitoba. These three primary watersheds are subdivided into 17 and 144 secondary and tertiary watershed divisions respectively. The secondary and tertiary divisions range from 4000-150,000 and 700-31,000 km^2 respectively. The Hudson Bay Watershed captures about 30% of total Canadian runoff (OMNR, 2009b). Dolan et al. (2000) assessed that 60% of Ontario's surface water flow is away from the heavily populated and industrialized areas in the south, but towards Hudson Bay in the north. Gabriel and Kreutzwiser (1993) estimated that Ontario utilizes over 50% of Canada's total water resources.

2.1.2.1 Management of farm water

Two mechanisms exist for the management of farm water in Ontario; the Permit to Take Water Program (PTTW) and the Ontario Low Water Response Plan (OLWRP).

Water abstraction in Ontario is governed by the *Ontario Water Resources Act* (OWRA) of 1961 and the Water Taking and Transfer Regulation (O.Reg.387/04) which fall under the mandate of the Ministry of the Environment. The objective of the Act is to facilitate sustainable use of the resource through conservation, protection and management in order to promote holistic and long-term environmental, social and economic well-being (Environmental Commissioner of Ontario, 2001).

The Permit to Take Water Program (PTTWP) is facilitated through Section 34 of the OWRA. This permit requires anyone abstracting more than 50,000 litres of water daily from a lake, stream, river or groundwater source, with some exceptions, to obtain a permit to harvest water. Water taking permits are issued for a maximum period of up to 10 years. Three classifications for water taking applications are available. Category 1 involves water abstraction with low risk of negatively impacting or interfering with the environment. Categories 2 and 3 relate to water abstraction with the potential to cause adverse environmental impacts or interference. The granting of a category 2 or 3 permit is contingent on the provision of scientific studies (Ontario Ministry of Environment, 2005).

The Low Water Response Program emanated as a proactive approach to manage future stressed water resource conditions in Ontario. Prior to the establishment of this initiative, Ontario experienced a series of localized dry spells which affected agricultural production almost every year in the province from 1960 to 1989 (Brown et al., 1968; Gabriel & Kreutzwiser, 1993). By May 1999, the Provincial Low Water level Response Task Force was formed and by March 2000 the LWRP was implemented (Ontario Ministry of Natural Resources et al., 2003). The program involves and solicits partnership at both the provincial and local levels. The LWRP has legitimacy through existing legislation and regulation. Its implementation is facilitated under the Municipal Act, the Lakes and Rivers Improvement Act and the Ontario Water Resources Act (Ontario Ministry of Natural Resources et al., 2003).

2.1.2.2 Water use and trends in Ontario

In 2004, Canada was ranked the highest water user in the world; with a 343 litres used per person. This represents twice the volume used by residential users in Europe (Environment Canada, 2007).

In 2006, of the 60.5 billion m^3 of surface water withdrawn by Canada's five major users, agriculture accounts for approximately 8%, thermal power 60%, municipalities 9.5%, mining 4% and manufacturing 18.5%. Agriculture was the fourth largest water user in 2005, accounting for 9% of total withdrawals, with 92.4% and 6.4% of the total being diverted toward irrigation and livestock respectively. (Environment Canada, 2011). Since 71% of the water withdrawn for agriculture is consumed, agriculture holds the position as the greatest water consumer in Canada (Harker et al., 2008).

The Great Lake Commission which is the repository for the Great Lake Regional Water Use Database provides detailed annual summaries of water use data for eight US States, and the two Canadian provinces of Ontario and Quebec (Great Lake Commission, 2011). Table 2.3, indicates abstraction from the Great Lakes including the St. Lawrence River, ground water and other surface water sources. Also reflected are the intra-basin (transfers that take place between one of the Great Lakes watersheds) and inter-basin (transfers that take place between the Great Lakes basin and another watershed). Both types can be either incoming or outgoing. In 2008, Ontario reported incoming inter-basin diversions into the Lake Superior basin from the James Bay basin for hydroelectric purposes (the Ogoki and Long Lac projects) amounting to 15.17 Mm^3 day^{-1}. Table 2.3 indicates the value as negative due to the fact the water was transferred from another watershed into the Great Lake Basin (Great Lake Commission, 2011).

In 2008, Ontario abstracted 769.3 Mm^3 per day. This withdrawal was divided among hydroelectric usage (93%), nuclear plant usage (5%) and 1% representing all other categories including municipal, agriculture, domestic and fossil fuel (Table 2.3). Figure 2.1 reflects the water abstraction volumes for 2008, with hydroelectric withdrawals omitted and users expressed as a fraction of the remainder (51.85 Mm^3 per day). Irrigation accounted for 0.5% and nuclear power 74% of the total abstraction. The calculation of consumptive use represents the portion of a resource reduced, withdrawn or withheld from the supply or source without returning an equal amount. The daily consumptive use for 2008 was calculated to be 1059.62 million litres per day (1.06Mm^3 day^{-1}). Public supply consumptive use amounted to 433.24 million litres per day (41%), followed by nuclear power and industry use at 32% and 21% respectively (Great Lake Commission, 2011).

2.1.2.3 Irrigated agriculture sector in Ontario

The Canada Land Inventory indicated that 11% of Canada's lands are arable and less than 1% falls in the category of Class One agricultural lands. Ontario, Manitoba, Saskatchewan and Alberta consist of 99% of Canada's Class One lands. Ontario is one of the major agricultural regions of Canada and possesses 56% of Class One agricultural lands. Almost all of these lands are located in the southern part of the province. By 2001, 11% of Ontario's best agricultural land had been utilized for urban settlement. (Hofmann et al., 2005).

Approximately 1.9% of Ontario farmlands were irrigated in 2005. Irrigated lands are concentrated primarily in the south and southwestern parts of the province, representing approximately 85% (53,874 ha) of all irrigated lands. A number of favorable factors contributed to this area under irrigation such as climate, geography, soil and water. These combined factors facilitate the cultivation of a large range of fruits (grapes, peaches, cherries, and berries), vegetables (sweet corn, peppers, tomatoes, and beans). 45%, 31% and 11.5% of the irrigated land were cultivated with field crops, vegetable and fruit trees, respectively (Statistics Canada, 2006a). Tables 2.4 and 2.5 provide data on land type and agricultural regions, respectively.

2.1.3 Field tomato production in Ontario

Over 120 years ago, tomato production commenced in Canada, it was cultivated in home gardens for fresh consumption by the French settlers. However tomatoes grown for the processing industry started about 1908, when the H.J. Heinz Company built a processing plant in the Leamington area of the Essex County, in South Western Ontario (Tiessen, 1979). Due to the establishment of processing plants in Eastern Ontario and Prince Edward County, 70% of the processing tomato acreage was concentrated in the East. Other companies subsequently built processing plants in South Western Ontario which further facilitated tomato cultivation. As a result, over time, the South Western area dominated in the production of processing tomatoes (Tiessen, 1979). By the 1980's, the two counties of Essex and Kent in South Western Ontario produced 76% of the total tomato acreage. The unique combination of climate, (more optimal climate for vegetable production) and lighter soils in those areas supported the constant production of higher, and more reliable tomato yields.

In 1977, Canada grew 9376 hectares of processing tomatoes, estimated at 414,987 Mg (at 42 Mg per ha) valued at $37, 112, 000.00. Ninety-three percent of total acreage was grown in Ontario (8940), with the remaining 7% grown in Quebec and British Colombia (Tiessen, 1979). As early as the 1970's, Ontario became the major processing tomato producing area in Canada. Today, virtually all tomatoes grown in Canada for processing are produced in the Ontario Counties of Essex and Kent.

In 1998, there were 12,749 ha under processing tomato cultivation by 533 growers, producing a total of 570,293 Mg of tomatoes (44 Mg/ha). Over time, acreages declined due to improvements in yield performance attributed to the application of technologies such as irrigation, soil fertility enhancement, crop storage practices, chemical means of controlling pests and diseases, and mechanization of production. These gains could also be attributed to improved plant breeding, producing crops with higher yields and with the ability to resist pests and adverse climatic conditions (Tilman et al., 2001).

By 2004, tomato production attained its highest level. Annual production was estimated at 651,890 Mg, produced by 153 growers, cultivating 6,246 ha, valued at $61 million dollars. By 2010, production reduced by 21% to 513,724 Mg due to cutbacks of tomato quotas for contracted farmers (Figure 2.2). Canada's processing tomato production is approximately 5% of production in the USA (Table 2.6).

There are 11 tomato processing facilities in the Ontario province, with the three largest being H.J Heinz Company of Canada Ltd., CanGro Foods Inc. formerly known as Kraft Canada Inc., and Sun-Brite Canning Ltd. 85% of the total volume of tomatoes are processed by these three companies. 70%, 20% and 10% of tomato production are transformed into tomato paste, whole peeled tomato and juices respectively (Tomato Processing in Canada, 2006).

Ontario greenhouses produce all seedlings required for the processing tomato industry. There are about 40 acres of greenhouses used for transplant production and they produce approximately 200,000,000 tomato seedlings for Ontario and U.S growers. Ontario tomato processing industry utilizes 100% transplants for planting (Tomato Processing in Canada, 2006). The seedlings are transplanted from early to mid-May. Some danger of frost still exists at that time. The duration of time from germination to transplanting is approximately 43 days. Early maturing varieties require approximately 90 to 95 days while later maturing varieties require 110 to 125 day for harvesting. The plants are grown on raised beds to facilitate harvesting operations as well as to reduce the potential for water damage that may result from a wet harvest season. Harvesting is fully mechanized and is undertaken during early August and mid-October (Sims, 1992).

2.2 Overview of irrigation scheduling methods

Scientific irrigation scheduling (SIS) allows the control of when (frequency) to irrigate, and how much water (time and quantity) to be applied to the crop (Thompson, 2007a). This technique facilitates timely and accurate provision of water to the crop and is key to conserving water and energy; improving irrigation performance, crop yields and quality (Pardossi & Incrocci, 2011; Tacker et al., 1996). Additional benefits of SIS include reduction of non-point pollution (Nguyen et al., 1996; Pardossi et al., 2009) and sustainability of irrigated agriculture (Smith et al., 1996; Tebal, 2011). LeBoeuf et al. (2007) suggested that irrigation should supply crops with the requisite amount of water, at the exact time, at the lowest cost, and with the least impact on the environment. Therefore, irrigation scheduling is the process of determining and planning, when to irrigate, the volume of water required, the application rate, and the frequency at which water is to be applied. LeBoeuf et al. (2007) further added that irrigation is a significant production cost; maximum economic benefit can only be achieved with a practical and effective irrigation scheduling program. This technology aims to achieve optimum water status for productivity, by keeping soil moisture close to field capacity (Jones, 2004). This is accomplished by taking physical measurements that estimate crop water use and soil water status (Leib et al., 2002). Bailey and Spackman (1996) established that achieving optimum benefit from irrigation in a variable climate is dependent on regulating the timing and quantity of applied water, to provide for continuously changing crop water requirements. Irrigation scheduling requires frequent measurements or continuous estimation of soil water depletion. Martin et al. (1990) stated that irrigation scheduling assists in the development of irrigation systems for different crops under different soil and climatic conditions.

Research over the past decades broadened our knowledge of plant-water relations and provided a large number of tools; that may enhance irrigation management, improve irrigated crop production, and water use efficiency(Pardossi & Incrocci, 2011). Smith et al. (1996) lamented that despite considerable efforts to promote the introduction of modern irrigation scheduling tools, their application in practice has so far fallen well below expectations. Pleban & Israeli (1989) identified two main reasons why real time irrigation scheduling programs have not been widely used. The first is that programs have been oriented towards research and for use by professionals; and secondly, scheduling was examined from the perspective of the crop and the academic researcher, and not from the view of the farmer. Tollefson and Wahab (2007) attributed its limited applicability to technical and operational constraints.

Irrigation scheduling can be economically feasible because of significant water and energy conservation, improved crop production and environmental benefits (Barragan & Wu, 2001; Cancela et al., 2006; Sammis et al., 1990). Proper irrigation management will help prevent economic losses (yield and quality) caused by over or under irrigation; reduce the movement of nutrients, pesticides and other chemicals to ground water and other water bodies; prevent waste of water resources and support more efficient energy consumption. Well managed irrigation can lead to increased yields, greater farmer profit, significant water savings, reduced environmental impacts, and improved sustainability of irrigated agriculture (Evett et al., 2011a; Gill et al., 2011; Livellara et al., 2011; Montoro et al., 2011).

When irrigation scheduling is used in conjunction with drip irrigation methods and fertigation, it can lead to improved nutrient efficiency . Battilani and Ferreres (1999) identified a number of positive effects of fertigation practices with reduced negative impacts on the environment. Fertigation supports higher efficiency in nutrient use and reduced fertilizer volumes. Further, the precise distribution of small amounts of nutrients reduces or eliminates the risk of leaching.

Hoffman et al. (1990) categorized quantitative irrigation scheduling into three main groups; soil monitoring, plant monitoring and soil water balance computations. The meteorological method is also utilized as an irrigation scheduling method. Stegman et al. (1980) highlighted that soil monitoring would include assessing appearance and feel, to subjectively ascertain moisture content, gravimetric measurement of soil water content; electromagnetic sensors measurement; and tensiometric measurements of soil water potential. Irrigation allows soil moisture to deplete or soil matric potential to increase, to some predetermined threshold (of field capacity or soil available water capacity). The primary advantage to this approach is that field conditions are directly monitored. The disadvantage of this approach however, is that it is time consuming. The following discussion focuses on three main categories of irrigation scheduling.

2.3.1 Soil water monitoring

There are generally two ways of measuring soil water for plant growth; by measuring soil moisture content, and the water potential (Smith et al., 1996). Soil moisture is described as gravimetric soil moisture (mass of soil water divided by weight of dry soil), volumetric water content (volume of soil water in a given volume of soil) and depth of soil moisture per depth of soil (mm of water per metre of soil). The measurement of the moisture content can be accomplished directly or indirectly; while the water potential is measured through tensiometry (Bittelli, 2011; Gardner, 1986). Soil based measurements generally require tedious calibration procedures, frequent servicing and supervision. These measurements are site specific and need many observations for accurate characterization of a field, which is laborious and expensive (Tollefson & Wahab, 2007).

2.3.1.1 Direct methods

Direct methods of water content determination are those where water is removed from a sample by evaporation, leaching or chemical reaction, with the amount removed being determined (Evett, 2008; Gardner, 1965; Munoz-Capena & Dukes, 2005). Direct methods of monitoring soil moisture are not commonly used for irrigation scheduling. The problems associated with these methods arise because they are destructive; labor intensive; inapplicable to automatic control; with a long response time (>24 hours) and cannot provide real time feedback (Bittelli, 2011; Blonquist Jr et al., 2006; Zazueta et al., 1994). However, Hankin and Sawhney (1978) proposed the microwave method to determine gravimetric water content within six minutes, which may offset the disadvantage of long response time associated with the conventional gravimetric method.

2.3.1.2 Indirect methods

Indirect methods estimate soil water content based on measurement of soil properties assumed to be correlated with water content (Evett, 2007; Gardner, 1986). The indirect methods are either volumetric or tensiometric (Dukes et al., 2010; Pardossi et al., 2009)

2.3.1.2.1 Volumetric Moisture Sensors

Most of the sensors suitable for irrigation are dielectric. Emerging from this principle are two types of soil measuring methods. The first are sensors that measure the electrical capacitance of the soil. The second utilizes time domain reflectometry (TDR) to measure the velocity of a wave travelling along a waveguide embedded in the soil (Yoder et al., 1998).

Time domain reflectometry (TDR)

TDR began as a point source measurement technique used in the laboratory to obtain field soil water content profiles. The technique offers high spatial and temporal resolution relative to other methods (Wraith et al., 2005). The TDR instrument generates an electric pulse signal down steel probes called wave guides buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the return signal varies with the soil dielectric, which is related to the water content of the soil surrounding the probes (Ledieu et al., 1986). O'Brain and Veldkamp (2000) stated that TDR measures the apparent dielectric permittivity of soil (ε_a). Since the apparent dielectric permittivity of water is significantly greater than other soil constituents, changes in ε_a can be attributed to changes in water content in non swelling soils. Evett and Heng (2008a) further added that the estimates of water content are made on the basis of calibration equations, represented by the relationships between θ_v and travel time or between θ_v and apparent dielectric permittivity (ε_a), which is estimated from travel time.

A large number of experiments have proven that the TDR technique is useful in studies of real-time soil water content dynamics, with an average interpretation ranging from 2 to 5% error in volumetric water content (Ayars & Phene, 2007; Evett et al., 2011b; Jabro et al., 2009; Madramootoo et al., 2007; Mehdi et al., 2008; Soler & Hoogenboom, 2007; Topp & Davis, 1985b; Topp & Reynolds, 1998; Wraith et al., 2005).

Capacitance probe

One of the first studies to use a high frequency capacitance technique for soil water content determination was conducted by Thomas (1966). Over the years the technology has improved and capacitance soil moisture sensor have been utilized in facilitating irrigation scheduling for a wide range of crops (Evett et al., 2012b; Irmak & Irmak, 2005; Miller, 2012; Rufat et al., 2011; Zotarelli et al., 2011) Capacitance sensors utilize an electronic circuit called an oscillator, which produces a repetitive sinusoidal waveform for the measurement of soil water and operates typically in the radio-frequency regime from 10 MHz up to several hundred MHz. (Bogena et al., 2007; Dean et al., 1987; Evett & Cepuder, 2008).

Capacitance probes measure soil water levels at different depths along the soil profile, record information on a data logger, which can then be transferred to a computer. The sensor is placed in a waterproof access tube in the ground and records are made at 100 mm increments down the profile. The information collected can graphically display the soil moisture content at different depths along the soil profile. The sensor has a high response time to changes in moisture with a precise monitoring of the water content in the soil (IIda et al., 2005). Capacitance sensors consist essentially of a pair of electrodes (either an array of parallel spikes or circular metal rings) that form a capacitor with the soil acting as the dielectric in between. This capacitor works with the oscillator to form a tuned circuit, and changes in soil water content are detected by changes in the operating frequency.

2.3.1.2.2 Tensiometric sensors

Measurements of soil water tension (SWT) can be determined with tensiometers, gypsum blocks, heat dissipation sensors, granular matrix sensors, psychrometers, and other devices. Measurements of SWT are particularly useful for irrigation scheduling when a SWT irrigation criterion that maximizes crop performance is determined for a given crop in a particular environment (Shock & Wang, 2011).

Tensiometer

The tensiometer is one of the oldest and most widely used instruments for irrigation scheduling around the world. Over time these instruments went through significant developmental changes in terms of diameter, length, pressure sensing and automation (Evett & Heng, 2008b). These instruments were used to measure soil water potential from the early 1900's (Gardner et al., 1922; Livingston, 1908; Richards, 1928); and used for irrigation scheduling from the late 1950s (Richards & Marsh, 1961; Smajstrla et al., 1998).

The practical operating range for tensiometers is from zero to 75 kPa. Readings of zero, 10 kPa and 30kPa correspond to field saturation, field capacity for coarse textured soils and field capacity for fine textured soils respectively. The upper limit of 75 kPa represents depletion levels of 30% and 90% of AWC for fine textured soil and coarse textured soils respectively. This limits the practical use of tensiometers to coarse textured soils or to high frequency irrigation, where soil water content is maintained at high values (Evett & Heng, 2008b). The main disadvantage of the tensiometer is that it functions only from zero to about 80 kPa, which represents a small part of the entire range of available soil water (Zazueta et al., 1994).

A range of threshold/refill values have been used for tension-based soil moisture sensors. Haise and Hagan (1967) used refill points of -60 to -70 kPa for high and low evaporative demand conditions for producing cabbages. Stanley and Maynard (1990) recommended that soil water potential levels in the -10 and -30 kPa range is needed for vegetables grown under irrigation high and low evaporative demand respectively. Thompson et al. (2007b) reported soil matric potential threshold values of -35 kPa for melon production and -38 to -58 kPa for tomato production. Marouelli and Silva (2007) tested tension threshold values between -5 kPa to -120 kPa for processing tomatoes and found that soil moisture tension thresholds of -35, -12 and -15 kPa produced the highest yields for vegetative, fruit development and maturation growth stages, respectively.

Gypsum block

The most common electrical resistance sensors of the gypsum block were first introduced in 1940. The blocks are constructed by casting gypsum around two concentric electrodes manufactured with pore sizes similar to the surrounding soil. This allows the water content of the block to become similar to the water content in the surrounding soils (Yoder et al., 1998). As the water content of the block increases, the electric resistance between the electrodes decreases. The range of soil water determined by gypsum blocks is generally given as field capacity to the permanent wilting point. The measurement error of gypsum blocks is soil dependent and can be up to 20% and higher (Yoder et al., 1998).

Granular matrix sensor

Granular matrix sensors use the same principle as the gypsum block. Electrodes are embedded in a patented granular quartz material, protected by a synthetic membrane, and additionally, a stainless steel mesh. The material selected enables the sensor to measure wetter soil than a gypsum block (up to -10 kPa). The sensor includes internally installed gypsum which provides buffering against the effect of salinity (Charlesworth & Munro, 2005).

The watermark moisture sensor measures water potential between -10 and 200 kPa and can be attached to a data logger. It consists of two concentric electrodes embedded in a reference granular matrix material. The granular matrix material surrounded by a synthetic membrane provides protection against deterioration. There is an internal gypsum tablet which buffers against salinity levels found in irrigated soil (Campbell scientific Inc. 2005). The watermark sensor operates on the same principles as other electrical resistance sensors. Water conditions inside the watermark sensor changes with corresponding variation of water conditions in the soil. These changes with the sensor are reflected by differences in electrical resistance between two electrodes embedded in the sensor. Resistance between the electrodes decreases with increasing soil water (Irmak et al., 2006). Intrigliolo and Castel (2004) identified limitations in the use of watermark sensors because they do not respond to changes at soil water potential higher than -10kpa. This may be problematic in cases where irrigation practices maintain low water tension.

It also does not respond accurately to rapid drying and partial rewetting of soil showing hysteretic behavior, which can lead to incorrect estimation of actual soil water status.

2.3.1.2.3 Sensor placement

Sensors need to be placed in sensitive and representative locations in the crop root zone. Soil moisture or tension varies in three dimensions (Shock & Wang, 2011). Stieber and Shock (1995) noted these dimensions included; variability in soil wetting from irrigation and rainfall, soil drying from evaporation, and root water extraction for plant transpiration. Interaction of these dimensions is important in the installation of soil moisture sensors. The performance of a sensor-based drip irrigation scheduling scheme is dependent on both sensor location and the operational threshold. In general, a wide range of locations within the wetted soil volume can be used for the installation of soil moisture sensors. The issue however, it that the extent of variations in soil water dynamics may be unsuitable in some locations; while in others, it may exceed the sensor's range of operation. Further, the purpose of irrigation is to create a favorable ambience within the plant rooting zone which is more representative of the integrated conditions experienced by the rooting system. At the periphery of the wetted soil volume, soil moisture is excessively low, so root activity will define the outermost boundaries for sensor installation. On the other hand, positions near the center of plant root uptake experience large fluctuations in matrix head, often exceeding the tensiometric range, especially for two-day intervals (Coelho & Or, 1996).

Haise and Hagan (1967) recommended that sensors should be placed at the top and bottom of the active rooting. In contrast, Phene and Howell (1984) and Levin et al. (1885) recommended sensor placement relatively close to drippers. In general, soil water should be measured at the center of the effective root zone (Evans et al., 1996), at representative locations of the soil water status of the field. Stegman (1983) indicated that two sensors should be installed at different depths according to the root layer, with the deeper sensor, twice the depth of the first. Tensiometers should be placed 12" to 18" from the emitter in a representative area, where plants take up water (British Columbia Ministry of Agriculture and Food, 1998). Hendrickx and Wierenga (1990) installed tensiometers at a distance of 0.1 m from the trickle line and the centre of the rows for Chile peppers; however no justification was given for this action. Under a one-dimensional flow scenario, which obtains under sprinkler irrigation, the soil water content is uniformly distributed. As a result, sensor placement should be limited to root distribution. In the scenario of three-dimensional flow as is the case for drip irrigation, sensor placement is both a function of root distribution and water distribution in the wetted volume (Coelho et al., 2007). Pogue and Pooley (1985) noted that guidelines for the location of sensors for irrigation scheduling are qualitative and empirical. Further, Hodnett et al. (1990) added that they lack generalities, and are valid for the specific soil, crop, and positions for which results were obtained.

A successful approach for developing sensor placement guidelines is contingent on proper parameterization of soil hydraulic properties and plant uptake patterns. Complex patterns of soil dynamics is created by the spatial variability of the soil profile, coupled with the temporal variation in plant uptake patterns, and the intensity and non-uniformity of water distribution from the dripper. To this end, the criteria for the selection of sensor locations and subsequent interpretation of data should be governed by a broad understanding of soil water dynamics within the entire domain, to make sound and reliable irrigation decisions (Coelho and Or, 1996).

2.3.2 Plant indicators

Yazar et al. (1999) suggested that irrigation scheduling based upon crop water stress should be more advantageous, since it responds to the combined soil and aerial environment. Jones (2004) identified most physiological changes in plants are directly related to changes in the water status of plant tissues (roots or other tissues), rather than actual changes in soil moisture content or potential. The novel approach of plant stress sensing may provide greater precision in irrigation scheduling than soil moisture monitoring (Jones, 1990). Steppe et al. (2008) recommended the use of the plant as a rigorous and sensitive measure to effect irrigation scheduling. Root water relations need to be studied in concert with shoot water relations, for a fuller understanding of their adaptation to water deficits (Turner, 1986).

Plant indicators of water stress can be characterized into two broad groups, direct and indirect. Direct indicators include: leaf water potential, stomatal conductance, stem water potential and sap flow. Indirect indicators comprise; canopy temperature, thermal imaging and fruit/stem diameter, leaf thickness, sap flow, xylem cavitation and γ-ray attenuation (Jones, 2004).

A critical factor in determining the most suitable plant-base measure is dependent on sensitivity to water deficit (Jones, 2004). Bates and Hall (1981) hypothesized that as soil water changes, a corresponding change in root water status occurs which influences stomatal conductance, as the soil dries or evaporative demand increases. Such changes are manifested both in the short term through changes in leaf angle, stomatal conductance and hydraulic properties of the transport system. In the long term, changes are realized in the leaf area and root extension. Cell growth has been identified as most sensitive to tissue water stress, followed by wall and protein synthesis. On the other hand, photosynthesis was identified as moderately sensitive (Jones, 2004). An excellent and comprehensive discussion to detail various plant base methods and the advantages and disadvantages of recent approaches have been reviewed by Jones (2004) and more recently, by Fernàndez and Cuevas (2010).

2.3.3 Meteorological method

The most common procedure for estimating crop water use or crop evapotranspiration (ETc) is the crop coefficient (Kc) approach (Doorebos and Pruit, 1977; Allen et al., 1998). Mainly used in ETc computation, potential evapotranspiration (ETo) can be determined either by direct measurements from lysimeters situated with a standard reference crop or estimated by empirical methods. Direct measurement of ETo is often expensive and laborious, requiring complex instrumentation (Vaughan & Ayars, 2009); which supports the used of empirical methods. The literature is inundated with methods for the calculation of ETo from meteorological data (Azhar & Perera, 2011; Irmak et al., 2008; Jensen et al., 1990; Sabziparvar & Tabari, 2010). The FAO Penman-Monteith method is the standard recommended method for the definition and computation of ETo. ETo represents the evaporative demand of the atmosphere, independent of crop type, crop development and crop management practices. The assumption is that water is abundantly available at the evapotranspirating surface. Factors affecting ETo include climatic parameters computed from weather data. Researchers suggest that soil factors do not affect ETo (Allen et al., 1998). The equation utilizes standard agro-meteorological data of solar radiation (sunshine hours), air temperature, humidity and wind speed. This method consists of a combination of three equations (the original Penman-Monteith, the aerodynamic and surface resistance equations) (Allen et al., 1998). The equation (Eq.2.1) is in the form:

$$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \left(\frac{900}{T + 273}\right) * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)} \qquad \text{Eq. 2.1}$$

Where

ETo	= Reference Evapotranspiration (mmday^{-1})
Rn	= Net radiation at the crop surface (mMJm^{-2}day^{-1})
G	= Soil heat flux density (MJm^{-2}day^{-1})
T	= Mean daily air temperature at 2m height (°C)
U_2	= Wind speed at 2m height (ms^{-1})
e_s	= Saturation vapour pressure (kPa)
e_a	= Actual vapour pressure (kPa)
e_s-e_a	= Saturation vapour pressure deficit (kPa)
Δ	= Vapour pressure curve (kPa °C^{-1})
γ	= Psychrometric constant (kPa°C^{-1})

Significant developments in irrigation management over the past decades have led to the introduction of tools that facilitate real or near real-time irrigation scheduling. Cai et al. (2009) indicated that when using weather forecast data provided by commercial services to estimate ETo, real-time irrigation scheduling proved successful. Many of these applications have been used in potato, lettuce and maize production (Cabelguenne et al., 1997; Gowing & Ejieji, 2001; Wilks & Wolfe, 1998). Climate data generators are able to produce localized time series of weather data based on statistics of local characteristics over time (Donatelli et al., 2003; Stockle et al., 2004).

2.3.3.1 Actual evapotranspiration

Actual evapotranspiration can be calculated from the reference crop evapotranspiration value with adjustments made for the crop type, stage of growth and restriction due to soil water deficit (Hess, 1996). Drip irrigation very seldom allows crops to be stressed below the 50% available soil water content threshold; therefore, the soil coefficient does not influence the actual evapotranspiration.

The daily actual crop evapotranspiration is calculated from the daily ETo and the crop coefficient based on the crop growth stage and can vary from 0.2 to 1.2 (Allen ,1998). However researchers have identified alternative methods of determining crop ET for irrigation scheduling purposes. The use of remote sensing; ground and satellite weather data to estimate actual crop evapotranspiration for effecting irrigation scheduling have been highlighted. (Chavez et al., 2008; Consoli et al., 2006; Santos et al., 2008; Tasumi & Allen, 2007). Evett et al. (2012a) supported the use of Eddy covariance (EC), the Bowen ration method (BR) and other aerodynamic methods to determine actual evapotranspiration.

2.3.4 Soil water balance method

Water budgeting is a widely promoted method of irrigation scheduling. It seeks to predict water status by means of a water conservation equation. The simple single layer water balance model determines daily soil moisture status by accounting for all system inputs and outputs, (Figure 2.2) (Smith et al., 1996) and maintaining favorable soil moisture. The most important components of the water budgeting model in cropped field condition are the accurate determination of soil evaporation, root water uptake and soil water content (Ji et al., 2007). When available soil moisture within the rooting zone has attained a predefined level or the management allowable deficit (MAD); irrigation is triggered. Soil moisture deficit is calculated on a daily basis according to the following equation:

$$SMD_t = SMD_{t-1} + Cr_t + R_t + I_t - ETa_t - D_t - Rn_t \qquad \text{Eq.2.2}$$

$$
\begin{aligned}
&Where\\
&\text{"}t\text{" and "}t-1\text{" is the day in question and the previous days respectively.}\\
&SMD = Soil\ moisture\ deficit\\
&ETa = Actual\ Evapotranspiration\\
&R = Rain\\
&I = Irrigation\\
&D = Drainage\ or\ percolation\ from\ the\ rooting\ zone\\
&Rn = Runoff\\
&Cr = Capillary\ rise\\
&\underline{All\ units\ are\ in\ mm}
\end{aligned}
$$

Initial soil moisture status can be determined from either the soil moisture instruments or by gravimeter sampling at the beginning of the growing season. Soil moisture sensors can be used throughout the growing season. These sensors are advantageous because they support the determination of changes in soil moisture storage at an instantaneous rate or as integrated values over some period of time (day, week or cropping season).

The FAO Penman-Monteith method (Allen et al., 1998), can be utilized to determine potential evapotranspiration (ETo) from which actual evapotranspiration (Eta), and is determined as a function of ETo, and crop coefficient (Kc) (Hess, 1996). In addition to the FAO Penman-Monteith reference method, rainfall and irrigation volumes can be fairly accurately measured with commercial rain gauges, representatively located and replicated and with water meters or weirs. Evett at al. (2012c) suggested that the construction of berms and dykes can control runoff and "run on" to near zero. The authors stated that upward flow due to capillary rise can be controlled by avoiding shallow water table when providing water to plants. In the tomato lands of South Western Ontario, shallow subsurface drains also limits the capillary rise.

If the infiltration capacity of the soil system is large relative to rainfall intensities or irrigation application rate, no surface runoff will occur. Further, drip irrigation tends to be very efficient, applying water at rates less than the soil infiltration capacity and hence deep percolation tends to be minimal. However, if the depth of irrigation or rainfall is greater than the depth of water depleted from the root zone; the difference is considered as deep percolation or water that is drained below the root zone, and is not available for plants.

If depth to the ground water is large, then upward capillary flow into the root zone will be negligible. With negligible upward capillary rise and surface deep percolation, the above equation can be further simplified (Eq. 2.3), namely:

$$SMD_t = SMD_{t-1} + R_t + I_t - ETa_t \qquad Eq. 2.3$$

Where:

“t” is the day in question and all units are in mm

SMD = Soil moisture deficit

ETa =Actual Evapotranspiration

R =Rainfall

I Irrigation

Apart from using the water balance model as an accounting system to effect irrigation scheduling, Evett et al. (2012c) noted that water balance can be used to solve for crop evapotranspiration (ETcrop). The use of electromagnetic (EM) sensors enables the determination of real time incremental changes in soil moisture over the growing season; with the other measurable parameter of the water balance (rainfall and irrigation), therefore, the unknown ETcrop can be determined. Evett (2012b) highlighted that weighing lysimeters are accurate but expensive, difficult to manage and afford little replication. For all these reasons EM sensors are a viable alternative. Jones (2004) stated that the water balance approach is not very accurate, but is sufficiently robust to be used under a wide range of conditions. It is prone to accumulative errors over time and often requires recalibration at intervals by using actual soil water measurements.

2.4 Modern irrigation scheduling approaches

The past decades witnessed significant improvement in irrigation methods and technology. Concurrently, there has been interest in using physiological mechanisms of plants to effect irrigation management. The ability to control the soil water potential in various parts of the rooting systems has been a challenge. Different type of irrigation methods have been developed in an attempt to manipulate root signals; thereby increasing water use efficiency, canopy architecture, fruit quality and fruit bud differentiation (Bravdo, 2005).

The overarching goal of deficit irrigation is to increase WUE of a crop by reducing irrigation during non-critical crop growth stages (particularly during crop vegetative stage) without negatively impacting crop yield. Kirda (2002) suggested that the reduction in yield may be small; relative to the benefit gained. The potential exists to divert saved water to irrigate other crops, which would otherwise be rain-fed under traditional practices. Kirda and Kanber (1999) indicated that an understanding of crop yield response to water deficit either during critical growth stages or throughout the whole growing season is important before effecting a deficit irrigation program. Kirda (2002) proposed that where limited water resources are available, deficit irrigation is a feasible and acceptable option. The implementation of such a program is required at the flowering and boll formation stages in cotton; during vegetative growth of soybean; flowering and grain filling stages of wheat; and vegetative and yielding stages of sunflower and sugar.

Deficit irrigation strategies may optimize water potential in horticultural crops; however, its effect on crop yield and quality is crop specific. Deficit irrigation strategies are irrigation management practices; which allow crops to sustain some degree of water dearth with some yield decrease. The classic deficit irrigation strategy (DI) implies that crop water is supplied below full evaporative demand of the crop throughout the growing season. Two additional major deficit irrigation strategies based on the physiological knowledge of crop response to water stress, are regulated deficit irrigation (RDI) and partial root zone drying (PRD) (Costa et al., 2007).

2.4.1 Full irrigation

Full irrigation is the practice of applying the amount of water to a crop equal to that removed from the field by evapotranspiration throughout the growing season. Although full irrigation has the potential for the highest yield, water use efficiency may be reduced.

Further, potential for erosion may increase, if precipitation occurs just after irrigation, depending on the mode of irrigation (Unger, 2006). In humid regions with high potential of periodic rains, the practice of full irrigation often does not maximize soil moisture contributed by rainfall. The literature suggests that there is an increased trend away from full irrigation, to deficit irrigation strategies. However, in a number of crops, such as grains or many fruits and vegetables there are phenological stages that can be significantly affected by moisture stress with impacts on yield and quality (Costa et al., 2007). In such cases, the only logical decision is to fully irrigate reduced acreages.

2.4.2 Deficit irrigation

Maximizing returns to water generally involves some degree of deficit irrigation, particularly when water supplies or system constraints, limit water availability. However, few farmers are well equipped to deal with the analytical challenges associated with managing water deficits (Abourached et al., 2007). Demir et al. (2006) noted that the rationale behind well-regulated deficit irrigation is to conserve water by depriving the crop to periods with minimal effect on yields. This stress results in reduced evapotranspiration (ET) by closure of the stomata, reduced assimilation of carbon, and decreased biomass production. When the crop can compensate in terms of reproductive capacity then reduced biomass production has little effect on ultimate yields.

For many crops, plant growth is most sensitive to water stress during reproductive stages; (the development of seed or fruit) hence water stress at this critical stage will negatively impact yields than other growth stages (Hanson et al., 2004). In the case of the sunflower crop, reduced plant heights during the early vegetative period can result from severe water deficit, but may increase root depth. Adequate water during the late vegetative period is required for proper bud development. The flowering period is the most sensitive to water deficit, which may cause considerable yield decrease, as fewer flowers come to full development (Doorenbos & Kassam, 1979).

When water deficit occurs during a specific crop development period, the yield response can vary depending on crop sensitivity at that growth stage. Therefore appropriate timing of the water deficit, is a tool for scheduling irrigation, with limited water supply (Moutonnet, 2000). Hanson et al. (2004) warned that crops where the entire crop is harvested (Alfalfa), water stress reduce yields regardless of the stage of growth at which stress occurs. Deficit irrigation has been successfully used in the irrigation of fruits and vineyards; (Chaves et al., 2007; Collins et al., 2010; Fereres & Soriano, 2007) and annual crops (Kirda et al., 2007; Wang et al., 2010).

2.4.2.1 Regulated deficit irrigation

RDI is the practice of depriving the plant to a predetermined level; relative to maximum water potential for a prescribed part or parts of the seasonal cycle of the plant development. The aim is to control reproductive growth and development, vegetative growth and/or improve water use efficiency. The principle governing RDI is that plant sensitivity to water stress is not constant throughout the growing season. However intermittent water deficit during specific periods may benefit WUE; increase water savings, and improve harvest qualities (Cameron et al., 2006; Chalmers et al., 1981; Loveys et al., 2004; McCarthy et al., 2002).

Johnstone et al. (2005) determined that the imposition of deficit irrigation and pre-harvest water cut-off times contributed to increased soluble solids in tomatoes. Warner et al. (2004a) indicated that cutting off water application or deficit irrigation during the fruit ripening stage can counteract the reduction in soluble solids associated with drip irrigation for processed tomatoes. Jones (2004) identified a major disadvantage of regulated deficit irrigation; the requirement that the plant's water status be maintained within narrow limits, which are difficult to maintain. In this scenario, an excess application of water negates the advantage of regulated deficit irrigation. On the other hand however, a lower application of water may cause yield and volume declines.

2.4.2.2 Partial root zone drying

Partial root-zone drying (PRD) is a new irrigation technique that may improve water use efficiency in crop production without significant yield reduction (Kang et al., 1997). This technique requires half of the rooting system exposed to alternate wetting and drying. The frequency of these alternate states is a function of the crop, growing stage and crop water requirements. This technique has the potential to reduce crop water use, increase canopy vigor and maintain yields, when compared with normal irrigation methods (Kang & Zhang, 2004).

Li et al. (2007) clarified that this technique is based on two theoretical assumptions. Firstly, fully irrigated plants usually have widely opened stomata; and a small narrowing of the stomatal opening may reduce water loss substantially with little effect on photosynthesis (Jones, 1990). Secondly, part of the root in drying soils can respond to changing soil conditions, by sending a root-sourced signal to the shoots where stomata may be inhibited so reduce water loss (Kang and Zhang, 2004). Davies and Zhang (1991) identified the role played by the hormone abscisic acid in stomatal closure, as soil dries. Bravdo (2005) highlighted that cytokinins, abscisic acid and gibberellins are the major plant growth regulators formed in the root tip; their transport to various parts of the plant canopy influences physiological processes. There is evidence of non-hydraulic chemical signaling in the root/shoot system which influences the regulation of physiological processes in plants (Blackman & Davies, 1985; Gowing et al., 1990; Passioura, 1988). Bravdo (2005) claimed that while the existence of the signal system was confirmed, the exact physiological mechanism is complicated, and interactions between chemicals poorly understood.

Bravdo (2005) indicated that due to the redistribution process by which water is transferred among roots, PRD cannot be adequately achieved under field conditions by manipulating irrigation regimes. Further, the method works efficiently when split roots of various plants are subjected to alternate irrigation regimes. Gu et al.(2004) proposed that the amount of water applied, rather than the application system can explain the effects of partial root drying.

A potential advantage of partial root zone drying over regulated deficit irrigation is that precise irrigation control is less critical for success of the former. This benefit obtains because plants can obtain sufficient water from the adequately watered side of the root system, whilst the drying side initiates the signal to modify growth and stomatal opening (Jones, 2004).

Zegbe et el. (2006) conducted PRD experiments on processing tomatoes at different phenological stages to ascertain the effects on yield, fruit growth, and quality. The findings indicated that PRD plants could produce fruit of similar quality and yield to fully irrigated plants depending on the PRD intervention at the phenological stage. PRD from the first truss to fruit set is not recommended because of high incidents of blossom end rot. So far PRD has been reported mainly with horticulture crops such as tomato, pepper, grapevine, pear and peach (Bravdo, 2005; Gong et al., 2004; Gu et al., 2000; Kang et al., 2003; Kirda et al., 2004).

2.5 Water use efficiency

Notwithstanding the considerable changes and improvements in irrigation and water management that have ensued over the past decades, Dr. Marvin Jensen's comment, "The greatest challenge for agriculture is to develop the technology for improving water use efficiency," (Karasov, 1982) still resonates today. The use of the word efficiency is contingent on the discipline involved. The physiologists understand this to mean that transpiration efficiency, irrigation efficiency to agronomists, and water application efficiency to engineers (Hsiao et al., 2007). However, the genesis of the term Water Use Efficiency (WUE) or water productivity originated from the ideas of drought resistance and drought tolerance (Passioura, 2006). WUE is a broad concept that can be defined in many ways. For farmers and land managers, WUE is the yield of harvested crops achieved from the water available to the crop through rainfall, irrigation and the contribution of soil water storage. Further it can be used on the farm, the field, the plant, or down to plant parts level, such as leaves (Morison (Morison et al., 2008) et al., 2008). To irrigation engineers, it can mean the amount of water used to produce a crop (Ali & Talukder, 2008). Sinclair (1984) simply defined WUE as the crop yield per unit of water used. At the biological level this is expressed as the carbohydrate formed through photosynthesis from CO_2, sunlight, and water per unit of transpiration. WUE has been generally defined in agronomy (Viets, 1962) as (Eq. 2.4):

$$WUE = \frac{Crop\ Yield\ (usually\ economic\ yield)}{Water\ used\ to\ produce\ yield} \qquad \text{Eq. 2.4}$$

Howell (2001) showed that water used in Eq 2.4, is not easily determined and a, benchmark WUE is used by many irrigation practitioners in the form of Eq 2.5.

$$WUE_b = \frac{Crop\ Yield\ (usually\ economic\ yield)}{(Pe + I + SW)} \qquad \text{Eq. 2.5}$$

Where:

Pe =Effective rainfall

I =Irrigation

SW =Soil moisture depleted during season

In crop production, WUE can be expressed by different indicators resulting with varying results (Ali & Talukder, 2008):

$$WUE_1 = \frac{Grain\ or\ seed\ yield}{Water\ used\ to\ produce\ yield}\left(kgha^{-1}cm^{-1}\right) \qquad \text{Eq. 2.6}$$

$$WUE_2 = \frac{Total\ dry\ matter}{Water\ used\ to\ produce\ yield}\left(kgha^{-1}cm^{-1}\right) \qquad \text{Eq. 2.7}$$

$$WUE_3 = \frac{Total\ monetary\ value}{Water\ used\ to\ produce\ yield}(\$m^{-1}) \qquad \text{Eq. 2.8}$$

Ali (2006) indicated that Eq. 2.6 and 2.7 are appropriate for single crops while Eq. 2.8 is suitable for multiple cultures or water constraints without land limits.

Bos (1980) however refers to irrigation WUE as the yield produced above the rainfed field yields or dryland yields divided by the net evapotranspiration (ET) difference for the irrigated crop. Bos (1985) also proposed the irrigated difference from the dry land yield divided by the gross applied water volumes, which he called the yield/water-supply ratio. These relationships can be expressed in the following equations:

$$ET_{WUE} = \frac{Y_i - Y_d}{ET_i - ET_d}\left(kg\ m^{-3}\ or\ g\ kg^{-1}\right) \qquad \text{Eq. 2.9}$$

$$ET_{WUE} = \frac{Y_i - Y_d}{I_i}\left(kg\ m^{-3}\ or\ g\ kg^{-1}\right) \qquad \text{Eq. 2.10}$$

Where

Y_i =Yield
ET_i =ET for irrigation level "i"
Y_d =Yield under dryland
ET_d =ET for an equivalent dryland or rainfed only plot
I =Amount of irrigation applied for irrigation level "i"

Many authors have debated the applicability of this general concept to agricultural WUE. Howell (2001) warned that WUE gets distorted when used in irrigated agriculture. Further, he charged that various definitions of WUE are difficult to apply because of management factors. These factors can impact yield between irrigated and dry land agriculture and include; fertility, crop variety, pest management, sowing date, soil water content, planting density and rows spacing. Jensen (2007) added that water not used by the plant through transpiration may not necessarily be called wasted. He further emphasized that the leaching fraction used to flush soil salts below the root zone in arid and semi-arid regions should be accounted for in sustainable irrigated agriculture. Weiner et al. (2010) highlighted the use of abscisic acid (ABA) as a very practical option for improving WUE by controlling physiological processes that affect plant transpiration and yield.

2.5.1 Saving water for agriculture

An improvement in WUE by 40% on rainfed and irrigated lands would offset the need for additional withdrawals for irrigation over the next 25 years to meet increasing global demands for food. Clearly this is an enormous undertaking for many countries (García-Tejero et al., 2011). Passioura (2006) proposed wise management of crops and water resources in addition to improved genetic material of crops, to maximize water use in plant biomass production in rainfed agriculture. Irrigated lands can (Karoun & El-

Mourid, 2009) improve resources; not only because of limited resources, but also to support increased environmental sustainability.

Many promising strategies for increasing WUE are available. Ali and Talukder (2008) identified deficit irrigation; proper sequencing of water deficit; surge irrigation in vertisol; increasing soil fertility; improving harvest index; manipulation of seedling age, wet-seeded or directed seeded rice; priming or soaking of seed; application of organic matter; tillage and sub-soiling; water harvesting; minimizing transpiration; water saving irrigation; crop selection; and modernization of irrigation system and integrating agriculture-aquaculture. García-Tejero et al. (2011) categorized these interventions under the broad heading of appropriate integrated land-water management practices. Wallace and Bachelor (1997) on the other hand proposed four broad categories of suggestions to enhance I_{WUE} including; agronomic, engineering, management and institutional interventions.

2.6 Tomato

Globally, tomato (***Solanum Lycopersicum***) is the second most important vegetable crop produced, following after Irish potato. FAO has reported tomato production in 144 countries, with China as the major producing country both in terms of hectares of harvested production, (1,255,100 hectares) and weight of fruit produced (30,102,040 Mt). The top five leading fruit-producing countries in the world displayed in order include; China, United States, Turkey, Italy, and India. World tomato production is in excess of 100 million tons (Figure 2.10) produced on 3.7 million hectares (FAOSTAT Database, 2004).

Tomato is a short-lived perennial produced as an annual in temperate regions because it is easily destroyed by frost. It is an herbaceous plant and can grow to about 2 m high. Globally, tomato is commercially important in the fresh fruit market and processed food industry (Jones Jr, 2007). Processing tomato products are most often classified into four major subcategories: tomato paste, tomato sauces, ketchup, and products mainly consisting of puree, whole canned tomatoes, and juices.

Tomato grows rapidly with a growing period of 90 to 150 days. It is a day length neutral plant under conditions of short or long days. Optimum mean daily temperature for growth is from 18.5 to 25ºC with night temperatures between 18 and 21ºC (Jones Jr, 2007). Tomato can be grown on a wide range of soils but it thrives under well drained, light, loam soil, with pH ranging from 5 to 7. Fertilizer requirements for high producing varieties range from 100 to 150 kg ha^{-1}, 65 to 110 kg ha^{-1}, and 160 to 240 kg ha^{-1} for N, P, and K, respectively. The crop is moderately sensitive to soil salinity. Yields decrease from 0% to 100% for ECe values of 2.5 $mmhoscm^{-1}$ to $12.5mmhoscm^{-1}$, respectively (Doorenbos & Kassam, 1979).

Most commercially grown processing and fresh market tomatoes have a determinate growth habit. Additionally their shorter stature makes them easier to stake and the concentrated maturity reduces the harvest period, and labor costs (Jones 2007).

Mechanical harvesting of processing tomatoes results in only one picking and hence, water supply needs to be adjusted according. Highest yield of salad tomatoes are generally obtained with frequent and light irrigation; while processing tomatoes require heavier and more infrequent irrigation, with the last irrigation applied before harvest (Doorenbos et al 1979).

2.6.1 Tomato crop water requirements

Total crop water requirements for tomato ranges from 400 to 600 mm for field grown tomatoes, from 90 to 120 days. Water requirements can be expressed as a function of ETo, Kc and duration for each growth stage. Table 2.8 provides average values for Kc and duration for the various plant growth stages. (Doorenbos & Kassam, 1979). Based on research work done in southwestern Ontario, OMAFRA (2004) has divided the growing season for processing tomatoes into three distinct stages (Table 2.9) as compared to FAO's four stages.

Research in Ontario has shown that irrigation often cools the soil by 2 to 5°C, especially when irrigation water is cool or irrigation wets the soil surface (causing evaporative cooling). While this can be beneficial in the summer, it is not recommended at low temperatures (15°C or lower) early in the season, as this could cool the soil and retard early crop growth (LeBoeuf et al., 2007).

2.6.2 Growing phases

There are four growing stages of tomatoes for the first harvest. The first, the germination, emergence and establishment stages takes 25 to 35 days. The vegetative stage is the period from the end of stage one to flowering and covers 20 to 25 days. The Flowering from reproductive stage occurs until the first full size mature green fruit and usually takes 20 to 30 days from yield formation, until 20% of the fruit changes color. The final ripening stage takes 15 to 20 days. For high yield and good quality, the crop needs a controlled supply of water throughout the growing period. Whereas under water limiting conditions, some water savings may be made during the vegetative and ripening periods (Doorenbos et al., 1979).

LeBouef (2007) reported that tomatoes are more tolerant to moisture stress than peppers and cucumbers. Tomatoes are better at adapting their physiological processes to make maximum effective use of the limited soil water while maintaining some growth. Irrigation of tomatoes can result in higher and more consistent yields, better quality, less blossom-end rot, and less cracking. Further, when tomatoes experience moisture stress, fewer flowers develop per truss and results in lower numbers of fruit set and lower yield (LeBouef, 2007). The increase in total soluble solids translates into higher recovery in the processing plant, and generally improves the taste of fresh or processed tomatoes. The reduction in fruit size converts to lower yield; resulting in unmarketable fresh fruit; and greater harvest loss in mechanical harvesting of processing tomatoes.

2.6.3 Impact of irrigation on different growth stages

The crop is most sensitive to water deficit during and immediately after transplanting, during flowering and yield formation (Doorenbos et al., 1979). LeBoeuf (2007) identified the most critical times for moisture are during flowering, fruit set and fruit sizing. Tomato transplants should be stressed prior to field setting so that they can more successfully deal with the transition to less favourable field conditions. Although the plant can survive dry conditions, optimal yield and quality will not be achieved (LeBouef, 2007).

Doorenbos et al, (1979) identified the highest demand of the plants for water taking place during the flowering stage. The strategy of withholding of irrigation is recommended to facilitate less mature plants into flowering and to encourage uniform flowering and ripening. However, any extended water deficiency during this growth phase may cause flower drop. Flower drop and reduced fruit set have been associated with excessive irrigation during the flowering period. There is also the potential for excessive vegetative growth and delay in ripening. Water supply during and after fruit set must be limited to a set rate, to prevent stimulation of new growth at the expense of fruit development. Heavy, irregular irrigations or dry periods alternating with wet periods should be avoided.

Irrigation management during fruit development and ripening can substantially influence yield, product quality, solids, and viscosity. Fruit stress increases soluble solids but reduces yield and viscosity. May and Gonzales (1994), found that depleting the available moisture in the top 1.2 m of the soil by 60% and 40% reduced yields by 15 mg/ha and 4mg/ha respectively, less than the 20% depletion during fruit development. May and Gonzales (1994) found that the 60 day cut-off before harvest significantly increased solids over the 20 and 40 day cut-off; however significant fruit loss, cracked and broken fruit increased; and viscosity was significantly poorer.

2.6.4 Management allowable deficit for tomato

Despite a number of studies on tomatoes, the literature (Marouelli & Silva, 2007; Renquist & Reid, 2001) revealed that the differential effects of soil-water deficit on tomato fruit yield and quality are complex and poorly defined. Prieto et al. (1999) recommended that irrigation thresholds should be determined for site specific conditions; because they may be influenced by climate, soil conditions, cultivars and the irrigation system.

Hartz et al. (2005) recommended a varying soil water tension threshold for tomatoes during the growing cycle. Maturation threshold levels of 20to 35 kPa were advised and then a range of 40-50 kPa. Marouelli et al. (2007) found maximum tomato fruit yield on well-drained clayey red Oxysol were attained with varying soil moisture tension thresholds of 35, 12 and 15kPa during vegetative, fruit development and maturation growth stages respectively.

Studies suggest that under maximum evapotranspiration ranges between 5 to 6 mm/day, a MAD of 60% is necessary (Doorenbos et al., 1979). Hartz et al. (2005) indicated that tomatoes can tolerate a moderate degree of stress. Their research showed that tomatoes can tolerate depletion of 20-30% in available soil moisture in the active root zone with no yield loss. Soil water depletion levels during the different tomato growth periods should remain below 40% of available soil moisture content (a MAD of 60%). If a singular uniform tomato harvest is required then depletion level during this period may increase from 60 to 70 percent (Doorenbos et al., 1979).

2.6.5 Fruit quality and irrigation

Soluble solids (sugar and acid in fruit) are an important quality factor for processing tomatoes and are measured in ° brix (which is the measure of the mass ratio of dissolved sucrose to water in a liquid). Cahn et al. (2001) observed that in an attempt to improve fruit quality, farmers tended to cut back on irrigation during ripening and pre-ripening stages, which can negatively impact fruit production in terms of quality and yields.

The use of drip irrigation often results in undesirably low soluble solids concentrations (SSC). Phene (1999) further established that non irrigated tomatoes were found to have high soluble solids (9.4º brix) but low commercial yields. Warner et al. (2007) found that minimizing irrigation coupled with pre-harvest cut-off time; may be a useful management tool to address the issue of reduced soluble content associated with irrigation. Johnstone et al. (2005) supported end of season water management; to induce sufficient moisture stress, and to achieve acceptable SSC with minimum yield loss. They further indicated that after the tomato fruit reaches the pink stage of maturity (color change on 30% of the fruit surface), its SSC remains unchanged by irrigation management. SSC of green fruit is however affected by irrigation and hence some moisture stress must be imposed before the majority of the fruit has ripened. As a general guideline, application of 30-70% of ETo over the last 6 weeks before harvest is a reasonable compromise between maximizing yield and achieving acceptable SSC.

Warner et al. (2004b) also examined the effects of nitrogen fertilization on fruit yield and quality of processing tomatoes. Yields and quality were also examined under different treatments of nitrogen and phosphorous regimes. (Liu et al., 2011; Zhang et al., 2010). Tan et al (2003) studied the effect of surface and subsurface drip irrigation on yield; quality, as well as WUE and nutrient use efficiency of processed tomatoes.

2.7 Drip irrigation

2.7.1 Soil water dynamics in the root zone under drip irrigation

Soil moisture is water held in the pores of the unsaturated zone (Paris et al., 2008). Nielsen et al. (1986) represented the unsaturated zone as that part of the soil profile where the water content is less than soil porosity, or where the soil water matric potential is negative. It constitutes the medium through which liquid and gaseous constituents are attenuated and transformed, as they are exchanged in both directions between the soil surface and the water table. Despite the importance of soil moisture, its accurate assessment is difficult due to strong spatial and temporal variability, related to topography, soil type variations, land use, vegetation, solar radiation, issues specific to the contributing area, and mean soil moisture (Canton et al., 2004; Cosh et al., 2004; Famiglietti et al., 2008; Hebrard et al., 2006; Wilson et al., 2005) Soil moisture is a complex and dynamic parameter. Its depletion from the root zone is controlled by soil, plant and climatic factors. Root length or root length density most directly relates to plant water uptake (Lubana & Narda, 2001). Drip irrigation continuously replenishes soil moisture in the root zone and as a result, the role of the soil as a reservoir is of lesser importance in contrast to conventional modes of irrigation. However, soil type and emitter application rates both influence soil water dynamics (Lubana & Narda, 1998).

The wetting pattern in the soil and the spatial distribution of soil water, matric potential and nutrient concentration are contingent on soil hydraulic properties, drip discharge rates, spacing and their placement, irrigation amount and frequency, crop water uptake rates and root distribution patterns (Elmaloglou et al., 2010; Gärdenäs et al., 2005). Badr, (2007), however, noted that while field scale uniformity is possible under drip irrigation, water and nutrient arrangements around the periphery of the drip line are non-uniform. Further, he added that both soil moisture and nutrient concentration are highest near the drip line after application, but due to soil physical properties, redistribution occurs thereafter. Surface drip irrigation allows for infiltration of only a small area of the soil surface. In such conditions, infiltration occurs in three dimensions for point source and two dimensions for line source (Gärdenäs et al., 2005; Patel & Rajput, 2008) as compared to one dimension for other methods. The water withdrawal patterns by plant root systems under trickle irrigation also differ considerably from other irrigation systems. (Lubana & Narda, 2001).

A traditional way of conceptualizing spatial and temporal soil water distribution involves the determination of water content at various points around the emitter and drawing contours between these soil moisture points. This analysis provides detail on the position and shape of the wetted volume (Dasberg and Or, 1999). Devasirvatham (2009) stated that the volume of wetted soil represents the amount of water stored in the root zone. The depth of wetted soil should coincide with rooting depth, while its width should be related to the spacing between emitters. Roth (1974) calculated the wetted volume of soil as a hemisphere and assumed that the soil was wetted from an initial volumetric water content (VWC) θ_i to a final VWC θ_f in m^3m^{-3}. The radius and volume of the hemisphere are represented as follows (Eq. 2.11 and 2.12):

$$r = \frac{3qt}{\left[2\pi\left(\theta_f - \theta_i\right)\right]^{\frac{1}{3}}} \qquad \text{Eq. 2.11}$$

Where

q	=	*Volumetric flow rate* ($m^3\ h^{-1}$)
t	=	*time (h)*
r	=	*radius (m)*

$$V = \frac{4}{3}\pi r^3$$

where Eq. 2.12

$V = volume\ (m^3)$

Subsequent experiments by Roth (1974) found that instead of a hemispheric formation, the wetted volume was more elongated in the vertical direction. He also found that the higher the application rate the greater the influence of gravity resulting in a narrower wetted area. Mostaghimi et al. (1981) also found that wetted area changed as a function of application rate.

(Bresler, 1977) identified that the trickle discharge rate and soil hydraulic properties both impact the shape of the wetted soil zone; an increased flow rate showed a decrease in the saturated hydraulic conductivity; this resulted in an increase in the horizontal component of the wetted area, and a decrease in the vertical component of the wetted soil depth. Many investigators have used descriptions of the extent of wetting, including the surface wetted diameter, wetted depth, and wetted volume (Cook et al., 2003; Dasberg & Or, 1999; Hammami et al., 2002b; Thorburn et al., 2003) Goldberg et al. (1976) identified soil properties, dripper discharge and volume of water applied as factors determining the region wetted by trickle emitters.

There are a number of analytical and empirical models used to describe the soil moisture dynamics for point and line sources that can be used to design, install, and manage drip irrigation systems (Camp, 1998; Cook et al., 2003; Cook et al., 2006; Kandelous et al., 2008; Kandelous et al., 2011; Singh et al., 2006; Skaggs et al., 2004). Kandelous and Šimůnek (2010) established that empirical models have typically been developed using a regression analysis of field observations, while analytical and numerical models usually solve governing flow equations, particularly for initial and boundary conditions. A different approach using a moment analysis was introduced by Lazarovitch et al. (2007) to describe spatial and temporal subsurface wetting patterns for irrigation from surface/subsurface drip irrigation systems.

2.7.2 Soil nutrient dynamics under drip irrigation

Fertigation is defined as the application of fertilizers dissolved in irrigation water to allow water and nutrients to be placed in the zone of greatest root activity, allowing rapid utilisation by plants (Bar-Yosef, 1999). Improved fertigaton and drip irrigation mangement is contingent on an improved understanding of solute dynamics in the crop root zone. It has the potential to reduce leaching of salts and, therefore, optimize nutrient uptake by plants. Further, fertigation provides control of the application of saline water at the most salinity sensitive stage of the plants and the opportunity for potential reuse of considerable amounts of water that is of low quality from other uses or users (Mmolawa & Or, 2000a).

Drip irrigation has been recognized as a popular, effective and economic method of applying soluble fertilizers to irrigation water through fertigation (Badr, 2007). This is primarily due to the highly localized application and the flexibility in scheduling water and chemical applications simultaneously (Clothier, 1984). Mantell et al. (1985) added that salt concentration in the rooting zone remains manageable due to high application frequency associated with drip irrigation.

A properly designed drip fertigation system delivers the requisite amount of water and nutrients at a rate, duration and frequency consistent with the crop water and nutrient uptake, while minimizing leaching of nutrients from the root zone of agricultural fields (Gärdenäs et al., 2005). It also ensures substantial saving in fertilizer usage (Mmolawa & Or, 2000a; Patel & Rajput, 2004). However, Badr (2007) suggested that improper management even of drip irrigation can leach nutrients beyond the rooting zone and pollute groundwater resources. There are no clear guidelines for nutrient movement and distribution under drip irrigation systems (Cote et al., 2003).

Solute transport in the wetted soil volume is governed by a large number of complicated and often interactive physical, chemical, and microbiological processes (Toride et al., 1993). Processes involved in various transport modes are described as follows; hydrodynamic dispersion, molecular diffusion and convective transport (Jury et al., 1991). In convective transport, solutes are carried by mass flow of water. Diffusive transport occurs when solutes diffuse from locations of higher solute concentration to lower concentrations. Soils have different sizes and shapes of pores, these differences in pore velocities cause solutes to be transported at different rates to different locations. This leads to mixing of incoming solutes with resident concentrations, a phenomenon referred to as hydrodynamic dispersion (Mmolawa & Or, 2000b).

2.8 Conclusion of literature review

Despite the abundance of water in the world, it is nevertheless classified as a scarce and vulnerable resource that needs to be sustainably managed (FAO, 2011). 1.6 billion ha of the world best lands are under crop production of which, 275 million ha are irrigated. Agriculture accounts for over 70% of the world's water withdrawals (Raskin et al., 1997), producing 40% of global crop production from the 18% of irrigated agricultural lands and employs about 30% of the global population in rural areas. In contrast, rain-fed agriculture accounts for 80% arable lands and produces 60% of the world’s food (De Wrachien, 2003; Rockstrom & Falkenmark, 2000) The daunting task facing the global community is to double food production to provide nutritional sustenance for the expected ten billion inhabitants of earth by the year 2050 (FAO, 2011). The greatest challenge for agriculture still remains to develop the technology for improving water use efficiency.

Canada is blessed with an abundance of water. Approximately 9% of Canada's total area is covered by freshwater although the country has less than 1% of the world’s population. About 60% of Canada's freshwater drain north whiles 90% of the Canadian population lives in the south. This discrepancy highlights Canada’s unique water resource issues. About 75% of all agricultural water withdrawals in Canada take place on the Prairies, mainly for irrigation (Harker et al., 2008). Holm (2008) highlighted that Alberta’s irrigated lands represent 65% of all of Canada’s irrigated lands. Ontario’s strategic position provides the province with a large supply of fresh water. The Great Lakes contains 20% of the world's fresh surface water supply (OMNR, 2009a).

The following sections provided an overview of irrigation scheduling methods and modern irrigation scheduling strategies. Four primary irrigation scheduling methods are currently utilized and include: soil monitoring, plant indicators, meteorological and water balance approaches. Each of these irrigation scheduling methods have unique advantages and limitations. Once these limitations are understood and mitigated, then it is possible to successfully undertake irrigation scheduling programs with the various methods.

The soil moisture monitoring approach can be either direct or indirect. Direct methods of water content determination are those where water is removed from a sample by evaporation, leaching or chemical reaction, with the amount removed being determined (Evett, 2008; Gardner, 1965; Munoz-Capena & Dukes, 2005). Indirect methods estimate soil water content based on measurement of soil properties assumed to be correlated with water content (Evett, 2007; Gardner, 1986).The indirect methods are either volumetric or tensiometric. They have grown in prominence over the past decade primarily because they are portable, accurate, easy to use, adaptability to electronic measurement and recording, low labor requirement and non-destructive sampling. (Yoder et al., 1998). For best results, all indirect sensors should be calibrated for the specific soil under study.

Yazar et al. (1999) contended that irrigation scheduling based upon plant indicators should be more advantageous, since it responds to the combined soil and aerial environment. Jones (2004) highlighted that most of the plant's physiological changes are directly related to the changes in the water status in the plant tissues (roots or other tissues), rather changes in soil moisture content or potential.

Jones (2004) suggested that the water balance approach is not very accurate, but is sufficiently robust to be used under a wide range of conditions. It is prone to accumulative errors over time and often requires recalibration at intervals by using actual soil water measurements. The most common Meteorological procedure for estimating crop water use or crop evapotranspiration (ETc) is the crop coefficient (Kc) approach (Doorebos and Pruit, 1977; Allen et al., 1998). Mainly used in ETc computation, potential evapotranspiration (ETo) can be determined either by direct measurements from lysimeters situated with a standard reference crop or estimated by empirical methods. Direct measurement of ETo is often expensive and laborious, requiring complex instrumentation (Vaughan & Ayars, 2009); which supports the used of empirical methods. The literature is inundated with methods for the calculation of ETo from meteorological data (Azhar & Perera, 2011; Irmak et al., 2008; Jensen et al., 1990; Sabziparvar & Tabari, 2010). The FAO Penman-Monteith method is the standard recommended method for the definition and computation of ETo. ETo represents the evaporative demand of the atmosphere, independent of crop type, crop development and crop management practices.

The sole purpose of irrigation scheduling is to increase water use efficiency without negatively impacting crop yields. Dr. Marvin Jensen's beautifully encapsulated these sentiments when he said "The greatest challenge for agriculture is to develop the technology for improving water use efficiency," (Karasov, 1982).

The past decades witnessed significant improvement in irrigation methods and technology. Concurrently, there has been interest in using physiological mechanisms of plants to effect irrigation management. The ability to control the soil water potential in various parts of the rooting systems has been a challenge. Different type of irrigation methods have been developed in an attempt to manipulate root signals; thereby increasing water use efficiency, canopy architecture, fruit quality and fruit bud differentiation (Bravdo, 2005). The overarching goal of deficit irrigation is to increase WUE of a crop by reducing irrigation during non-critical crop growth stages (particularly during crop vegetative stage) without negatively impacting crop yield.

The final sections of the literature review addressed cultivation of irrigated tomatoes with a special focus on field processing tomatoes, and conclude with the soil nutrient and water dynamics associated with drip irrigation within the rooting zone. Despite the importance of soil moisture, its accurate assessment is difficult due to strong spatial and temporal variability, related to topography, soil type variations, land use, vegetation, solar radiation, issues specific to the contributing area, and mean soil moisture (Canton et al., 2004; Cosh et al., 2004; Famiglietti et al., 2008; Hebrard et al., 2006; Wilson et al., 2005) Soil moisture is a complex and dynamic parameter. Solute transport in the wetted soil volume is governed by a large number of complicated and often interactive physical, chemical, and microbiological processes (Toride et al., 1993). Processes involved in various transport modes are described as follows; hydrodynamic dispersion, molecular diffusion and convective transport (Jury et al., 1991).

Table 2.1 - Provinces and Territories ranked by their fresh water surface

Provinces /Territories	**Total Area (land + water) (km²)**	**Freshwater Area (km²)**	**Percentage of Jurisdiction Covered by Freshwater (%)**	**Percentage of Total Canadian Freshwater Area (%)**
Quebec	1 542 056	176 928	11.5	19.9
Northwest Territories	1 346 106	163 021	12.1	18.3
Ontario	1 076 395	158 654	14.7	17.8
Nunavut	2 093 190	157 077	7.5	17.5
Manitoba	647 797	94 241	14.5	10.6
Saskatchewan	651 036	59 366	9.1	6.7
Newfoundland and Labrador	405 212	31 340	7.7	3.5
British Columbia	944 735	19 549	2.1	2.2
Alberta	661 848	19 531	2.9	2.2
Yukon	482 443	8 052	1.7	0.9
Nova Scotia	55 284	1 946	3.5	0.2
New Brunswick	72 908	1 458	2.0	0.2
Prince Edward Island	5 660		0.0	less than 0.1
Canada	9 984 670	891 163	8.9	100.0

Source: Canada. Natural Resources Canada. The Atlas of Canada. Facts about Canada: Land and Freshwater Areas. Ottawa, 1999

Table 2.2- 2006 crop and irrigated lands in Canada

Province	Total Farm Area (Ha)	Land Cropped 2006 (Ha)	2006 Total Irrigated lands (Ha)	% Irrigated (relative to 2006 cropped lands)	% Irrigated (relative to total)
Newfoundland	36,211	7,183	141.7	2.0	0.0
Prince Edward Island	250,966	170,434	1,086.6	0.6	0.1
Nova Scotia	403,216	112,412	2,234.4	2.0	0.3
New Brunswick	395,396	135,065	1,421.5	1.1	0.2
Quebec	3,464,413	1,739,553	33,379.4	1.9	3.9
Ontario	5,388,751	3,546,440	65,962.3	1.9	7.7
Manitoba	7,721,864	4,701,151	24,208.5	0.5	2.8
Saskatchewan	26,013,702	14,404,796	97,415.0	0.7	11.4
Alberta	21,104,396	9,550,620	516,815.8	5.4	60.2
British Columbia	2,836,668	565,981	115,355.1	20.4	13.4
Total (Ha)	67,615,583	34,933,635	858,020	2.5	100.0

Source: 2006 Agricultural census of Canada

Table 2.3-Total daily water withdrawals, diversions and consumptive use for 2008

Category	Withdrawals Mm^3/day				Diversions (Mm^3/day)		Consumptive Use (Mm^3/day)	% of Total
	GLSW	OSW	GW	Total	Intrabasin	Interbasin		
Public Supply	1.87	0.67	0.35	2.89	0.00	0.00	0.43	0.38
Domestic	0.00	0.00	0.41	0.41	0.00	0.00	0.06	0.05
Irrigation	0.01	0.15	0.12	0.28	0.00	0.00	0	0.04
Livestock	0.01	0.03	0.10	0.14	0.00	0.00	0	0.02
Industry	3.41	0.00	0.09	3.49	0.00	0.00	0.22	0.45
Fossil Fuel Power	5.56	0.00	0.00	5.56	0.00	0.00	0.00	0.72
Nuclear Power	38.33	0.00	0.00	38.33	0.00	0.00	0.34	4.98
Hydroelectric Power	492.14	225.35	0.00	717.49	0.00	-15.17	0.00	93.26
Others	0.00	0.76	0.00	0.76	0.23	0.00	0.00	0.10
	541.32	226.96	1.06	769.34	0.23	-15.17	1.06	100.00

GLSW - Great lake Surface Water, GW - Ground Water, OSW - Other Surface Sources

Table 2.4-Irrigation by type of land use in Ontario for calendar year 2005

Land Type	**Farms Reporting**	**Acres**	**Hectares**
Total area irrigated	2,983	156,445	63,311
Irrigated field crops	1,063	70,730	28,623
Irrigated hay and pasture	89	2,773	1,122
Irrigated vegetables	1,122	48,750	19,728
Irrigated fruit	794	18,003	7,286
Other irrigated areas (nursery, sod, etc.)	357	16,189	6,551

Source: Statistics Canada 2007

Table 2.5-Irrigated land per region in Ontario (2005)

Agricultural Region	Irrigated Area	
	Ha	%
Southern	43,491	68.7
Western	10,383	14.4
Central	5,727	9.1
Eastern	3,122	4.9
Northern	588	0.9
Total	63311	100

Table 2.6-Processing tomato production in Canada and the USA from 1982 to 2010

Year	Growers	Acreage (Ha)		Yield (Mg)		Yield Mg ha^{-1}		Value $,000	
	Canada	USA	Canada	USA	Ontario	USA	Canada	USA	Canada
1982	1187	119,555	10962	7,299,000	520,157	61.1	47.5	$ 522,608	$ 56,962
1983	1007	118,219	10842	7,029,800	442,473	59.5	40.8	$ 480,838	$ 45,736
1984	1004	89,028	12656	7,681,200	593,418	86.3	46.9	$ 517,713	$ 66,625
1985	734	107,490	10592	7,177,100	523,198	66.8	49.4	$ 475,842	$ 58,791
1986	637	102,146	11144	7,398,500	539,097	72.4	48.4	$ 472,764	$ 57,837
1987	620	104,211	11670	7,607,700	549,167	73.0	47.1	$ 449,615	$ 57,113
1988	533	111,296	12749	7,409,900	570,293	66.6	44.7	$ 449,781	$ 63,895
1989	477	129,879	11455	9,484,000	572,734	73.0	50.0	$ 640,170	$ 64,621
1990	400	143,603	8372	10,355,260	626,734	72.1	74.9	$ 702,367	$ 71,790
1991	264	144,121	6980	10,872,990	458,289	75.4	65.7	$ 722,114	$ 52,502
1992	289	110,895	6980	8,777,430	419,141	79.2	60.1	$ 509,413	$ 43,492
1993	260	124,482	7773	9,676,540	514,192	77.7	66.1	$ 567,571	$ 53,328
1994	237	137,676	8030	11,542,310	575,044	83.8	71.6	$ 716,628	$ 57,970
1995	228	139,425	7521	11,286,040	578,584	80.9	76.9	$ 713,544	$ 60,620
1996	222	137,296	6453	11,408,740	502,000	83.1	77.8	$ 723,914	$ 52,475
1997	192	114,725	5992	9,972,650	497,000	86.9	82.9	$ 605,350	$ 50,310
1998	183	121,442	6097	9,402,010	562,000	77.4	92.2	$ 613,954	$ 58,942
1999	187	141,866	6828	12,836,020	544,940	90.5	79.8	$ 912,988	$ 57,286
2000	173	117,247	6404	10,858,240	450,490	92.6	70.3	$ 649,066	$ 44,233
2001	173	111,279	6810	9,248,720	533,440	83.1	78.3	$ 547,473	$ 50,866
2002	176	126,397	6934	11,670,820	618,830	92.3	89.3	$ 679,823	$ 62,015
2003	173	118,996	6017	9,819,710	540,968	82.5	89.9	$ 576,441	$ 53,149
2004	169	121,709	6666	12,266,410	651,890	100.8	97.8	$ 719,285	$ 61,218
2005	156	114,146	6651	10,193,120	650,610	89.3	97.8	$ 620,987	$ 59,520
2006	160	121,215	6185	10,611,820	625,740	87.5	101.2	$ 704,669	$ 60,423
2007	153	126,964	6234	12,659,890	620,977	99.7	99.6	$ 901,454	$ 61,270
2008	150	120,040	6194	12,305,820	613,868	102.5	99.1	$ 950,450	$ 59,184
2009	147	132,713	5365	13,970,560	544,832	105.3	101.6	$ 927,000	$ 65,385
2010	141	116,964	5141	12,800,000	513,724	109.4	99.9	$ 926,000	$ 50,003

Sources:

1982-2005-Ontario Horticultural Crop Research and Services Committee 2006 Report

2006-2010-http://www.opvg.org/crops/tomatoes/

United States Department of Agriculture -National Agricultural Statistics

1982-2010Service

Table 2.7-Growth stages, Kc and duration (days) per growth stages for tomatoes

Growth Stage	Crop Coefficient	Duration (days)
Initial stage	0.4-0.5	10-15
Development stage	0.7-0.8	20-30
Mid-season	1.05-1.25	30-40
Late season	0.8-0.9	30-40
Harvest	0.6-0.65	rest

Source FAO 24

Table 2.8-OMAFRA-growth stages, Kc and duration per growth stage for tomatoes

Growing Season	Crop Coefficient (Kc)	Duration (Days)
Transplanting -1st flower	0.4	22-30
1st Flower-max.row fill	0.7	26-35
Remainder of Crop	1.0	30-50

Source OMAFRA (2004)

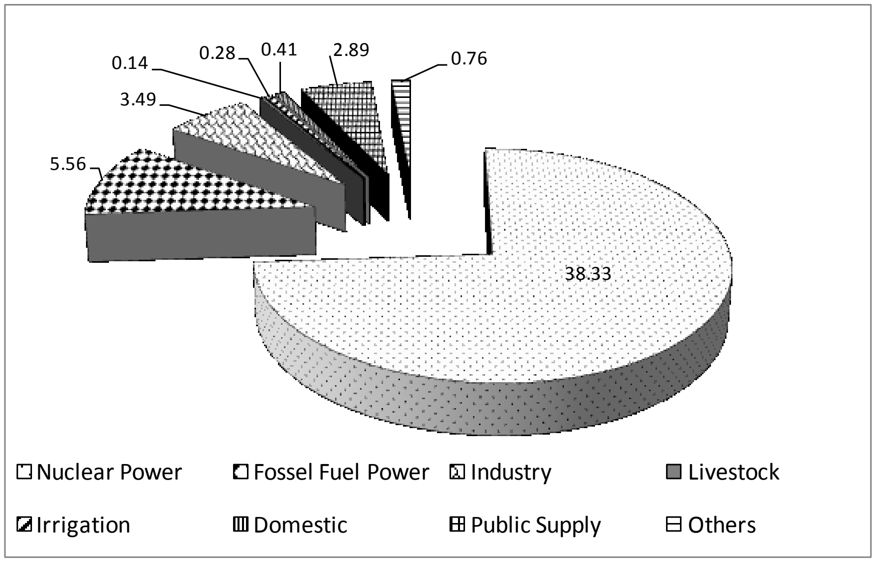

Figure 2.1-Ontario water use (Mm^3day^{-1})-total water withdrawal (excluding hydropower)

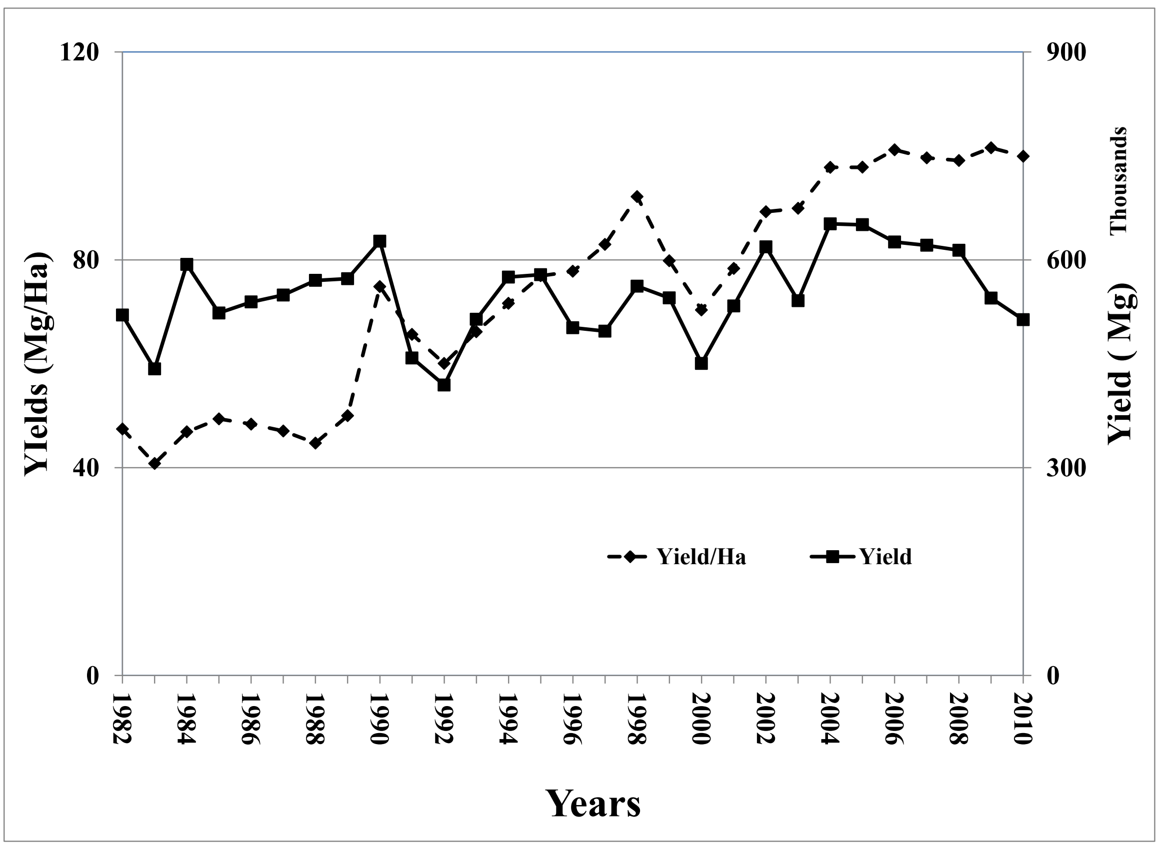

Figure 2.2-Annual production and average yields per ha of processing tomatoes in Canada

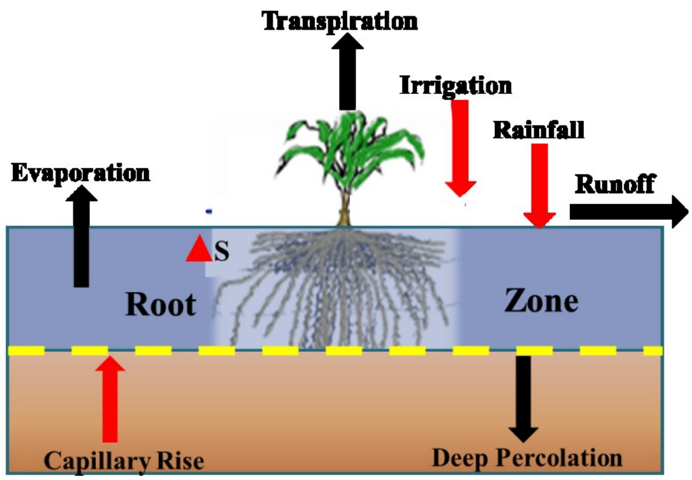

Figure 2.3-Soil water balance model-(single layer) for the root zone

Connecting text to Chapter 3

This Chapter is a manuscript presently under review and waiting to be published in February 2013. The manuscript is co-authored by my supervisor, Dr. C. A. Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis.

Chapter 3 covers the use of volumetric and tensiometric soil moisture sensors to effect scientific irrigation scheduling and therefore discusses objective 1 of this research. As articulated in Chapter 1, this paper addresses the knowledge gap in the determination of the upper and lower soil moisture threshold level for carrying scientific irrigation scheduling of field grown processing tomatoes in the humid region of Southwestern Ontario and addresses objective one. This is the topic of the following article.

Chapter 3 - Determination of threshold for irrigation management of processing tomatoes using continuous soil moisture monitoring sensors in south-western Ontario

F. Jaria, C.A. Madramootoo

Abstract

Processing tomatoes (Lycopersicon esculentum Mill.) are an economically important vegetable crop in southwestern Ontario. Processing tomato (cultivar H9553) fruit yield and quality were evaluated in field experiments in southwestern Ontario over a three year period (2008-2010). A split-plot randomized complete block model with four blocks was used in 2008 and 2010. The irrigation types (buried and surface drip) served as the main plots, while four moisture depletion levels constituted the split plots. In 2009, a (2*4) factorial complete randomized block design with four blocks was used, with the same two factors. The moisture treatments represented lower soil moisture triggers which initiated irrigation scheduling. Irrigation was terminated for each treatment when FC was reached. Continuous soil moisture status over the growing season was monitored with a combination of volumetric and tensiometric sensors. Seven fruit quality parameters were monitored: fruit weight, color, pH, size, firmness, brix yield and soluble solids. In each year the most stressed treatment produced the highest soluble solids (6.0, 4.8 and 5.2 ºBrix for 2008, 2009 and 2010 respectively). Total and marketable fruit yields ranged from 91.9 to 121.1 Mg ha^{-1} and 91.4 and 119.7 Mg ha^{-1} respectively. Statistical significance was obtained amongst treatment and irrigation type in 2008 only.Irrigation water use efficiency (IWUE) was not statistically significant over the three years. Seasonal irrigation depth ranged from 58 to 196 mm and statistical significance among the moisture treatments were obtained in 2008 and 2010.

Key words: FDR, TDR, Irrigation Scheduling, irrigation thresholds

3.1 Introduction

Agriculture is a key driver for the Canadian economy, providing 1 in 7 jobs within the country. The agri-food sector accounts for 8.3% of Canada's Gross Domestic Product,

\$26.5 billion comes from exports, employing nearly 2.1 million persons (AAFC, 2006). In 2010, Canadian vegetable growers reported sales of \$659 million dollars with two provinces - Ontario and Quebec accounting for more than 80% of sales (Statistics Canada, 2011a). Vegetable and dry bean productions are critical parts of the food and agriculture industry in Ontario.

Virtually all tomatoes grown in Canada for processing are produced in Ontario, with the main producing areas located in the counties of Essex and Kent. In 2008, 0.62 million tons of processing tomatoes were produced by 150 growers generating over US\$60.5M (OHCRSC, 2006). In most years, rainfall during the growing season is insufficient to support optimum production (Warner et al., 2007). Tan et al. (2003) noted that through the 1990's, rainfall during the growing season decreased by about 25 mm per year. The 30 year climate normal rainfall (1971 to 2000) for Windsor and London averaged 254.3 and 251.3 mm respectively. Over the growing season, an average cultivar requires 400 mm of water (LeBoeuf et al., 2007). Thus intensive tomato production in these two counties necessitates the use of supplemental irrigation to offset the deficiencies in rainfall, and maintain high production levels (Warner et al., 2007).

There is increasing pressure for more efficient and judicious use of limited water resources to reduce negative environmental impacts. Shock et al. (2001) identified economic competition in marketing produce, competition for water, and political pressure as the three forces operating to minimize off site impacts of irrigation-induced runoff and leaching. It is desirable to optimize crop yield and quality while reducing water use and increasing the efficient use of agricultural chemicals.

Irrigation scheduling is a technique that allows timely and accurate application of water to crops and is the key to conserving water, improving irrigation performance and sustainability of irrigated agriculture (Thompson et al., 2007b). Several irrigation scheduling methods based on water budget, soil and plant indicators have been used for different crops, with the former featuring as the most widely used technique (Fareres et al., 2003). However, over the past decade, a new generation of soil moisture sensors based on certain electrical properties, such as resistance, capacitance, and time domain reflectometry have been developed (Fares et al., 2006; Fereres et al., 2003). These devices have been used extensively for efficient irrigation and nutrient management in different crops (Fares & Alva, 2000; Lukangu et al., 1999; Thompson et al., 2007b). Soil moisture sensors facilitate frequent but low water application volumes, which have been found to be superior to traditional scheduling of fewer irrigation events of larger volumes. Soil moisture sensors measure either soil matric potential or volumetric soil water content (Thompson et al., 2007b).

Soil moisture sensors can be used as a standalone method to effect irrigation scheduling or in conjunction with other methods, like FAO and water budget methods (Thompson et al., 2007a; Thompson et al., 2007b). However, optimal irrigation scheduling using soil moisture, whether soil matric potential or volumetric soil water content, necessitates accurate threshold values or indices for individual crops in a given agricultural system (Lukangu et al., 1999). The upper and lower thresholds are described as fill and refill points respectively, with the fill point corresponding to field capacity. The refill point is the soil moisture content below which crop growth is measurably decreased or where a crop begins to experience water stress (Campbell & Campbell, 1982).

For volumetric soil moisture content sensors, the concept of Available Water Content (AWC) is often employed as triggers or thresholds for irrigation management (Thompson et al., 2007b). Since the AWC is the moisture available to the plant between field capacity and permanent wilting point, a management allowable depletion (MAD) ranging between 20% to 40% of AWC is often used as the refill threshold for different crops (Evett et al., 2011a). FAO 56 provide guidelines on these levels and recommends a depletion of 40% for tomatoes (Allen et al., 1998). Hartz (2005) added that tomatoes can tolerate a depletion of 20% to 30% of available soil moisture in the active root zone without experiencing yield losses. It is also possible to establish threshold values for soil moisture sensors as a percentage of field capacity instead of the MAD, since the two are related. Shock et al. (2007) added that irrigation thresholds should be determined for site-specific conditions to account for variability in climate, soils, crop cultivars and irrigation systems.

A range of threshold/refill values have been used for tension-based soil moisture sensors (Shock & Wang, 2011). Haise and Hagan (1967) used refill points of -60 to -70 kPa for high and low evaporative demand conditions for cabbages. Stanley and Maynard (1990) recommended soil water potential levels in the -10 and -30 kPa range for vegetables grown under irrigation high and low evaporative demand respectively. Thompson et al. (2007b) reported soil matric potential threshold values of -35 kPa for melon and -38 to - 58 kPa for tomatoes. Marouelli and Silva (2007) tested tension threshold values between -5 kPa and -120 kPa for processing tomatoes and found that soil moisture tension thresholds of -35, -12 and -15 kPa produced highest yields for vegetative, fruit development and maturation growth stages, respectively.

Numerous studies have found that irrigation substantially increased fruit yield of processing tomatoes (Hanson et al., 2006; Patanè & Cosentino, 2010). Warner et al. (2007) obtained processing tomato yields ranging from 126.1 to 181.5 Mg ha^{-1} under different irrigation application rates as a function of ETc (0.5 to 1.2 ETc) in Harrow, Ontario. At the University of California, Johnstone et al. (2005) carried out drip irrigation experiments between 2000 and 2002 on processing tomatoes in loam soils, as a function of reference evapotranspiration and found yields ranging from 78 to 125 Mg ha^{-1}. Drip irrigation experiments using varying amounts of potassium from 0 to 600 kg ha^{-1} produced total yields for processing tomatoes (cultivar H9478) ranging from 86.6 to 92.5 Mg ha^{-1} at Harrow, Ontario (Liu et al., 2011).

In the humid climate of Southwestern Ontario, determining the optimum water to application to meet crop water requirements (especially after a rainfall event) can be a challenge. To this end, the objective of this research was to use a combination of tension and volumetric based continuous soil moisture monitoring sensors as standalone devices to determine the optimum trigger point (refill) and to effect irrigation scheduling of field processing tomatoes grown in loamy sand soils.

3.2 Materials and methods

3.2.1 Location

A three year field experiment was conducted during the summer months of May through September, from 2008 to 2010 on a commercial farm in Leamington, in Southwestern Ontario. The climate is classified as humid, with hot summers complemented by dry, cold winters. Average annual temperature and precipitation are approximately 9.5°C and 750 mm (Tan & Reynolds, 2003) respectively. The growing season for field processing tomatoes extends from mid-May to September with an average growing season maximum and minimum daily temperatures of 24.9°C and 15.0°C respectively and an average seasonal rainfall of approximately 261.1 mm. Rainfall is typically spread throughout the year, with no predominant rainy months. The dominant soil within the production zone (0 to 30 cm) is loamy sand (86% sand, 8% silt and 6% clay), with an average bulk density of 1450 kg m^{-3}. Measured field soil water capacity ranged between 20 to 25% by volume. Chemical properties of the soil (0 to 30 cm) are provided in Table 3.1. Agronomic soil test P and NO_3-N were determined using the Olsen P procedure, 0.5M $NaHCO_3$, pH 8.5 (Olsen et al., 1954) and the 2.0 M KCl procedure (Keeney & Nelson, 1982), respectively.

3.2.2 Experimental design

Table 3.2 provides a summary of the experimental design over the 3 years. A split-plot randomized complete block design (RCBD) was used in 2008 and 2010, and a (2*4) factorial RCBD in 2009. The split plot design involved two experimental factors. The irrigation types (buried and surface drip irrigation) and the moisture levels (three moisture levels and a tension treatment) were assigned to the whole plot (main plot) and split plots respectively. The factorial experimental design of 2009 also had the same two factors. The volumetric moisture treatments were expressed as a fraction of field capacity and represented the depletion to which the soil moisture reached to initiate irrigation scheduling. The volumetric moisture treatments were changed from 60%, 70% and 80% of FC in 2008 to 74%, 82% and 91% of FC respectively, in 2009. This was done to examine the effects of a less stressed irrigation scheduling program. In 2010, the moisture treatments were again changed to 55%, 70% and 80% of FC. This change was to increase the range between moisture treatments, making it more practical for monitoring. The change in the experimental design from split-plot RCBD to a factorial design was undertaken because the parameters involved fitted both models and it was an opportune occasion to change the model in one of the three years.

The experiment for each year consisted of four blocks (replicates) each subdivided into eight plots making up a total of 32 plots (16 with buried drip and 16 with surface drip irrigation). Due to the annual crop rotation, the experimental site on the farm was changed each year. In 2008, blocks were oriented across the beds. Each plot comprised adjacent twin beds (2 beds * 1.5 m * 7.5 m), having an area of 22.5 m^2 per plot and located between guard beds (1.5 m * 7.5 m) on either side. There was a 1.5 m buffer between blocks. In 2009 and 2010, the blocks were oriented along the beds. Each of the plots (treatments) per block comprised single beds (1.5 m * 8.0 m), with an area of 12 m^2 per plot and located between guard beds (1.5 m * 8 m) on either side. The guard beds formed the separation between blocks and there was a 1.5 m buffer between plots in the blocks.

One drip line (irrigation tape, Streamline 636 006 F, Netafim Irrigation Inc., Fresno, CA) was aligned along the surface of each twin-row bed for the surface irrigated plots. For the buried irrigated plots, drip lines were installed to a depth of 20 cm (in 2008) and 15 cm (in 2009 and 2010). The inline emitters were spaced 30 cm apart, with a flow rate of 0.46 L h^{-1} @ 55 kPa in 2008 and 0.68 L h^{-1} @ 62 kPa in 2009 and 2010, providing a uniform soil wetting pattern. Each plot had the same number of drippers. The volume of water applied during each irrigation event to each plot was determined as the product of the irrigation duration and the flow rate per plot at the requisite water pressure. The equivalent irrigation depth was determined as the quotient of the irrigation volume and effective wetted area. Figures 3.1 and 3.2 provide a schematic of the 2008 and 2009 experimental and irrigation layout.

3.2.3 Cropping details

Processing tomatoes (*Lycopersicon esculentum* Mill. cultivar Heinz H9553) were grown in the study area during the three years. Seedlings (42 days old) were transplanted in soil with water content near field capacity in the top 30 cm. Transplant dates were 29 May 2008, 25 May 2009 and 15 May 2010. The crop was harvested after 105 days in 2008 (on 10 Sept.), after 112 days in 2009 (on 14 Sept.) and 101 days in 2010 (on 24 Aug.). Seedlings were spaced 42 cm apart within two rows, which were 50 cm apart. Each twin-row was centered on a 1.5-m-wide raised bed. The plant density was 31,746 plants ha^{-1}.

3.2.4 Soil moisture sensors, data collection and sensor calibration

Three types of soil moisture sensors were installed in the field for continuous data collection: a time domain reflectometer (TDR) (CS625 water content reflectometer, Campbell Scientific Inc., UT); a frequency domain reflectometer (FDR) (EnviroSMART, Sentek Sensor Technologies, Stepney, Australia) and an electronic tensiometer (Irrolis Sense Tx, Hortau Inc., QC, Canada).

The TDRs were installed with the aid of an insertion guide. The procedure for installation of the FDR access tube and the FDR sensors to the probe guide is articulated in the Sentek manual (Sentek Sensor Technologies, 2003). The tensiometers were installed in the conventional manner. For irrigation scheduling purposes, the critical depth at which the three soil moisture sensors were monitored included: 0 to 30 cm for the TDR, at the 20 cm FDR sensor, (which effectively measured the soil moisture content over the 5 to 25 cm depth) and at the 15 cm depth for the tensiometer. In relation to the drip lines, all sensors (in the case of the FDR, it was the access tubes) were installed 10 cm away from the centrally aligned drip line and 10 cm away from the nearest emitter, to ensure consistency in data collection.

Some changes occurred during the 2009 and 2010 experimental seasons. In 2009, the critical monitoring depth of the TDRs was between 5 to 25 cm. The top 5 cm of soil was removed (at the site of installation) and the sensor was installed at a 33.6° angle to the vertical plane. In 2010, only TDRs and tensiometers were installed in the experimental plots. The monitoring depth for the TDRs was reverted back to the 0 to 30 cm. Also in 2010, an upgraded version of the Irrolis Sense Tx electronic tensiometer, called the Irrolis MultiSense Tx3 probe, was used.

All devices were equipped with wireless communication system to transmit data from the field to an onsite computer. All volumetric sensors were connected to 12 solar powered data loggers (model CR205/6, Campbell Scientific Inc.). The data was scanned every 5 minutes and recorded every 15 minutes¸ hourly and daily. The data was retrieved from the CR205/6 using a computer and Campbell Scientific Inc. LoggerNet software. The electronic tensiometer data was transmitted in real-time by wireless radio signals to the onsite desktop computer, which was equipped with the requisite proprietary hardware and software. Meteorological data was collected on site from a weather station from 1 May to 31 Aug. in 2008, 2009 and 2010. The weather parameters measured included: temperature, rainfall, relative humidity, solar radiation and wind speed.

Generic calibration curves for the TDR and FDR sensors were developed for site specific conditions over the rooting depth of the crop (0 to 30 cm) against measured volumetric data. The tensiometers were not calibrated. In situ field capacity measurements were determined using the combined procedures outlined by Peter (1965) and Ratliff et al. (1983).

3.2.5 Irrigation scheduling

From the calibration curves for the TDR and FDR sensors, the upper and lower volumetric water content and sensor threshold values (in µsec and SFU for the TDR and SFU respectively) were determined. The predetermined upper and lower threshold values for the tension based treatment were -10 and -30 kPa respectively. For all treatments the upper threshold value was FC. The soil moisture sensors from all 32 plots were continuously monitored at a central location. When soil moisture content for each (buried and surface drip irrigated) plot depleted to its requisite moisture treatment threshold value, irrigation was initiated. Irrigation was terminated when the upper trigger (FC) moisture content was reached. The irrigation scheduling process for each plot was done throughout the growing season. The volume of irrigation and the equivalent irrigation depth applied at each irrigation event for each plot throughout the irrigation scheduling program was determined. The irrigation scheduling procedure was implemented throughout the irrigation season, which began on 7 July, 29 June and 21 June and was terminated on 1 Sept., 31 Aug. and 15 Aug. in 2008, 2009 and 2010 respectively. In addition to the pre-planting and side dressing nutrient applications, all plots were fertigated simultaneously during each of the three years and for the same duration.

3.2.6 Crop yield and quality and irrigation water use efficiency

Fruits were harvested approximately 10 days after spraying Ethrel. To evaluate fruit yield and quality, all fruits were harvested from six plants (2008, 2010) or four plants (2009) for each sub-plot. Fruits were categorized into red, green, or cull and weighed to determine total and marketable yields. Marketable yields were obtained by subtracting the weight of the culled fruits from the total yield. A random sample from each plot was tested for soluble sugar content, pH, firmness, fruit size and color. Total solids were determined as the product of soluble solids and harvestable yields. From each plot a random sample of approximately 50 marketable fruits were used to determine average fruit weight (Warner et al., 2007). A random sample of approximately 20 marketable fruits from each plot was tested for firmness with the use of a penetrometer (model FT 0110, Facchini, Italy). The penetrometer was equipped with a cylindrical pin, 5 cm long with a 2 mm diameter flat end. The average of two firmness measures was taken on each fruit at opposite sides of the equatorial zone. A random sample of 20 red ripe fruits from each plot was washed, skinned, deseeded and made into a pulp. The soluble solid (° Brix) and the pH were measured in the homogenised juice by using a digital refractometer and pH meter respectively. Irrigation water use efficiency (IWUE) was determined by taking the ratio of the marketable yields (kg ha^{-1}) and the total seasonal irrigation volume applied per ha (m^3 ha^{-1}) including effective rainfall. It was expressed as kg m^{-3} (Howell, 2001).

3.2.7 Statistical analysis

Statistical analysis was performed on individual years of data but not across years because of the yearly treatment differences. In both experimental design models, the blocks were considered random effects while the irrigation types and the moisture levels (treatments) were fixed effects parameters. Statistical analysis were performed using PROC MIXED procedure of SAS (SAS, 2007) designed to fit mixed effect models. Analysis of fruit yield, fruit quality and irrigation parameter were also conducted. Differences at $P < 0.05$ were considered statistically significant. Least squares means of fixed effects parameters were pair-wise compared at a P value of 0.05. Model assumptions (normal distribution, and consistent variance of error terms) were verified prior to carrying out the above analysis.

3.3 Results and discussion

3.3.1 Weather patterns and climatic conditions

The weather data is summarized in Table 3.3. There was no significant difference in the rainfall totals (3.5 mm difference) over the monitoring period in 2008 and 2009; however, the distribution was very different. In 2008, May and June had higher rainfall than July and August, whereas in 2009, the opposite was true. A comparison with the 30 year climate normal (1971 to 2000) indicated that the summer months of 2008 and 2009 received 15% and 16% lower than normal precipitation, respectively. The 2010 monthly rainfall exceeded the normal rainfall for the growing season with the exception of August. The 2010 total rainfall also exceeded the 30 year average by 42.7%. The average over the three years (May to August) was 261.2 mm. Zhang et al. (2010) also reported average rainfall of 291.8 mm over the growing period (May to Sept) in Harrow, Ontario, Canada.

Air temperature gradually increased from about 15°C at the beginning of May to about 30°C between June and mid-August, after which there was a gradual decrease towards the end of August for all three years of the project. Just prior to planting in May 2010, there was a four day period in which the temperatures dipped below 15°C. Though the trends were similar in the three years, the average monthly air temperatures showed variation. Jones Jr. (2007) highlighted the fact that tomato is a day length neutral plant under conditions of short or long days, requiring optimum mean daily temperature of

18.5 to 25ºC for growth with night temperatures between 18 and 21ºC. At the time of planting, these conditions were met.

3.3.2 Field capacity (FC) and available water content (AWC)

The FC and PWP for 2008 to 2010 were 20%, 9%, and 22%; 9%, 25%, and 10% volumetric water content (VWC) respectively. The varying FC values obtained may be attributed to the changing organic matter content over the years due to crop rotation and land preparation. Hudson (1994) noted that within each textual group, as organic matter (OM) content increased, the volume of water held at field capacity increased at a much greater rate than that held at the permanent wilting point. He further added that 1% to 6% OM by weight was equivalent to approximately 5 to 25% by volume and hence can have a significant effect on available water content (AWC). The AWC ranged between 10 to 15 % θ_v and was within the range (9-15%) of values for the soil type as provided by Schwab et al. (1993). Table 3.4 summarizes the FC and tension treatments over the three years as factions of AWC. Doorenbos and Pruitt (1977) recommended a management allowable deficit (MAD) for tomatoes of 30 to 40% of AWC to facilitate maximum yields. In 2008 and 2010 two of the four treatments and in 2009, three of the four treatments fell within that range.

3.3.3 Applied water (2008 to 2010)

3.3.3.1 Applied water -2008

The irrigation scheduling summary and their statistical results are shown in Tables 3.5 and 3.6. In 2008, irrigation duration was not statistically significant amongst the moisture treatment, irrigation types or the interaction between moisture treatments and irrigation types. However, statistical significance for irrigation events, equivalent depths and irrigation volumes were obtained amongst the moisture treatments but not between the irrigation type and the interaction between irrigation type and moisture treatments.

The -30 kPa treatment represented the least stress treatment, corresponding to a soil moisture content of approximately 88% FC or 24% depletion in AWC. It would invariably trigger more frequently than other moisture treatments and therefore, would receive the most irrigation. Further, the tension treatment represented a point measurement of the moisture content at the 15 cm depth as compared to the TDRs and FDRs reflecting the integrated moisture content over the 0 to 30 cm and 15 to 25 cm depths respectively. This shallower depth would also mean that the tension treatment would tend to trigger more frequently.

The 70% FC was irrigated for a longer duration, received more water, and was irrigated more frequently than the 80% FC. Two factors contributed to this discrepancy. Firstly, one of the eight, 80% FC plots recorded unusually high moisture content throughout the growing season and was only irrigated four times as compared to an average of 17 times for the 80% FC moisture treatment. The consistent high moisture content at that plot was due to a depression in the field which allowed for lateral movement of soil moisture to accumulate in the vicinity of the plot. Secondly, one of the 70% FC plots was irrigated 14 times more than the average 70% FC treatment while another was irrigated for 50 hours more than the average 70% FC treatment.

Although the 80% FC treatment was irrigated more regularly than the 60% FC treatment, the average seasonal irrigation depth was higher for the 60% FC than the 80% FC. This was due to a combination of factors. One of the factors was highlighted above, with reference to the high moisture content of one of the 80% FC plots. Secondly, one of the 60% FC plot was irrigated more frequently than the average 80% FC treatment. Thirdly, the 60% FC treatment represented a wider threshold range, which meant that the average application duration per irrigation event for the 60% FC was longer than the 80% FC.

3.3.3.2 Applied water - 2009 and 2010

In 2009, treatments reflected a less stressed irrigation scheduling program than the 2008 experiment, resulting in statistical significance only in the irrigation events amongst the moisture treatments. There was no statistical significance amongst the irrigation types or the interaction between irrigation type and moisture treatments. The average seasonal irrigation volume per plot was less than 2008 because the plot area was reduced by approximately 47%. The equivalent depth of irrigation applied increased with the increase of the FC treatments (from the 74% FC to the 91% FC) and decreased for the -30 kPa treatment. Despite having a higher effective rainfall in 2009 and using less stressed irrigation treatments, the equivalent irrigation depth for two of the FC treatments in 2009 were higher than 2008 values. In 2008, rainfall was concentrated during the first two months of the growing season; as a result more effective use was made of rainfall. Therefore the need for irrigation during the early part of the season was minimal. In 2009, the rainfall was concentrated towards the end of the growing season. There was therefore more need to irrigate during the early season. The major rainfall was in August, by then the crop was close to harvesting and the need for irrigation was minimal. The August rainfall therefore was not very effectively used.

In 2010, the FC treatments were changed to reflect a larger range between treatments, which contributed to statistical significance between irrigation duration, irrigation events, equivalent depth, and irrigation volume among moisture treatments. There was no statistical significance among the irrigation type, and interaction between irrigation type and moisture treatments. There was a consistent trend amongst treatments, with the most stress moisture treatment reaching trigger the least number of times, and therefore receiving the least seasonal irrigation and shortest irrigation duration. The reciprocal was obtained for the least stressed treatment. All FC treatments were monitored at the 0 to 30 cm depth and the tension treatment at the 15 cm depth. The shallower soil depth at which the tension treatment was measured would account for it reaching trigger more frequently. The distribution and the total depth of the effective rainfall over the growing season would have contributed to the fewer overall irrigation events for all treatments.

Warner et al. (2007) reported seasonal irrigation water depths ranging from 58 mm to 267.6 mm during a three year experiment (average rainfall 247.1 for June to August) in Harrow, Ontario, for different surface drip irrigation treatments for processing tomatoes in Granby sandy loam. Machado et al. (2005) also reported values of 243.1 to 560.9 mm for subsurface drip irrigation in Coruche, Portugal, in sandy soils, with rainfall over the growing season amounting to 76.1 mm. In both cases irrigation was applied as a function of crop evapotranspiration.

3.3.4 Fruit yield (2008-2010)

3.3.4.1 Fruit yield -2008

Tables 3.7 and 3.8 summarize yield results and yield statistics. In 2008, the average fruit yield for the four treatments ranged from 91.9 to 121 Mg ha^{-1}. The highest and lowest average yields were from the 70% FC and the 60% FC treatments respectively. There was a direct relationship between seasonal irrigation depth and crop yields (Fig 3.2). As a result statistical significance was obtained for total and marketable yields among moisture treatments as well as between irrigation types. The pair wise comparisons between the moisture treatments reveal statistical significance only between the 60% FC and 70% FC, 60% FC and -30 kPa, and 70% FC and 80% FC, but not between 60% FC and 80% FC, and -30kPa and 80% FC (Table 3.10). No significant difference was found in the interaction between the moisture treatments and the irrigation type.

The 70% FC treatment represented a depletion in the AWC of approximately 54%, which was substantially lower than the 30 to 40% AWC recommended by Doorenbos and Pruitt (1977). It was therefore surprising that the 70% FC treatment should produce the highest yield. A review of the data revealed that two of the eight, 70% FC plots had yields of 130.7 and 176.2 Mg ha^{-1}. The 176.2 Mg ha^{-1} was also the highest yield of the 32 plots, as well as the plot receiving the highest equivalent depth of irrigation (249.2 mm). These two exceptionally high yields therefore skewed the average yield for the 70% FC treatment, making it the treatment with the highest yield.

The 60% FC treatment represented a 74 % depletion of the AWC. The plant physiological stress associated with the 60% FC treatment undoubtedly contributed to the lowest yields. The 80% FC, which corresponded to 36% depletion in AWC, had unusually low yields. Five of the eight, 80% FC plots had yields of less than 100 Mg ha^{-1} and resulted in an average yield that was lower than the 70% FC.

In relation to the irrigation type, all surface drip irrigated treatments produced higher yields than their corresponding buried drip irrigated treatments in 2008. The major factor contributing to this difference was attributed to the depth of the buried drip lines. During the 2008 season, the buried drip lines were installed at 20 cm below the ground surface; however, in 2009 and 2010 they were installed at 15 cm below the ground. Processing tomato has an effective rooting depth of approximately 30 to 40 cm in loamy sand. It was believed that the drip line placement at 20 cm may have limited the wetting pattern and the capillary rise during irrigation, limiting the requisite amount of water needed for the crop within the rooting zone, particularly between the 0 to10 cm depths. Visual observations indicated that the soil surface for the buried drip irrigated plots were often dry which may have been due to low capillary rise. The surface irrigated plot, however, provided a longer period for the irrigation water to move through the root zone and by extension supplied a greater amount of water in the effective rooting depth of 30 cm. This undoubtedly would have contributed to the significant difference between the yields of the irrigation types. Tan (2003) reported similar trends but attributed the higher yield for the surface irrigated plots to root intrusion into the sub-surface emitters, preventing uniform water distribution. Phene et al. (1987) reported conflicting results for surface and buried (at 45 cm below the surface) drip irrigated processing tomatoes grown in clay loam soils in California. Manual and machine harvest yields were 10.3% and 17% greater in the subsurface drip treatments than the high frequency surface drip treatment, and 29.2% and 24.1% than the low frequency surface drip. It must however be noted that both the soil type and depth of drip lines were different for this current experiment.

3.3.4.2 Fruit yield-2009 and 2010

In 2009, the average fruit yield for the four treatments ranged from 101.6 to 105 Mg ha^{-1}. The highest and lowest average yields were from the -30 kPa and the 91% FC treatments respectively. There was very little variation in yields between treatments during the 2009 season, therefore no statistical significance was obtained amongst the moisture treatments, irrigation type or the interaction between the two. This was primarily due to the fact that the soil moisture depletion levels of the four treatments were reduced, such that three of the four treatments were within the MAD of 30% to 40% AWC. The fourth moisture treatment, the 74% FC, was just outside the range of the MAD recommended by Doorenbos and Pruitt (1977) by 5% and had approximately the same average yield as 91% FC treatment. This may be due to the masking effect of the effective rainfall (186 mm) which would have minimized the treatment effect of particularly the 74% FC treatment. The 91% FC treatment (depletion of 15% AWC) also had a lower yield than the -30kPa treatment (depletion of 22% AWC). It was very possible that the 91% FC treatment created too wet a soil environment in the rooting zone thus negatively impacting plant growth and development, resulting in a slightly lower plant yield. Figure 1 indicated that maximum yield was reached with a seasonal irrigation depth of approximately 150 mm. After this point, fruit yields decrease with increased irrigation.

In 2010, average fruit yield ranged from 104.4 to 121.1 Mg ha^{-1}. Two treatments fell within the MAD range of 30% to 40% AWC, and they had higher yields while the two treatments falling outside the range had lower yields. The 2010 season produced the highest average yields amongst the treatments (113.7 Mg ha^{-1}). It is believed that the large effective rainfall over the growing season, with each month's rainfall greater than the 30 year average (a seasonal average having 43% more rainfall than the 30 year average) would have masked the effects of all treatments and reduced plant stress during critical plant growth stages. It is therefore not surprising that there was no statistical difference between moisture treatments, irrigation type or the interaction between them.

The results over the three years indicated a direct relationship between irrigation volume and yields (Fig. 1). Total and marketable production increased with increasing irrigation depths. Similar results were reported by (Machado & Oliveira, 2005; Machado et al., 2000; Sezen et al., 2010) for both surface and buried drip irrigation. Machado and Oliveira (2005) obtained comparable yields, ranging from 78.8 to 141.7 Mg ha^{-1} and 69.9 and 130.1 Mg ha^{-1} for total and marketable yields respectively. Warner et al. (2007) reported total and marketable yields of 130 to 173.3 Mg ha^{-1} and 126.7 and 168.5 Mg ha^{-1}. Zhang et al. (2010) also reported total and marketable yields of 64 to 166.7 Mg ha^{-1} and 56 to 138 Mg ha^{-1}, respectively. In each of the three years, the treatments with ≤ 40%

AWC depletion generally produced the highest yields and thus validated Doorenbos and Pruitt (1977) recommendation. The -30 kPa treatment represented depletion in the AWC ranging from 22 to 24% VWC over the three years. Apart from the anomaly in 2008, where the 70% FC treatment had the highest yield, the tension treatment had the highest yields (in 2009 and 2010), despite not being statistically significant. The threshold values (-10 and -30 kPa) for fill and refill levels were comparable to similar works done with processing tomatoes. Marouelli and Silva (2007) used soil water thresholds (SWT) ranging from 5 to 120 kPa and found that best yields were obtained when irrigation was performed at SWT thresholds of 35, 12 and 15 kPa during the vegetative, fruit development and maturation growth stages respectively at Embrapa Vegetables, Brasília, Brazil. Hartz and Hanson (2005) recommended thresholds should be in the range of 20 to 35 kPa until fruit maturation and then fall within the range of 40 to 50 kPa. However the above values were for deep clayey soils in California. It is also worth noting that while these researchers varied the threshold values over the developmental stages of the crop, the current experiment kept the threshold values constant.

3.3.5 Fruit quality and IWUE

3.3.5.1 Fruit quality - 2008

Fruit quality parameters and their statistics are summarized in Tables 3.9 to 3.11. In 2008, the average fruit weights from the different treatments reflected a similar trend to yields with similar statistical results. Two of the seven fruit quality parameters (weight and soluble solids) indicated statistical significance among the treatments and would undoubtedly be influenced by the irrigation scheduling program and the irrigation depths for the various treatments over the season. All other fruit quality factors indicated no statistical significance. In relation to the irrigation type, there was statistical significance in fruit weight, firmness, soluble solids and brix yields, which may be attributed to the fact that the surface irrigated plot received more irrigation than the buried irrigated plots. There was no statistical significance for the interaction between moisture treatments and irrigation types for all seven fruit quality parameters.

3.3.5.2. Fruit quality – 2009 and 2010

In 2009 individual fruit weight was not measured due to unavailability of equipment. All six fruit quality parameters measured indicated no statistical significance among moisture treatments, irrigation type or the interaction between the moisture treatments and irrigation type. Three factors would have contributed to the absence of statistical significance in 2009. Firstly, the moisture treatments reflected a less stress moisture irrigation scheduling program than 2008 and 2010. The range between FC treatments was very small and hence the differences would be minimal. Three of the four moisture treatments were within the 30% to 40% MAD range and the other (74% FC) represented a depletion in the AWC of 45%. The second factor was the depth to which the buried drip lines were installed in 2009. The drip lines were raised by 5 cm to a depth of 15 cm below the soil surface which facilitated better moisture distribution and improved yields for the buried drip irrigated plots as compared to 2008. The third factor would be the relatively high effective rainfall over the growing season which would have masked the treatment effects, particularly the 74 % FC treatment.

In 2010, the range between the FC treatments was increased; as a result greater differences were realized in the fruit quality parameters amongst the moisture treatments. Four of the seven fruit quality parameter (fruit weight, size, color and soluble solids) indicated statistical significance between the irrigation treatments. There was no statistical significance amongst the irrigation type and the interaction moisture treatment and irrigation type. As was the case in 2009, the shallower installing depth of the drip lines accounted for the improved yields amongst the buried irrigated plots, comparable to the surface drip irrigated plots, which resulted in the absence of statistical significance among irrigation type.

Over the three years, both irrigation depth and fruit yields had converse effects on soluble solids (Figs. 3.4 and 3.5). Fruit weight and fruit size showed a positive relationship with irrigation depth, while fruit firmness reflected an inverse relation with irrigation depth. pH indicated no real relationship with moisture content (Figs. 3.6 and 3.7). In all three years there was a negative relationship between irrigation depth and soluble solids. A negative correlation was also obtained between fruit yield and soluble solids in 2008 and 2010. A similar negative correlation was reported by Machado et al. (2005). In 2009, the soluble solids increased with increasing irrigation to some critical irrigation depth (150 mm) and subsequently decreased with increasing irrigation. It was found that pH was not statistically affected by irrigation depths, type or by treatment interaction. This was consistent with observations made Machado et al. (2003) and Davis et al. (1985). The brix yield which is the product of fruit soluble solids and the marketable yields ranged from 4.77 Mg ha^{-1} to 5.96 Mg ha^{-1} over the three years. Statistical significance was realized only between irrigation types for 2008. This was attributed to the large difference in yield between the irrigation types. Machado et al. (2005) reported values ranging from 4.51 to 6.07 ºBrix, 4.30 to 4.38 and 4.20 to 5.85 Mg ha^{-1} for the fruit quality parameters of soluble solids, pH, and Brix yields respectively which were within comparable range with this research.

A possible water conservation approach to large scale processing tomato production in Canada is to remunerate tomato growers based on soluble solid content (SSC). High SSC are highly desirable for processing, and processors pay a premium for tomatoes with a high SSC (Dumas et al., 1994; Iddo, 2008). A practical approach would be to establish a threshold brix yield, which can be achieved by setting a slightly higher fruit soluble solid content. This would necessitate a reduction in irrigation water application, which inevitably would result in a slight decrease in yield. However the net brix yield would be the same. The savings to the grower would be in reduced irrigation costs. The unused surplus water could be used for further expansion. However, further research is necessary in a Canadian context.

The IWUE ranged from 30.5 to 35 kg m^{-3}, 28.10 to 37.6 kg m^{-3}, and 24.4 to 28.9 to kg m^{-3} for 2008, 2009, and 2010 respectively. In 2008, the 70% FC treatment yielded the highest IWUE (Table 3.9). This was due to the unusually high yield for the 70% FC treatment. 2008 IWUE depicted a positive relationship with irrigation depth (Fig 3.8). Both of these factors can be attributed to the unusually higher yields for the 70% FC treatment. In 2009 and 2010, the lowest moisture treatment produced the highest IWUE due to the comparatively lower irrigation depth. Both of these years depicted a converse relationship with irrigation depths, such that an increase in irrigation depths resulted in a corresponding decrease in IWUE. Though the effective rainfall was substantial over the three years, the IWUE was not significantly affected by moisture treatments, irrigation type or their interaction. This trend is in agreement with Machado et al. (2005), who reported IWUE values ranging from 20.2 to 22.8 kg m^{-3}. These values were substantially lower than that obtained from this research and is attributed to the higher water applied (irrigation and rainfall) ranging from 326.2 to 644.0 mm.

3.4 Conclusions

In Southwestern Ontario, irrigated agriculture is a prerequisite for large scale field tomato production. Commercial yield was higher for the moisture treatments wherein the quantity of water applied was the greatest. This also corresponded to the moisture treatments in which the depletion level in soil moisture was $\leq$ 40% AWC. The tension based treatment (-30 kPa) produced the highest yields in two of the three years of the experiment. The 2008 results indicated that surface drip irrigation produced significantly higher yields than buried drip irrigation for each moisture treatment, which was attributed to the depth of the buried drip in 2008; however, in the other two years of the project (2009, 2010), there was no statistical significance in yield between the surface drip and buried drip irrigated plots after the buried drip lines were raised from a depth of 20 to 15 cm. The rainfall distribution particularly during the critical periods of the crop may have contributed in masking the moisture treatment, reducing crop stress. The fruit quality parameters of greatest interest were weight, size, firmness, soluble content and brix yield. The heavier and larger fruits were associated with the wetter moisture treatments. Brix yield showed statistical significance only between the surface and buried irrigation systems of 2008. IWUE showed no statistical significance between the moisture treatments, irrigation types or their interaction for each of the three years; however, 2010 had the lowest irrigation water use efficiency which was due primarily to the higher rainfall than the previous two years. As a water conservation approach for large scale processing tomato production in Canada, there may be some benefit in exploring changing the system of remuneration of tomato growers to one based on soluble solid content (SSC) and brix yield rather than total yields.

Table 3.1- 2008-2010 pre-planting soil properties at experimental site over the 0-30 cm depth

Soil Parameter	2008	2009	2010
NO_3N (ppm)	52	101	37
Available P (ppm)	144	121	154
Potassium (ppm)	243	219	191
pH	7.3	7.0	7.0
Organic Matter (%)	2.1	2.9	2.9

Table 3.2- Experimental designs for 2008 to 2010

Year	Experimental Design	Factor 1 – Irrigation Types		Factor 2 – Moisture levels			
2008	Split Plot RCBD	Surface Drip irrigation	Buried Drip irrigation	60% FC	70% FC	80% FC	Tension base (-30kPa)
2009	Factorial RCBD	Surface Drip irrigation	Buried Drip irrigation	74% FC	82% FC	91% FC	Tension base (-30 kPa)
2010	Split Plot RCBD	Surface Drip irrigation	Buried Drip irrigation	55% FC	70% FC	85% FC	Tension base (-30kPa)

AWC=Available Water Content, FC= Field Capacity, RCBD=Randomized Complete Block Design

Table 3.3-Rainfall comparison to 30 year normal (1971-2000)

Months	Climate Normal 1971-2000		Rainfall (mm)						Average Temperature (°C)		
	Rainfall (mm)		Leamington			% > Normal (relative to Windsor)			Leamington		
	London	Windsor	2008	2009	2010	2008	2009	2010	2008	2009	2010
May	82.6	80.7	66.4	12.5	114.7	-18.7	-84.7	72.7	12.5	14.7	15.4
Jun	86.8	89.8	108.1	65.0	91.4	22.4	-26.4	1.8	20.6	18.8	21.1
Jul	82.2	81.8	30.6	34.4	135.5	-62.7	-58	57.8	22.7	20.1	24.4
Aug	85.3	79.7	9.5	98.6	16.9	-88.5	19.5	78.8	20.7	21.0	23.4
Total	254.3	251.3	214.6	210.5	358.5	-15.1	-16.7	42.7			

Table 3.4-Treatments expressed as depletion of AWC

2008		2009		2010	
Treatments	AWC Depletion (% VWC)	Treatments	AWC Depletion (% VWC)	Treatments	AWC Depletion (%VWC)
80% FC	36	91% FC	15	85% FC	25
70% FC	54	82% FC	30	70% FC	58
60% FC	73	74% FC	45	55% FC	75
-30 kPa	24	-30 kPa	22	-30 kPa	20

Table 3.5 - Irrigation scheduling summary per treatment

2008 Season Average per Treatment						**2009 Season Average per Treatment**						**2010 Season Average per Treatment**					
Treatment (% FC)	**Duration (hrs)**	**Volume of Appl. (l)**	**Equivalent Depth (mm)**	**Effective Rainfall (mm)**	**Total Irrigation Events**	**Treatment (% FC)**	**Duration (hrs)**	**Volume of Appl. (l)**	**Equivalent Depth (mm)**	**Effective Rainfall (mm)**	**Total Irrigation Events**	**Treatment (% FC)**	**Duration (hrs)**	**Volume of Appl. (l)**	**Equivalent Depth (mm)**	**Effective Rainfall (mm)**	**Total Irrigation Events**
60%	59.8	1464	114	167.2	12	74%	32.9	582	85	186	11	55%	22.5	399	58	294.2	4
70%	81.9	2006	156	167.2	20	82%	66.8	1182	173	186	16	70%	39.9	705	103	294.2	7
80%	53.7	1317	103	167.2	17	91%	73.6	1302	190	186	23	85%	70.0	1238	181	294.2	15
30kPa	88.1	2160	168	167.2	30	30kPa	58.6	1036	151	186	27	30 kPa	75.9	1342	196	294.2	18

Table 3.6- Statistical results of fixed effect parameters- irrigation parameters (2008-2010)

Irrigation parameters	2008			2009			2010		
	Moisture treatment	Irrigation type	Moisture trt X irrigation type	Moisture treatment	Irrigation type	Moisture trt X irrigation type	Moisture treatment	Irrigation type	Moisture trt X irrigation type
Irrigation Duration	NS	NS	NS	NS	NS	NS	*	NS	NS
Total Irrigation Events	*	NS	NS	*	NS	NS	*	NS	NS
Irrigation Equivalent Depth	*	NS	NS	NS	NS	NS	*	NS	NS
Irrigation Volume	*	NS	NS	NS	NS	NS	*	NS	NS
NS,* Not significant or significant at $p \leq 0.05$ respectively,									

Table 3.7-Fruit yield per treatment for 2008-2010

Year	Treatment	Average Fruit Yield (Mg ha^{-1})					
		Total	**S.E**	**Marketable**	**S.E**	**Red Fruits**	**S.E**
2008	60% FC	91.9	8.6	91.4	8.6	80.3	8.6
	70% FC	117.8	9.5	117.0	9.3	107.2	9
	80% FC	95.9	8.7	95.3	8.6	88.6	8.5
	-30kPa	114.1	5.2	114.0	5.2	107.0	4.1
2009	74% FC	102.5	3.2	99.8	2.7	98.5	2.8
	82% FC	104.7	4.2	102.1	4.4	100.9	4.4
	91% FC	101.6	3.3	98.0	3.3	97.8	3.2
	-30kPa	105.3	3.3	102.9	3.2	102.3	3.3
2010	55% FC	104.4	5.4	102.0	5.6	90.6	8.6
	70% FC	110.0	6.9	107.1	6.9	99.7	7.1
	85% FC	119.1	5	115.9	5.4	110.8	5.8
	-30kPa	121.1	6	119.7	6.2	114	6.3

S.E- Standard Error

Table 3.8- Statistical results of fixed effect parameters-Yields (2008-2010)

Production characteristics	2008			2009			2010		
	Moisture treatment	Irrigation type	Moisture trt. X irrigation type	Moisture treatment	Irrigation type	Moisture trt. X irrigation type	Moisture treatment	Irrigation type	Moisture trt. X irrigation type
Total Yield	*	*	NS	NS	NS	NS	NS	NS	NS
Marketable Yield	*	*	NS	NS	NS	NS	NS	NS	NS
Reds	*	*	NS	NS	NS	NS	*	NS	NS

Table 3.9-Fruit quality parameters per treatment from 2008 to 2010

Year	Treatment	Fruit Weight (g)	S.E (g)	Fruit Firmness (MPa)	S.E (MPa)	Fruit Length (mm)	S.E (mm)	Fruit Diameter (mm)	S.E (mm)	Fruit Area (cm^2)	S.E (cm^2)	Fruit Color (Agtron)	S.E (Agtron)	Fruit SS (° Brix)	S.E (°Brix)	Fruit pH	S.E pH	Brix Yield (Mg ha^{-1})	S.E (Mg ha^{-1})
2008	60% FC	39.7	1.2	2.31	0.04	49.6	0.59	41.3	1.6	16.1	0.8	18.7	0.5	6.0	0.2	4.2	0.01	5.38	0.3
	70% FC	43.9	2.0	2.25	0.06	50.7	0.65	41.3	0.5	16.5	0.4	18.3	0.5	5.2	0.2	4.3	0.01	5.96	0.2
	80% FC	40.3	1.4	2.29	0.05	47.2	1.27	41.0	1.3	15.2	0.5	18.1	0.8	6.0	0.2	4.2	0.01	5.74	0.6
	-30kPa	45.4	2.0	2.23	0.06	51.1	0.76	41.3	0.6	16.6	0.4	17.7	0.5	5.3	0.2	4.3	0.01	5.96	0.1
2009	74% FC	-	-	2.03	0.05	46.7	0.65	38.5	0.5	14.1	0.4	19.6	0.4	4.8	0.1	4.3	0.01	4.81	0.1
	82% FC	-	-	1.88	0.06	48.4	0.24	39.1	0.2	14.8	0.1	19.7	0.3	4.7	0.1	4.3	0.01	4.77	0.2
	91% FC	-	-	1.85	0.05	48.0	0.60	39.2	0.5	14.7	0.3	19.9	0.5	4.5	0.1	4.3	0.01	4.44	0.2
	-30kPa	-	-	1.89	0.04	48.7	0.40	39.1	0.5	15.0	0.3	19.9	0.4	4.6	0.1	4.3	0.01	4.76	0.2
2010	55% FC	45.1	1.9	2.68	0.09	50.2	0.55	40.3	0.5	15.9	0.4	18.8	0.6	5.2	0.2	4.2	0.01	5.22	0.2
	70% FC	50.7	1.7	2.59	0.12	52.1	0.43	42.3	0.4	17.3	0.3	18.6	0.4	4.9	0.2	4.3	0.01	5.15	0.3
	85% FC	54.1	1.6	2.73	0.11	53.3	0.38	42.9	0.3	18.0	0.2	18.3	0.4	4.5	0.1	4.3	0.01	5.22	0.2
	-30kPa	56.3	2.4	2.74	0.08	54.0	0.67	43.7	0.6	18.6	0.5	18.0	0.4	4.5	0.1	4.3	0.00	5.38	0.3

S.E Standard Error

Table 3.10- Statistical results of fixed effect parameters-fruit quality (2008-2010)

Production characteristics	2008			2009			2010		
	Moisture treatment	Irrigation type	Moisture trt X irrigation type	Moisture treatment	Irrigation type	Moisture trt X irrigation type	Moisture treatment	Irrigation type	Moisture trt X irrigation type
Fruit Weight	*	*	NS	NA	NA	NA	*	NS	NS
Fruit firmness	NS	*	NS	NS	NS	NS	NS	NS	NS
Fruit Area	NS	NS	NS	NS	NS	NS	*	NS	NS
Fruit Color	NS	NS	NS	NS	NS	NS	*	NS	NS
Soluble Solid	*	*	NS	NS	NS	NS	*	NS	NS
Fruit pH	NS	NS	NS	NS	NS	NS	NS	NS	NS
Brix Yield	NS	*	NS	NS	NS	NS	NS	NS	NS
IWUE	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 3.11 – Pairwise comparison of fixed effect parameters.

Year	Pairwise comparison	Statistical Results (Pr>|t|							
		Total yield	Marketable yield	Irrigation duration	Irrigation events	Irrigation depths	Fruit weight	Fruit firmness	Brix yield
2008	60%FC-70%FC	0.020*	0.019*	0.11**	0.024*	0.11**	0.06**	0.004*	0.24**
	60%FC-80%FC	0.71**	0.70**	0.65**	0.15**	0.65**	0.77**	0.88**	0.46**
	60%FC-30 kPa	0.037*	0.042*	0.06**	<.0001*	0.041*	0.010*	0.008*	0.24**
	70%FC-80%FC	0.044*	0.045*	0.046*	0.36**	0.043*	0.10**	0.003*	0.65**
	70%FC-30 kPa	0.77**	0.72**	0.73**	0.003*	0.64**	0.46**	0.769*	1.00**
	80%FC-30 kPa	0.08**	0.09**	0.022*	0.0004*	0.015*	0.021*	0.006*	0.65**
2009	74%FC-82%FC	0.68**	0.66**	0.06**	0.29**	0.06**	-	0.07**	0.86**
	74%FC-91%FC	0.85**	0.72**	0.023*	0.011*	0.023*	-	0.027*	0.14**
	74%FC-30 kPa	0.60**	0.55**	0.14**	0.0009*	0.14**	-	0.07**	0.84**
	82%FC-91%FC	0.55**	0.42**	0.69**	0.10**	0.69**	-	0.68**	0.18**
	82%FC-30 kPa	0.91**	0.87**	0.63**	0.011*	0.63**	-	0.97**	0.97**
	91%FC-30 kPa	0.48**	0.34**	0.38**	0.29**	0.38**	-	0.65**	0.20**
2010	55%FC-70%FC	0.42**	0.47**	0.013*	0.040*	0.013*	0.046*	0.41**	0.85**
	55%FC-85%FC	0.043*	0.06**	<.0001*	<.0001*	<.0001*	0.003*	0.68**	0.97**
	55%FC-30 kPa	0.023*	0.020*	<.0001*	<.0001*	<.0001*	0.0005*	0.62**	0.62**
	70%FC-85%FC	0.20**	0.22**	0.0002*	<.0001*	<.0001*	0.23**	0.22**	0.88**
	70%FC-30 kPa	0.12**	0.09**	<.0001*	<.0001*	<.0001*	0.060*	0.20**	0.50**
	85%FC-30 kPa	0.77**	0.60**	0.36**	0.020*	0.39**	0.47**	0.94**	0.60**

*,** Statistical and not statistical significant at $\alpha=0.05$

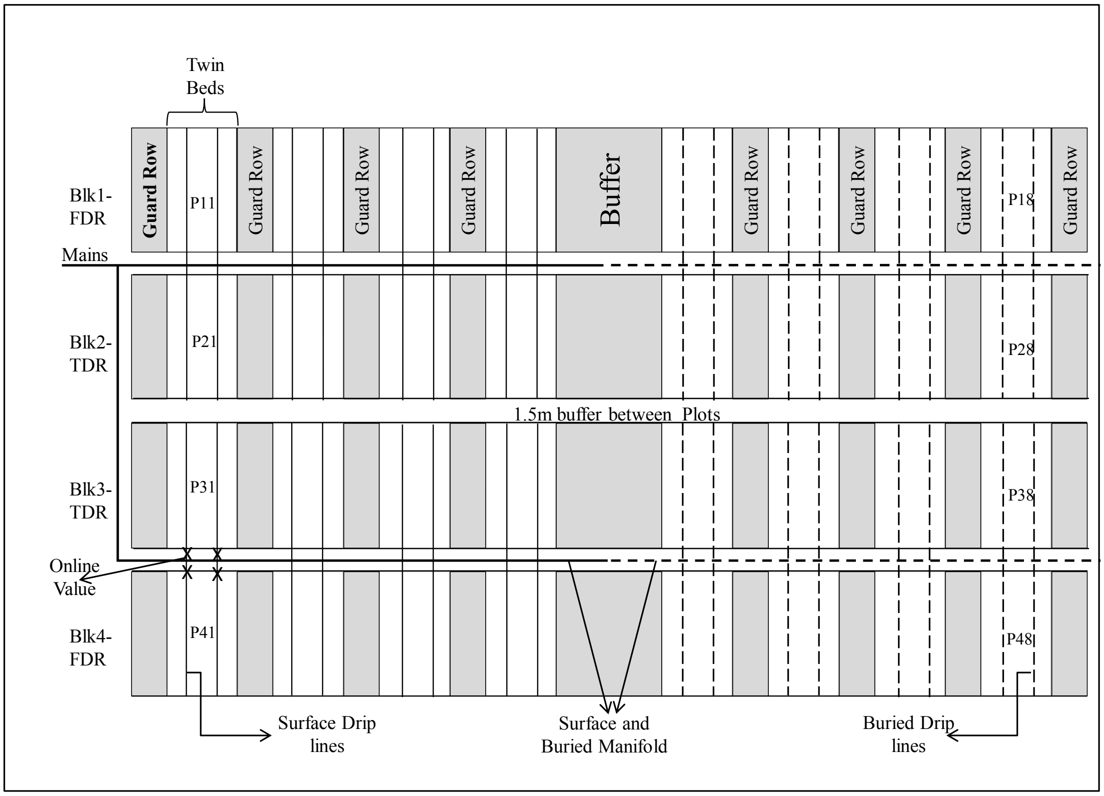

Figure 3.1-Experimental layout for 2008, with block oriented across beds

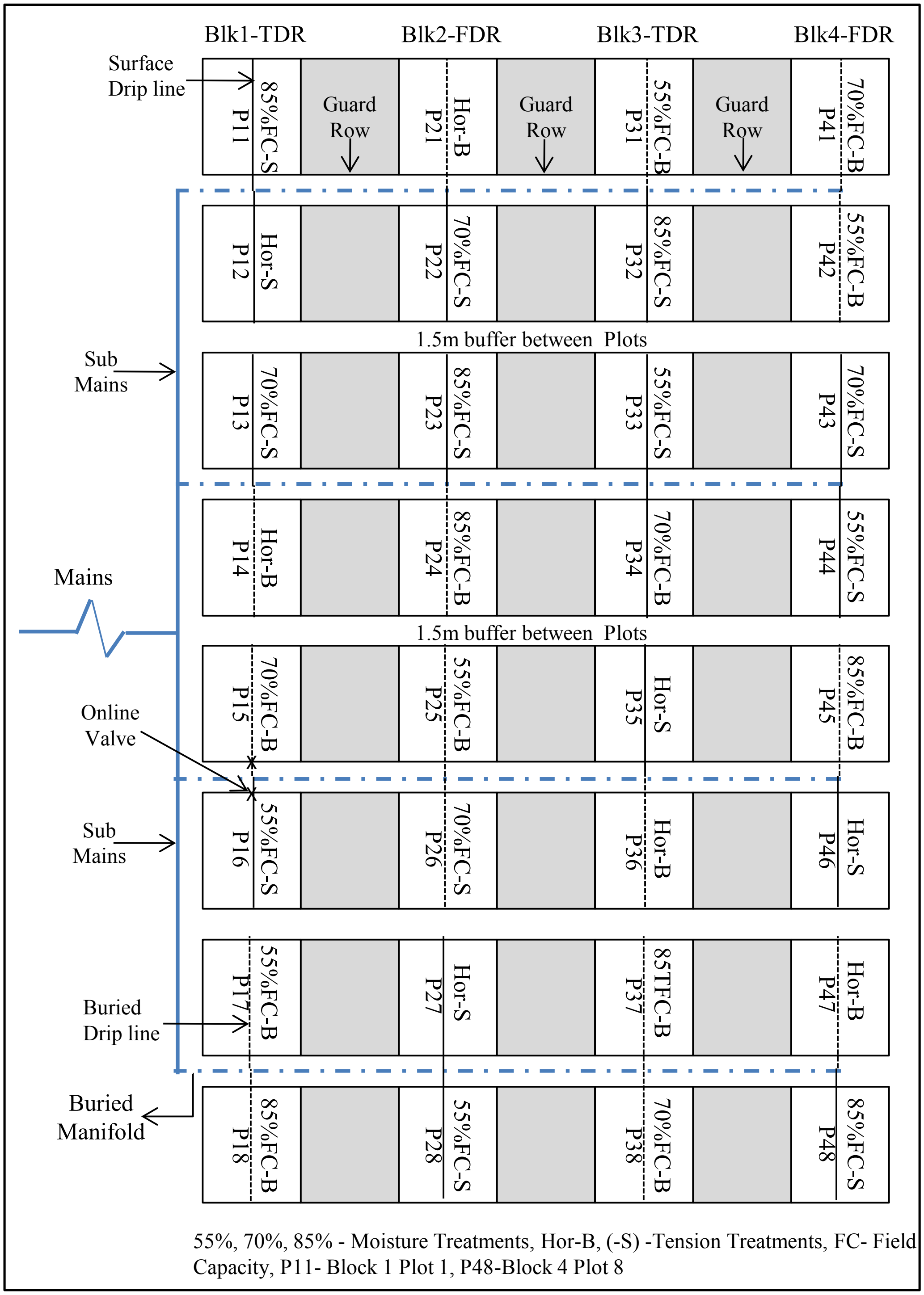

Figure 3.2-2009 experiment and irrigation layout, with block oriental along beds

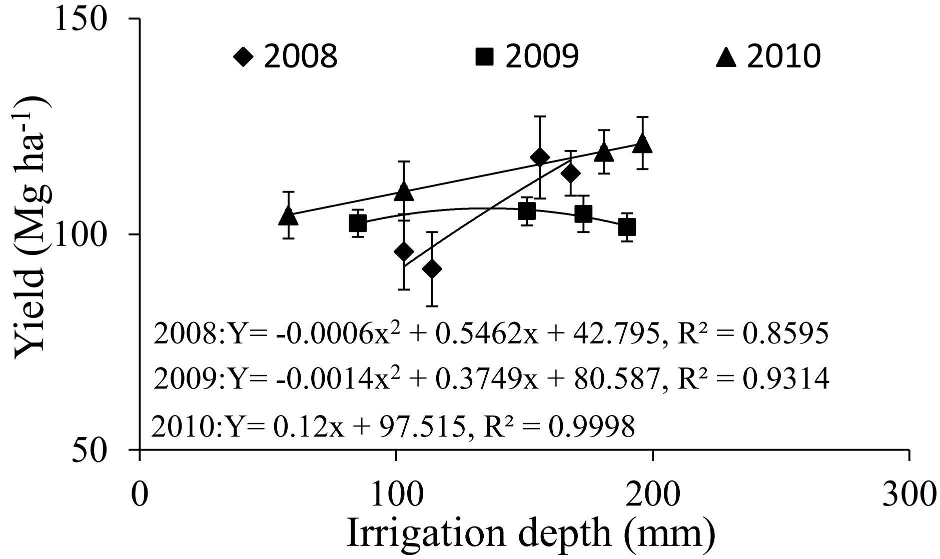

Figure 3.3-Irrigation depth vs. fruit yield (Mg ha^{-1}) and soluble solid irrigation depth (mm) (Y and x represented yields and irrigation depths respectively)

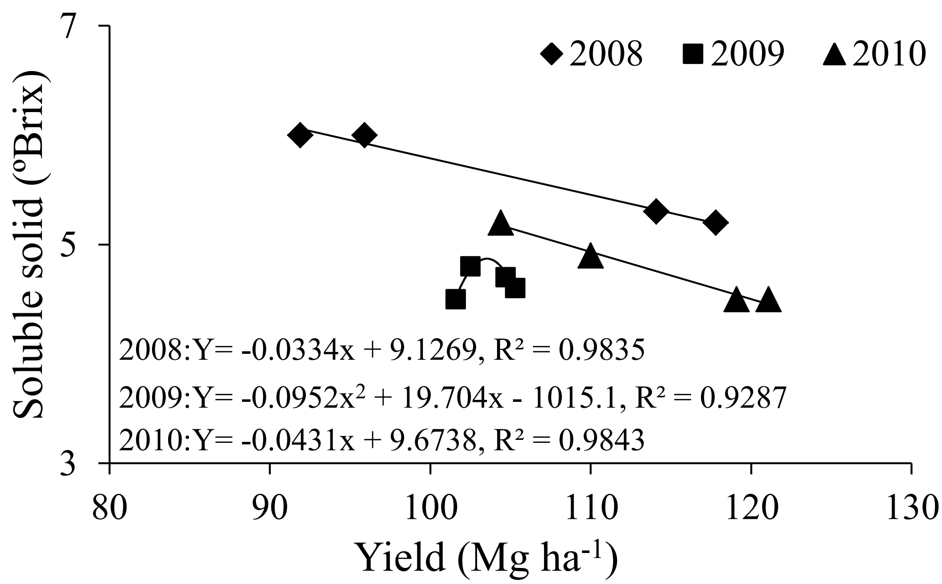

Figure 3.4-Yields vs. Soluble Solids,

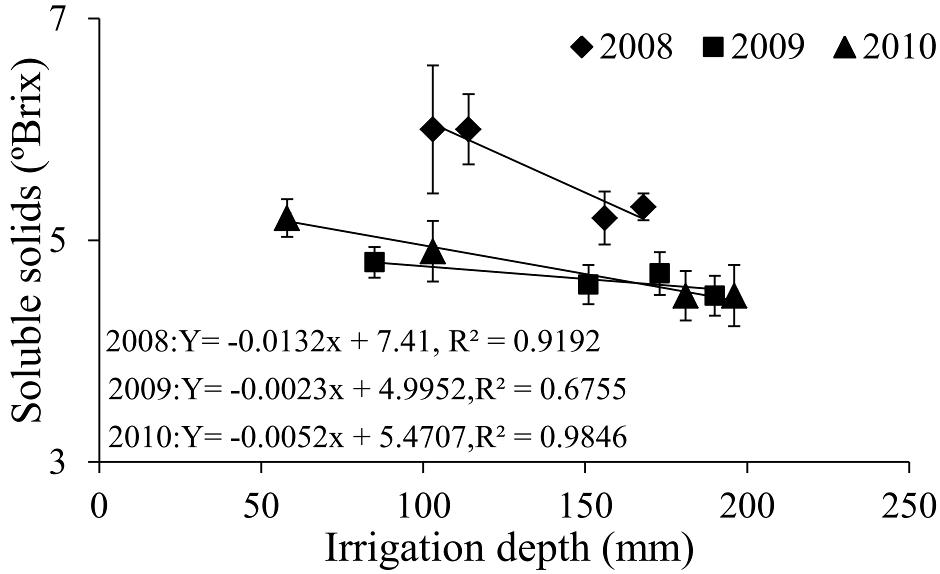

Figure 3.5-Irrigation Depth vs. Soluble Solids

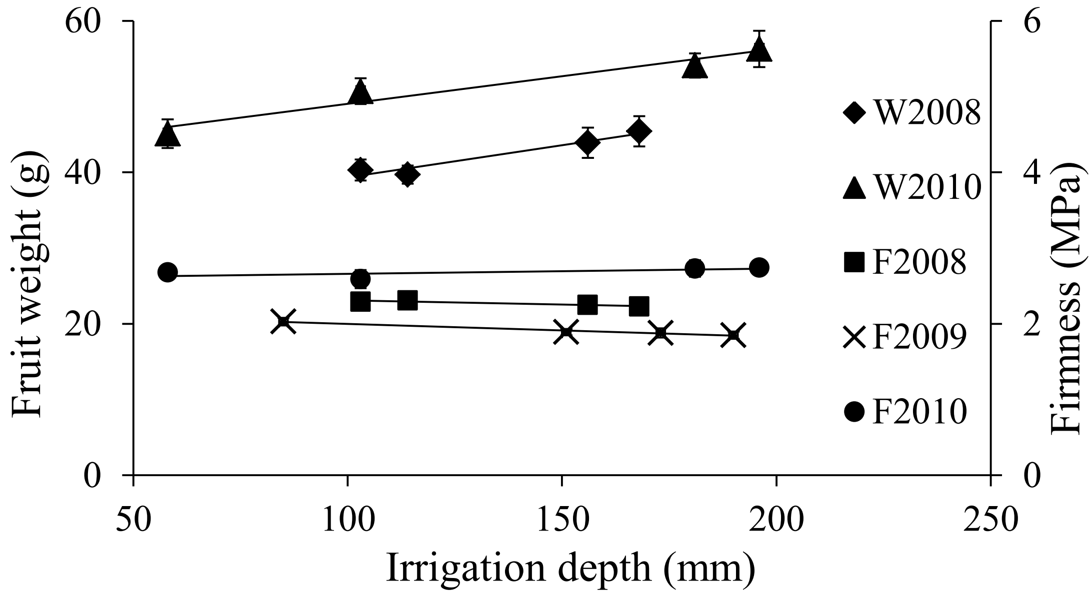

Figure 3.6-Irrigation depth vs. fruit weight and firmness (W and F represented fruit weight and firmness respectively)

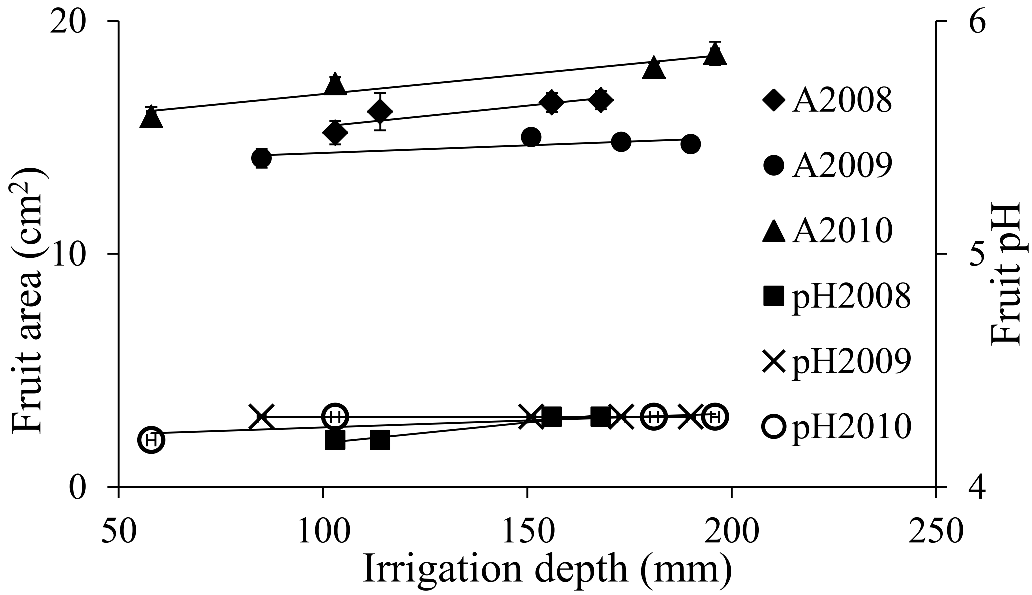

Figure 3.7-Irrigation depth vs. fruit area and pH (A and pH represented fruit area and pH respectively, error bars are standard error of mean).

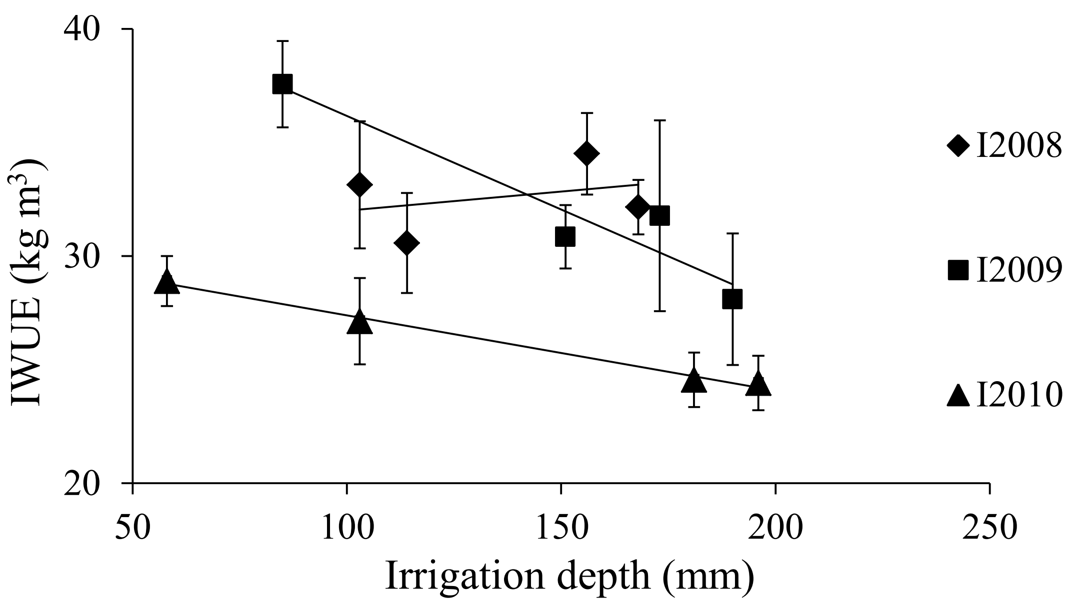

Figure 3.8-Irrigation depth Vs IWUE

Connecting text to Chapter 4

This Chapter is a manuscript awaiting publication in 2013. The manuscript is co-authored by my supervisor, Dr. Chandra A. Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis.

The success of precision irrigation scheduling using soil moisture sensor technology is contingent on proper site specific calibration of sensor, which is generally different from the manufacture's equations. Therefore, emanating from the field based study; the need for articulating the procedure for calibration of volumetric soil moisture sensors became apparent. It contributes to objective two in developing a protocol for an automated, real-time soil moisture monitoring system for scheduling irrigation. This is the topic of the following chapter.

Chapter 4 –In situ calibration of volumetric moisture sensors in a drip irrigated loamy sand soil

F. Jaria and C.A. Madramootoo

Abstract

The scientific technique of irrigation scheduling facilitates timely and accurate provision of water to crops, conserves water and energy, improves irrigation performance, crop yield and quality. A number of different volumetric water content sensors are now available to quantitatively measure soil water content (θ, m^3m^{-3}). In this study, generic field calibration curves were developed for TDR (Campbell Scientific CS625) and FDR (Sentek EnviroSMART) sensors over a three-year period to effect irrigation scheduling of field tomatoes in Southwestern Ontario. A combination of linear and quadratic, and linear and power calibration equations were developed for the TDR and FDR sensors, respectively. The root zone depths of interest were 0-30 cm and 15 to 25 cm for the TDR and FDR respectively. Calibration curves were developed using regression analysis and the coefficient of determination ranged from 0.62 to 0.97. The field calibration curves were compared with the manufacturer's equations using root mean square error (RMSE) with values ranging from 0.025 to 0.125. The results indicated that there were variations between manufacturer's equations and field calibration equations which emphasize the need for site specific calibration to enhance irrigation scheduling.

Key words: FDR, TDR, calibration, irrigation scheduling, soil water content.

4.1 Introduction

Scientific irrigation scheduling is a combined management and technical approach to ensure that crop water needs are met. This technique facilitates timely and accurate provision of water to crops, conserves water and energy, improves irrigation performance, crop yield and quality (Tacker et al., 1996) and reduces non-point pollution (Nguyen et al., 1996) and sustainability of irrigated agriculture (Smith, 1996). It is aimed at achieving an optimum water status for productivity by keeping soil moisture close to field capacity (Jones, 2004). This is accomplished by taking measurements that estimate crop water use and soil water status (Leib et al., 2002). Achieving optimum benefit from irrigation in a variable climate is dependent on regulating timing and quantity of water applied to provide continuously changing crop water requirements (Bailey & Spackman, 1996).

Recent technological advances have led to the development of a range of sensors suited for continual soil moisture monitoring. These sensors provide farmers with the tools to accurately meet crop water requirements of individual crops (Thompson et al., 2007b). Most of the volumetric sensors suitable for irrigation are dielectric (Munoz-Capena & Dukes, 2005). The main techniques used by these sensors can be classified as Frequency Domain Reflectrometry (FDR) and Time Domain Reflectrometry (TDR) (Francesca et al., 2010; Leib et al., 2003). Both methods take advantage of the high dielectric constant of water, compared to that of soil, to quantify its volumetric water content (Francesca et al., 2010). TDR-based devices are commonly used for multi-site and continuous soil moisture monitoring (Blonquist et al., 2005; Jones et al., 2002; Robinson et al., 2003) Detailed descriptions of the physical principles of TDR have been given in many papers (Dalton et al., 1984; Dasberg & Dalton, 1985; Topp et al., 1980). TDR instruments operate by generating a signal along steel probes called wave guides buried in the soil. When the signal arrives at the end of the probe, it is reflected back to the TDR control unit. TDR calibration changes with soil type, salinity, and temperature (Topp, 1987; Topp & Davis, 1985a; Topp & Davis, 1985b; Topp et al., 1980; Wraith & Or, 1999). Capacitive sensors calculate the apparent moist soil dielectric constant by measuring the charge time of a capacitor buried in soil (Francesca et al., 2010) . The FDR is a capacitance probe which uses an electronic circuit called an oscillator, producing repetitive waveform, usually sinusoidal. The capacitive element of the sensor is placed within an access tube in the soil. Changes in soil moisture can be detected by changes in the circuit operating frequency (Leib et al., 2003).

Soil monitoring instruments should be relatively inexpensive, portable, accurate, easy to use, facilitate immediate display of results that are easily understood by visual display.

Sensors should follow the criteria of having low labour requirements, non-destructive application (after installation) and adaptable to electronic measurement and recording (Stangl et al., 2009; Yoder et al., 1998). The relationship between soil properties, climate factors and crop performance are highly complex and rapid, therefore reliable field sensors capable of monitoring parameters pertinent to crop performance are essential to the development of management tools (Grismer, 1987). Soil moisture sensors simplify these complexities by providing farmers with a single value for the fill and refill thresholds to effect irrigation scheduling. The fill value is usually taken as field capacity while the refill value is a predetermined soil moisture threshold value as a fraction of field capacity or available water capacity. Paltineanu and Starr (1997) added that there is a continued need for better methods to perform accurate, real time, nearly continuous soil water measurements at specific depth intervals, with minimal soil disturbance, and covering field scale areas.

Standard calibration provided by manufacturers for soil moisture sensors tends to provide relative soil moisture content for different soils; however, inadequacies arise because of over or underestimates of site specific soil moisture content. It is therefore essential to carry out in situ, site specific calibration of volumetric sensors to enhance the accuracy of irrigation scheduling. Leib et al. (2003) advised that attempts to obtain accurate soil moisture without site specific calibration is unlikely. Dielectric sensors exhibit susceptibility to electrical conductivity, temperature, soil texture, soil compaction, soil disturbance, soil-air interface, small sphere of influence and soil mineralogy (Chanzy et al., 1998; IIda et al., 2005; Regalado et al., 2003). Therefore specific calibration of sensors would be necessary to obtain a high degree of absolute accuracy in soil water content measurements (Leib et al., 2003). Evett (2007) added that field calibration is preferred because it places the sensor in the actual soil to be studied rather than a laboratory setting. Silva et al.(2007) cautioned that field calibration is laborious and has to be done properly to provide good results.

The objectives of this study were to: (1) determine the field calibration equations for FDR and TDR sensors used for irrigation scheduling of processing tomatoes in Southwestern Ontario and (2) compare field calibrations with the manufacturers' calibration equation.

4.2 *Materials and methods*

In situ calibration of volumetric moisture sensors formed part of a larger experiment comprising a combination of tension and volumetric soil moisture sensors to effect irrigation scheduling of large-scale field growing processing tomatoes in Leamingtion, Ontario. This paper discusses the specificities related to in situ calibration of volumetric soil moisture sensors.

4.2.1 Study area

A three year field experiment conducted during the summer months of May through September, from 2008 and 2010; established in Leamington, Southwestern Ontario, on the private farm of Wayne Palichuk Ltd. The farm site was located at 187 m above sea level, 42° 05’08.52” N Latitude and 82° 33’05.7”W. The local climate is classified as humid with hot summers, dry and cold winters. Average annual temperature and precipitation are approximately 9.5°C and 950 to 1050 mm respectively. Rainfall is typically spread throughout the year, without a predominant rainfall month. The dominant soil within the production zone (0 to 30 cm) is loamy sand (86% sand, 8% silt and 6% clay), with an average bulk density of 1450 kg m^{-3}. Field soil water capacity ranged between 0.20 to 0.25 m^3 m^{-3}. The top soil (0 to 30 cm) responded to wet and dry periods with distinct day to day fluctuations, the sub soil (30 to 60 cm) was characterized by near constant volumetric water content (θ_v).

4.2.2 Experimental design

A split-plot randomized complete block design (RCBD) was used during the 2008 and 2010 experiments and a (2*4) factorial RCBD in 2009. The split plot design involved two experimental factors - irrigation types (buried and surface drip irrigation) and moisture levels (three moisture levels and a tension treatment). Irrigation types were assigned to the whole plot (main plot) and moisture levels (treatments) were randomly superimposed upon the split plots (subplots) within each plot. The factorial design also had the same two factors.

Experiments were designed with four blocks (replicates), each having eight plots, totaled at 32 plots (16 buried drip and 16 surface drip irrigation). Moisture treatments and irrigation types were considered as fixed effect parameters while blocks represented the random effect. Table 1 encapsulates the experimental design over the three years of the project.

4.2.3 Installation of volumetric moisture sensors

Two types of volumetric soil moisture sensors were permanently installed at the experimental site during the growing season for continuous data collection and included: a time domain reflectometer (TDR) (CS625 water content reflectometer, Campbell Scientific Inc., UT) and a frequency domain reflectometer (FDR) (EnviroSMART, Sentek Sensor Technologies, Stepney, Australia).

Water content Reflectometer (TDR)

A pair of sensors was installed - one in each of the adjacent twin beds in 2008. The installation depths were between 0 to 30 cm and 30 to 60 cm. The TDR measured an integrated reading over the 0 to 30 cm and 30 to 60 cm depths, representing average volumetric moisture content for the section of the profile being monitored. To install the probe at the 30-60 cm depth, a shallow pit was dug to a depth of approximately 30 cm. The instrument was subsequently inserted vertically using an insertion guide and soil re-compacted into place.

FDR Probes

Each FDR probe rod was equipped with 5 sensors installed at various depths (10, 20, 30, 40 and 60 cm) down the soil profile, installed in one of the twin beds. Each sensor measured the moisture content over a range of ± 5 cm, the sensor depth. Therefore a sensor located at 20 cm depth effectively measured moisture content over the range of

15-25 cm. The procedure for installation of the EnviroSMART access tube is chronicled in the Sentek manual (Sentek Sensor Technologies, 2003).

Relative to the drip line, all sensors (in the case of the FDR, it was the access tubes) were installed 10 cm away from the centrally aligned drip line and 10 cm away from the nearest emitter to ensure consistency in data collection. All sensors were monitored wirelessly, in real time from a base station approximately 120 m away.

Some changes ensued during the 2009 and 2010 experimental seasons. In 2009 and 2010, there was only one bed per treatment and hence each pair of sensors (for the TDR) installed in the same bed approximately 1 meter apart (along the bed). The other variation in 2009 involved the TDR installation depth. They were installed at the 5-25 cm and 25-55 cm depths respectively. At the shallower depth, the top 5 cm of soil was removed (at the site of installation) and the sensor installed at a 33.6° angle to the vertical plane. The deeper sensor was installed vertically, using the 2008 procedure. In 2010, only TDRs were installed in the experimental plots. The depths of installation reverted to 0-30 cm and 30-60 cm respectively.

Prior to installation and to ensure uniformity of the CS625 sensor measurement, raw period (μsec) readings were taken in air and water. Readings were in close proximity (mean ±SD): in air 15.02±0.02 μsec; in water 43.31±0.04 μsec.

4.2.4 Portable TDR- Field Scout TDR 300 soil moisture meter

The Field Scout is a portable TDR probe which enables easy and rapid measurement of soil moisture content. Equipped with a built-in data logger, the instrument automatically records the data operating on the basic TDR principle. Specialized software was used to download data to a computer via a PC-3.5 serial cable.

A pair of 20 cm probes was used to take random volumetric soil moisture samples throughout the experimental plot. Gravimetric soil moisture samples were collected concurrently with TDR measurements, to conduct regression analysis.

4.2.5 Field measurements

Calibration curves for the sensors consisted of four sets of field measurements and included; bulk density, gravimetric and volumetric soil moisture content and soil moisture sensor readings.

A number of random soil bulk density measurements were taken prior to planting, at the 0-10, 10-20 and 20-30 cm depths throughout the experimental plots. A representative average bulk density was obtained for each depth, which was used to convert the mass water content determined by gravimetric analysis into volumetric water content. In 2009, additional bulk density measurements were done at the 5 to15, 15 to 25, 25 to 35 cm depths. Bulk density samples were taken using aluminum cores (10 cm diameter * 10 cm height), consistent with that proposed by Gardner (1965). Gravimetric water content measurement were used to verify soil water content from the soil moisture sensors. Soil samples were taken at 10 cm depth intervals up to 30 down the soil profile using a 19 mm soil sampler. Samples were taken within 20 cm radius of the CS625 and EnviroSMART sensors to avoid influencing ongoing measurement. Samples were oven dried at 105ºC for 24 hours to determine mass water content. Volumetric water content for each depth was calculated using equation 4.1 and an average over the 0 to 30 cm depth was determined. Holes caused by gravimetric sampling were subsequently refilled with soil and re-compacted to prevent preferential flow around the sensors. Simultaneously with gravimetric sampling, spot TDR period readings (in μSec) and FDR scale frequency units (SFU) were taken in order to develop their respective field calibration curves.

$$\theta_v = \left(\frac{\rho_b}{\rho_w}\right) * \theta_m \qquad Eq. 4.1$$

Where: θ_v is volumetric water content ($cm^3\ cm^{-3}$); θ_m is mass water content ($g\ g^{-1}$); ρ_b is the bulk soil density ($g\ cm^{-3}$) and ρ_w ($g\ cm^{-3}$) is water density

In 2009 and 2010, a slight modification to the microwave method as proposed by (Hankin & Sawhney, 1978) was used to verify gravimetric water content. Samples were heated for 3 minutes in filter paper cups and flipped over for an additional 3 minutes.

Prior to adopting this approach, it was validated through a comparison with the conventional oven heating method.

In situ field capacity measurements were determined prior to planting using the combined procedures outline by Peter (1965) and Cassel and Sweeney (1974). Determination of field capacity is important for use as the upper trigger (or fill level) to which soil moisture must attain during irrigation.

4.2.6 **Soil moisture calibration procedure**

Site specific calibration curves were developed for each of the three years of the project. The critical depth at which the TDR's and FDR's sensors were monitored to effect irrigation scheduling was the 0 to 30 cm (5 to 25 cm in 2009) and 15 to 25 cm respectively. The manufacturer's curves (linear and quadratic) were also compared with the field calibration curve for each of the years.

4.2.6.1 2008 Calibration curves for CS625 water content reflectometer (TDR Sensors) at 0-30 cm and EnviroSMART (FDR Sensors) at 20 cm

In 2008, a three stage calibration procedure was used to calibrate the TDRs. Firstly, a portable soil moisture TDR meter (*Fieldscout TDR 300*) was calibrated with the permanently installed CS625 and generated equation 4.2 using regression analysis. In this calibration stage, the CS625 sensor output (period in μs) was applied as the dependent variable and the portable TDR values as the independent variable to obtain the regression function, y=f(x) and its coefficient of determination. This was followed by a second calibration between the portable TDR and the actual field measured volumetric soil moisture content resulting in equation 4.3. In this calibration stage, the dependent and independent variables were the portable TDR readings and the measured θ_v respectively. The third step involved the combination of the two relationships (Eq. 4 2 and Eq. 4 3) to obtain a working calibration curve between the actual volumetric soil moisture content and the permanently installed CS625's period readings, as reflected in equation 4.4. During the second stage six field soil measurements were done. In this third stage, the dependent and independent variables were the CS625 output and the actual measured θ_v, respectively.

$$Y_1 = 0.0037X_1 + 16.58 \qquad Eq.\,4.2$$

Where: Y_1 is the CS625 period value (μsec); X_1 is the portable TDR value

$$Y_2 = 59.44X_2 + 1803.9 \qquad Eq.\,4.3$$

Where: Y_2=X_1 is the Portable TDR value (μsec) and X_2 is the Measured VWC (%)

$$By\ Sub.\,Y_2\ from\ Eq\ 4.3\ for\ X_1\ in\ Eq\ 4.2$$
$$Y_1 = 0.0037(59.44X_2 + 1803.9) + 16.58$$
$$Y_1 = 0.21993X_2 + 23.25 \qquad Eq.\,4.4$$

Where: Y_1 is the CS625 Period Value (μSec) and X_2 is the measure VWC (%)

FDR regression analysis was conducted with measured volumetric moisture content and corresponding scale frequency units (SFU) from sensors at 20 cm depth, measuring moisture content at 15 to 25 cm depth. The dependent and independent variables were the EnviroSMART sensor output (SFU) and the measure θ_v respectively, to obtain the regression function, y=f(x) and its coefficient of determination.

4.2.6.2 2009 Calibration curves for WCR (CS625) TDR sensors at 5-25 cm and FDR sensors at 20 cm

A slightly different approach (involving three stages) was used in the development of the calibration curves for the 2009 TDR (CS625) and FDR sensors. Firstly, a time series plot of average daily soil moisture trends for the 12 TDR sensors (installed at the 5 to 25 cm depths) was developed for June 2009. A similar average time series plot was developed FDRs (in SFU) for installed at the 10 and 20 cm depths, effectively representing soil moisture content at 5 to 25 cm depth, similar to the TDR's. Two time series plots (average daily TDR and FDR) were superimposed on each other to obtain best fit (Fig. 4.4). Secondly, a generic calibration curve for FDR sensors at 20 cm depth was developed against measured volumetric data, from which FDR trigger values (in SFU's) were determined for the various moisture treatments (74%, 82% and 91% FC). Thirdly, with the use of FDR trigger data and combined time series plots, requisite trigger values for TDRs were determined (Fig. 4.4 and Table 4.4).

4.2.6.3 Calibration curve 2010

Approximately 133 gravimetric moisture content measurements were taken over the 0 to 30 cm depth from 27 May to 20 June to capture as large a range of soil moisture content as possible. TDR sensor readings were taken simultaneously with gravimetric moisture measurements. Regression analysis was performed between sensor values and volumetric water contents to develop a generic calibration curve for TDR sensors over the rooting depth of the crop (0 to 30 cm).

4.2.7 Data analysis

Regression analysis were conducted to determine calibration curves for volumetric soil moisture sensors using measured volumetric water content with TDR periods and FDR scale frequency units (SFU). Coefficient of determination (R^2), which reflect the goodness of fit, were determined for the linear, quadratic and power curves developed. Root Mean Square Error (RMSE) was used to quantitatively evaluate the manufacturer's curves and the derived calibration curves. The RMSE was determined with the following equation (Eq. 4.5):

$$RMSE = \sqrt{\frac{\sum(\theta_v - \theta_a)^2}{n}} \qquad Eq. 4.5$$

Where n was the number of measurements, θ_v, θ_a was the manufacturer's derived and actual measured VWC, respectively ($m^3\ m^{-3}$).

4.3 Results and discussion

4.3.1 Soil properties

The bulk density results (Table 4.2) indicated a gradual increase with depth down the profile. Some variations were observed from year to year, particularly over the shallow soil depth. This inevitably may be due to the land preparation prior to planting and possibly to the impact of the organic matter incorporated into the soil which often mediates bulk density. Average bulk density for loamy soil ranges between 1.50 to 1.70 g cm^{-3}; however, average bulk density obtained ranged from 1.41 to 1.55 g cm^{-3}. Arthur et al. (2011) reported bulk density and total porosity for loamy sands treated with different types of compost ranging from 1.27 to 1.36 g cm^{-3} and 52% to 49% respectively. Bulk density is an indicator of soil compaction and soil health. It affects infiltration, rooting depth/restrictions, available water capacity, soil porosity, plant nutrient availability, and soil microorganism activity, which influences key soil processes and productivity (Brady & Weil, 2002). Dominant soil within the rooting zone (0 to 30 cm) was loamy sand (85.8% sand, 8.1% silt and 6.1% clay), with an average bulk density of 1.45 g cm^{-3}.

Below the 30 cm depth and up to the subsurface drainage system installed at 70 cm depth, the predominant soil type was sand. Measured field capacity over the 0 to 30 cm depth ranged between 0.20 to 0.25 m^3 m^{-3} by volume (60 to 75 mm). Saturated moisture content or porosity was approximately 0.46 m^3 m^{-3}. This value was consistent with the VWC obtained at zero tension using the pressure plate. Bulk density typically increases with soil depth since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers, and therefore contains less pore space (Ward & Trimble, 2004) . Munoz-Capena and Dukes (2005) added that the computation of volumetric water content necessitates a correct measure of bulk density. Bulk density is the mass of soil solids per unit volume (kg m^{-3}). Carter (1965) identified that some level of error is usually associated with the determination of bulk density. He contended that where volume-based water content values are required, the error is probably not that significant, when compared to the error involved in assigning a single value to represent the moisture content over a particular field depth.

4.3.2 Field capacity (FC) and permanent wilting point (PWP)

Table 4.3 summarized the FC volumetric soil moisture contents over 0 to 30 cm (5 to 25 cm in 2009) depth for 2008-2010. Values ranged from 0.20 to 0.25 m^3 m^{-3}, within the range (0.15 to 0.27 m^3 m^{-3}) expected as per current literature (Schwab et al., 1993) Kirkham (2005) indicated that field capacity is not a unique value but rather, expressed as a range of values of soil water content. Brady (1974) reported that field capacity represents the upper limit of water available for plants and hence this threshold value (fill) is important during irrigation scheduling. Irrigation applied above this threshold value will most likely be lost by gravitational flow through soil macro pores. PWP values obtained from a disturbed sample analyzed by A & L Canada Laboratories in Ontario, ranged from 0.09 to 0.10 $m^3 m^{-3}$.

4.3.3 Calibration curves

4.3.3.1 2008 Calibration curves – TDR CS625 sensors 0-30 cm and FDR EnviroSMART sensors 20 cm

Field measurements were taken during 6 to 27 June 2008 from a number of CS625 TDR sensors located in the experimental area. During this period, soil moisture content was above field capacity range (0.25 to 0.30 m^3 m^{-3}) due to early spring rains and high antecedent soil moisture conditions caused by spring snow melt. This led to a cluster of VMC measurements within a narrow range of moisture content, outside the required critical moisture range of 0.12 to 20 m^3 m^{-3}. The 2008 initial regression analysis to generate the generic calibration curve for the TDR did not produce satisfactory results between the actual measured volumetric water content and the sensor period values (R^2 <0.1). A three stage calibration approach was therefore needed to generate a working calibration curve to inform the irrigation scheduling program during the 2008 season. Figures 4.1a to 4.1b represent the calibration between CS625 and the Field Scout TDR 300, and between the Field Scout TDR 300 and the measured VWC, respectively. The significant F and coefficient of determination (R^2) associated with the two regression analysis were 0.0001 and 0.81 and 0.019 and 0.78, respectively. This result indicated that the model explained the deviations in the dependent variables and were statistically significant *($P<0.05$)*. Fig. 4.2a represents the combined relations of Eq. 4.2 and 4.3 to develop the CS625 linear calibration curve with an R^2 of approximately 0.63. This very low coefficient of determination was undoubtedly due to the combined variations associated with the two analysis.

The major limitation to this method was that moisture measurements were concentrated at the upper range of the soil moisture spectrum (0.25 to 0. 30 m^3 m^{-3} VWC). Although curves used to generate the final calibration curve had good r^2 values (0.81 and 0.78) for the upper range of moisture content values, the absence of actual moisture measurements at lower moisture contents meant that the curve has to be extrapolated downwards to obtain relative values for the 0.12 to 0.20 m^3 m^{-3} VWC range. In the absence of actual measurements to validate the lower range of the calibration curve, accuracy of the curve may be questioned. A comparison with manufacturer's linear and quadratic curves showed that the derived linear calibration curve was much steeper, with the curve veering to the right as the moisture content decreased relative to the manufacturer's curve (Fig.4.2b)

The development of the calibration curve for the 2008 FDR sensors posed less of a problem. Regression analysis of the measured VWC and FDR scale frequency units yielded a coefficient of determination (R^2) of 0.83 and an F value of 0.0006. Unlike water content reflectometers (TDRs), where most of the soil moisture measurements were concentrated at the upper range of moisture content, there were two measurements obtained at the 12 and 20% VWC which facilitated development of the calibration curve over the range of interest. However a few more measurements at lower moisture content (13% to 17%) would have proven useful in better defining the lower section of the linear calibration curve. Fig. 4.3a depicts the linear calibration curve for the FDR sensors and trigger points for various moisture treatments. Table 4.4 summarizes trigger values for 2008 to 2010.

4.3.3.2 2009 Calibration Curve

This slightly different approach was to ensure that moisture treatment values for both TDRs and the FDRs were comparable. During the month of June 2009, the assumption was that the average moisture condition throughout the field would be comparable. This was due to the fact that the 24 sensors (12 TDRs and 12 FDRs) were randomly placed within the 782.3m^2 research site and were influenced by the same weather (no irrigation was done during the month of June), soil, crop and general conditions. By extension, moisture trends measured by the TDR and FDR were approximately equal as is reflected in Fig. 4.4. Superimposing two daily average plots and obtaining best fit, provided an opportunity to equate two sets of sensor values (TDR's and FDR's). An observation of the two plots indicated that they mimicked soil moisture trends very well (Fig 4.4).

The second step in the process necessitated regression analysis for development of the field calibration curve for FDR sensors and obtaining requisite SFU trigger values for the 91%, 82% and 74% FC treatments (Fig. 4.5 and Table 4.4). The coefficient of determination yielded a value of 0.84. With the superimposed June daily moisture plots and the trigger values obtained from the FDR calibration, it was then possible to obtain the trigger values for the TDRs triggers (Fig. 4.6 and Table 4.4).

One of the limitations worth noting is that during the month of June 2009, soil moisture content was still very high due to June rains, and spring snow melt and hence soil moisture plots did not drop to lower trigger marks of 82% and 74% FC (Fig 4.4). The assumption was made that the moisture content would follow a similar trend and hence the values were considered realistic.

A comparison of FDR field calibration with manufacturer's curve indicated a similar trend. However, the manufacturer's curve would have underestimated trigger values (Fig. 4.5). The TDR derived field calibration curve was substantially different from the manufacturer's curve, particularly at the lower moisture content (Fig. 4.6). This may have been influenced by the limitation mentioned above.

4.3.3.3 Calibration Curve 2010

Substantially more field measurements/sampling were made and over a larger range of soil moisture to generate the field calibration curve for the 2010 field season. After removing outliers and analyzing the data, an R^2 value of 0.97 was obtained for both linear and quadratic field calibration curves. Four curves were possible based on data grouped by period or moisture content (Fig. 4.7). At the end, an average of the four curves was used to obtain the final field calibration curve (Fig. 4.8). Table 4.4 summarizes trigger values for 2010.

Manufacturer's curves (linear and quadratic) were also plotted against the field calibration curve with excellent fit particularly over the range of trigger moisture contents (12 to 25% VWC). Some discrepancy obtained at higher moisture content, which may be attributed to the higher variability in the sampled measurements. The final field calibration equation for each year is summarized in Table 4.5.

4.3.4 Comparison of field calibration to manufacturer's curves

Apart from the 2008 calibration curve with a 0.63 coefficient of determination, all other calibration curves had relatively good correlations, having R^2 values ranging from 0.83-0.97. All calibration curves showed some variations from the manufacturer's curve, either by being parallel (Figure 5a) to or crossing each other (Fig. 4 3b, 4.6, 4.8). This was further substantiated by the Root Means Square Error (RMSE) analysis, with values ranging from 2.5% to 12.5% (Table 4.6).

One major source of the discrepancy with the manufacturer's linear and quadratic calibration curves for the TDR is that they were developed in a controlled environment using disturbed soil, with a bulk density of 1.4 g cm^{-3} and bulk electrical conductivity at saturation of 0.4 dS m^{-1} (Campbell Scientific Inc, 2006), while the existing experiment was conducted in situ, in a loamy sand exposed to fluctuating climatic conditions.

In 2008, manufacturer's standard equation for FDR led to substantial over estimation of θ_v, for $\theta_v \leq 0.27$ m^3 m^{-3} and underestimated for $\theta_v >$ than 27 m^3 m^{-3} (Fig. 4.3b). In 2009 it overestimated θ_v over the entire range of soil moisture contents (Fig. 4.5). Stangl et al. (2009) attributed the discrepancy to soil heterogeneity. The discrepancies obtained between the manufacturer's mode and the in situ calibration further established the need to calibrate volumetric moisture sensors prior to using them for irrigation scheduling. Robinson et al. (1994) and Loiskandl et al. (2003) strongly recommended site specific sensor calibration over standard manufacture calibrations.

4.3.5 Limitations to developing field calibration curves.

While it would be ideal to carry out field calibration curve analysis before the growing season, such luxury is not always practical. It is worth noting that the growing season for field tomato in Southwestern Ontario is from May to September (5 months). Planting generally occurs from 15 to 30 May with harvesting 110 to 115 days later. Prior to May, soils are saturated and after harvesting in September, ground condition would be substantially different from what obtained during the actual cultivation of the crop. To this end, the period best available for the development of field calibration curves is after planting to the end of June. This period however coincides with relatively higher soil moisture contents due to spring melt or early spring rains. Soil moisture measurements done during this period tended to influence the upper part of the field calibration curve resulting in the determination of the higher moisture treatments threshold values. The lower part of the field calibration curve tended to be extrapolated downwards to determine the lower moisture treatment threshold values and is a possible source of error.

Generic in situ field calibration curves were determined from data collected from a number of TDR and FDR sensors installed throughout the experimental site. There were slight differences between sensors and therefore the data had to be manipulated (removing outliers, and lumping of data) to obtain representative calibration curves to effect the irrigation scheduling.

It was not possible to measure bulk density after planting of the tomato crop since this destructive sampling would damage a number of the plants within close proximity to sensors and rearrange soil texture and structure and sensor micro climate. Bulk density measurements were randomly carried out within the experimental site just prior to planting to obtain representative bulk densities since the moisture data was taken from a number of the sensors. This however, may be a potential source of inconsistency in the conversion of gravimetric water content to volumetric water content.

The impact of soil electrical conductivity (EC) and temperature were not considered in the development of the field calibration curve. Due to the soil type and annual rainfall, there have been no known cases of EC related problems in the past. A comparison of the actual and the temperature corrected period values for TDR's sensors showed very little difference and hence it was thought that it would not significantly affect the results. Further Gardner et al.(1991) and Paltineanu and Starr (1997) alluded to the fact that because of the high frequency used by EnviroSMART, the sensors are not significantly affected by the normal fertilizer application ranges used in agriculture.

4.4 Conclusions

A variety of volumetric soil moisture sensors are currently available on the market to implement irrigation scheduling. Generally these sensors are provided with default calibration curves. However, this work highlighted the need for site specific calibration of volumetric soil moisture sensors as this enhances the accuracy over the manufacturer's default equations in precision irrigation scheduling.

Three different approaches were used to calibrate the volumetric sensors. The method utilized in 2010 is recommended in situations where only one type of volumetric moisture senor is used. It involved a regression analysis with measured VWC and sensor period values (in μSec). A linear or quadratic relation could be used depending on which calibration curve generated the better coefficient of determination.

In situations where different types of volumetric soil moisture sensors are utilized, the three stage calibration curve approach as obtained in 2009 would be recommended. In this approach one of the sensors were calibrated first. The second was calibrated based upon the moisture data from the two types of sensors and the calibration obtain from the first sensors. The approach facilitated comparative thresholds for the two types of sensors. The three-stage TDR calibration used in 2008 is the least recommended due to the fact that it introduces three levels of error and reduces the accuracy of the calibration.

In situ calibration curves are often quite good over the range of data collected. However, one of the major limitations to in situ field calibration is obtaining moisture data over the full range of moisture contents of interest during the time period required. This often leads to extrapolation of the calibration curves which may introduce uncertainty in the values obtained. This is particularly important in developing calibration curves of volumetric sensors used in field processing tomatoes in Southwestern Ontario, due to the narrow growing window.

Due to the crop rotation and land management practices, it was not possible to ascertain a standard calibration equation that can be used at all times for each sensor type. However, the procedures for determining the in situ calibration for the different sense sensors have been outlined.

Table 4.1-Experimental designs over the three years of the project

Year	**Experimental design**	**Factor 1 –Irrigation types**		**Factor 2 –Moisture levels**			
2008	Split plot RCBD	Surface drip irrigation	Buried drip irrigation	60% FC	70% FC	80% FC	(-30kPa)
2009	Factorial RCBD	Surface drip irrigation	Buried drip irrigation	74% FC	82% FC	91% FC	(-30 kPa)
2010	Split plot RCBD	Surface drip irrigation	Buried drip irrigation	55% FC	70% FC	85% FC	(-30kPa)

FC= Field Capacity, RCBD=Randomized Complete Block Design

Table 4.2-Bulk densities down the soil profile (2008-2010)

#	**2008**		**2009**		**2010**	
	Depth (cm)	Bulk Density (g cm^{-3})	Depth (cm)	Bulk Density (g cm^{-3})	Depth (cm)	Bulk Density (g cm^{-3})
1	00-10	1.29	05-15	1.26	00-10	1.08
2	10-20	1.38	10-20	1.43	10-20	1.40
3	20-30	1.55	15-25	1.54	20-30	1.71
4			20-30	1.64	30-40	1.70
5			25-35	1.64		
6			35-45	1.66		
7			45-55	1.68		
	Average	**1.41**		**1.55**		**1.47**

Table 4.3-VWC from in situ FC measurements and laboratory PWP measurements

2008			**2009**			**2010**		
Depth (cm)	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	Depth (cm)	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	Depth (cm)	FC (m^3 m^{-3})	PWP (m^3 m^{-3})
00-30	0.20	0.09	05-25	0.22	0.09	00-30	0.25	0.10

Table 4.4 Trigger values obtained from calibration curves -2008-2010 for TDR and FDR

2008 Triggers (%VWC)				**2009 Triggers (%VWC)**				**2010 Triggers (%VWC)**		
2008 Triggers	% VWC	TDR	FDR	2009 Triggers	% VWC	TDR	FDR	2010 Trigger	% VWC	TDR
		μSec	SFU*			μSec	SFU*			μSec
FC	20.0	27.35	73.1	FC	22.0	27.3	74.0	FC	25.0	25.72
80% FC	16.0	26.35	72.0	91% FC	20.1	25.6	71.0	85% FC	21.3	24.24
70% FC	14.0	25.73	69.7	82% FC	18.1	24.4	69.0	70% FC	17.5	22.81
60% FC	12.0	25.15	68.6	74% FC	16.2	22.6	66.0	55% FC	13.8	21.43
PWP	9.0	24.28	67.0	PWP	9.0	16.0	55.0	PWP	10.0	20.09

SFU *–Scale frequency Units *100, VWC- Volumetric Water content, FC- Field Capacity, PWP – Permanent Wilting Point

Table 4.5- Field calibration and manufacturer's equations for different sensors

Year	Sensor Type	Field Calibration Type	Field Calibration Equation for VWC	R^2	Units VWC	Depth cm
2008	TDR-CS625 WCR	Linear	4.5469X-105.72	0.63	%	0 to 30
	FDR-EnviroSMART	Linear[a]	1.3854X-87.56	0.83	%	15 to 25
2009	TDR-CS625 WCR	Linear	1.145X-9.4804	0.99	%	5 to 25
	FDR-EnviroSMART	Power	$0.0002X^{2.7249}$	0.85	%	15 to 25
2010	TDR-CS625 WCR	Quadratic	$-0.00035X^2+0.04275X-0.61815$	0.97	$m^3\ m^{-3}$	0 to 30

Sensor Type	Type	Manufacturer's Equation for VWC	Units VWC
TDR- CS625 WCR	Linear	-0.4677+0.0283Period	$m^3\ m^{-3}$
	Quadratic	$-0.0663-0.0063\text{Period}+0007\text{Period}^2$	$m^3\ m^{-3}$
FDR-EnviroSMART	Power	$-0.0045+ 0.5321(\text{SFU})^{2.5282}$	$m^3\ m^{-3}$

X=TRD period (μSec) or FDR (SFU), [a] SFU*100

Table 4.6- Root Mean Square Analysis of Field and Manufacturer's equation

Year	Sensor Type	Field Calibration Type	Manufacturer's Equation Type	N	RMSE	Soil Water Content Range (m^3/m^3)	
						Low	High
2008	TDR-CS625 WCR	Linear	Linear	9	0.125	0.10	0.40
	TDR-CS625 WCR		Quadratic	9	0.107	0.10	0.40
	FDR-EnviroSMART	Linear	Power	9	0.042	0.11	0.38
2009	TDR-CS625 WCR	Linear	Linear	5	0.064	0.09	0.22
	TDR-CS625 WCR		Quadratic	5	0.048	0.09	0.22
	FDR-EnviroSMART	Power	Power	19	0.025	0.16	0.28
2010	TDR-CS625 WCR	Quadratic	Linear	12	0.053	0.01	0.50
	TDR-CS625 WCR		Quadratic	12	0.096	0.01	0.50

N= Number of Observation, RMSE=Root Mean Square Error

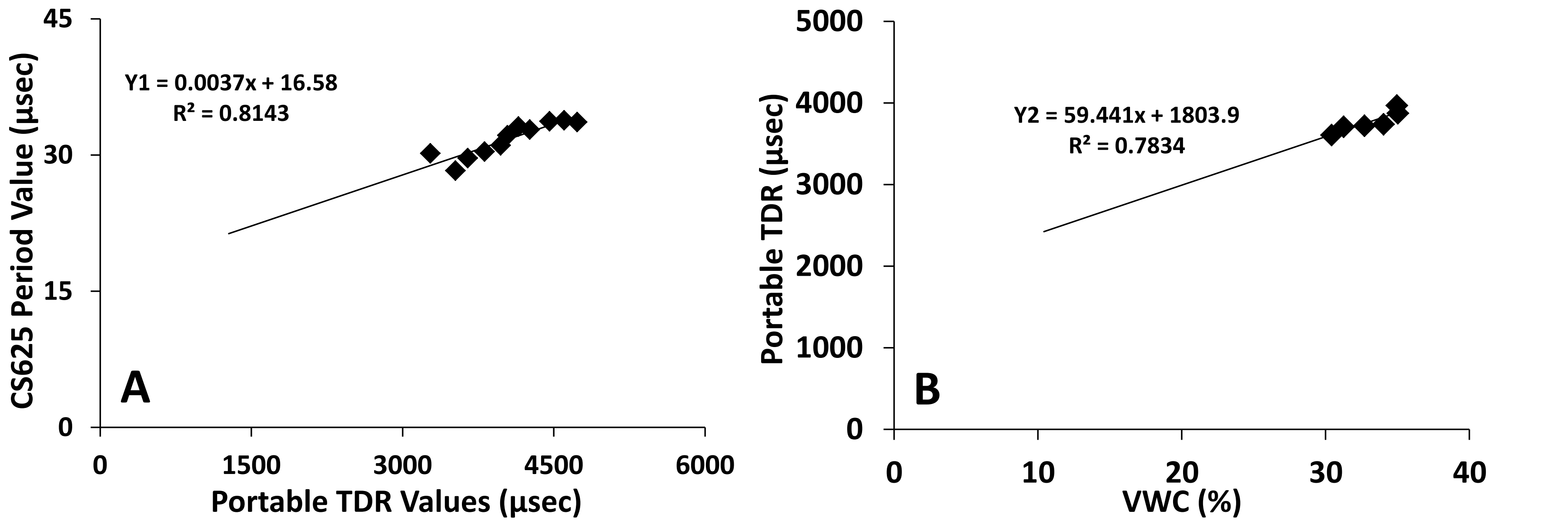

Figure 4.1 - Figure 4.1a- Plot of CS625 Sensor Values vs. Portable TDR Values (µsec). Figure 4.1b- Plot of Portable TDR vs. Measured VWC (%) in 2008

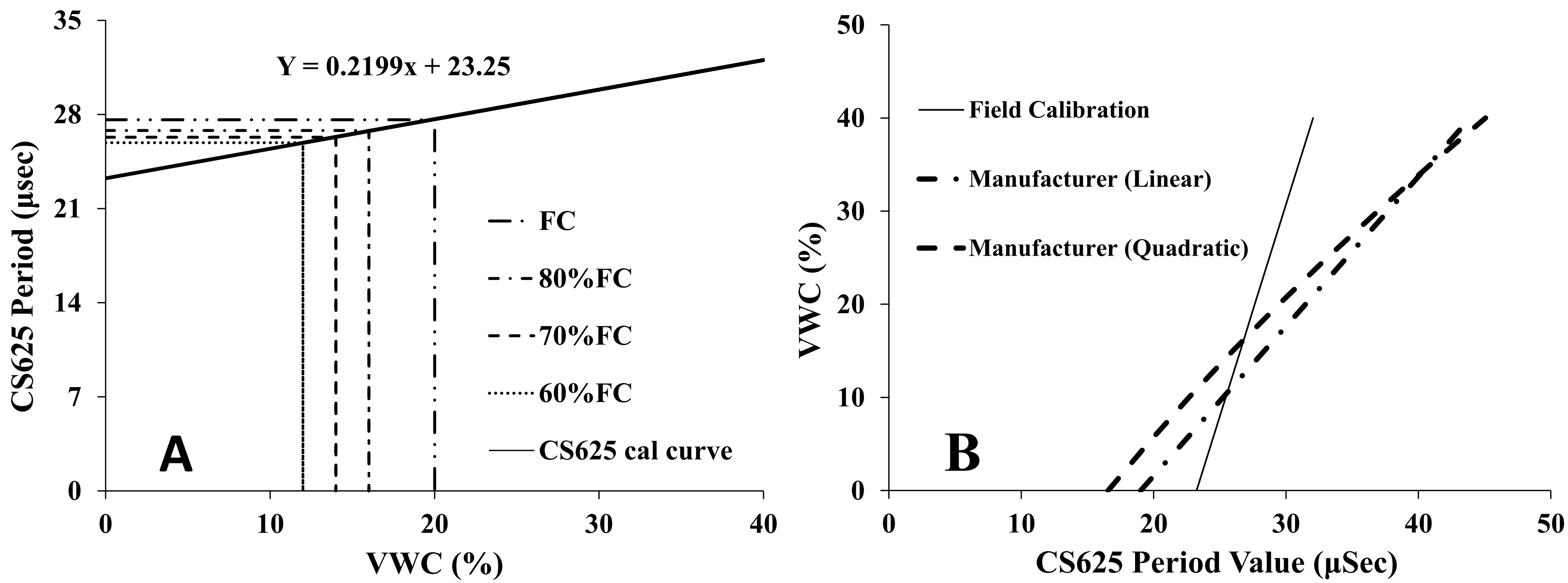

Figure 4.2- Figure 4.2a- Working calibration curve for TDR sensors -2008, with (FC, 80%, 70% and 60% FC) trigger points identified. Figure 4.2b-Comparison of CS625 field calibration to manufacturer's default calibration.

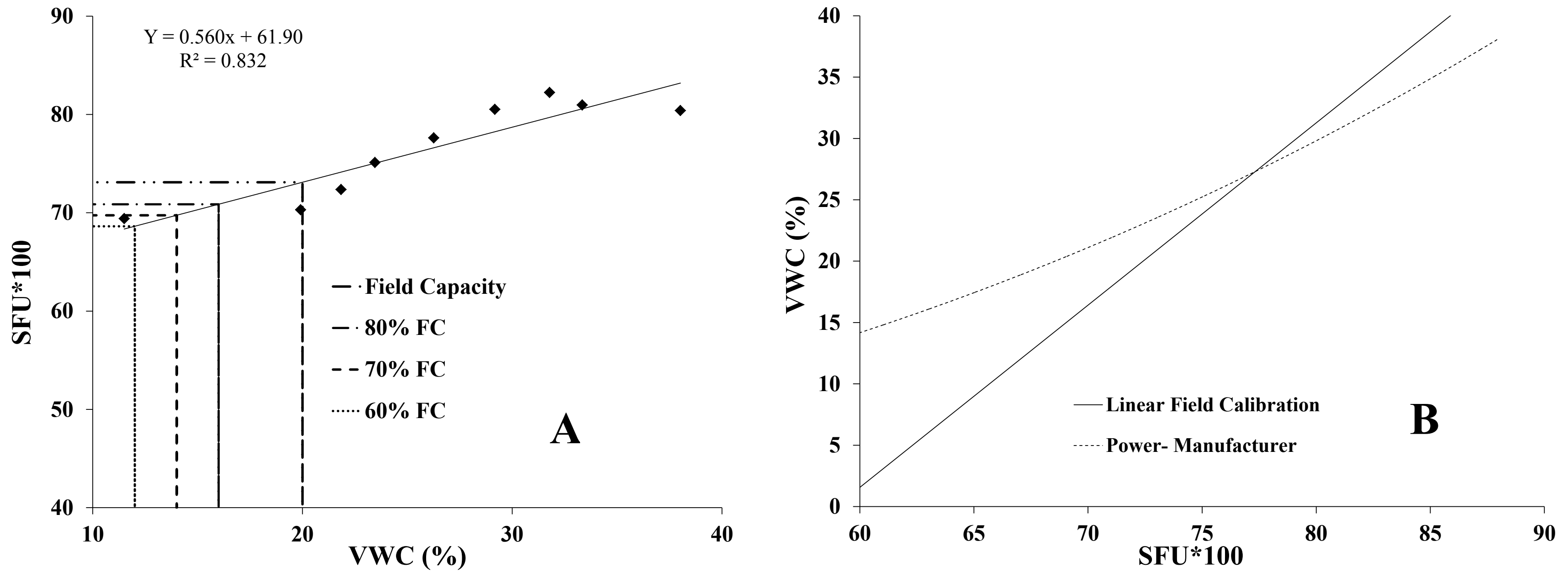

Figure 4.3- Figure 4.3a - Field calibration curve for FDR at 15-25 cm depth for 2008. Figure 4.3b- Comparison of FDR at 15-25cm depth field calibration to manufacturer's default calibration

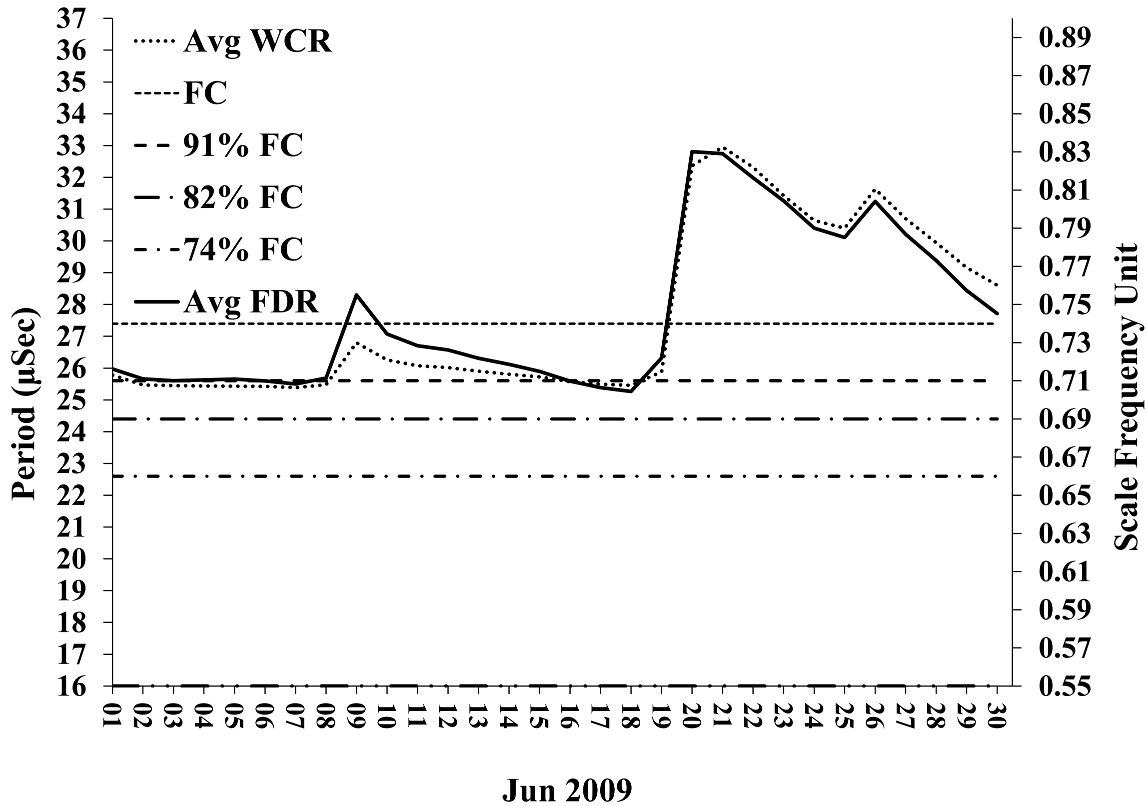

Figure 4.4-Superimposed TDR and FDR moisture distribution along with Trigger values (Avg WCR and Avg FDR – Averages from TDR and FDR sensors, respectively)

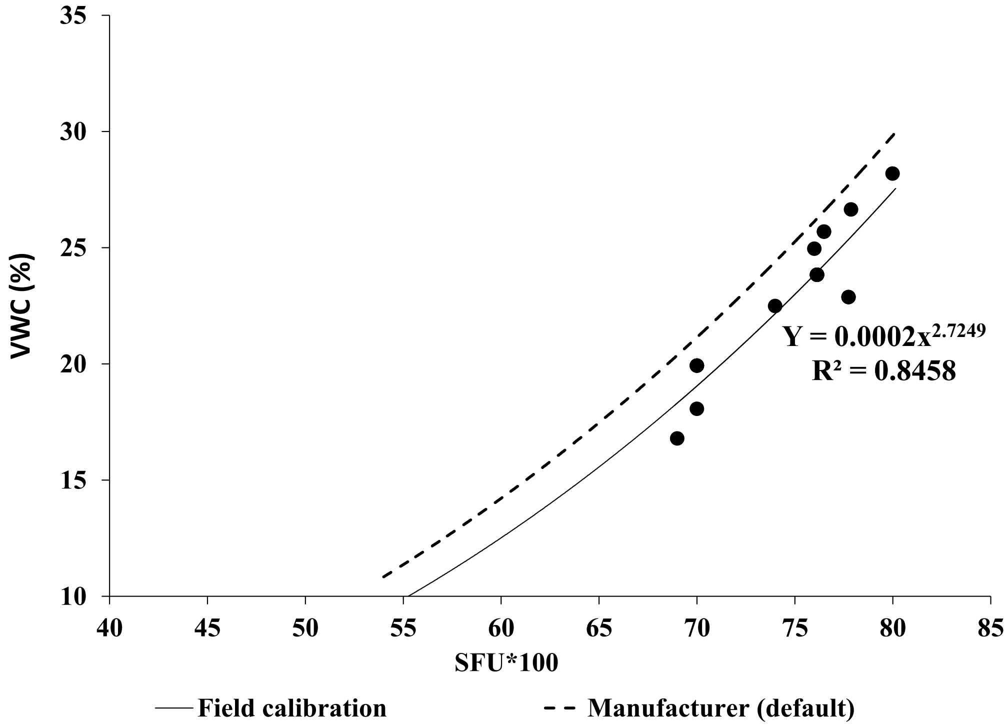

Figure 4.5-Comparison of FDR at 15-25cm depth field calibration to manufacturer's default calibration (equation is for field calibration)

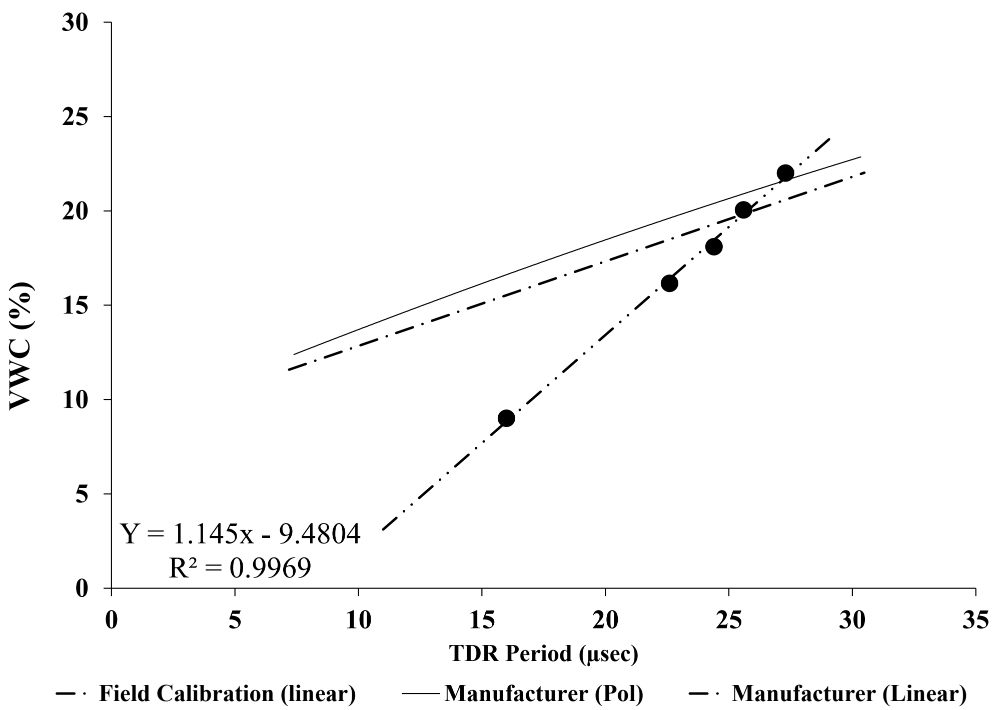

Figure 4.6-2009 Derived TDR calibration curve with trigger point and Manufacturers' curves (equation is for field calibration).

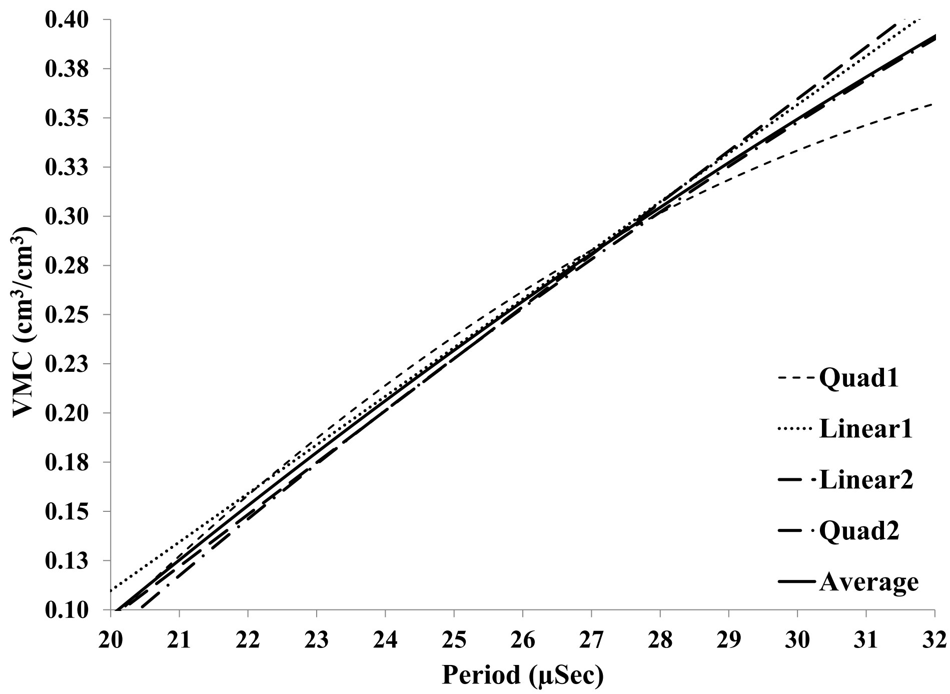

Figure 4.7-2010 Field calibration curve for the 0 to 30 cm TDR sensor with corresponding trigger points and Manufacturer's curve

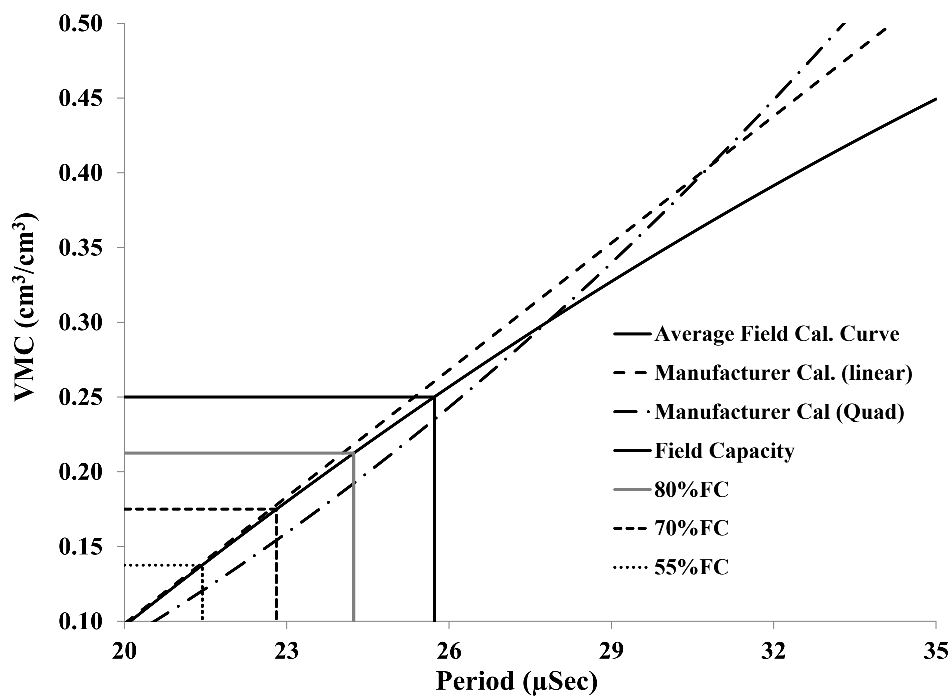

Figure 4.8-2009 Derived TDR calibration curve with trigger point and Manufacturers' curves.

Connecting text to Chapter 5

This chapter is a manuscript is currently under review and waiting to be published in 2013. The manuscript is co-authored by my supervisor Dr. C.A Madramootoo. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Chapters 3 and 4 focused on the use and calibration of soil moisture sensors for accomplishing precision irrigation scheduling respectively. With the increased use of soil moisture sensor, it become necessary to compare the irrigation application via standalone soil moisture sensor with the generally recommend FAO method to ascertain differences that may arise. Further it is being suggested that the two approaches can be integrated as a management tool to enhance precision irrigation scheduling from both a planning and implementation perspective. This chapter addresses the latter part of objective two.

Chapter 5 –Comparison of Irrigation and Crop Water Requirements of Processing Tomato (Lycopersicon esculentum L.) Using Soil Moisture Sensor and Weather data

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Abstract

In south western Ontario, irrigated agriculture is a prerequisite for large scale field tomato production and with irrigated agriculture under increasing pressure to manage water more judiciously, effective ways are needed to improve irrigation scheduling of field tomatoes. A three year (2008-2010) irrigation study was conducted to compare ETc based on FAO Penman Monteith method (FAO-56 PM) with stand-alone volumetric and tensiometric soil sensor triggered irrigation scheduling. Weather data, crop data along with irrigation data were measured throughout the study. ETc computed with FAO-56 PM was compared with four moisture treatments at each growth stage over the growing season. The seasonal crop water requirements ranged from 296 to 332 mm for the three years. The equivalent irrigation depth applied ranged from 102.0 to 168.4 mm, 85.1 to 190.3 mm and 58.3 to 196.1 mm and the seasonal moisture applied (initial soil moisture, effective rainfall and sensor irrigation depth) ranged from 272 to 338 mm, 301 to 367 mm and 320 to 459 mm for 2008 to 2010, respectively. Moisture treatments with soil moisture depletion of ≤ 40% available water content (AWC) received adequate moisture to meet crop water requirements and correspondingly produced the highest yields. Two, three and all treatments received seasonal moisture greater than the ETc in 2008, 2009 and 2010 respectively. Irrigation scheduling based on soil moisture sensors were comparable with irrigation scheduling based on FAO-56 PM.

Key words: crop evapotranspiration, FAO Penman-Monteith, soil moisture sensors, crop water requirement, irrigation water requirement

5.1 Introduction

Vegetable crops are an important component of Canada's agricultural industry. Ontario has been the major processing tomato producing area in Canada, where a unique combination of climate and soils create a suitable environment for the production and processing of tomatoes (Madramootoo et al., 2007). In 2005 and 2010 processing tomatoes were grown in an area 6635 and 5141 ha, respectively. Total production amounted to 641,404 and 513,724 Mg at an average yield of 89.2 and 99.9 Mg ha^{-1}, generating \$59.5 and \$50.0 million, respectively. An additional 1,012 ha were grown in 2005 for the fresh market with a farm value of \$18.2 million (OHCRSC, 2006; OVPG, 2011). In 2008, the farm cash receipt from vegetables in Ontario was \$932 million. Southern Ontario produces about 73% of most important vegetables in the province, 30% of these vegetables are produced under irrigation (Statistics Canada, 2006b). Ontario produces more than 95% of the tomatoes in Canada, 83% of which is concentrated in Essex and Kent counties in the southwest. Approximately 80% of all field tomatoes are processed, the remainder being used for fresh-market consumption. It is estimated that approximately 40 to 50 per cent of the processing tomato acreage was irrigated in 2007 (LeBoeuf, 2007).

The intensive cultivation of horticultural crops, coupled with a changing climate and competing water demands are placing increasing pressure on the region's existing water resources to meet irrigation needs. Tan (2003) reported increasing incidents of low rainfall and high temperatures in South-western Ontario that has negatively impacted processing tomato growth, yield and quality. Intensive tomato production in Ontario necessitates the use of supplemental irrigation to offset the deficiencies in rainfall and to maintain high and consistent levels of production. Over the growing season, most tomato cultivars require 400 mm of water. The growing season extends from May to September and the average rainfall ranges from 200-700 mm (LaBoeuf, 2007). Good knowledge of irrigation water requirement and proper irrigation scheduling will ensure efficient water use, as accurate estimation of irrigation demands (and other water uses) is a key requirement for improved water management (Maton et al., 2005).

Recent technological advances have led to the development of a wide range of sensors that allows for continual soil moisture monitoring. They provide farmers with the potential to accurately meet crop water requirements of individual crops (Thompson et al., 2007b). While the relationships between soil properties, climate factors and crop performance are highly complex, and dynamic, reliable field sensors capable of monitoring parameters pertinent to crop performance are essential to the development of management aids (Grismer, 1987). Continuous soil moisture monitoring integrates these complexities (of climate, soil and crop factors), thus facilitating irrigation scheduling by ensuring that the soil moisture is kept within a predetermined upper and lower threshold throughout the growing season. Evett (2007) established that indirect methods provide estimates of soil water content based on measurement of soil properties assumed to be correlated with water content. (Gardner, 1965) added that it involves measurement of some property of the soil affected by soil water content or measurement of a property of some object placed in the soil.

Most of the sensors suitable for irrigation are dielectric. This group of sensors estimate soil water content by measuring the soil bulk permittivity (or dielectric constant) that determines the velocity of an electromagnetic wave or pulses through the soil (Munoz-Capena (Munoz-Capena & Dukes, 2005). Iida et al. (2005) argued that the dielectric behavior of a material is described by its permittivity (ε, expressed in $F.m^{-1}$) or by its relative permittivity known as dielectric constant, defined as: the permittivity of the material related to vacuum (ε_o). The dielectric constant is a measure of the capacity of a nonconductive material to transmit electromagnet waves or pulses. In a composite material like soil, (i.e. made up of different components like minerals, air and water) the value of permittivity consist of the relative contribution of each soil component (Munoz-Capena & Dukes, 2005).

The most common procedure for estimating crop water use or crop evapotranspiration (ETc) is the crop coefficient (Kc) approach (Allen et al., 1998; Doorenbos & Pruitt, 1977). Mainly used in ETc computation, potential evapotranspiration (ETo) can be determined either by direct measurements from lysimeters situated with a standard reference crop or estimated by empirical methods. Direct measurement of ETo is often expensive and laborious, requiring complex instrumentation (Vaughan & Ayars, 2009). The literature is inundated with methods for the calculation of ETo from meteorological data (Azhar & Perera, 2011; Irmak et al., 2008; Jensen et al., 1990; Sabziparvar & Tabari, 2010). The FAO Penman-Monteith method is the standard recommended method for the definition and computation of ETo. ETo represents the evaporative demand of the atmosphere, independent of crop type, crop development and crop management practices. The assumption is that water is abundantly available at the evapotranspirating surface. Factors affecting ETo include climatic parameters computed from weather data. Researchers suggest that soil factors do not affect ETo (Allen et al., 1998). The use of climate and crop evapotranspiration data and soil moisture sensors are required for precise irrigation scheduling and best irrigation management practice (Bernier et al., 2010; Leib et al., 2002; Mermoud et al., 2005). Bernier et al. (2010) determined on farm water use efficiency and potential water savings by using soil moisture sensors to schedule irrigation for a single season in 2007 in southern Ontario.

While sensor based irrigation scheduling has proven to be useful in accomplishing irrigation scheduling, by ensuring that soil moisture content is kept within an upper and lower threshold throughout the growing season. It is also important that the irrigation depth applied is adequate to meet the crop water requirement of the growing crop over the season. This would therefore be dependent on the moisture depletion level that defines the lower trigger, since the upper trigger is often set to field capacity.

There is a need for a comprehensive assessment of irrigation water requirements of tomatoes in southern Ontario over a longer period. Therefore, the objective of this study was to assess the irrigation water requirement for large scale field tomatoes grown in Leamington, Ontario using climate, crop evapotranspiration data and soil moisture sensors.

5.2. Material and methods

A three year field experiment was conducted during the summer months of May through September, from 2008 to 2010 on a commercial farm in Leamington, in south western Ontario. The water applied was compared with the crop water requirement estimated with FAO-56 Penman-Monteith model (Allen et al., 1998).

5.2.1 Study area

Essex County in Ontario is Canada's southernmost county, spanning 1720.00 km^2; it is one of the most agriculturally productive counties in the country, having a large concentration of vegetable growers (de Loë et al., 2001). Leamington which forms part of the Essex County is generally referred to as the tomato capital of Canada. It has a warm climate and soil that is ideal for vegetable production (Madramootoo et al., 2007). The farm site was about 187 m asl and was located at 42.08° N Latitude and 82°.55°W. The local climate is classified as humid with hot summers and dry and cold winters. Average annual temperature and precipitation are approximately 9.5 °C and 950-1050 mm respectively. Rainfall is typically distributed throughout the year, with no predominant rainy months. The dominant soil within the production zone (0 to 30 cm) is loamy sand (86% sand, 8% silt and 6% clay), with an average bulk density of 1450 kg m^{-3}. In situ soil water holding capacity ranged between 20 to 25% by volume (60 to 65 mm) over the rooting depth (300 mm).

5.2.2 Experimental design

A split-plot randomized complete block design (RCBD) was used in 2008 and 2010, and a (2*4) factorial RCBD in 2009 (Table 5.1). The split plot design involved two experimental factors. The irrigation types (sub-surface drip irrigation (SDI) and on-surface drip irrigation (ODI) and the moisture levels (three moisture levels and a tension treatment) were assigned to the whole plot (main plot) and split plots respectively. The factorial experimental design of 2009 also had the same two factors. The volumetric moisture treatments were expressed as a fraction of field capacity and represented the depletion to which the soil moisture reached to initiate irrigation scheduling. The volumetric moisture treatments were changed from 60%, 70% and 80% of FC to 74%, 82% and 91% of FC respectively, in 2009. This was done to examine the effects of a less stressed irrigation scheduling program. In 2010, the moisture treatments were again changed to 55%, 70% and 80% of FC. This change was to increase the range between moisture treatments, making it more practical for monitoring. The change in the experimental design from split-plot RCBD to a factorial design was undertaken because the parameters involved in the experiment fitted both models and it was an opportune occasion to change the model in one of the three years.

5.2.3 Cropping Details

Processing tomato (*Lycopersicon esculentum* Mill. cultivar Heinz H9553) was grown in the study area during three years. Seedlings (42 days old) were transplanted during the time when the soil moisture content was near field capacity within the top 30 cm. Transplant dates were 29 May 2008, 25 May 2009 and 15 May 2010. The crop was harvested after 105 days in 2008 (on 10 September), after 112 days in 2009 (on 14 September) and after 101 days in 2010 (on 24 August). Seedlings were planted in double rows on raised beds (to facilitate harvesting operations as well as to reduce water logging problems which may occur during a wet harvest season). Plant spacing was maintained at 42 cm along and 50 cm between rows respectively, resulting in a planting density of 31,746 plants per hectare. Fig. 5.1 provides a layout of the 2008 experiment.

5.2.4. Soil moisture sensors installation and irrigation scheduling

Three types of soil moisture sensors were permanently installed in the field for continuous data collection: time domain reflectometers (TDR) (Campbell Scientific CS625 water content reflectometer); frequency domain reflectometers (FDR), (Sentek Sensor Technologies EnviroSMART) and electronic tensiometers (Irrolis Sense Tx from Hortau^{TM}). The TDR's were installed in pairs at the 0 to 30 cm and 30 to 60 cm depths in 2008 and 2010 and at 5 to 25 cm and 25 to 55 cm in 2009 respectively. Tensiometers were installed at 15 cm and 45 cm. FDR's were equipped with 5 sensors (at the 10, 20, 30, 40 and 60 cm depths) and were used in 2008 and 2009. In 2010 only TDR's and tensiometers were installed. The critical depth at which soil moisture was monitored for the three sensors to effect irrigation scheduling was 0 to 30 cm for the TDR sensors (5 to 25 cm in 2009), the 15 to 25 cm for the Sentek sensor and 15 cm for the tensiometer.

All the devices were equipped with wireless communication system to transmit data from the field to an onsite computer. The volumetric sensors were connected to 12 data loggers (model CR206, Campbell Scientific International, Loan UT, USA) strategically located throughout the project site. The electronic tensiometer measurements were read directly on the LCD display in the fields or remotely from a base computer. The TDR and FDR sensors were calibrated against measured volumetric soil water content, from which the upper and lower thresholds were determined for each treatment. No calibration was done for the tensiometric sensors; however the upper and lower triggers for the tension based treatment were -10 and -30 kPa respectively.

All 32 experimental plots were monitored and upon soil moisture depleting to the requisite lower moisture thresholds, the particular plot(s) was/were irrigated. Irrigation was terminated when field capacity (upper trigger moisture content) was reached. The times (on and off), duration and operating pressure were recorded when each plot was irrigated. This allowed for the determination of the actual amount of water applied to each treatment; since the flow rate and the number of drippers per plot was known. After the 2009 irrigation season, flow rates from the surface and buried drippers were randomly measured and found to be consistent with the manufacturer's specification, with an average flow rate of 0.68±0.01 l hr^{-1}.

5.2.5 Estimation of irrigation water requirements

Two automatic weather stations were installed at the experimental site. Weather data collected on site included; wind speed, relative humidity, daily maximum and minimum temperature, solar radiation and rainfall. Daily sunshine hours (2008 to 2010) and wind run for 2009 and 2010 were not recorded (due to faulty equipment). As a result average daily sunshine hours from 1974 to 1994 and wind speed for 2009 and 2010 from Harrow weather station, approximately 27 km away (latitude 42.03° N, longitude 82.9° W and elevation 190.5 m asl) were obtained from Environment Canada and was used to estimate irrigation water requirements. The sunshine data was use to supplement the incomplete radiation data. The steps taken in estimation of irrigation water requirements are as described:

5.2.5.1 Reference evapotranspiration (ETo)

The modified PM equation (Eq. 5.1) is the recommended procedure by FAO for the calculation of Reference Evapotranspiration (ET_o) (Allen & Huntington, 2009; Allen et al., 1998). The PM model requires a large number of weather parameters as input data. Most of the data were collected on site while some (sunshine hours and wind run) were obtained from the Harrow weather station. Non recorded variables such as saturation vapour pressure, actual vapour pressure, psychometric constant were estimated using available weather and altitude data (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad \text{Eq. 5.1}$$

Where

ET_o - reference evapotranspiration (mm day^{-1})
R_n - net radiation at the crop surface (MJ m^{-2} day^{-1})
G - soil heat flux (MJ m^{-2} day^{-1})
T - mean daily air temperature at 2 m height (^oC)
u_2 - wind speed at 2 m height (m s^{-1})
e_s - saturation vapour pressure (kPa)
e_a - actual vapour pressure (kPa)
e_s-e_a - saturation vapour pressure deficit (kPa)
Δ - slope vapour pressure curve (kPa $^oC^{-1}$)
γ - psychrometric constant (kPa $^oC^{-1}$).

5.2.5.2 Crop coefficient (Kc) and crop evapotranspiration

The relationship between ETo and ETc is given by a crop specific coefficient (Kc). Kc varies predominately with the specific crop characteristics and only to a limited extent with climate (Allen et al., 1998). Crop coefficients vary between crops and crop growth stages. In this study the Kc values were obtained from Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) (OMAFRA, 2004). OMAFRA divides the growing season for processing tomatoes into three growth stages. The stages are presented in Table 5.2, with their corresponding K_c values. The growth stages will henceforth be referred to as Phases 1, 2 and 3, respectively. Crop evapotranspiration (ETc) was estimated as the product of the reference crop evapotranspiration (ETo) and the crop coefficient (Eq. 5.2).

$$ET_c = K_c * ET_o \qquad \text{Eq 5 2}$$

Where

ET_c = crop evapotranspiration (mm d^{-1})

K_c = crop coefficient (dimensionless)

ET_o = reference crop evapotranspiration (mm d^{-1})

5.2.5.3 Effective rainfall

Dastane (1978) defined annual or seasonal effective rainfall as the fraction of the total or annual rainfall that is utilized directly or indirectly for crop production at the location of falling and without being pumped. A number of empirical equations have been utilized for calculation of effective rainfall. However, the one utilized for this experiment was proposed by the U.S. Department of Agriculture's Soil Conservation Service (USDA, 1967) and is utilized in the FAO CROPWAT 8.0 software (FAO, 2009). It was developed by processing long term climatic and soil moisture data. The effective rainfall can be expressed as follows: (Eq. 5.3 and 5.4):

$$R_{eff} = \frac{\left(P*(125-0.2*P)\right)}{125} \quad for\ P \leq 250\,mm \qquad Eq.5.3$$

$$R_{eff} = 125+0.1*P \quad for\ P > 250\,mm \qquad Eq.5.4$$

Where

R_{eff} = Effective rainfall (mm) over period

P = Actual precipitation total (mm)

5.2.5.4 Calculation of irrigation water requirements

Crop water requirement and the crop evapotranspiration are synonymous. The former represents the moisture applied while the latter signifies the moisture lost through evapotranspiration. Crop water requirement is met in part by a combination of effective rainfall, ground water, soil moisture storage and the rest is made up through irrigation

(Allen et al., 1998). The net seasonal irrigation requirement (NIR) therefore was determined by subtracting the total seasonal effective rainfall and the available soil moisture stored in the rooting zone at the beginning of the growing season from the crop water requirement (ETc). An application efficiency is generally applied, depending on the type of irrigation method. 90% irrigation efficiency was used in this research. The net irrigation water requirement was calculated using the following equation:

$$\text{Irrigation Water Requirement} = \frac{ET_c - ASW - EP}{I_{eff}} \qquad \text{Eq. 5.5}$$

Where

ET_c - crop evapotranspiration (mm)

ASW - soil water storage in rooting depth (300 mm) at the start of growing season *(mm)*

EP - effective precipitation (mm)

I_{eff} - irrigation system efficiency

5.2.6 Crop yields

The fruits were harvested approximately 10 days after spraying Ethrel (a liquid plant growth regulator). Fruits were harvested and weighed from sub-plot (comprising of 6 plants in 2008 and 2010 and 4 plants in 2009) for each of the 32 plots. They were categorized into red, green, or cull and weighed to determine total and harvestable or marketable yields. Marketable yield was obtained by subtracting the weight of the culled fruits. The yields were expressed on a per hectare basis.

5.2.7 Statistical analysis

Statistical analysis was performed on individual years of data. In both experimental design models, the blocks were considered random effects while the irrigation types and the moisture levels (treatments) were fixed effect parameters. Statistical analysis were performed using PROC MIXED procedure of SAS (SAS, 2007), designed to fit mixed effect models. Analysis were done on fruit yield and equivalent water application. Differences at $P < 0.05$ were considered statistically significant. T-tests were also carried out between the ETc over the three years.

5.3 Results and discussion

5.3.1 Reference evapotranspiration (ETo) and crop evapotranspiration (ETc)

ETo ranged from 2.0 to 6.0, 2.5 to 6.0 and 2.5 to 6.6 mm d^{-1} for 2008, 2009 and 2010, respectively (Fig. 5.2). OMAFRA reported historic daily average maximum ETo for Southwestern Ontario ranging from 2.0 and 5.6 mm d^{-1} (OMAFRA, 2004). Tan (1990) also reported values within the same range. The minimum and maximum values were generally obtained in May/September, and July, respectively. Seasonal ETc ranged from 297 to 331 mm from transplanting to the termination of the irrigation season for the three years (Table 5.3). Termination of Irrigation coincided with spraying of Ethrel, two weeks before harvesting. There was no statistical difference in seasonal ETc between the three irrigation years (*t*-test, $\alpha = 0.05$). This was most likely due to the similarity in the climatic conditions over the growing season for the three years and the fact that the growing season up to the termination of irrigation was also similar in duration (ranging from 93 to 99 days). The average ETc over the three growth phases for 2008, 2009 and 2010 were 104 mm (SD=67.8 mm), 110 mm (SD = 70.8 mm) and 99 mm (SD = 45.3 mm) respectively. LeBoeuf et al. (2007) noted that transplanted field tomatoes are a long-season crop with high water requirements. An average cultivar requires about 400 mm.

Over the three years (2008 to 2010), the total ETc up to the time of harvest was 342.6, 376.3, and 338.2 mm, respectively. The differences in the total ETc were primarily due to the time of transplanting (29 May in 2008 as compared to 25 May and 15 May in 2009 and 2010) and the length of the growing (105 days as compared to 113 days). Total ETo ranged from 413 to 447 mm up to the termination of irrigation and 444 to 492 mm up to harvesting for the three years. ETo is a function strictly of climatic parameters and expresses the evaporation power of the atmosphere, while ETc represent evapotranspiration under ideal conditions(disease free, well fertilized crop, grown in large fields, under optimum soil water conditions, and achieving full production) under the given climatic conditions. Due to crop management and environmental constraints that impact crop growth and limit evapotranspiration, ETc under non-standard conditions generally requires a correction (Allen et al., 1998).

5.3.2 Seasonal irrigation application

The treatment representing the lowest moisture depletion in two of the three years (74% FC in 2009 and 55% FC in 2010) received least irrigation. In 2008, the 60% FC represented the treatment with the lowest moisture depletion; however, it received more irrigation than the 80% FC moisture treatment (Table5.4). Two factors contributed to this inconsistency. Firstly, two of the replicates associated with the 60% FC treatment attained to trigger more regularly than the other replicates probably due to preferential flow or soil heterogeneity, thus skewing the average irrigation applied for the 60% FC treatment in 2008. The other reason was due to unusually high soil moisture content throughout the growing season for one of the 85% FC replicates. As a result, this plot was irrigated for only 11 hours as compared to the seasonal average of 70 hours over the 32 plots.

Tensiometric treatment received the most irrigation in 2008 and 2010, because it represented the treatment with the highest management allowable deficit and attained to trigger the quickest. Further the tension sensors were installed at the shallowest depth resulting in a faster response time to changes in moisture content. In 2009, tensiometric treatment received less irrigation than both the 82% and 91% FC moisture treatments. The tensiometric treatment was however irrigated most frequently (30 events) as compared to the other three treatments. There was statistical significance (at $p \leq 0.05$) among the moisture treatments for equivalent irrigation depth in 2008 and 2010 but none in 2009.

Interaction between irrigation type (buried and surface drip irrigation) and moisture treatment revealed that the surface drip irrigated plots for 2008 and 2009 received more irrigation than the buried irrigated plots for each of the four treatments except for the 74% FC treatment for 2009, in which the opposite was true. This occurred because two of the 74% FC replicates in 2009, received unusually higher irrigation than normal, which may be due to the heterogeneity of the research plot. In 2010, however, all the buried irrigated treatments received more irrigation that the surface irrigated treatment (Tables 5.4 and 5.5). This was found to be rather unusual and may be attributed to the rainfall distribution during the 2010 season, in which 18 days (from the 1 May) out of the growing season received rainfall ≥ 5 mm. This would impact the frequency with which the surface treatments would have been irrigated.

Over the three years, equivalent irrigation depths ranged from 67 to 222 mm and 49 to 250 mm for buried and surface irrigated treatments respectively. Warner et al. (2007) reported values of ETc values ranging from 59 mm to 268 mm for different moisture treatments ranging from 0.5 to 1.2ETc for experiments conducted in sandy loam soils in Southwestern Ontario between 2003 to 2005. These values were comparable with results obtained from this research.

The estimated irrigation water requirement ranged from 36 to 150 mm. Even though the 2010 year has the highest seasonal rainfall (359 mm), the rainfall was not evenly distributed throughout the growing season; as most of the heavier rains occurred towards the end of the growing season. The highest water application was associated with some of the treatments during that year (Table 5.4). The interpretation of the net irrigation requirement in isolation, without considering the rainfall distribution over the season may be misleading. This further emphasized how significantly the rainfall component impacted the determination of irrigation water requirement. In 2008 and 2009, the two sample t-test between irrigation applied and net irrigation requirement were not statistically different but was found to be statistically significant in 2010. This was primarily due to the high effective rainfall in 2010.

5.3.3 Yield

Fruit yield -2008

Tables 5.4 and 5.5 summarized yield results. In 2008, the average fruit yield for the four treatments ranged from 91.9 to 121 Mg ha^{-1}. The highest and lowest average yields were from the 70% FC and the 60% FC treatments respectively. There was a direct relationship between seasonal irrigation depth and crop yields. As a result statistical significance was obtained for marketable yields among moisture treatments and between irrigation types. No significant difference was found in the interaction between the moisture treatments and the irrigation type.

The 70% FC treatment represented a depletion in available water content (AWC) of approximately 54%, which was substantially lower than the 30 to 40% AWC recommended by Doorenbos and Pruitt (1977). It was therefore surprising that the 70% FC treatment should produce the highest yield. The data revealed that two of the eight, 70% FC plots had yields of 130.7 and 176.2 Mg ha^{-1}. The 176.2 Mg ha^{-1} was also the highest yield of the 32 plots, as well as the plot receiving the highest equivalent depth of irrigation (249.2 mm). These two exceptionally high yields skewed the average yield for the 70% FC treatment, making it the treatment with the highest yield.

The 60% FC treatment represented a 74 % depletion of the AWC. The plant physiological stresses associated with the 60% FC treatment undoubtedly contributed to the lowest yields. The 80% FC, which corresponded to 36% depletion in AWC, had unusually low yields. Five of the eight, 80% FC plots had yields of less than 100 Mg ha^{-1} and resulted in an average yield that was lower than the 70% FC.

In relation to the irrigation type, all the surface drip irrigated treatments produced higher yields than their corresponding buried drip irrigated treatments in 2008. The major factor contributing to this difference was attributed to the depth of the buried drip lines. During the 2008 season, the buried drip lines were installed at 20 cm below the ground surface; however, in 2009 and 2010 they were installed at 15 cm below the ground. Processing tomato has an effective rooting depth of approximately 30 to 40 cm under drip irrigation. It was believed that the drip line placement at 20 cm may have limited the wetting pattern and the capillary rise during irrigation, limiting the volume of irrigation within the rooting zone. The surface irrigated plot provided a longer period for the irrigation water to move through the root zone and supplied a greater amount of water in the effective rooting depth of 30 cm. This undoubtedly would have contributed to the significant difference between the yields of the irrigation types. Tan (2003) reported similar trends but attributed the higher yield for the surface irrigated plots to root intrusion into the sub-surface emitters, preventing uniform water distribution. Phene et al. (1987) reported conflicting results for surface and buried (at 45 cm below the surface) drip irrigated processing tomatoes grown in clay loam soils in California. Manual and machine harvest yields were 10.3% and 17% greater in the subsurface drip treatments than the high frequency surface drip treatment, and 29.2% and 24.1% than the low frequency surface drip.

Fruit yield -2009 and 2010

In 2009, the average fruit yield for the four treatments ranged from 101.6 to 105 Mg ha^{-1}. The highest and lowest average yields were from the -30 kPa and the 91% FC treatments respectively. There was very little variation in yields between treatments during the 2009 season therefore no statistical significance was obtained amongst the moisture treatments, irrigation type or the interaction between the two. This was primarily due to the fact that the soil moisture depletion levels of the four treatments were reduced, such that three of the four treatments were within the MAD of 30% to 40% AWC. The fourth moisture treatment, the 74% FC, was just outside the range of the MAD recommended by Doorenbos and Pruitt (1977) by 5% and had approximately the same average yield as 91% FC treatment. This may be due to the masking effect of the effective rainfall (186 mm) which would have minimized the treatment effect of particularly the 74% FC treatment. The 91% FC treatment (depletion of 15% AWC) also had a lower yield than the -30kPa treatment (depletion of 22% AWC). It was very possible that the 91% FC treatment created too wet a soil environment in the rooting zone thus negatively impacting plant growth and development, resulting in a slightly lower plant yield.

In 2010, the average fruit yield ranged from 104.4 to 121.1 Mg ha^{-1}. The two treatments which were within the MAD range of 30% to 40% AWC had higher yields while the two treatments outside the MAD range had lower yields. The 2010 season produced the highest average yields amongst the treatments (113.7 Mg ha^{-1}). It is strongly believed that the large effective rainfall depth over the growing season, between May to August, with each of the months having rainfall greater than the 30 year average and a seasonal average having 43% more rainfall than the 30 year average would have undoubtedly masked the effects of all the treatments and thus reduce the plant stress, particularly during the critical plant growth stages. It is therefore not surprising that there was no statistical difference between moisture treatments, irrigation type or the interaction between them.

The results over the three years indicated a direct relationship between irrigation volume and yields. Marketable production increased with increasing irrigation depths. Similar results were reported by (Machado & Oliveira, 2005; Machado et al., 2000; Sezen et al., 2010) for both surface and buried drip irrigation. Machado and Oliveira (2005) obtained comparable yields, ranging from 69.9 and 130.1 Mg ha^{-1} for marketable yields. Warner et al. (2007) reported marketable yields ranging from 126.7 to 168.5 Mg ha^{-1} and Zhang et al. (2010) also reported marketable yields 56 to 138 Mg ha^{-1} respectively. In each of the three years, the treatments with ≤ 40% AWC depletion generally produced the higher yields thus validating Doorenbos and Pruitt (1977) recommendation. The -30 kPa treatment represented depletion in the AWC ranging from 22 to 24% VWC over the three years. Apart from the anomaly in 2008, where the 70% FC treatment had the highest yield, the tension treatment had the highest yields (in 2009 and 2010), despite not being statistically significant. The threshold values (-10 and -30 kPa) for fill and refill levels were comparable to similar works done with processing tomatoes. Marouelli and Silva (2007) used soil water thresholds (SWT) ranging from 5 to 120 kPa and found that the best yields were obtained when irrigation was performed at SWT thresholds of 35, 12 and 15 kPa during the vegetative, fruit development and maturation growth stages respectively at Embrapa Vegetables, Brasília, Brazil. Hartz and Hanson (2005) recommended thresholds should be in the range of 20 to 35 kPa up to fruit maturation and after this a range of 40 to 50 kPa. However the above values were for deep clayey soils in California. It is also worth noting that while these researchers varied the threshold values over the developmental stages of the crop, the current experiment kept the threshold values constant throughout.

5.3.4 Sensor based irrigation depth vs. empirical crop water requirement (ETc) estimate

Table 5.6 summarizes the irrigation depth, effective rainfall, initial soil moisture, ETc for each crop growth stage and the seasonal irrigation water requirement over the three years.

FAO has indicated that Penman-monteith method is the recommended method for the determination of potential Evapotranspiration (ETo). This model is preferred because of the combination of energy balance and aerodynamic considerations. It has been proven to give better results in ETo estimation methods' comparative studies (Allen et al., 1998; López-Urrea et al., 2006; Mohan & Arumugam, 1996; Pereira & Pruitt, 2004; Smith et al., 1991; Stockle et al., 2004). ETc is determined by the crop coefficient approach. The effect of the various weather conditions are incorporated into ETo and the crop characteristics into the Kc coefficient.

No irrigation was applied to the crops during Phase 1; hence the rooting depth was not critical. The ETc during this period was small ranging from 40 to 51 mm; this was adequately met by the combination of the initial high antecedent soil moisture due to spring melt and effective rainfall. During Phase 2, the ETc ranged from 92 to 109 mm over the three years. Due to heavy rainfall events (175 mm) during the first and second growth stages, minimal irrigation (1 to 20 mm) was necessary in 2008. However in 2009 and 2010 the depth of irrigation ranged from 20 to 71 mm and 48 to148 mm for the different moisture treatments over the three years, respectively. Irrigation began toward the end of June in the Phase 2, by then the rooting system would have elongated. An average rooting depth of 30 cm was used for the remainder of the season, since drip irrigation tended to restrict plant root development downwards (Bucks et al., 1982).

During Phase 3, the ETc ranged from 138 to 189 mm over the three years while the depth of irrigation between the four treatments ranged from 112 to 148 mm, 65 to 80 mm and 10 to 48 mm for 2008, 2009 and 2010, respectively. The depth of irrigation applied during Phase 2 and particularly Phase 3 was dependent on the distribution of the rainfall. In 2008, the bulk of rainfall was concentrated during Phase 1, while in 2009 and 2010;

the heaviest rainfall was during the latter part of the season, thus reflecting a lower irrigation application depth.

A comparison between the accumulated ETc and accumulated soil moisture inputs (via irrigation, effective rainfall and initial soil moisture) showed that all the moisture treatments for each year, received more water than the accumulated ETc up to Phase 2 of crop growth for all the three years with the exception of the 74% FC treatment of 2009 which received 6.3 % less water than the accumulated ETc (Table 5.6). This may be attributed to the rainfall pattern over the three years. At the end of Phase 2 in 2008 and 2010, a total of 125 and 113 mm of effective rainfall had occurred while in 2009, only 75 mm of effective rainfall was measured.

The seasonal irrigation depths applied were less than the seasonal ETc for all the treatments. The accumulated moisture inputs (irrigation depth, initial soil moisture, and effective rainfall) up to the termination of irrigation, indicated that two, three and all the treatments in 2008, 2009 and 2010 had received greater. In 2008 the 70% FC and 30 kPa treatments were 3.8 and 8.3% greater than seasonal ETc, in 2009 the 82% FC, 91% FC and 30 kPa treatments were 17.1%, 22.0% and 10.9% higher than the seasonal ETc, while in 2010 the treatments ranged between 8.1% to 55.1% higher than the seasonal ETc (Table 5.6, Figure 5.3). The results indicated that the optimum treatments were those with depletion levels of ≤ 40% AWC, which was consistent with the recommendation of Doorenbos and Pruitt (1977). For each of the three years, the treatments with seasonal moisture ≥ ETc correspondingly had higher yields. There was only one exception, the 91% FC treatment in 2009. It was possible that the 91% FC treatment created too wet a soil environment in the rooting zone which may have contributed to slightly lower yields. The large effective rainfall contributed to all the treatment receiving greater moisture than the ETc in 2010 and undoubtedly masked the treatment effects.

This research reveals that the sensor based irrigation integrates the soil, plant and weather factors in a very effective way to provide irrigators with a needs-based tool to effect proper irrigation scheduling. The seasonal ETc and the accumulated moisture applied via sensor based irrigation scheduling were comparable.

5.3.5 Seasonal irrigation water requirement vs. sensor based irrigation depths

Table 5.7 summarizes the seasonal ETc, sensor irrigation depths, NIWR and potential water savings. The net irrigation water requirement represented ETc less than the initial soil moisture and effective rainfall. The seasonal net irrigation water requirements were 158, 129 and 38 mm for 2008, 2009 and 2010, respectively, while the actual irrigation depth base on the soil moisture sensors among the four treatments over the corresponding period ranged from 113 to 168 mm, 85 to 190 mm and 58 to 196 mm, respectively. Two factors can be attributed to the differences between NIWR and the sensor irrigation depths. Firstly, different moisture treatments were used, which would result in different seasonal amounts of irrigation depths being applied and therefore would account for the range of values seasonal irrigation depths for each of the three years. Secondly, the rainfall distribution and the calculation of the effective rainfall would impact the NIWR. In 2009 and 2010, the bulk of the heavy rainfall occurred towards the end of the season after much sensor based irrigation had taken place. Further, the empirical equation for calculating effective rainfall does not take into consideration the antecedent soil moisture, the frequency of the rainfall or the synchronicity of rainfall with the crop water needs, which can often results in an over estimation of the effective rainfall as obtained particularly in 2010. The irrigation water requirement estimates can be skewed or underestimated if these factors are not taken into consideration. In 2008 (60% FC) and 2009 (74% FC), the most stressed moisture treatments indicated water savings. However, these treatments also produced the lowest yields. The 80% FC treatment in 2008 also indicated savings. This was due to the anomaly associated with a few of the 80% FC treatments in 2008.

In arid or semi-arid regions, where the rainfall over the growing season, for all practical purposes is zero, one can assume that the net seasonal irrigation water requirement and the actual irrigation depth from sensor irrigation should be approximately equal. The irrigation water requirement can be considered a fairly constant value. In the humid regions however, where rainfall is never zero and very variable, such assumption can be misleading. Further the calculation of the seasonal irrigation water requirement only takes into account the effective rainfall over the season but does not necessarily reflect the day to day conditions as does the soil moisture sensors nor does it take into consideration the distribution of the rainfall over the season. Neither does it address the incidents of a rainstorm after an irrigation scheduling event.

5.4 Conclusions

This three year study was conducted to compare crop water demands based on FAO Penman Monteith method with sensor based irrigation scheduling. Comparisons were made at each growth stage and at the end of the irrigation season. The results indicated that irrigation was not necessary during the first growth stage which extends from transplanting to first flowering. The crop water demand (ETc) was adequately met by the initial soil moisture and the rainfall over this initial period. During the second growth phase (from 1st flowering to maximum row fill), the accumulated soil moisture inputs (via rainfall, initial soil moisture and irrigation) was found to be higher than the ETc in all but one of the treatments (74% FC in 2009) over the three years. The third growth phase (remainder of the crop) was the longest and the ETc ranged from 138 mm to 189 mm for the three years, and was higher than the irrigation applied for each of the treatments over the three years.

The seasonal ETc for 2008, 2009 and 2010 were 296, 313 and 332 mm, respectively while the seasonal moisture applied (via effective rainfall, irrigation and initial soil moisture) ranged from 271 to 338 mm, 301 to 406 mm and 320 to 459 mm for the four moisture treatments. The net seasonal irrigation water requirement calculated for the same period was 158, 129 and 38 mm respectively. The equivalent depths of irrigation for the four treatments ranged from 102 to 168, 85 to 190 and 58 to 196 mm over the three years. The requisite soil moisture to satisfy crop water requirement was met by two (70% FC and 30 kPa), three (82% FC, 91% FC and 30 kPa) and all the treatments in 2008, 2009 and 2010, respectively. The optimum treatments were found to be those having a soil moisture depletion of ≤ 40% AWC.

The experiment showed that soil moisture sensor based irrigation scheduling can be effectively used to adequately meet crop water requirement over the crop growing season and is excellent for real time irrigation application. Further the use of climatic data is useful in estimating irrigation water requirement for planning purposes. However a combination of the two approaches to accomplish irrigation scheduling can greatly assist growers to better manage their irrigation water.

Table 5.1- Experimental designs over the three years of the project

Year	Experimental Design	Factor 1 – Irrigation Types		Factor 2 – Moisture levels			
2008	Split Plot RCBD	Surface Drip irrigation	Buried Drip irrigation	60% FC	70% FC	80% FC	30 kPa
2009	Factorial RCBD	Surface Drip irrigation	Buried Drip irrigation	74% FC	82% FC	91% FC	30 kPa
2010	Split Plot RCBD	Surface Drip irrigation	Buried Drip irrigation	55% FC	70% FC	85% FC	30 kPa

FC= Field Capacity, RCBD=Randomized Complete Block Design

Table 5.2- Summary of K_c for processing tomatoes and corresponding dates(2008 to 2010)

Growing Stage (phases)	Crop Coefficient (K_c)	Duration for each Years		
		2008	2009	2010
Transplanting to 1st flower (phase 1)	0.4	29th May-19th June 22 days	25th May-23rd June 30 days	15th May-14th June 31 days
1st Flower to Maximum row fill (phase 2)	0.7	20th June-20th July 31 days	24th June-19th July 26 days	15th June-16th July 32 days
Remainder of Crop (phase 3[a])	1.0	21st July- 10th Sept 52 days	20th July- 14th Sept 57 days	17th July- 24th Aug 53 days
		Total =105 days	Total =113	Total = 102

[a] up to harvest

Table 5.3-ETc and ETo calculations for growing stages 2008-2010

Growing Season	2008			2009			2010		
	Duration (days)	ETc (mm)	ETo (mm)	Duration (days)	ETc (mm)	ETo (mm)	Duration (days)	ETc (mm)	Eto (mm)
Phase 1	22	40.0	99.9	30	51.0	127.6	31	49.4	123.5
Phase 2	31	96.9	138.4	26	91.6	130.8	32	109.4	156.3
Phase 3[a]	43	175.1	175.1	43	188.8	188.8	30	138.1	138.1
Total (Termination of Irrigation season.)	97	311.9	413.4	99	331.4	447.2	93	296.9	417.9
Total to harvest	105	342.6	444.1	113	376.3	492.1	102	338.2	459.2

[a] up to termination of irrigation (1st Sept, 31st Aug and 15th Aug. for 2008, 2009and 2010, respectively)

Table 5.4-Season averages per treatment - duration, water applied and the marketable yield.

Treatment	2008 Seasonal Average per Treatment			Treatment	2009 Seasonal Average per Treatment			Treatment	2010 Seasonal Average per Treatment		
	Duration (h)	Water Applied (mm)	Marketable Yield (Mg ha^{-1})		Duration (h)	Water Applied (mm)	Marketable Yield (Mg ha^{-1})		Duration (h)	Water Applied (mm)	Marketable Yield (Mg ha^{-1})
60% FC	59.8	113.0	91.4	74% FC	32.9	85.1	99.8	55% FC	22.5	58.3	102.0
70% FC	81.9	156.4	117.0	82% FC	66.8	172.8	102.1	70% FC	39.9	101.1	107.1
80% FC	53.7	102.0	95.3	91% FC	73.6	190.3	98.0	85% FC	70.0	180.9	115.9
-30kPa	88.1	168.4	114.0	-30kPa	58.6	151.4	102.9	-30kPa	75.9	196.1	119.7

Table 5.5-Season averages per irrigation type*moisture treatment interaction for water applied and Marketable yields

Irrigation type	2008			2009			2010		
	Treatment % FC	Water applied (mm)	Marketable Yield (Mg ha^{-1})	Treatment % FC	Water applied (mm)	Marketable Yield (Mg ha^{-1})	Treatment % FC	Water applied (mm)	Marketable Yield (Mg ha^{-1})
Buried	60%	96.8	80.1	74%	104.16	98.88	55%	67.3	100.6
	70%	117.2	102.6	82%	107.82	104.96	70%	108.7	110.5
	80%	92.4	84.8	91%	131.08	98.57	85%	222.4	122.9
	-30kPa	163.6	104.4	-30kPa	141.78	98.48	-30kPa	199.4	122.0
Surface	60%	131.5	103.7	74%	66.01	100.8	55%	49.2	103.4
	70%	195.5	133.0	82%	237.75	99.21	70%	97.5	103.8
	80%	113.0	107.0	91%	249.58	97.49	85%	139.4	108.9
	-30kPa	173.2	123.9	-30kPa	161.02	107.34	-30kPa	192.8	117.3

Table 5.6-Irrigation depth, effective rain, initial soil moisture, ETc and seasonal irrigation water requirement 2008-2010

Growing Season	Irrigation Depths applied per Moisture Treatment (mm)				Effective Rainfall (mm)	Acc. Effective Rainfall (mm)	Available Moisture Content at Planting (mm)	ETc (mm)	Accumulated ETc (mm)	**Accumulated Soil Moisture via Irrigation, Effective Rainfall and Initial Soil Moisture (mm)**				Seasonal Irrigation Water Requirement (mm)
2008 irrigation season	60% FC	70% FC	80% FC	30kPa						60% FC	70% FC	80% FC	30kPa	
Phase 1	0	0	0	0	66	66		40	40	99	99	99	99	
Phase 2	1	2	1	20	59	125	33	97	137	159	160	159	178	
Phase 3	112	154	101	148	12	137		175	312	283	326	272	338	
Total (at end of Irr. season)	113	156	102	168	137	137	33	312	312	283	326	272	338	**158**
2009 irrigation season	74% FC	82% FC	91% FC	30kPa						74% FC	82% FC	91% FC	30kPa	
Phase 1	0	0	0	0	48	48		51	51	87	87	87	87	
Phase 2	20	42	43	71	27	75	39	92	143	134	156	157	185	
Phase 3	65	131	147	80	102	177		189	332	301	389	406	367	
Total (at end of Irr. season)	85	173	190	151	177	177	39	332	332	301	389	406	367	**129**
2010 irrigation season	55% FC	75% FC	85% FC	30kPa						55% FC	75% FC	85% FC	30kPa	
Phase 1	0	0	0	0	87	87		49	49	132	132	132	132	
Phase 2	48	88	145	148	26	113	45	109	158	206	246	303	306	
Phase 3	10	13	36	49	104	217		138	296	320	363	443	459	
Total (at end of Irr. season)	58	101	181	196	217	217	45	296	296	320	363	443	459	**38**

Table 5.7-Sensor irrigation depth and net irrigation water requirement

Year	Treatment	Eff. rainfall (mm)	Soil moisture[a] (mm)	ET_C (mm)	Irr. applied (mm)	Net irr. water requirement (mm)	Savings relative to NIWR		Marketable Yield (Mg ha^{-1})
							Water Savings (mm)	Water Savings (%)	
2008	60% FC	137	33	312	113.0	158	44.8	28%	91.4
	70% FC	137	33	312	156.4	158	1.4	1%	117.0
	80% FC	137	33	312	102.0	158	55.8	35%	95.3
	-30kPa	137	33	312	168.4	158	-10.6	-7%	114.0
2009	74% FC	177	39	332	85.1	129	43.8	34%	99.8
	82% FC	177	39	332	172.8	129	-43.9	-34%	102.1
	91% FC	177	39	332	190.3	129	-61.4	-48%	98.0
	-30kPa	177	39	332	151.4	129	-22.5	-17%	102.9
2010	55% FC	217	45	296	58.3	38	-20.5	-54%	102.0
	70% FC	217	45	296	101.1	38	-63.3	-168%	107.1
	85% FC	217	45	296	180.9	38	-143.1	-379%	115.9
	-30kPa	217	45	296	196.1	38	-158.3	-419%	119.7

[a] Soil moisture over the 0-30cm depth.

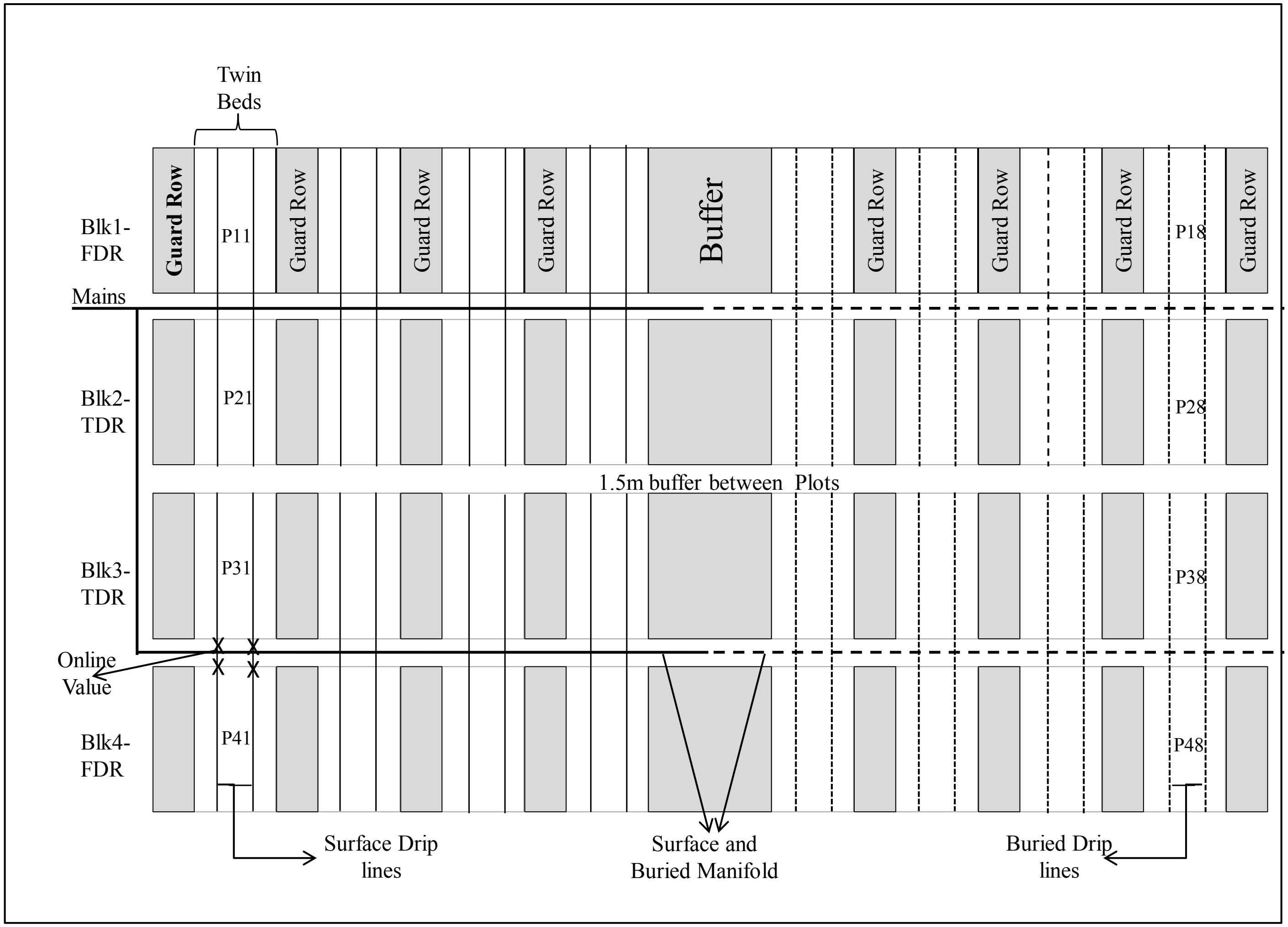


Figure 5.1- *2008 irrigation layout*

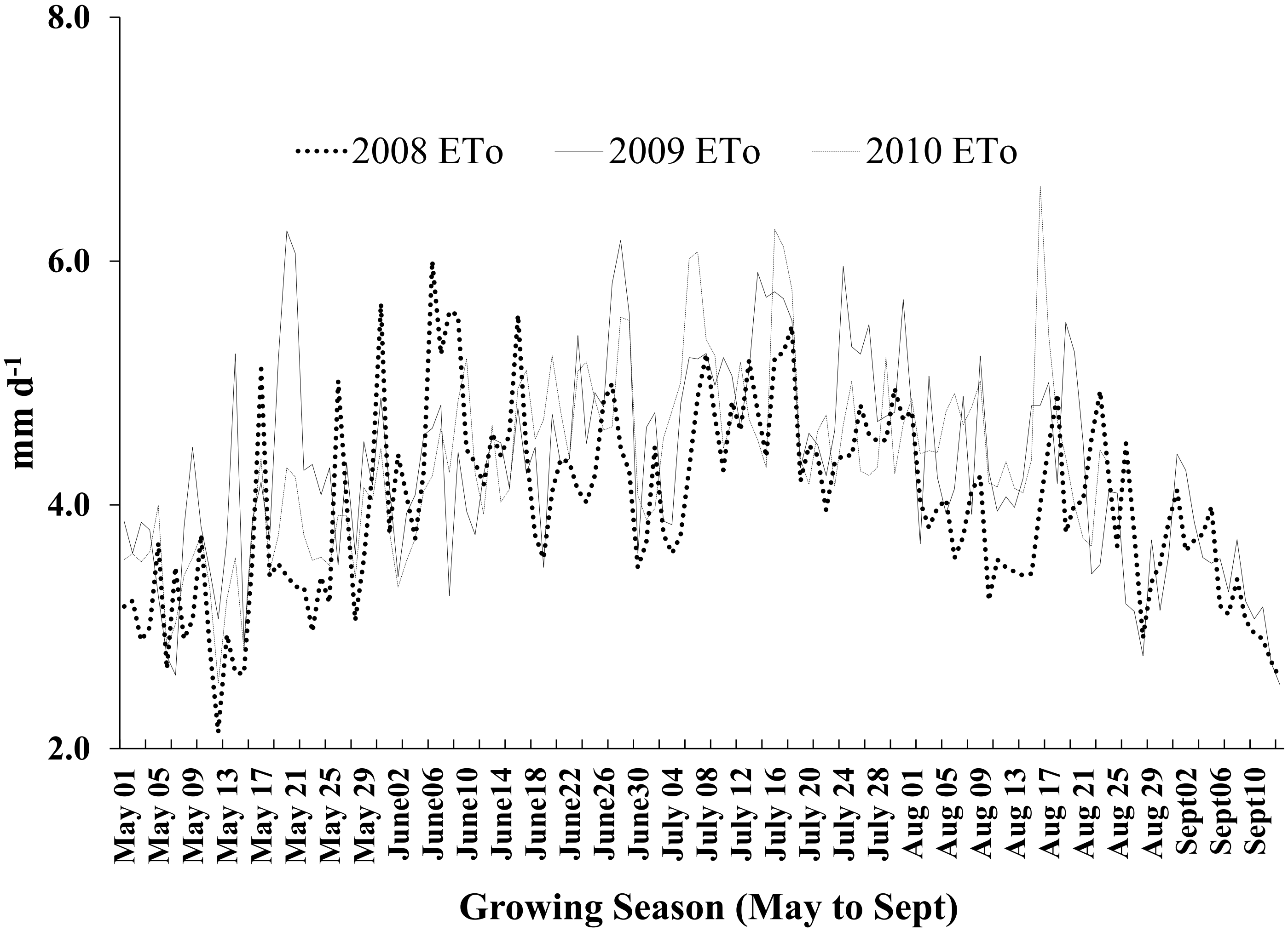


Figure 5.2-Seasonal variation of Reference Evapotranspiration 2008-2010

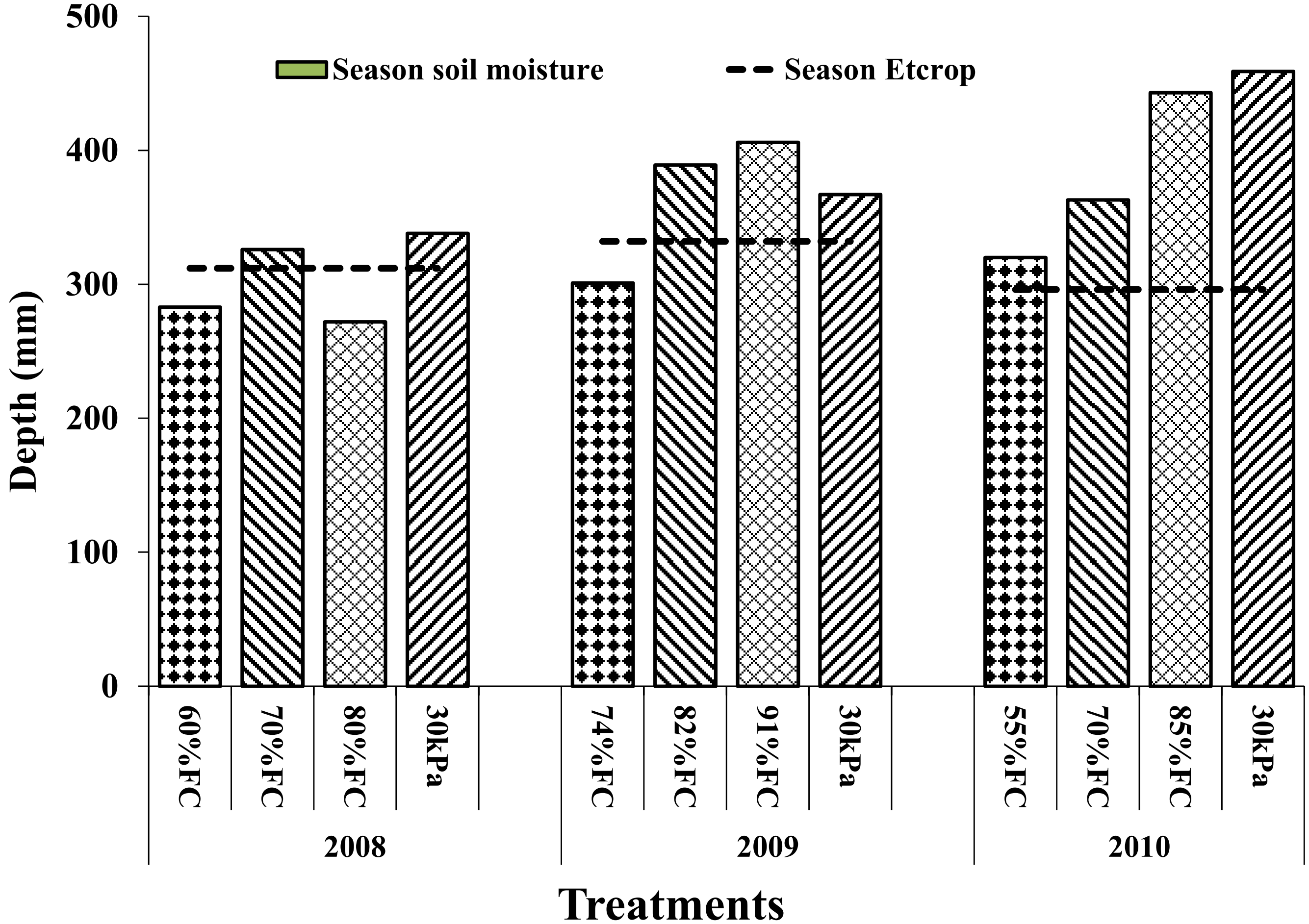


Figure 5.3- Seasonal ETc vs. seasonal soil moisture

Connecting text to Chapter 6

This chapter is a manuscript waiting to be published in 2013. The manuscript is co-authored by my supervisor Dr. C.A Madramootoo. All literature cited in this chapter is listed in the reference section at the end of this thesis.

This paper addresses the aspect of objective two which deals with the testing and development of a protocol for an automated, real-time soil moisture monitoring system for scheduling irrigation. It focuses on the different types of volumetric moisture sensors, their installation, data acquisition and information display. It also addresses the evaluation of the different sensors used.

Chapter 6 – Using Real Time Soil Moisture Measurement to Schedule irrigation

Felix Jaria and Chandra Madramootoo

Abstract

Agricultural production is under growing pressure to more judiciously manage water resources, particularly for irrigated agriculture. The advent of soil moisture sensor technology is recognized as a practical, easy to use, needs based tool to successfully implement precision irrigation. A three year irrigation scheduling project was conducted in Leamington, Ontario using three different soil moisture sensors namely; 625 Campbell Scientific water content reflectometer, Sinteck EnvrioSmart capacitance probe and Hortau tensiometer (Tx and Tx3). The performance of the sensors were evaluated under 10 attributes. The scores were 103, 93 and 71 for the Hortau tensiometer, water content reflectometer and the EnviroSmart respectively. It must however be noted that all three soil moisture sensors could be used as standalone instruments for managing irrigation scheduling for large scale field processing tomatoes. Due to some of the constraints experienced by wired sensors, Wireless Sensor Networks (WSNs) technology is identified as a natural progression. There are promising signs for its use in precision irrigation scheduling.

Keywords: FDR, TDR, tensiometer, irrigation scheduling, irrigation thresholds, Wireless Sensor Network

6.1 Introduction

In the context of irrigation water management, measuring and monitoring soil water status are essential components of best management practices (BMPs) to conserve water and improve water quality. Water content can be measured directly or indirectly. The suitability of each method depends on several issues like cost, accuracy, response time, installation, management and durability (Munoz-Capena & Dukes, 2005). Since the late 1970s, a wide range of competing technologies for sensing soil water have been utilized; however, most have been found deficient in some way (Hignett & Evett, 2008).

Sensor based irrigation is getting increased prominence in agricultural for a wide range of crops due to technological advances. They provide a unique advantage, in that they are now relatively inexpensive, portable, accurate, and easy to use, facilitates immediate display of results and have a visual display that is easily understood. Further they do not require labour, are not based on destructive sampling (after installation), and are adaptable to electronic measurement and recording (Yoder et al., 1998). These indirect methods of monitoring soil moisture are classified as either volumetric or tensiometric. Irrigation scheduling is achieved by allowing soil moisture to deplete or soil matric potential to increase within the root zone to some predetermined threshold (of field capacity or soil available water capacity). The target soil water status is usually set in terms of soil tension (kPa) or volumetric moisture (m^3 m^{-3}) (Muñoz-Carpena and Dukes, 2005).

Most of the sensors suitable for irrigation are dielectric. More than 75 years of research at the international level has gone into establishing the correlation between the apparent dielectric constant (ε_a) of the soil-air-water mixture and soil volumetric water content at different electromagnetic field frequencies. The two main methods which have emerged over the past 30 years are TDR and capacitance (Dean et al., 1987; Evett et al., 2012c; Hoekstra & Delaney, 1974.; Nadler & Lapid, 1996; Smith-Rose, 1933; Thomas, 1966; Topp et al., 1980; Zotarelli et al., 2011). Several investigations also discuss the use of TDR as a tool for irrigation scheduling. A large number of experiments have proven that the TDR technique is useful in studies of real-time soil water content dynamics, with an average interpretation ranging from 2 to 5% error in volumetric water content (Ayars & Phene, 2007; Evett et al., 2011b; Jabro et al., 2009; Madramootoo et al., 2007; Mehdi et al., 2008; Soler & Hoogenboom, 2007).

The tensiometer is one of the oldest and most widely used instruments for irrigation scheduling. Significant developmental changes however have ensued over the years in terms of diameter, length, pressure sensing and automation (Evett & Heng, 2008b). It has been utilized for the measurement of soil water potential from the early 1900’s (Gardner et al., 1922; Livingston, 1908; Richards, 1928), while its use for irrigation scheduling began in the late 1950s (Richards & Marsh, 1961; Smajstrla et al., 1998).

The objectives of this paper are to (1) review the existing indirect methods used in soil moisture monitoring for irrigation scheduling, highlighting the strengths and weaknesses of each; (2) discuss the data processing system utilizing wireless and wired soil moisture sensor systems; and (3) to evaluate three different types of real time soil moisture sensors to effect irrigation scheduling of large scale field tomato production.

6.2 Monitoring soil moisture content

6.2.1 Indirect volumetric method -time domain reflectometry (TDR)

TDR began as a point source measurement technique used in the laboratory and for obtaining field soil water content profiles. The technique offered high spatial and temporal resolution relative to other methods (Topp, 1987; Wraith et al., 2005). TDR is widely used as a non-destructive method to measure soil-water content. TDR determines the relative dielectric of a soil by measuring the propagation velocity of an electromagnetic wave guide along electrodes (Miyamoto & Chikushi, 2006). The TDR instrument generates an electric pulse signal down steel probes called wave guides buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probes (Ledieu et al., 1986). O'Brain and Veldkamp (2000) stated that TDR measure the apparent dielectric permittivity of soil (ε_a). Due to the greater apparent dielectric permittivity of water than other soil constituents, changes in ε_a can be attributed to changes in water content in nonexpanding soils. The estimates of water content are made on the basis of calibration equations, which may be relationships between θ_v and travel time or between θ_v and apparent dielectric permittivity (ε_a), which itself is estimated from the travel time (Evett & Heng, 2008a).

Topp and Davis (1985a) clarified that waveguides could be installed either vertically or horizontally. Vertical guides can be easily installed and removed and provide an integrated measurement of the total soil moisture over the depth of the guide length. Horizontal guides provide a better integration of the spatial variability in the horizontal direction and reduce the potential of preferential flow from the surface to the sensor. However the major disadvantage to the horizontally installed TDR is the fact that an excavation pit is required for installation and removal. TDR is ideally suited to point source monitoring at fixed locations for continuous data collection over the growing season (Wraith et al., 2005). A commonly used empirical relationship between soil moisture and the dielectric constant known as Topp's Equation has been developed (Topp, 1993; Topp & Davis, 1985a; Topp et al., 1980):

$$\theta_v = (-530 + 292\varepsilon_a - 5.5\varepsilon_a + 0.04\varepsilon_a{}^3) * 10^{-4} \qquad Eq.\,6.1$$

Where: ε_a is the dielectric constant and θ_v is the volumetric water content (%)

$$\varepsilon_a = \left[C_0 t_t (2L)\right]^2 \qquad Eq.\,6.2$$

ε_a (F m^{-1}) can be calculated from Eq. 6.2, where C_o is the velocity of light (3 × 108 m s^{-1}), “t” is the travel time along the waveguide in seconds, and “L” is the length of the waveguide in meters. Topp and Reynolds (1998) found that Eq. [6.1] is equivalent to:

$$\theta_v = 0.115 C_o t_t / (2L) - 0.176 \qquad Eq.\,6.3$$

6.2.2 Indirect volumetric method -capacitance probe

The capacitance techniques (impedance probes) for the measurement of soil water operate typically in the radio-frequency regime from 10 MHz up to several hundred MHz. The method determines the dielectric permittivity of a medium by measuring the charge time of a capacitor, which uses that medium as a dielectric (Dean et al., 1987). Capacitance sensors utilize an electronic circuit called an oscillator, which produces a repetitive sinusoidal waveform. It measures the frequency of oscillation, which has an inverse relation with the bulk electrical permittivity such that as the frequency of oscillation decreases there is a corresponding increase in the soil bulk electrical permittivity (and water content) (Evett & Cepuder, 2008). The capacitance method includes the soil as part of a capacitor, in which the permanent dipoles of water in the dielectric medium are aligned by an electric field and become polarized. The electric dipoles must respond to the frequency of the electric field to contribute to the dielectric constant. The freedom of the dipoles to respond is determined by the local molecular binding forces so that the overall response is a function of molecular inertia, the binding forces, and the frequency of the electric field (Dean et al., 1987).

Capacitance probes have the ability to measure soil water levels at different depths down the soil profile and record information on a data logger which can then be transferred to a computer. The sensor is placed in a waterproof access tube in the ground and records are made at 100 mm increments along the profile. The information collected can be displayed as graphic display of the soil moisture content at different depths down the profile. It has a high response time to a change in moisture which makes it possible to obtain a precise monitoring of the water content in the soil (Evett et al., 2009; IIda et al., 2005). Capacitance sensors consist essentially of a pair of electrodes (either an array of parallel spikes or circular metal rings) which form a capacitor with the soil acting as the dielectric in between. This capacitor works with the oscillator to form a tuned circuit, and changes in soil water content are detected by changes in the operating frequency.

Compared with time domain reflectometer (TDR), FDR sensors are cheaper to build and have a faster response time. They also have lower power consumption. However because of the complex electrical field around the probe, the sensor needs to be calibrated for different soil types, particularly soils with high clay and organic content (O'Brain and Veldkamp, 2000).

Advantages and disadvantages of dielectric sensors

These sensors are attractive because they can be automated and can be safely installed in the field to generate continuous soil moisture data over the growing season without causing any environmental hazards. The response time is quick.

The main limitation is their small sphere of influence governed by the volume of soil surrounding the probe and this is limited to only a few centimeters, approximately 10 cm radius, with 95% of the sphere of influence within 5cm radius. This makes them sensitive to inconsistencies introduced through installation such as air gaps beside access tubes or probes. They require calibration in the field for the most precise results. Concerns about shrink-swell soils creating air gaps next to the access tube for FDR and probe for TDR give incorrect readings (Chanzy et al., 1998; Charlesworth & Munro, 2005; Evett, 2007; IIda et al., 2005). In addition, Dean et al. (1987) and Chanzt et al. (1998) have demonstrated that the heterogeneity of the soil around the electrodes can affect the response of the sensors to the volumetric moisture content (θ). The sensors are relatively expensive equipment due to complex electronics. They have potentially limited applicability under highly saline conditions or in highly conductive heavy clay soils. The presence of macro pores, rocks, roots channels, and large aggregates may influence field TDR measurements (Timlin & Pachepsky, 1996).

6.2.3 Indirect tensiometric- tensiometer

Tensiometers measure the soil water tension that can be related to the soil water content. A tensiometer is a sealed, water-filled device that exchanges water with the soil through a porcelain cup (Cassel & Klute, 1986; Hubbell & Sisson, 2003). Tensiometers work best in coarse textured soil or in fine soils, such as clay, when relatively high soil moisture content in maintained. A tensiometer is a cylindrical pipe approximately 25mm in diameter with a porous ceramic cup attached to one end and a vacuum gauge to the other. The porous cup allows water to flow in and out of the tensiometer as soil moisture content changes. As soil dries, soil moisture decrease and the soil moisture tension increases. This decrease in soil moisture content causes water to flow out of the tensiometer through the porous cup, and the tensiometer gauge reads higher and higher (Shock & Wang, 2011). During irrigation, soil moisture content increases and there is a corresponding decrease is soil moisture tension which facilitates the water flow into the tensiometer. This results in a decrease in the tensiometer readings (Hanson et al., 2004). Water flows in and out of the tensiometer only if the porous cup is saturated with water, If the cup desaturates, then little or no flow occurs and air enters the tensiometer and eventually the instrument stops working (Hanson et al., 2004; Shock & Wang, 2011).

Advantages and disadvantages of the tensiometer

There are a range of advantages associated with the tensiometer. The soil status could be read directly from an analog or digital display (Shock & Wang, 2011). It also has a measuring radius of approximately 0.1 m. Electronics and power consumption are avoidable, however, logging of tensiometers is possible via transducers and a communication cable back to a computer or data logger (Cassel & Klute, 1986; Hubbell & Sisson, 2003). Further it is well-suited for high frequency sampling or irrigation scheduling and requires minimum skill for installation and maintenance. It is not affected by soil salinity since salts can freely move in and out across the porous ceramic cup and it is relatively inexpensive. The soil suction reading relates directly to the plant water tension, and hence is a more meaningful measure of plant stress than the soil water content (Charlesworth and Munro, 2005; Cassell and Klute. 1986; Zazueta et al., 1994). Tensiometers with enhanced responsiveness are recommended for highly stress-sensitive crops grown in coarse or artificial soil mixes (Oki et al., 1995).

The main disadvantage of the tensiometer is that it functions only from zero to about 80 kPa, which represents a small part of the entire range of available water (Zazueta et al., 1994). Charlesworth and Munro (2005) added that while they may prove adequate for most annual vegetable crops, orchards, nuts and pastures, they are however inadequate for the controlled stressing of plants such as grapevines using regulated deficit irrigation and partial root zone drying, where suctions can be as high as 200 kPa. Tensiometers require protection from freezing by covering, removal from the field, draining, or filling with 25% isopropyl alcohol, depending on the severity of the freezing weather (Shock & Wang, 2011).

6.3 Data Acquisition and processing

The purpose of any data acquisition system is to gather useful measurement data for characterization, monitoring, or control. The acquisition of good and reliable data requires suitable sensors, data loggers, a reliable retrieval method and display of data. Bellingham (2009) indicated that real time data acquisition systems are the most effective tool for identifying and reaching soil moisture and water application targets for irrigation optimization.

The following section discusses the data acquisition process which included soil moisture sensors, data collection and retrieval mechanism, and the information display. Over the three years of the tomato irrigation project (2008 to 2010), three different soil moisture sensors were used as in situ instruments to monitor soil moisture in real time and to manage the irrigation scheduling program during the irrigation season. They included: two volumetric sensors (the Sentek EnviroSMART™ Sentek Sensor Technologies, Stepney, Australia, Campbell Scientific 625 Water Content Reflectometer, Campbell Scientific Inc., UT) and one tension based sensor (Irrolis™ Sense, Hortau Inc., QC, Canada).

6.3.1 Soil moisture sensors

Sentek EnviroSMART™ sensor

The EnviroSMART FDR is an in-situ multi-sensor soil water capacitance probe that continuously measures soil moisture over multiple depths in a crop's root zone and records information on a data logger which can then be transferred to a computer. The capacitive element of the sensor is placed within a waterproof access tube in the soil and records can be made at 100 mm increments along the profile (O'Brain & Veldkamp, 2000). It works on the capacitance principle and measures the change in capacitance of the soil depending on the moisture level, as there is a large difference in the apparent dielectric constant of soil (<10), air (1) and water (80). Each capacitor sensor consists of two metal rings (paired electrodes) mounted on the circuit board. An oscillating electrical field is generated between the two rings and extends into the soil medium through the wall of the access tube which forms the dielectric of the capacitor and completes the oscillating circuit. The output of the sensor is the frequency response of the soil's capacitance due to its soil moisture level (Bell et al., 1987; Dean et al., 1987).

CS625 Water content reflectometer

The CS625 water content reflectometer is designed to measure volumetric water content of soils and/or other porous media. The TDR measures the apparent dielectric permittivity of the media around the probe, which is related to the soil moisture content. The CS625 consisted of two 30 cm stainless steel rods connected to a printed circuit board (PCB), which is protected with an epoxy coating. A protected conductor cable from the circuit board of the TDR is connected to a CR200 series data logger which enables the probe and monitors the pulse output (Campbell Scientific Inc., 2006).

Irrolis Sense Tx sensor

The Irrolis Sense Tx (from Hortau^{TM}) electronic tensiometer operates on the classical tensiometer principle as previously described. It is equipped with a reservoir for water and a porous ceramic attached to the end to be installed in the soil. The sensor may be equipped with or without a temperature sensor. It is connected to an LCD above the ground via a cable which displaces both the tension and temperature readings (if attached).

6.3.2 Soil moisture data collection

The TDR and FDR sensors were connected to the CR200 series data logger while the Hortau tensiometers were connected through the Hortau wireless network.

6.3.2.1 Data logging and retrieval – for CS625 and EnvroSMART

The volumetric sensors (CS625 Water Content Reflectometers and EnviroSMART) were wired to 12 solar powered data loggers (model CR205/6, Campbell Scientific International, Canada Corp.) strategically located throughout the project site with each housed within a protective covering. The CR206 was connected to an external battery and had a built-in charging regulator for charging a 12 V lead-acid battery from an external power source, such as a solar panel. The power consumption of the logger is 0.7 and 12 mA during dormant and processing modes respectively.

Data was retrieved from the CR206 using a computer and Campbell Scientific Inc. software (LoggerNet). Logger Net 3.4.1 is the support software for many Campbell Scientific Inc. (CSI) data loggers. It enables the user to setup, configure, program and retrieve data from a network of Campbell Scientific Data loggers. Three modes of data retrieval were utilized to ensure that minimal data was lost during data retrieval over the season. Data was collected directly by connecting the CR206 data loggers to a field laptop through the female RS-232 9-pin interface for logger-to-PC communications. Data was also remotely retrieved by wireless telemetry via a RF400 Spread Spectrum Radio and field laptop and via an intermediate hub station (equipped with a RF400 Spread Spectrum Radio) and an onsite desktop computer. Soil moisture and soil temperature readings were scanned every 5 minutes and recorded every 15 minutes¸ hourly and daily.

6.3.2.2 Hortau Wireless Network

During the 2008 and 2009 irrigation seasons the Hortau wireless networks consisted of Irrolis Sense Tx monitoring station, tensiometers, Irrolis Com WR, Irrolis Com Base and Irrolis software (Irrolis light) for interfacing with an onsite computer. In 2010 a more elaborate wireless sensor network (WSN) was used, which included an Irrolis MultiSense Tx3 monitoring station, tensiometers, web base station and web server. Brief discussions follow on the two approaches. They will be referred to as Irrolis Sense Tx and Tx3 systems, respectively.

Irrolis Sense Tx System

The field monitoring station and Irrolis Sense Tx tensiometer was combined into one unit via a cable from the tensiometer. It was powered by 4 AA batteries and was equipped with an LCD, antenna, internal electronics and housed within a compact unit. The unit can be found with or without a temperature probe. The soil tension and temperature data could be read directly in the field from the LCD during irrigation but also communicated to the onsite desktop computer via the Irrolis COM WR (wireless receiver), Irrolis COM BASE and the Irrolis software installed on the onsite computer. A cable connected the Irrolis COM BASE with the computer's port. This enabled the software to access the near real time data from each of the sensors in the field, generating continuous tension plot and automatically saving the raw data. The Irrolis monitoring Software (Irrolis light 1.7) enabled the sensors in the field to communicate to the base computer. It comprised five main menus: the history, status, zone, communication and alarm set point screens. The history screen provided a graphical display of the soil tension over the day, week, month or year. It also allowed for the setting of the upper and lower tension threshold values. The status menu provided near real time tension values for each sensor, the sensor signal strength and battery status. The zoning menu facilitated the assignment and description of each sensor to the requisite plot or zone. The software also facilitated the downloading of the raw data which can be further processed by other software.

Irrolis Multisense Tx3 System

Hortau field monitoring Station

The Hortau Tx3 field monitoring station was installed directly in the field and had three ports to accommodate a soil temperature sensor, a radiation shield (which simultaneously measure air temperature and relative humidity) and a tensiometer. It was battery powered and was equipped with an LCD, antenna and internal electronics. While the Tx3 field monitoring station wirelessly transmitted information from the field to the Hortau Web Base Station, it had to be installed in the field and within close proximity to the sensors.

Web Base Station

The Hortau web station was powered by solar energy with a battery for storing the excess electrical energy. It received data from the field Tx3 field monitoring stations, which was subsequently processed and transmitted to the Hortau Web Server. The connection between the Web Base Station and the web server was facilitated through cellular networks. The Web Base Station was installed approximately 200 m east of the research site, on a metal pole with a free line of site for receiving signals from the field monitoring stations approximately 200 m east. Data from the base station was stored on the Hortau's web server using a web-based application software, Irrolis Web. The web software provided a number of options for viewing and retrieving data and included: a map providing a quick overview of the current measurements in the field. Historic data can be graphed using various time scales (15 minutes, hours, days, months and years). Reports could be generated and data can be retrieved using the export data option.

6.4 Information display

The LoggerNet 3.4.1, Irolis Light 1.7 and Irrolis Web software were used to interface with the volumetric and tensiometric sensors, and were equipped with numeric and graphical display capacity in near real time. The software facilitated the setting of threshold alarms that would inform the irrigation scheduling process. The raw data was also downloaded and processed using Excel.

6.4.1 Graphical display

Figures 6.1 to 6.8 depict a combination of soil tension and soil moisture profiles for the four moisture treatments during the irrigation scheduling programs of 2008, 2009 and 2010, using electronic tensiometers, TDR and FDR sensors. In 2008 and 2010, the -30 kPa treatment represented the least stress treatment, corresponding to a soil moisture content of approximately 88% FC or 24% depletion in AWC. It attained to trigger more frequently than the other moisture treatments (Fig. 6.1a, 6.1b) and therefore, would receive the most irrigation (Table 6.1).

The tensiometers monitored the soil tension at the 15 and 45 cm depths along the profile. However, the 15 cm depth represented the critical depth for accomplishing irrigation scheduling. The upper and lower irrigation thresholds were 10 and 30 kPa respectively. In 2008, an intermediate lower threshold of -20 kPa was used between the 13 and 23 July, to ensure that the growing seedlings were not unduly stressed and was subsequently lowered to 30 kPa for the remainder of the season. This intervention; however, was not implemented in 2009 and 2010.

The TDRs were monitored at two depths: 0 to 30 and 30 to 60 cm in 2008 and 2010 and at 5 to 25 and 25 to 55 in 2009. The FDRs were monitored at 5 depths (5 to 15, 15 to 25, 25 to 35, 45 to 55 and 55 to 65 cm). Only three depths (10, 20, and 30 cm depths) are depicted in the graphical display for the FDRs to avoid overcrowding (Figs. 6.4 and 6.5). The critical depths for undertaking irrigation scheduling for the TDR and FDR were the 0 to 30 cm (5 to 25 in 2009) and 15 to 25 cm, respectively.

The 2008 moisture display revealed high soil moisture content during the early part of the season due to the antecedent moisture condition as a result of snow melt and the subsequent spring rainfall. The soil moisture gradually depleted and reached field capacity about mid-July and irrigation scheduling commended in earnest about a week later. The objective of the irrigation scheduling program was to ensure that the soil moisture status was kept between the upper and lower thresholds throughout the growing season. This was satisfactorily accomplished as are reflected in the graphical displays. It must however be noted that the smaller the threshold interval (85% FC) the more challenging to maintain the moisture level within the upper and lower levels (Fig 6.2b), as more vigilance is required due to the redistribution of soil moisture after the irrigation events. During the latter part of the irrigation scheduling program, the rainfall impact was minimal, since there was only one rainfall event which had a rainfall depth of over 5 mm.

In 2009, there were fewer rainfall events at the beginning of the season. Towards the latter half of the season, rainfall events were more frequent; as a result the soil moisture attained to field capacity about a week earlier as compared to 2008 (Figs. 6.4 to 6.6). The rainfall distribution subsequent to the commencement of the irrigation scheduling program had a greater impact than the previous year. In 2010, rainfall was concentrated during the early part and latter part of the season. The irrigation was mainly concentrated during the middle part of the season (Figs 6.7 and 6.8).

Table 6.1 summarizes the average duration, irrigation depth, effective rainfall and the irrigation events for each of the moisture treatments over the three years of the research. Generally the most stressed treatment in each of the years received the least irrigation depth and irrigation events, while the least stressed treatment received the highest irrigation depth and irrigation events. The results indicated that the three different types of soil moisture sensors were capable of accomplishing irrigation scheduling.

6.5 Evaluation of sensors

Charlesworth and Munro (2005) lamented the lack of a universal test and calibration method for evaluation of soil moisture sensors and further added that due to this constraint, adoption of soil water sensing devices for irrigation scheduling by the agrarian community has been limited. The evaluation of the three types of sensors combined a selection method outlined by Cape (1997) along with on-field evaluation over the three years of the research. Close monitoring of the sensors was done during the growing seasons to ensure that all possible factors affecting or enhancing the performance of the sensors were identified and duly noted. A substantial amount of information was gathered to provide a realistic assessment. The sensors were evaluated under 10 attributes. Each attribute was given a weighted score based on its relative importance. Close ended question(s) were associated with each attribute or sub attribute. A value of "1" and "0" was assigned to each "YES" and "NO" answer, respectively (Table 6.2). The subtotal for each attribute was accumulated to give total scores for each sensor type. The final scores were 103, 93 and 71 for the Hortau tensiometer, CS625 Water content reflectometer and EnviroSMART respectively.

There were no differences in the first five attributes examined (effective range of measurement, accuracy, soil Type (for use with range of soils), reliability, and frequency of measurements). However, the latter five attributes (soil disturbance during installation, data handling, communication, operation and maintenance and availability and technical assistance) indicated some differences especially with the operation and maintenance attribute.

Soil disturbance was evaluated over two depths, < 30 cm and > 30 cm. The TDR contributed to minimal soil disturbance at the shallower depth due to the vertical mode of installation. The FDR caused the most soil disturbance during the installation of the PVC housing tube. Some soil disturbance was necessary for the installation of the tensiometer. However, once installed and connected to the base computer, the data handling and communication for the tensiometer was the easiest because the software provided a continual display of the real time data. The operation and maintenance attribute had 10 sub-components, with the tensiometer and EnviroSMART having scores of 16 and 4 out of 20, respectively.

Attribute 10 may be considered a bit subjective and would vary depending on the geographic location of the evaluation. The Hortau tensiometer is a Canadian product and hence would bias the result associated with attribute 10, whereas if the evaluation was done in USA or in Australia then the result would bias the CS625 and the EnviroSMART respectively. Attribute 10 results did not affect the overall outcome of the evaluation. Despite its apparent subjectivity, it is nevertheless an important point for consideration.

6.6 Wireless vs. wired technology

WSNs can operate in a wide range of environments and provide advantages in cost, size, power, flexibility and distributed intelligence, compared to wired technology. Bus architectures reduce wiring and required communication bandwidth. Wireless sensors further decrease wiring needs, providing new opportunities for distributed intelligence architectures (Baronti et al., 2007).

In a wired network, the risk of cutting communication from sensor to logger persists due to farm operations and traffic within the vicinity of the instrumentation. The WSNs eliminates all the problems arising from wires in the system. Due to the ability of WSNs to provide self-organizing, self-configuring, self-diagnosing and self-healing capabilities to the sensor nodes, wireless sensor networks allow faster deployment and installation of various types of sensors. Some of them also allow flexible extension of the network (Wang et al., 2006). Wireless sensor devices facilitates the installation of sensors in places where cabling is difficult or impossible, such as road crossings, water channel or along the travel path of farm machinery.

Another advantage of wireless sensors is their mobility. These sensors can be placed in transporting vehicles to monitor the “on-the-go” environment. Most wireless sensors have signal conditioning and processing units installed at the location of the sensors and transmit signals in the digital form. As a result, noise pick-up becomes a less significant problem. Moreover, since wires are deleted from the transmission, reliability of signal transmission is enhanced (Wang et al,. 2006). A major advantage of the wired network is that it is a very reliable and stable communication system for instruments and controls.

However, wireless technology promises lower installation costs than wired devices (Maxwell & Williamson, 2012).

6.7 Conclusions

The advent of soil moisture sensors technology is recognized as a practical, easy to use, needs base tool to successfully implement precision irrigation. Soil moisture sensors are broadly divided into two main categories; volumetric and tensiometric sensors. All sensors have advantages and disadvantages, however a proper understanding of the limitation of each sensor and respecting their limitations would allow for successful irrigation scheduling.

Three different soil moisture sensors were evaluated over a three year period using ten attributes. The score for each attribute was totaled to give a final score for each of the three sensors. The scores were 103, 93 and 71 for the Hortau tensiometer, CS625 Water content reflectometer and EnviroSMART respectively.

It must however be noted that all three sensors can be used as standalone instruments for managing irrigation scheduling for large scale field processing tomatoes. It was found that the tension based sensor was the most grower friendly sensor. The two volumetric sensors also performed very well but are more geared towards research work. The next logical step from wired sensors is WSNs. WSNs are emerging as an invaluable tool in agriculture. There are promising signs in its use in precision irrigation scheduling.

Table 6.1--Irrigation scheduling summary per treatment

2008 Season average per treatment						**2009 Season average per treatment**						**2010 Season average per treatment**					
Treatment (% FC)	Duration (h)	Volume of appl. (l)	Equivalent depth (mm)	Effective rainfall (mm)	Total irrigation events	Treatment (% FC)	Duration (h)	Volume of appl. (l)	Equivalent depth (mm)	Effective rainfall (mm)	Total irrigation events	Treatment (% FC)	Duration (h)	Volume of appl. (l)	Equivalent depth (mm)	Effective rainfall (mm)	Total irrigation events
60%	59.8	1464	114	167.2	12	74%	32.9	582	85	186	11	55%	22.5	399	58	294.2	4
70%	81.9	2006	156	167.2	20	82%	66.8	1182	173	186	16	70%	39.9	705	103	294.2	7
80%	53.7	1317	103	167.2	17	91%	73.6	1302	190	186	23	85%	70.0	1238	181	294.2	15
30kPa	88.1	2160	168	167.2	30	30kPa	58.6	1036	151	186	27	30kPa	75.9	1342	196	294.2	18

Table 6.2-Table 2-Sensor Evaluation

#	Attributes	Weight	Sensors					
			Water Content Reflectometer (TDR)		**EnviroSMART (FDR)**		**Irrolis™ Sense (Tension Base)**	
			Points	Score	Points	Score	Points	Score
1	**Effective Range of measurement.** Is SWS able to measure all ranges of soil water of interest to you? (Yes=1, No=0)	8	1	8	1	8	1	8
2	**Accuracy** Is Sensor accuracy enough for your purpose? (Yes=1;No=0)	14	1	14	1	14	1	14
3	**Soil Type (for use with range of soils)** Is sensor accuracy affected by the soil type? (Yes=1;No=0)	11	1	11	1	11	1	11
4	**Reliability** Do you have any personal, other users' feedback of the reliability of sensor and is the failure rate satisfactory to you? (Yes=1;No=0)	13	1	13	1	13	1	13
5	**Frequency** Can the sensor provide quick or frequent readings? (Yes=1;No=0)	13	1	13	1	13	1	13
6	**Soil disturbance during installation** Is there Minimal soil disturbance during installation of shallow sensor (0-30cm depth)? (Yes=1;No=0)	8	1	8	0	0	0	0
	Is there minimal soil disturbance during installation of deeper sensors (>30cm depth)? (Yes=1;No=0)	4	0	0	0	0	0	0
7	**Data handling** Is reading or interpreting data straightforward? (Yes=1;No=0)	8	0	0	0	0	1	8
8	**Communication** (for remote data manipulation) Does sensor provides data logging and downloading capabilities and software for analyzing and interpreting data? (Yes=1;No=0)	8	1	8	1	8	1	8
	Is software for analyzing and interpreting data Grower/Farmer	4	0	0	0	0	1	4

#	Attributes	Weight	Sensors					
			Water Content Reflectometer (TDR)		**EnviroSMART (FDR)**		**Irrolis™ Sense (Tension Base)**	
			Points	Score	Points	Score	Points	Score
	friendly? (Yes=1;No=0)							
9	**Operation and maintenance(**0.1 for every **Yes** answer)	**20**						
	Is sensor calibration universal?		0.0	0	0.0	0	0.1	2
	Has SWS got long life (>5 years)?		0.1	2	0.1	2	0.1	2
	Is sensor easy to Install?		0.1	2	0.0	0	0.1	2
	Is sensor maintenance free?		0.1	2	0.0	0	0.0	0
	Is sensor easy to be relocated if necessary?		0.1	2	0.0	0	0.1	2
	Is trouble shooting for sensor an easy task?		0.1	2	0.0	0	0.1	2
	Is sensor Grower Friendly?		0.0	0	0.0	0	0.1	2
	Is sensor and cables secure from machine damage after installation?		0.0	0	0.0	0	0.0	0
	Is senor unaffected by prolonged high water table?		0.1	2	0.1	2	0.1	2
	Is removal of sensors at the end of the season easy?		0.1	2	0.0	0	0.1	2
	Sub-Total		0.7	14	0.2	4	0.8	16
10	**Availability and Technical Assistance** (0.5 for every YES answer)*	8						
	Is technical Assistance is readily available?		0	0	0	0	0.5	4
	Is sensor readily available (within 1 month)?		0.5	4	0	0	0.5	4
	Sub-Total		0.5	4	0	0	1.0	8
	Overall Total			93		71		103

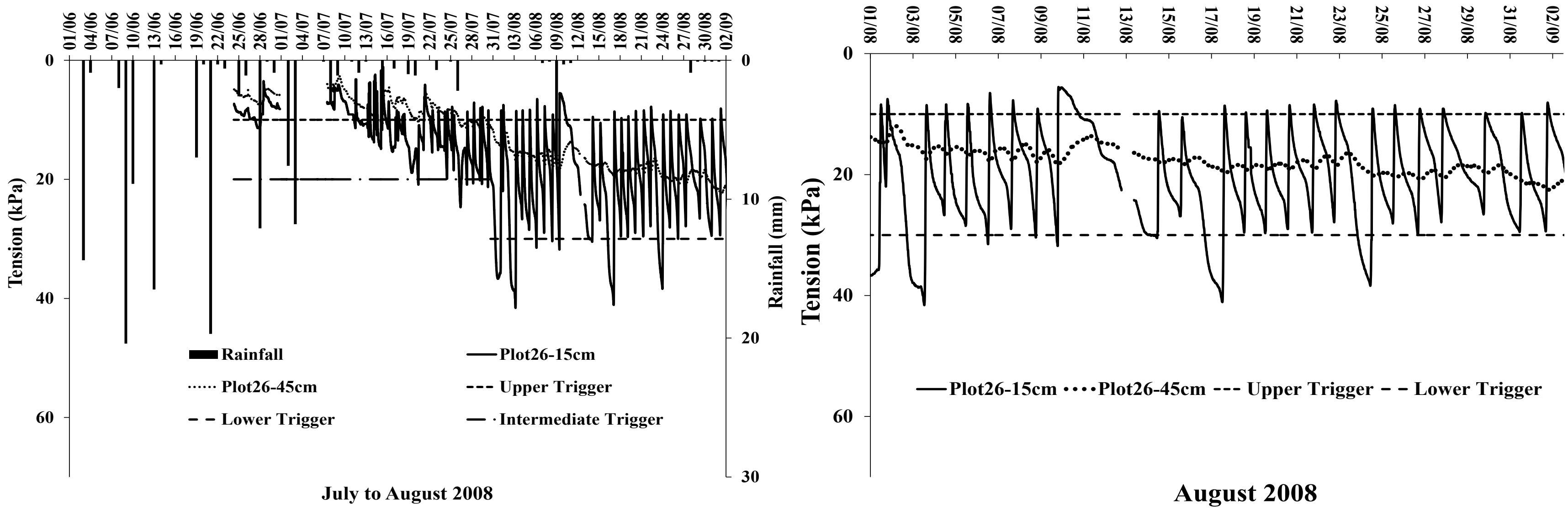


Figure 6.1-Figure 6.1a- Soil tension profile at 15 and 45 cm depths for plot 26 with rainfall superimposed. Figure 6.1b- Expanded version of soil tension profile at 15 and 45 cm depths for plot 26 for the month of August 2008.

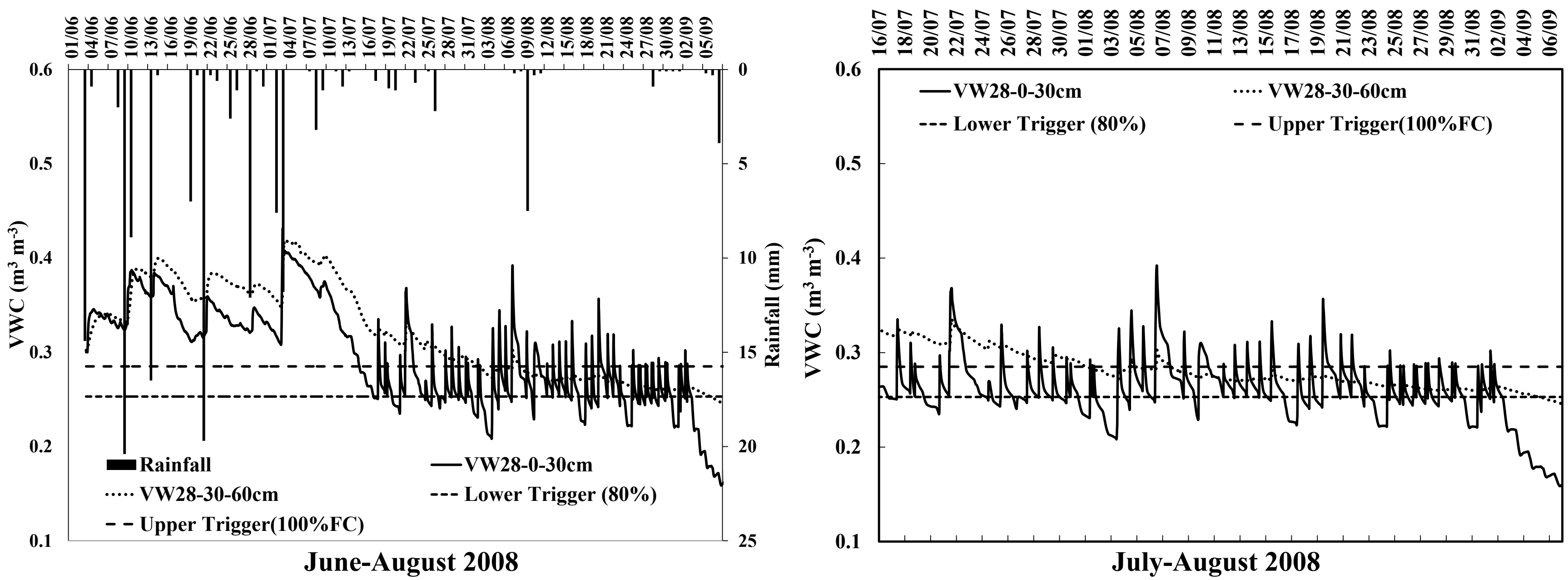
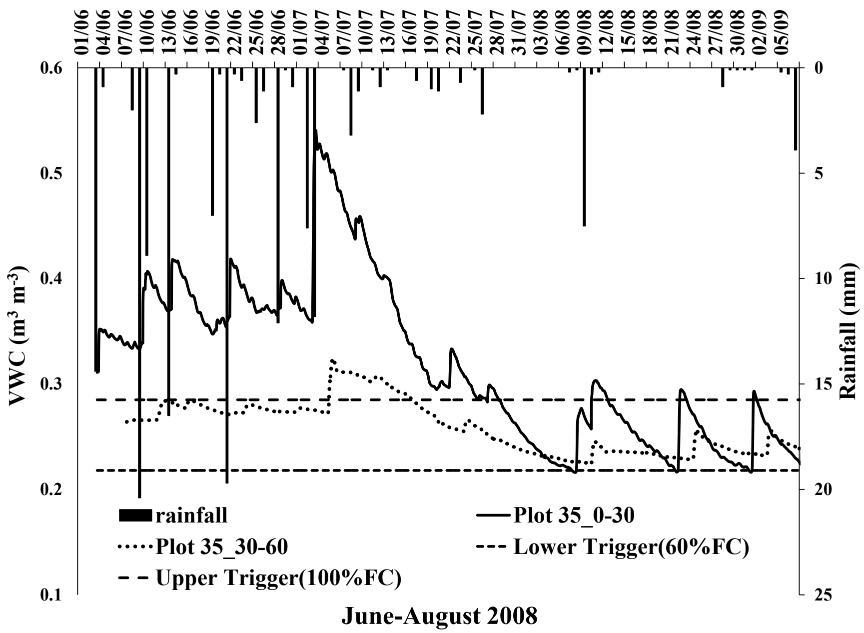


Figure 6.2-Figure 6.2a- VWC profile at 0 to 30 and 30 to 60 cm for plot 28 (80 % FC treatment) using TDR. Figure 6.2b – VWC profile at 0 to 30 and 30 to 60 cm for plot 28 (80 % FC treatment) from the 16 July to 2 September 2008 using TDR.



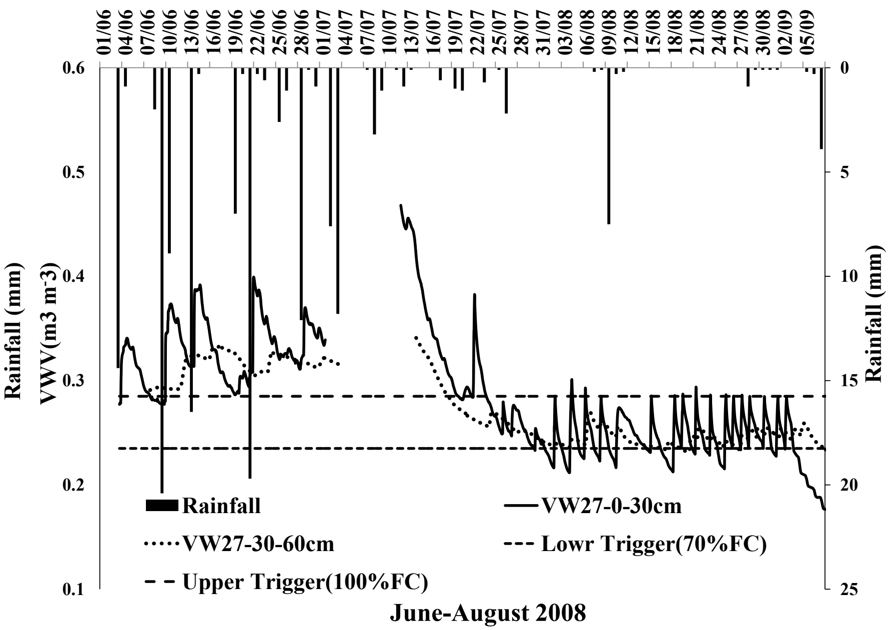
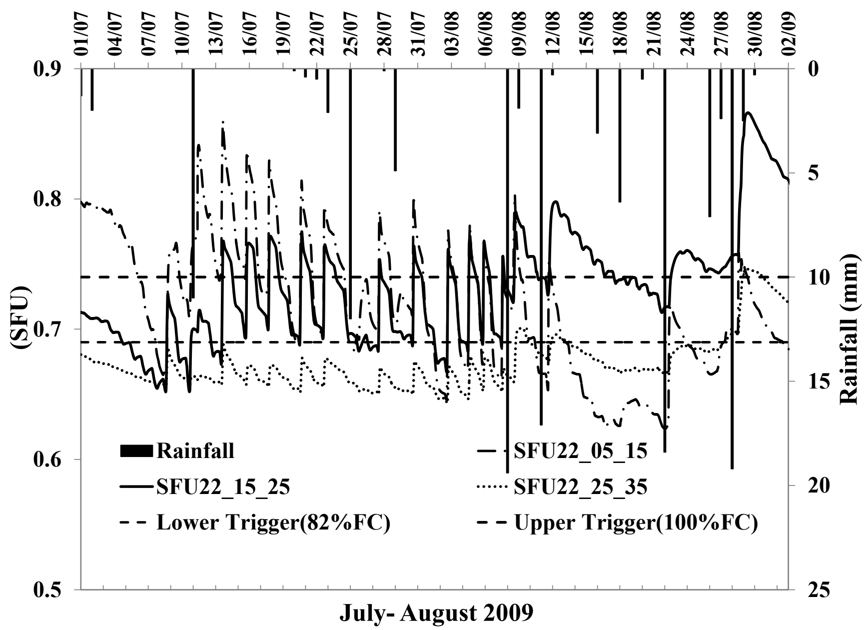


Figure 6.3-Figure 6.3a- VWC profile at 0 to 30 and 30 to 60 cm for plot 35 (60 % FC treatment) using TDR. Figure 6.3b – VWC profile at 0 to 30 and 30 to 60 cm for plot 27 (70 % FC treatment) using TDR - 2008



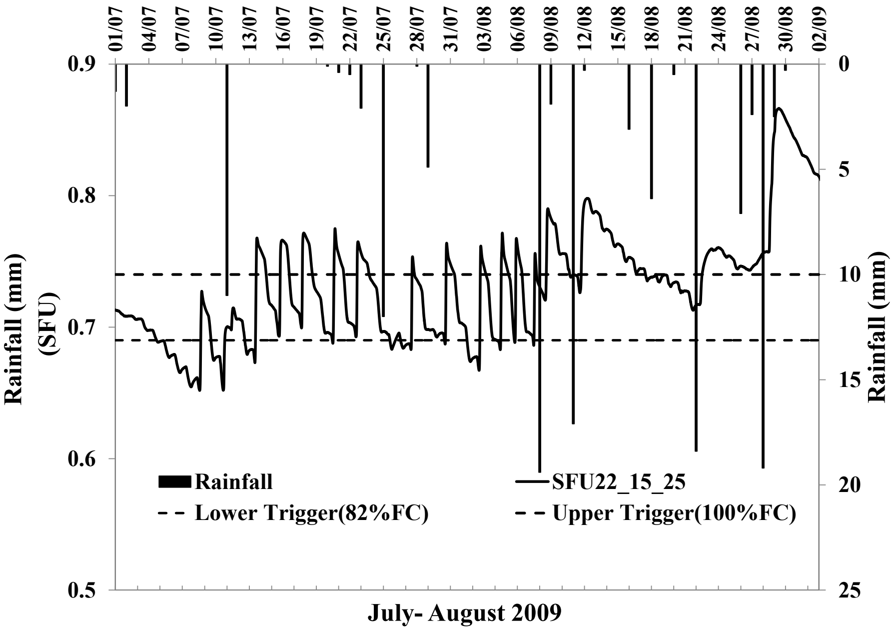


Figure 6.4 Figure 6.4a- Soil moisture profile at 5 to 15, 15 to 25 and 25 to 35depths for plot 22 (using FDR) with rainfall superimposed. Figure 6.4b- Soil moisture profile at 15 to 25 cm (critical irrigation depth) for plot 22 with rainfall superimposed – 2009

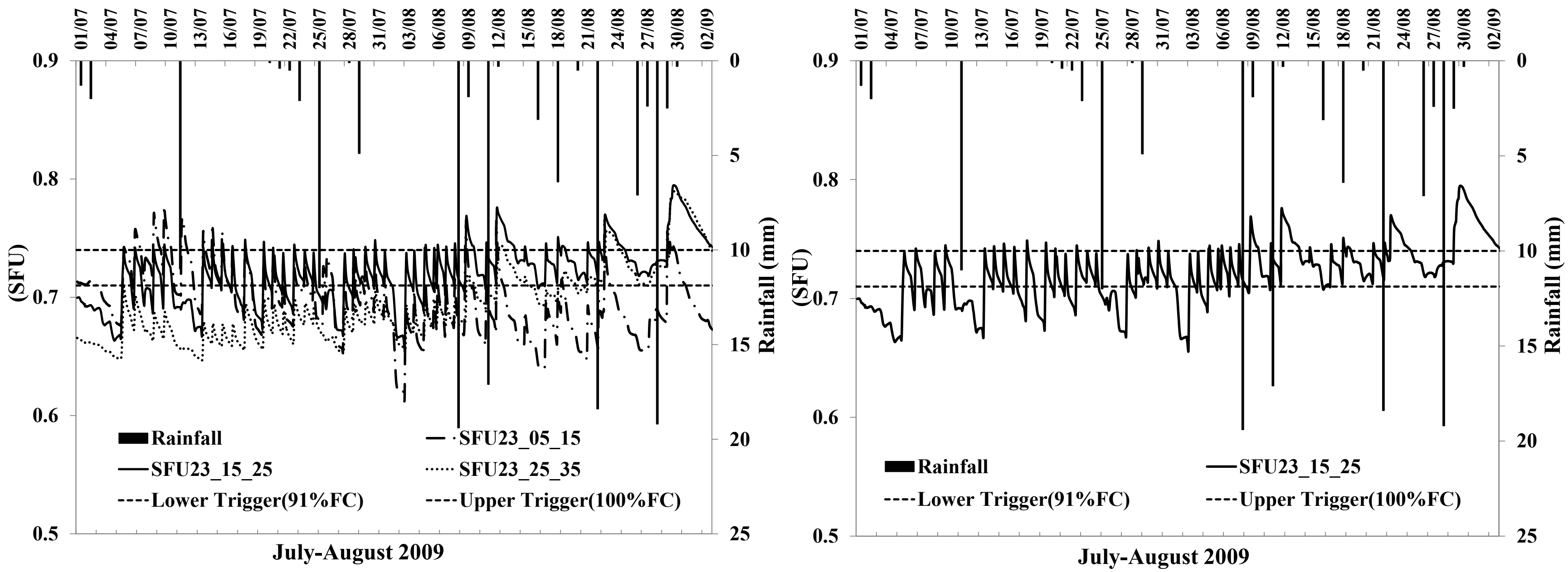


Figure 6.5- Figure 6.5a- Soil moisture profile at 5 to 15, 15 to 25 and 25 to 35depths for plot 23 (using FDR) with rainfall superimposed. Figure 6.5b- Soil moisture profile at 15 to 25 cm (critical irrigation depth) for plot 23 with rainfall superimposed – 2009

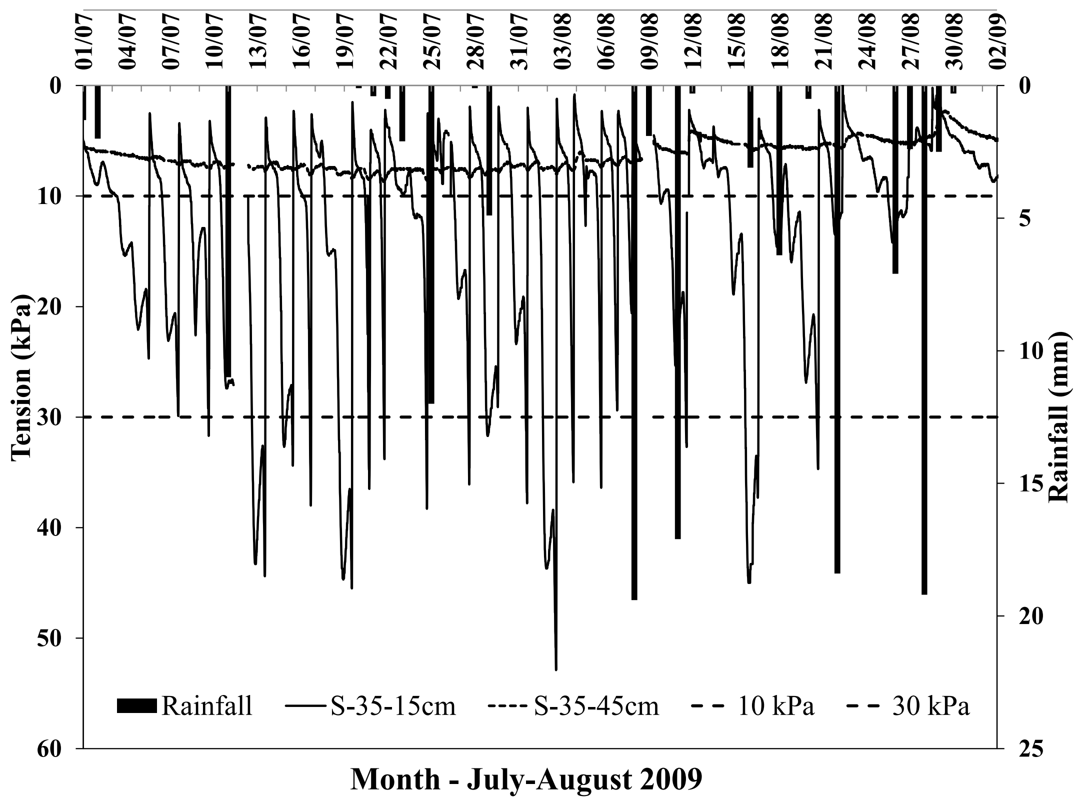


Figure 6.6- Soil tension profile at 15 and 45 cm depths for plot 35 with rainfall superimposed – 2009

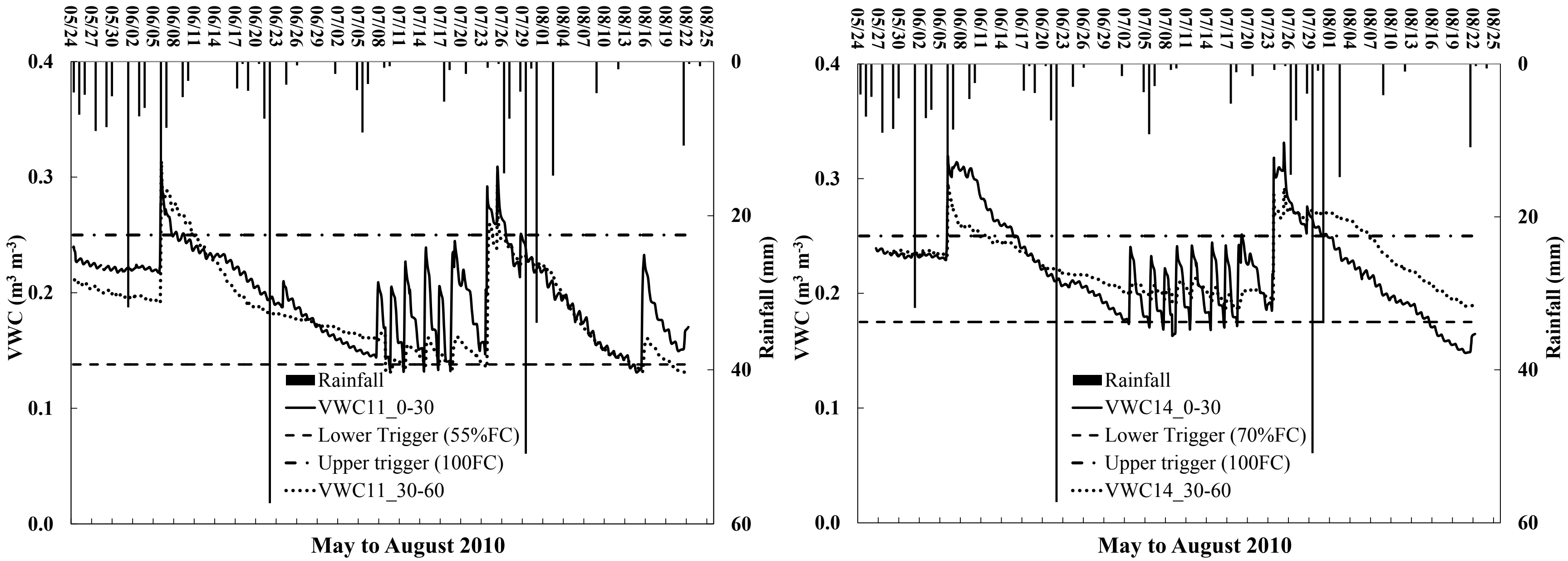


Figure 6.7- Figure 6.7a- VWC profile at 0 to 30 and 30 to 60 cm for plot 11 (55 % FC treatment) using TDR. Figure 6.7b – VWC profile at 0 to 30 and 30 to 60 cm for plot 14 (70 % FC treatment) using TDR – 2010

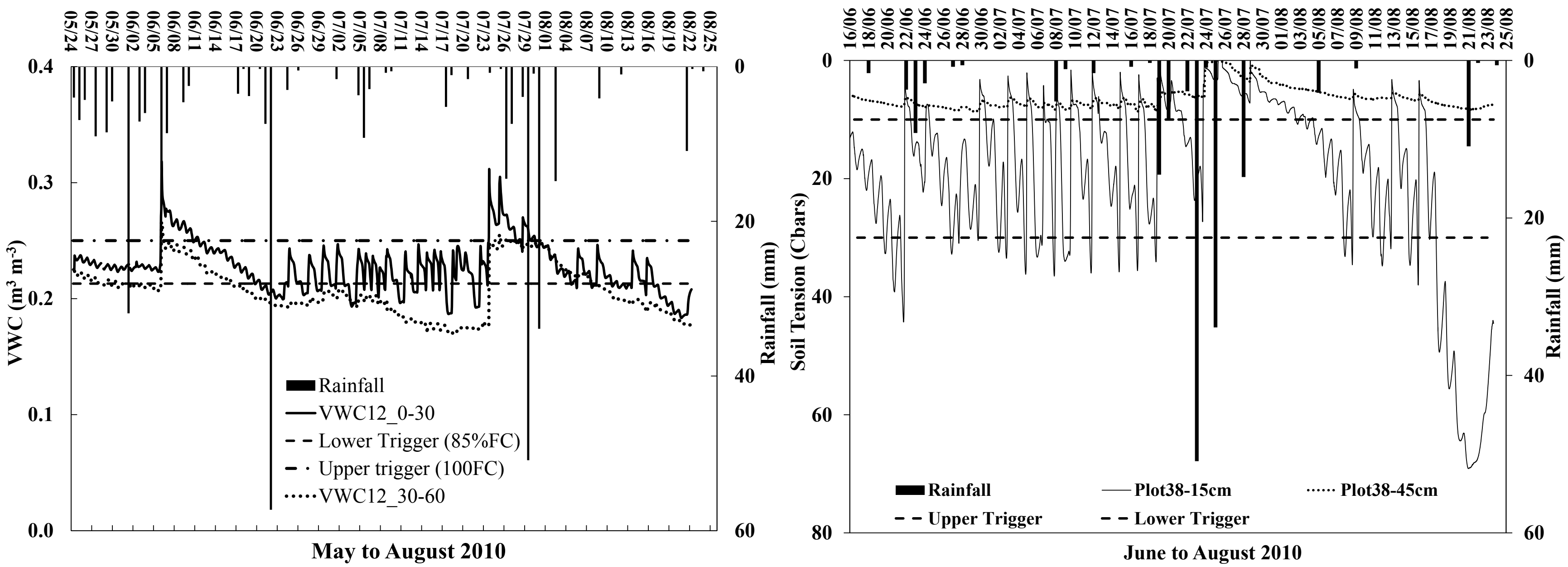


Figure 6.8-Figure 6.8a- VWC profile at 0 to 30 and 30 to 60 cm for plot 12 (85% FC treatment) using TDR. Figure 6.8b – Tension profile at 15 and 45 cm for plot 38 using Tensiometer-2010

Connecting text to Chapter 7

This chapter is a manuscript waiting to be published in 2013. The manuscript is co-authored by my supervisor Dr. C.A Madramootoo. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Soil moisture is a complex and dynamic parameter. Its depletion from the root zone is controlled by soil, plant and climatic factors. Despite the importance of soil moisture measurement, accurate assessment is difficult due to strong spatial and temporal variability. This paper addresses the third objective, which deals with determining the impact of spatio-temporal variability of soil moisture under drip irrigation for tomato cultivation. A controlled environment was used to undertake the experiment. This is the topic of the following article.

Chapter 7 –Determination of Spatio-temporal Variability of Soil moisture under Surface Drip Irrigation using Soil Moisture Sensors

F.Jaria and C.A Madramootoo

Abstract

A greenhouse experiment was conducted from January to April 2010, to study the moisture distribution patterns over the rooting depth (0 to 30 cm) throughout the growing season of "Trust" tomatoes planted in silty loam soil. A matrix of 24 time domain reflectometry (TDR) probes were used in a 1.5 m*1.5 m * 0.6 m plywood box to monitor the water distribution from five emitters discharging at a constant flow rate of 1.24 lph per emitter at 69 kPa providing irrigation to 5 pairs of double row plants under controlled conditions. The plants were irrigated 17 times between January and April, with durations and irrigation depths ranging from 9 to12 hours and 31.29 to 41.45 mm per irrigation event respectively. Irrigation intervals varied from 10 to 3 days during the study. Drip irrigation with a centrally aligned drip line was not uniformly distributed. As a result of the variability in roots' water uptake, surface evaporation, and partial soil wetting, there was considerable spatial–temporal variability in soil water distribution. The average daily moisture depletion over the initial, crop development, mid-season and late season growth stages were 2.0 mm, 3.2 mm, 5.3 mm, and 9.2 mm, respectively. The zone of highest moisture depletion over the first 24 hours after an irrigation event was located at a horizontal distance 15 cm from the drip line and 0.0 to 15 cm from the nearest emitter.

Keywords: TDR, unsaturated flow, soil moisture distribution, drip irrigation, soil water dynamics.

7.1 Introduction

Soil moisture is the water held in the pores of the unsaturated zone (Paris et al., 2008). Nielsen et al. (1986) represented the unsaturated zone, as that part of the soil profile where water content is less than soil porosity, or where the soil water matric potential is negative. Soil moisture is a complex and dynamic parameter. Its depletion from the root zone is controlled by soil, plant and climatic factors. Root length or root length density most directly relates to plant water uptake (Lubana & Narda, 2001). Despite the importance of soil moisture measurement, accurate assessment is difficult due to strong spatial and temporal variability, variation in topography, soil type, land use, vegetation, solar radiation, upslope or specific contributing area, and mean soil moisture (Canton et al., 2004; Cosh et al., 2004; Famiglietti et al., 2008; Hebrard et al., 2006; Wilson et al., 2005).

Drip irrigation moistens only a fraction of the soil root volume, compared with other irrigation methods (Lubana & Narda, 2001). During drip irrigation, a horizontal discontinuous wetting volume occurs. This phenomenon occur when emitters located along the drip line are relatively close resulting in overlapping of the wetted volume of adjacent emitters. However where drip emitters are spaced relatively far apart, the soil wetting pattern follows a series of wet and dry volumes and the crop's rooting system develop and gravitate towards the wetter zones (1979). Mmolawa and Or (2000b) highlighted that spatial and temporal distribution of water and solutes in the crop root zone are controlled by irrigation/fertigation methods, soil characteristics, crop root distribution and uptake patterns. The soil-water dynamics under trickle irrigation differs when compared to other forms of irrigation. Water normally percolates in three dimensions instead of the one-dimensional flow associated with sprinkler or surface irrigation (Elmaloglou & Diamantopoulos, 2009; Sammis et al., 1990). It approximates a two dimensional pattern when used as a line source (Elmaloglou & Diamantopoulos, 2009). In addition, only a fraction of the soil surface becomes wetted and hence evaporation losses and water withdrawal patterns by plant root systems under trickle irrigation also differ considerably from other irrigation systems (Lubana & Narda, 2001; Sammis et al., 1990). Assouline (2002) highlighted that the ponding zone created around emitters by drip irrigation and root water uptake patterns are contingent on the emitter's water application rate and soil properties. Therefore water application rate is one of the factors which determines the soil moisture distribution around the emitter (Brandt et al., 1971; Bresler, 1978); related root distribution and plant water uptake patterns (Coelho & Or, 1999; Coelho & Or, 1996; Phene et al., 1991).

Traditionally, conceptualizations of spatial and temporal soil water distributions involved the determination of water content at various points around the emitter and drawing contours between these soil moisture points. These analysis provide the position, and shape of the wetted volume (Dasberg and Or, 1999). Previous investigators reported on the extent of wetting, the surface wetted diameter, wetted depth, and wetted volume (Cook et al., 2003; Dasberg & Or, 1999; Hammami et al., 2002a; Thorburn et al., 2003) around the emitter (Brandt et al., 1971; Bresler, 1978). Wetting pattern can be obtained by site specific direct measurement of soil wetting in the field or by simulation using models (Bhatnagar & Chauhan, 2008; Cote et al., 2003; Gärdenäs et al., 2005; Ismail et al., 2006; Simunek et al., 1999; Skaggs et al., 2004).

Very little attention has been paid to the estimation of soil water distribution during trickle irrigation under realistic field conditions (Nafchi et al., 2011). The lack of understanding of how soil water content distribution is affected by unsaturated soil hydraulic properties may result in sub-optimal management and low water use efficiency (Lubana & Narda, 1998). An improved understanding needs to be determined so that the crops could be provided with an adequate wetted soil volume to meet their water requirements (Al-Qinna & Abu-Awwad, 2001) .Further, a prerequisite for better trickle irrigation design is more information about the moisture distribution pattern under a trickle source for different emitter discharge rates (Lubana & Narda, 1998).

To date there have been very few matrix studies of drip irrigated plots to ascertain the soil moisture spatial and temporal distribution across and along cultivated beds. The objective of this study was to examine the influence of irrigation scheduling on the spatial and temporal distribution of soil moisture for drip irrigated tomatoes grown under controlled greenhouse conditions. Water distribution in the upper (0 to 30 cm) soil profile was determined using a matrix of 24 permanently installed time domain reflectometry (TDR) sensors. The use of TDR supported the collection of continuous, undisturbed moisture content determination within the soil profile throughout the growing season. The water distribution can be monitored by evaluating selected sections of the irrigation scheduling process during the season.

7.2 Materials and Methods

7.2.1 Site and soil description

This experiment was carried out at McGill University, Macdonald Campus Greenhouse in Sainte Anne-de-Bellevue, Quebec (45°24' 30" latitude N and 73°56'23" longitude W). A 19 mm thick plywood box was constructed with dimensions of 1.5 m* 1.5 m* 0.6 m and the inside overlaid with plastic covering. A 50 mm diameter perforated corrugated polyethylene pipe, sleeved with synthetic geotextile was installed at the bottom of the box to evacuate runoff below the crop root zone. The soil used in the experiment was excavated from a field on the Macdonald campus. It was a loamy sand soil (St. Amable) with a sand, silt and loam content of 76.8%, 18.7% and 4.5%, respectively. The soil was manually sieved using 6.4 * 6.4 mm sieve size openings to remove the large clods. The soils were compacted in layers of 20 cm to a depth of 50 cm with an average bulk density over the 0 to 30 cm depth of 1300 kg m^{-3}, and an approximate bulk density of 1350 to 1400 kg m^{-3} at the 30 to 50 cm depth. Field capacity, 30% volumetric water content (θ_v)) was determined by the in situ method as outlined by Peters (1965). The saturation, permanent wilting and available water content (AWC) were approximately 44.3%, 18.0% and 12% θ_v respectively. Soil pH and organic matter content were estimated at 7.0 and 5.5%, respectively.

7.2.2 Cropping practices

Prior to planting, the soil was brought to field capacity. Five week old (Trust) tomato seedlings (*Lycopersicon esculentum* Mill.) were transplanted on December 30 2009, in twin rows, at spacing of 30 cm along, and 50 cm between rows. The experimental box accommodated 10 seedlings.

The combination of N-P-K (6-11-31) and Calcium Nitrate (with 15% N) were applied to the plants over the growing period. Each plant received approximately 8.4 g, 4.5 g and

12.5 g of N, P and K respectively. Fertilizer was applied manually by dissolving soluble fertilizers into a one litre cylinder and applying 100 cc of the homogenous solution to each of the 10 plants. The application of the fertilizer was systematically applied one hour into the irrigation cycle.

Additional artificial lighting was provided to augment the natural lighting, to replicate a 16 hour day length. The overhead lighting consisted of 400 w (fixtures rated for 485W, 208V, 2.5A) high pressure sodium bulbs (P.L. Light System, Canada). Average temperature over the period January to April was 23.5 °C, while average relative humidity was approximately 40% throughout the growing season.

7.2.3 Experimental layout

The experimental layout is depicted in Figure 7.1. The 1.5 m plywood box width was aimed at modeling the bed width used for field tomato cultivation. Twenty-four TDRs (Campbell 625 water content reflectometers) were installed in a (4 * 6) grid matrix with four sensors installed at a horizontal spacing of 30cm across and six sensors installed at a vertical 25 cm along rows.

Jain (Chapin) twin-wall drip tape with a flow rate of 1.24 lph at 69 kPa (10 psi) and an inside diameter of 16.2 mm was used. A single drip line with five emitters at 30 cm spacing was aligned along the centre of the plot, with a horizontal distance of 25 cm from both rows of plants. The emitters and the seedlings were aligned directly opposite each other.

7.2.4 Soil moisture sensors installation and calibration

The TDR soil moisture sensor probes (CS625 water content reflectometer, Campbell Scientific Inc., UT) consisted of two parallel stainless steel rods, each with a diameter of 3.2 mm and were installed vertically in the soil using a guide probe to a depth of 30 cm. The sensors were calibrated against measured volumetric water content and one generic site specific calibration curve was developed for the 24 TDR sensors. It was used to inform the irrigation scheduling program and to convert sensor run time values (period in μSec) into volumetric water contents.

TDRs were connected to six data loggers (model CR205/6, Campbell Scientific International, Logan, UT, USA) located within the greenhouse. Air temperature and relative humidity data were collected at the site using a Campbell Scientific CR23X data logger. The loggers recorded data every 5 minutes, and summarized on a 15 minute, hourly and daily bases.

7.2.5 Irrigation scheduling

One TRD sensor was used to initiate irrigation scheduling (sensor #22). It was selected due to its strategic location, installed at a horizontal distance of 15 cm away from the drip line and vertical distance of 10 cm from the nearest dripper and within the active root zone (Fig. 7.1). Irrigation was triggered when soil moisture was 75% field capacity, equivalent to 22.5% volumetric water content (θ_v). Irrigation was applied to bring the plot to field capacity (30% θ_v).

The equivalent depth of each irrigation event was computed as the quotient of the actual volume of water applied and the effective wetted area. Also computed was the corresponding equivalent depth of moisture at each sensor location after every irrigation event, as the product of the effective root depth and the change in volumetric water content at the start and end of irrigation events. The first three irrigation events were carried out at approximately 83% (25% θ_v) field capacity. This translated to approximately 40% depletion in AWC and was consistent with the FAO guidelines for irrigation of vegetables (Doorenbos & Pruitt, 1977). This was done to ensure that seedlings were not adversely stressed after transplant. The remaining 14 irrigation events were carried out at the requisite lower threshold triggers (25% θ_v). The final irrigation event was on the 22nd April.

7.2.6 Data analysis

It was assumed that the soil moisture content of the 12 moisture sensors on the left of the drip line were a mirror image of the 12 sensors on the right. In order to validate this assumption, the following performance measures (Wang, 2006), were calculated:

$$SE \qquad \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(L_i - R_i\right)^2} \qquad Eq.7.1$$

$$PE \qquad \frac{\sum_{i=1}^{N} L_i - \sum_{i=1}^{N} R_i}{\sum_{i=1}^{N} R_i} * 100\% \qquad Eq.7.2$$

$$R^2 \qquad \frac{\left(\sum_{i=1}^{n}\left(L_i - \overline{L}\right)\left(R_i - \overline{R}\right)\right)^2}{\sum_{i=1}^{n}\left(L_i - \overline{L}\right)^2 \sum_{i=1}^{n}\left(R_i - \overline{R}\right)^2} \qquad Eq7.3$$

$$AD \qquad \frac{1}{n}\sum_{i=1}^{N}\left|L_i - R_i\right| \qquad Eq.7.4$$

Where PE is percentage error, R^2 is coefficient of determination, SE. is the standard error or root mean square error, AD is the average deviation or mean absolute error, n = number of observations during the simulated period, L_i = Sensor reading at time interval $_i$ for first sensor. $\overline{L}$ = arithmetic mean soil moisture content for first sensor, R_i = Sensor reading at time interval "i" for second sensor, and $\overline{R}$ = arithmetic mean soil moisture content for second sensor. The best values for RMSE, PE, R^2 and AD are 0, 0, 1 and 0 respectively.

Surfer 8.04 software (Surfer, 2003) was used to generate daily soil distribution profiles from sensor data collected at the 24 locations in the plot. Daily soil moisture contour maps were produced from which daily moisture depletion rates were determined. Two sample T-tests on irrigation depth and sensor depletion rates were conducted.

7.3 Results and discussions

7.3.1 Field capacity (FC), permanent wilting point (PWP) and calibration curve

In situ field capacity for sandy loam was unusually high (30% θ_v). The PWP (18% θ_v) determined by the pressure plate apparatus method was also outside the normal range (9-15% θ_v). It is important to note that field capacity is not considered a constant or an intrinsic soil property, but rather an arbitrary value (Asgarzadeh et al., 2010). Schwab et al. (1993) provided a range (15-27% θ_v) for field capacity of sandy loam soils. The values obtained were over this range in both cases and may be attributed to relatively high organic matter found in soils (5.5%). Hudson (1994) noted that within each textual group, as organic matter (OM) content of soils increased, the volume of water held at field capacity increased at a much greater rate than that held at the permanent wilting point. He estimated that 1% to 6% OM by weight was equivalent to approximately 5 to 25% by volume and hence can significantly affect available water content (AWC). AWC was approximately 12% θ_v and within the range (9-15%) for this soil type as provided by Schwab et al. (1993).

The irrigation threshold was set as a function of field capacity (75% FC), equivalent to soil moisture content of 22.5% θ_v. This value represented a depletion of AWC by 62.5%. However, Doorenbos and Pruitt (1977) recommended a management allowable deficit (MAD) for tomatoes of 30 to 40% of AWC while Hartz (2005) recommended depletion of 20% to 30% for maximum yields. Since the primary objective of the experiment was an improved understanding of soil water variability, lowering the threshold from 40 to 65% AWC could prove advantageous in water conservation.

Figure 7.2 shows the soil moisture calibration curve. This study depended on site specific calibration rather than published or manufacturer calibrations. Quinones et al. (2003) reported that published calibration were unsatisfactory for many soils, and recommended site specific calibration. The quadratic was preferred to the linear curve which had a slightly better R^2 (0.99 vs. 0.98). The accuracy of the quadratic calibration curve was found to be valid within the range of soil moisture measured for the calibration (sensor period of 21-31.5 μSec).

7.3.2 Spatial moisture distribution

7.3.2.1 Applied irrigation depth vs. equivalent irrigation depth at each sensor

Table 7.1 summarizes the irrigation applications over the season and the average equivalent depths measured at the soil moisture sensors. Figure 7.3a displays the temporal soil moisture pattern from sensor #22 (trigger sensor) over the growing season. Over time, intervals between irrigation events gradually decreased from approximately 11 to 3 days. This was due to the gradual development of plant rooting systems, which were able to extract larger volumes of soil moisture over time, to sustain crop water requirements. Abrahamsen and Hansen (2000) reported that water uptake by roots depended on rooting depth and root density distribution in connection with soil water status within the rooting depth. Root system is the main plant factor which is directly related to the absorption of water from soils. About 40% of the total moisture used is extracted from the first quarter of the root zone, 30% from the second, 20% from third and only 10% from last quarter (Ward & Trimble, 2004).

The equivalent irrigation depth based on water applied over the 17 irrigation events ranged between 30.9 to 41.5 mm, and totaled 602.8 mm over the season (Table 7.2). A large discrepancy existed between equivalent depth calculated from actual irrigation applied and sensor measurements. This may be due to spatial variability associated with drip emitters (Rolston et al., 1991), such that soil moisture sensors installed further away from the drip line recorded lower moisture content than those located closer. Approximately 24% of the applied irrigation was either leached below the rooting zone or redistributed laterally away from soil moisture sensors and transpired by plants during irrigation events. However, excess moisture remained in the soil, some of which subsequently contributed to capillary rise, since there was no subsurface discharge collected from the plot over the growing season.

The equivalent depth at the trigger sensor (#22) totalled 505.6 mm or 84% of the actual applied equivalent irrigation depth, while average equivalent depth of the 24 sensors was 456.1 mm or 76% of applied irrigation. The average seasonal equivalent depths for the 12 sensors covering left and right half of the plot (relative to the centrally aligned drip line) as well as the inner and outer twelve sensors were 77%, 69%, 77% and 70% of the applied irrigation depth respectively (Table 7.2). A number of factors contributed to differences in applied irrigation depth and measured depth at the soil moisture sensors and included the following; time lag factor between start of irrigation and the time the moisture gets to the sensor, the redistribution of soil moisture due to differential soil tension, the relative distance of sensor to the emitter, leaching of water below the rooting zone and the simultaneous crop water uptake during the actual irrigation event. However, the distribution of the moisture content across the plot appeared to be consistent with the results witnessed by Schartzman and Zur (1986) and Ah Koon et al. (1990). They noted that wetting patterns during application generally consisted of two zones, a saturated zone close to the emitter and drip line, and a zone where the water content decreases toward the wetting front. This would account for the sensors close to the drip line having higher average moisture content than those located closer to the wetting front.

7.3.2.2 Soil moisture comparison across and along the plot

Across the plot were six rows of four TDR sensors. The two sensors that mirrored each other in each row (example, sensor 11 and 14) were analyzed together. Significant variability occurred among paired sensors (Figure 7.3a). However, the paired sensors horizontally closer to the drip line (Figure 7.3b) showed greater correlation than those further away. Paired sensors 12 and 13, and 32 and 33 indicated the most accurate results. A likely explanation for this close connection in results could be the short distance for lateral moisture movement since the inner sensors were only 15 cm away from either side of the drip line.

During the first half of the irrigation season, paired sensors furthest away from the drip line, showed better correlation than the second half of the season (Figure 7.3c). This was not very surprising since during the initial growth stage, soil evaporation predominated over transpiration. Further, for such a small plot area (1.5 m *1.5 m); exposed to the same environment, evaporation would be fairly uniform. However as the plants developed and the rooting system spreads non-uniformly in various directions (vertically and horizontally) transpiration eventually dominated over evaporation and may have contributed to paired sensor differences recorded towards the latter part of the season. The initial development of a crop root system in a uniform soil will tend to follow genetic patterns (Coelho & Or, 1999). However, these patterns are subsequently altered as roots interact with their environment in response to changes in soil conditions (Herkelrath et al., 1977; Michelakis et al., 1993). Root length or root length density (length per unit volume of the soil) appeared in most cases to be most directly related to plant water-uptake (Lubana & Narda, 2001). Table 7.2 summarizes the four performance measures, which when combined provided an unbiased evaluation of paired sensors.

Table 7.2 summarizes the two-sample t-test statistical analysis on the equivalent irrigation depths at each paired sensor over the 17 irrigation events. Six of the 12 pairs of sensors registered significant differences, which highlighted non-uniformity in moisture distribution across the plot after an irrigation event. Further, five of these six pairs found to be statistically significant were installed at the horizontal distance of 15 cm from the drip line. The statistical results may appear to contradict results obtained from performance measures. One explanation for this apparent contradiction is that the former analyzed soil moisture data every hour over the entire season, which was influenced by evapotranspiration, redistribution, and capillary rise, and to a lesser extent percolation below the root zone. The latter, compared irrigation depth after each irrigation event and did not account for the above factors.

Along the plot, there were four columns of six soil moisture sensors. The average irrigation depth for the six sensors in each of the four columns over the 17 irrigation events is depicted in Figure 7.4. During the first six irrigation events, average irrigation depths for both inner columns of sensors indicated higher irrigation depths than the outer columns, although irrigation depth from the left inner column was always higher than the inner right column. The difference between the inner sensors may be attributed to soil heterogeneity, while the differences between the inner and outer sensors was undoubtedly due to the close proximity of the sensors to the water source (15 cm as compared to 45 cm). As the season extended, the magnitude of these differences in the four columns decreased. From irrigation events #’s 9 to 12; the average irrigation depth was highest in the outer right column, while the inner right column was lowest from irrigation events #’s 9 to 17 except irrigation event # 16. The totals for the outer left and right columns were 425.7 and 405.0 mm while the inner left and right columns were 497.4 and 427.1 mm respectively. The left half of the plot received 10% more moisture than the right half and was found to be statistically significant.

The sensors in each column were installed at the same horizontal distance from the drip line and plants. However, the vertical distance of each sensor relative to the nearest tomato plant and emitter differed (Figure 7.1). Figures 7.5a to 7.5d depicts variability amongst the six sensors in each of the four columns. The results indicated that the column of sensors further away from the drip line showed greater variability. This result could be attributed to plant root development relative to the higher soil moisture content, the relative distance of the sensor from the nearest dripper, and moisture redistribution and percolation below the rooting zone after each irrigation event. All analysis indicated that moisture distribution was not uniformly distributed across or along the plot. Shock and Wang (2011) noted that as a result of the variability in root water uptake, surface evaporation, and partial soil wetting, there could be considerable spatial–temporal variability in soil water, which could be further pronounced with drip irrigation.

7.3.3 Temporal moisture distribution

7.3.3.1 Change in moisture content over the season

Daily changes in moisture content at each of the 24 sensors were evaluated. The season was divided into 4 distinct periods consistent with the plant growth stages, each period approximating 30 days duration. Figure 7.6 summarizes average daily depletion rates for each of the 4 columns of six sensors over the season. Average daily moisture depletion values over the four periods were 2.0 mm, 3.2 mm, 5.3 mm, and 9.2 mm for the initial, crop development, mid-season and late season respectively. The Trust tomato variety is indeterminate in nature but was grown as a determinate crop and can grow in excess of two meters in height. During the early season irrigation was applied every ten days;

however, by the end of the season, the irrigation cycle was administered every 3 days. With an average irrigation application depth of 35 mm per cycle, it is not surprising that by the end of the season, the depletion rate was approximately 9.2 $mmday^{-1}$. Daily depletion in soil moisture was a function of plant evapotranspiration demand and redistribution of soil moisture, particularly after an irrigation event. Under favorable soil water, soil temperature and aeration, the rooting system of the plants strongly influence water uptake. With increasing root growth, there is a corresponding increase in water uptake, particularly under favorable soil conditions. Other plant factors such as morphology of leaves, stomatal mechanisms and growth stage of the crop, all influence the rate of transpiration (Ward & Trimble, 2004). An increase in the rate of transpiration results in more water absorption by plants. Initially, depletion was low and dominated by evaporation from the soil, but with increases in the plant rooting system, there was a corresponding increase in daily depletion. During the initial and crop development phases, sensors horizontally closer to the drip line and tomato plants (sensors 12 to 62 and 13 to 63) indicated a higher daily moisture depletion rate than those further away (Sensors 11 to 61 and 14 to 64). This may be explained by the closeness of inner sensors to the rooting system of the young plants, which would be more responsive to crop water uptake. However at the late season, sensors further away indicated higher daily depletion rates. Over time the rooting system adapted to moisture distribution and developed vertically and laterally away from the drip line, thus utilizing the increased moisture at the locations of the outer sensors. Further the drier soil to the left and right of the outer sensors may have facilitated greater redistribution due to differences in soil moisture suction, and as a result indicated higher daily depletion rates than the two inner columns.

Two sample t-tests were carried out on each column of sensors for each of the growth stages. During the initial and developmental stages, statistical significance was realized only between the columns of sensor 12-62 and 14-64 (at $\alpha=0.05$). There was no significant difference during the mid-season as the percentage differences between the columns of sensors were small. However statistical difference was found between the column of sensors 11-61 and 13-63 for the end of season.

7.3.3.2 Average Soil moisture distribution – start and end of irrigation events.

Figures 7.7a and b display the average moisture distribution (for the 17 irrigation events) over the entire plot at the start and end of irrigation, respectively. The average irrigation depth and duration was approximately 20 mm over 10.3 hours. Average moisture within the plot at the commencement of the irrigation cycle indicated an uneven and undulating moisture distribution, with moisture ranging from approximately 22.0% to 29.5% θ_v. The left half of the plot showed higher depletion, with two of the six inner sensors (22 and 52) showing values of 22% and 24 % θ_v. This depletion was due primarily to abstraction by tomato plants in close proximity to the sensors. Three of the six sensors (11, 41 and 61) located at the 45 cm distance (from the drip line) showed low soil moisture content (23.5, 24.0 and 23.5 % θ_v). This would invariably reveal that the plant rooting system developed away from the centrally aligned drip line, which represented the zones of greater water content. On the right side of the plot moisture content ranged from 23 to 29.5% θ_v. The area of greatest depletion was at the location of sensors 14 and 24 (45 cm away from the drip line), while the area-surrounding sensor 23 showed the highest moisture content (29.5% θ_v). The higher moisture content on the right side of the plot may be attributed to plants having less developed rooting systems, compared to the plants on the left, and hence they lacked the ability to extract soil moisture at the same rate (Figure 7.7a).

Upon completion of an irrigation event, the soil moisture content ranged between 27 and 37% θ_v. The horizontal distance from zero to approximately 30 cm on either side of the drip line showed relatively high moisture content. The zones nearest to emitters were highest with the exception of the zones surrounding sensors 54 and 64. Elevated moisture at these locations would be due to high antecedent moisture at the commencement of the irrigation cycle. The moisture content on either side of the drip line showed a gradual decrease away from the drip line. Between sensors 11 and 22 on the left side of the plot and sensors 14 and 23, the moisture contours were much steeper than the rest of the plot and may be attributed to a more developed rooting system than the other plants. There may also be some boarder effect due to the close proximity of sensors 11 and 14 to the lower end of the box that could have resulted in preferential flow.

7.3.4 Placement of trigger sensor for irrigation scheduling

The assumption was such that sensor(s) with consistently high depletion rates over the first 24 hours after each irrigation event would indicate the critical zones for sensor installation. Fig. 7.8a depicts the average hourly moisture depletion rate for each sensor vs. the relative (horizontal and vertical) distances of each sensor from the drip line and the nearest emitter and Fig. 7.8b indicates average depletion rates vs. relative distances of tomato plants and sensor from nearest dripper. Sensors had a horizontal distance of 15 and 45 cm for the drip line and a vertical distance of 0, 5, 10 and 15 cm from the nearest emitter. The plants had a horizontal distance of 10 and 20 cm from the inner and outer sensors, respectively while the vertical distance of the sensors to the nearest tomato plant was the same as that of the emitters, since each plant was placed opposite to an emitter.

It must be noted that for the first 8 irrigation events, sensor #54 indicated soil moisture depletion within the first 24 hours. However, during irrigation events 9 to 17, moisture content increased over the 24 hours after irrigation, as a result average moisture depletion was a net positive value and not included in Figure 7.8.

The analysis identified six sensors with highest average hourly depletion rates and this is summarized in Table 7.3. The hourly depletion rate at each sensor after an irrigation event is a function of moisture redistribution, its proximity to the crop, drip line, emitter, and the rate of evapotranspiration. Sensor #63 which was installed at a horizontal distance of 15 cm from the drip line (10 cm for the tomato plants) and vertical distance of 0 cm (opposite) from the nearest emitter and plant, showed the highest depletion rate. It was a bit surprising that sensor #62 which is a mirror image of sensor #63 did not provide similar results. This was undoubtedly due to differences in rooting system development.

Though sensors 21 and 41 had relatively high depletion rates (0.27 and 0.291 mmh^{-1}) over the first 24 hours after irrigation, their location relative to the drip line cannot be considered as suitable zones for sensor installation during precision irrigation scheduling of large scale tomato production. Field tomatoes are generally grown on 1.5 m beds (with an effective bed width of 1.0 m) in double rows with a single centrally aligned drip line.

At a horizontal distance of 45 cm away from the drip line, sensors were far removed from high soil moisture and the effective rooting zone of the plants and would cause plants to be stressed before the soil moisture trigger is reached. Further, 45 cm on either side of the drip line was the approximate limit to which lateral soil moisture movement occurred at the surface after termination of each irrigation event and would indicate lower moisture content. Coelho and Or (1996) reported that at the periphery of the wetted soil volume, soil moisture is excessively low. Additionally, the high average depletion rates at these two sensors (#'s 21 and 41) relative to other sensors at similar locations may be due to preferential flow as a result of small cracks in the vicinity of the sensors. Also the possibility of soil moisture and soil water tension gradients to the left of these sensors would influence higher soil moisture redistribution.

Further analysis using the two sample t-test between soil moisture depletion rates for the first 24 hours (over the 17 irrigation events) at sensor locations #'s 63 and 33 was found to be statistically significant (at α=0.05), while the comparison of sensor #63 and the other sensors (#32 and #52) were not statistically significant. The results therefore suggest that three out of the four sensor locations can be considered as high moisture depletion zones. Therefore for sandy loam soils (in the context of this experiment), with an effective bed width of 1.0 m and a centrally aligned drip line, soil moisture sensors should be installed at a horizontal distance of 15 cm instead of 45 cm from the drip line, and at a vertical distance of 0.0 cm, 5.0 cm or 15.0 cm from the nearest dripper. Coelho and Or (1996) stated that positions near the center of plant root uptake experience large fluctuations in matrix head, often exceeding the tensiometric range, especially for two-day intervals.

It must be noted that only two horizontal distances (for the sensor locations) were used in this experiment, and therefore it may be prudent to examine other horizontal distances ranging from 0 to 25 cm from the drip line to conclusively determine more precise locations. The fact that soil moisture content is not uniformly distributed across the plot may require the installation of paired soil moisture sensors, one on either side of the drip line to give a better indicator of soil moisture depletion and to facilitate more accurate precision irrigation. Stegman (1983) also recommended the use of two sensors, but installed at different depths. Haise and Hagan (1967) recommended placing two sensors at the top and bottom of the active rooting layers, while both Howell et al. (1984) and Levin Levin et al. (1885) recommended that sensors be placed adjacent to emitters. Many researchers have placed sensors at 15 to 30-cm depth based on the effective rooting depth of the crop and soil wetting patterns (Shock & Wang, 2011).

7.4 Conclusions

The study indicated that soil moisture content is not uniformly distributed prior to, or after an irrigation event. After an irrigation event, soil moisture was highest within 25 cm either side of the centrally aligned drip line but gradually decreased away from the drip line. As the moisture content depletes over time, it reflected an undulating profile with a number of peaks and troughs dispersed throughout the plot. The zone nearer the drip line and closer to the emitters had more troughs. The peaks indicated zones of higher moisture content and were located between consecutive emitters. The zones of peaks and troughs provided a general indication of the zones of higher root water abstraction. Average daily moisture depletion over the four periods were 2.0 mm, 3.2 mm, 5.3 mm, and 9.2 mm for the initial, crop development, mid-season and late season respectively.

Maximum average soil moisture depletion rates within the first 24 hours after termination of each of the 17 irrigation events ranged between 0.27 to 0.34 mmh^{-1} and occurred at a horizontal distance of 15 cm from the drip line and 0, 5 and 15 cm from the nearest emitter on the drip line. The results indicated that for double row planting of tomatoes with a central drip line, row spacing of 50 cm may be adequate due to higher soil moisture content within that zone. Further due to the lack of uniform distribution of moisture in the soil profile, paired sensors (with one either side of the drip line) may provide a better estimate of soil moisture depletion for sensor based irrigation scheduling.

Table 7.1-Equivalent irrigation depth over the 17 irrigation events

Irrig. Events	Irrigation Applications		Trigger Sensor # 22	Average Equivalent irrigation depth				
	Water applied (l)	Equivalent Depth (mm)	Equivalent Depth (mm)	All Sensors (mm)	Left Half Sensors (mm)	Right Half Sensors (mm)	Inner Sensors (mm)	Outer Sensors (mm)
1	55.6	30.88	18.7	26.0	24.4	22.1	31.3	15.7
2	55.6	30.88	19.2	26.4	26.4	22.3	30.7	18.3
3	61.1	33.93	22.9	30.7	30.5	27.1	35.7	22.1
4	71.5	39.73	30.1	35.3	35.7	31.5	39.1	28.4
5	68.2	37.89	28.4	29.7	29.9	26.1	31.6	24.8
6	65.6	36.46	31.3	29.3	29.1	26.9	29.3	26.8
7	56.3	31.29	24.9	22.3	22.0	20.9	21.3	21.7
8	65.3	36.28	31.2	25.3	24.1	24.3	24.9	23.7
9	61.8	34.33	30.5	24.9	23.7	24.4	24.3	24.0
10	71.7	39.84	29.9	24.7	24.4	24.7	22.5	26.8
11	58.5	32.49	27.7	21.1	20.9	20.5	19.6	22.1
12	68.5	38.06	25.5	22.7	22.7	22.0	21.7	23.2
13	65.6	36.46	30.7	25.9	26.0	24.8	25.1	26.4
14	69.0	38.35	34.7	27.5	29.3	24.7	27.7	26.9
15	59.1	32.84	31.3	23.1	24.1	20.7	22.3	23.6
16	57.0	31.69	35.6	24.5	27.1	21.1	25.1	23.6
17	74.6	41.45	53.2	36.8	41.2	31.9	32.8	41.1
Total	1085.1	602.84	505.6	456.1	461.6	416.0	465.3	419.2

Note: Left half - sensors 11 to 61 and 12 to 62, Right half-sensors 13 to 63 and 14 to 64, Inner Sensor included -12, 13, 22, 23, 32, 33, 42, 43, 52, 53, 62 & 63, Outer Sensors included -11, 14, 21, 24, 31, 34, 41, 44, 51, 54, 61 & 64,

Table 7.2- Performance measure and two sample t-test result for paired sensors.

Sensors	RMSE	PE	R^2	AD	Comment	Sensors	RMSE	PE	R^2	AD	Comment
Sen. 11 vs. Sen. 14**	2.09	1.57	0.66	0.42	Fair	Sen. 41 vs. Sen. 44**	3.40	7.15	0.73	2.00	Fair
Sen. 12 vs. Sen. 13*	***0.69***	***1.46***	***0.99***	***0.44***	Good	**Sen. 42 vs. Sen. 43***	1.74	-3.38	0.93	0.99	Fair
Sen. 21 vs. Sen. 24**	2.97	-7.92	0.68	2.12	Poor	**Sen. 51 vs. Sen. 54***	1.94	1.09	0.60	0.33	Fair
Sen. 22 vs. Sen. 23*	5.89	16.19	0.84	5.08	Poor	**Sen. 52 vs. Sen. 53***	4.57	13.63	0.91	4.30	Poor
Sen. 31 vs. Sen. 34**	1.87	1.51	0.85	0.44	Fair	Sen. 61 vs. Sen. 64**	2.98	7.69	0.91	2.29	Poor
Sen. 32 vs. Sen. 33*	***1.18***	***2.09***	***0.92***	***0.60***	Good	Sen. 62 vs. Sen. 63**	1.35	-4.23	0.95	1.22	Fair

* and ** statistically and not statistically significant at $\alpha = 0.05$ for two sample t-test on irrigation depth. PE is percentage error, R^2 is coefficient of determination, S.E. is the standard error or root mean square error, AD is the average deviation

Table 7.3-Horizontal and vertical distance of sensors to drip line, plant and emitter with highest soil moisture depletion rates over the first 24 hours after irrigation

Sensor #	Horizontal Distance (cm)		Verticals Distance (cm)		Average Depletion Rates (mmh^{-1})
	Drip line	Plant	Emitter	Plant	
Sensor 21	45	20	10	10	0.27
Sensor 32	15	10	15	15	0.31
Sensor 33	15	10	15	15	0.28
Sensor 41	45	20	10	10	0.29
Sensor 52	15	10	5	5	0.34
Sensor 63	15	10	0	0	0.34

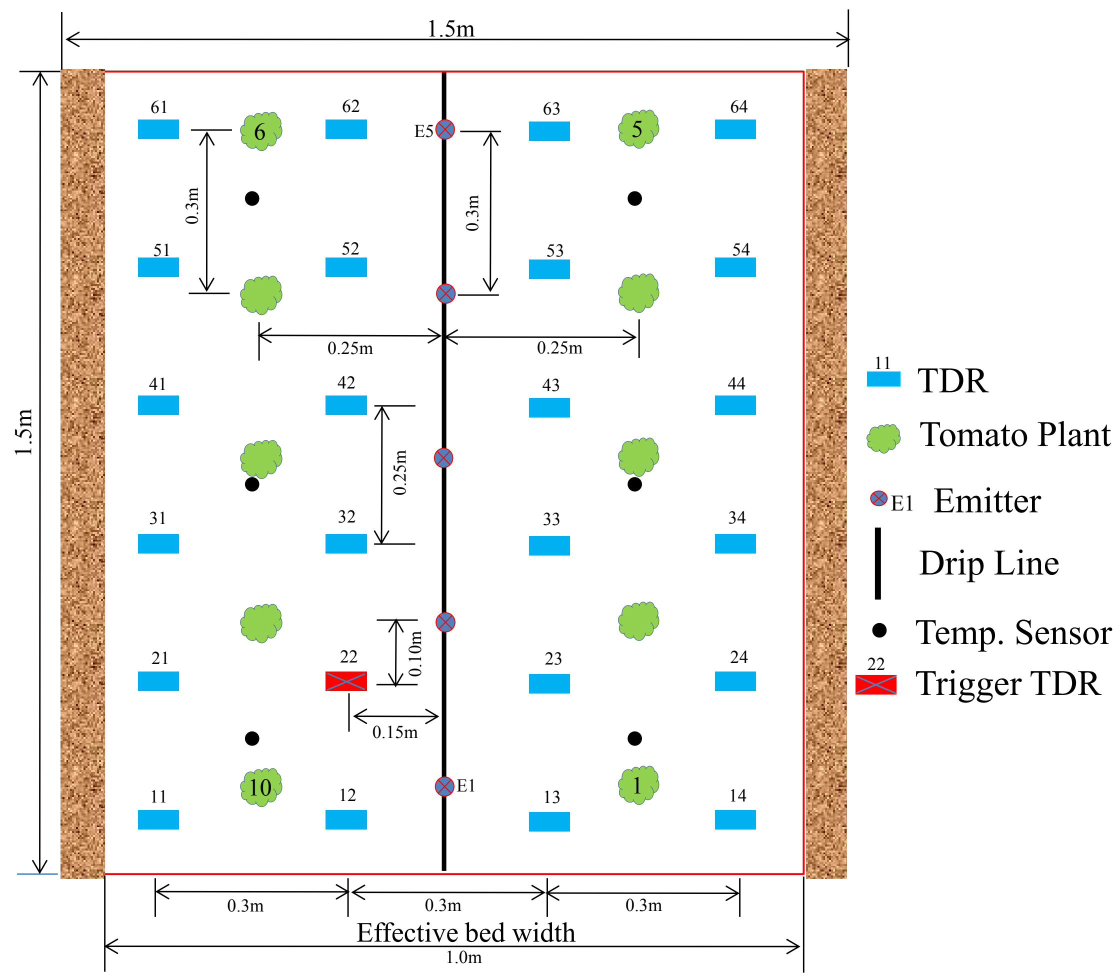


Figure 7.1- Experimental layout

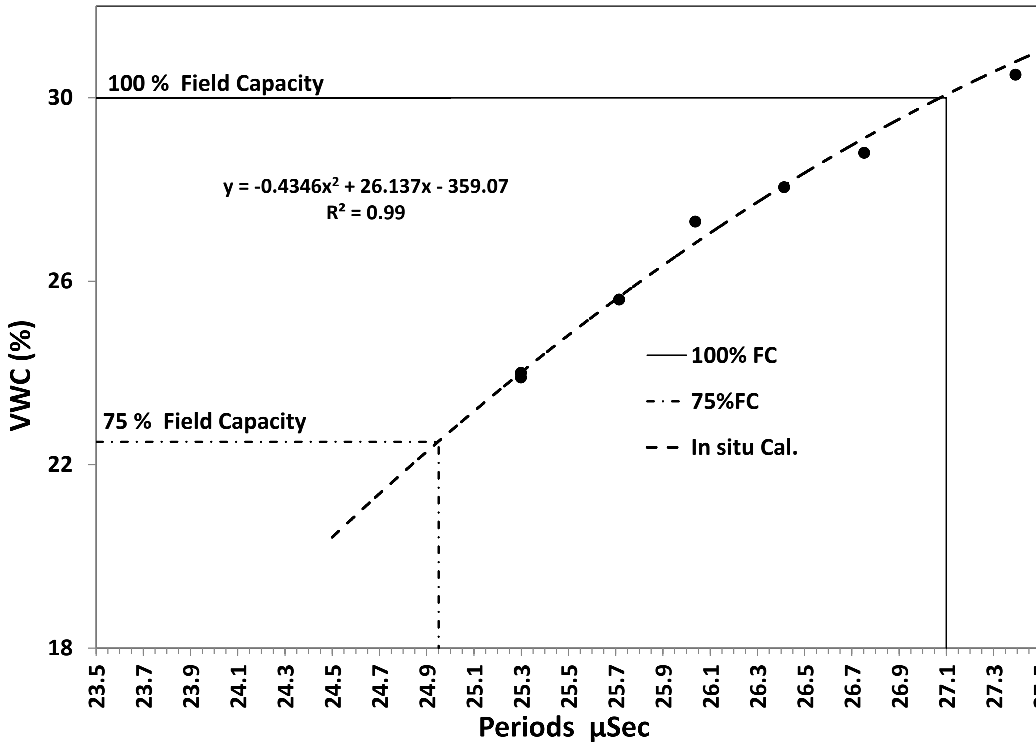


Figure 7.2 –In situ soil moisture calibration curve (Y and X are VWC (%) and runtime (periods) in µsec)

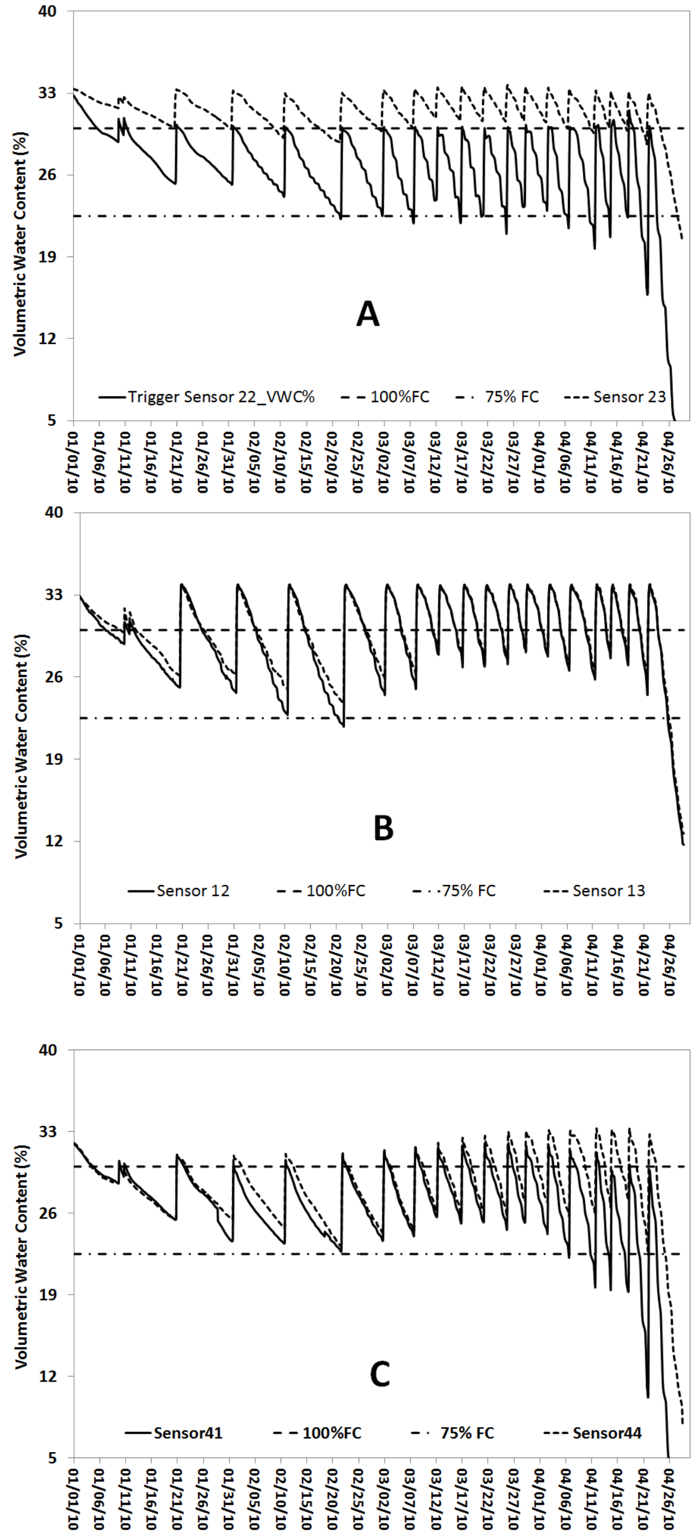


Figure 7.3-Figure 7.3a- θ_v for paired sensors 22 & 23- showing poor correlation. Figure 7.3b - θ_v for paired sensors 12 & 13 showing good correlation. Figure 7.3c - θ_v for paired sensors 41 & 44 – showing good correlation for the for the first half of the season

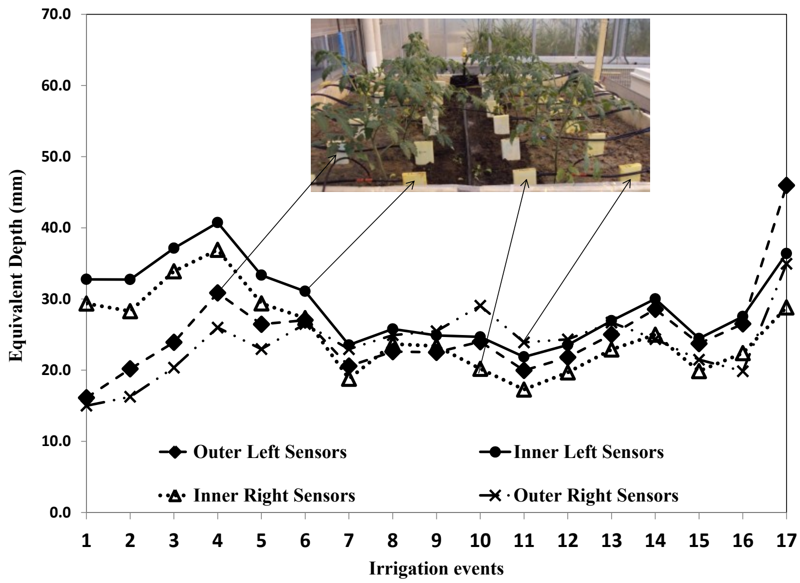
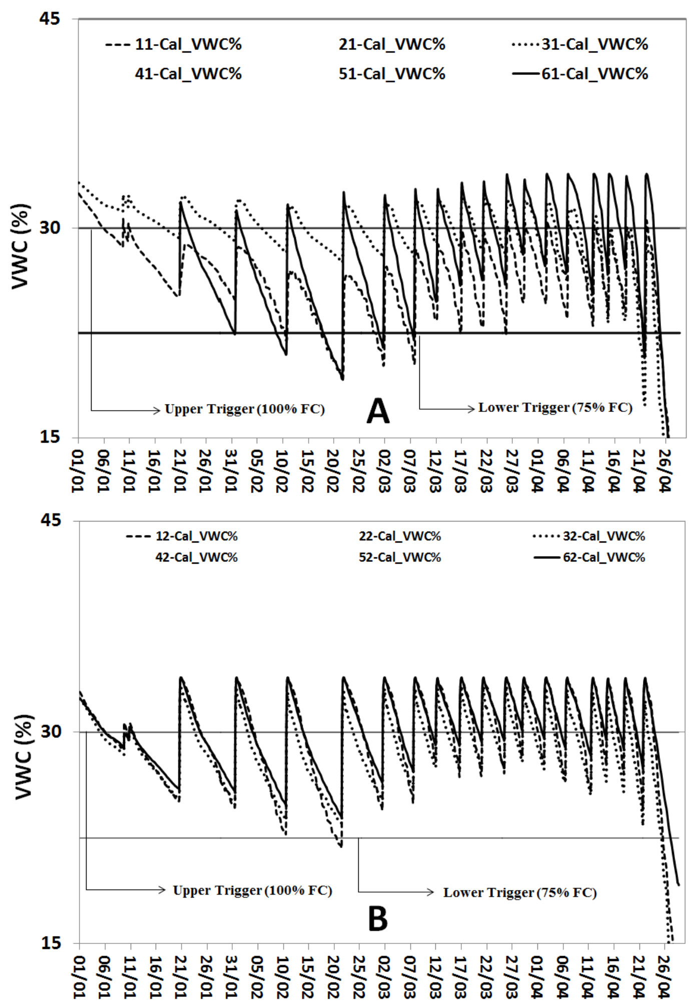


Figure 7.4- Average irrigation depths for each column of sensors over the 17 irrigation events across the plot



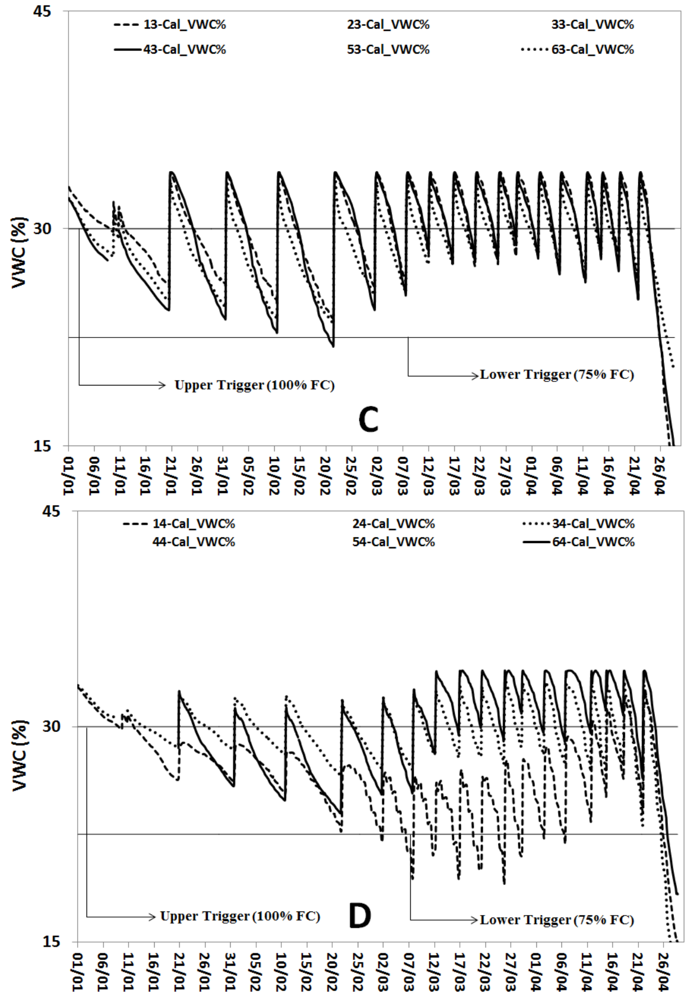


Figure 7.5[a] – Moisture profiles along columns of sensors. 7.5a-Sensors11-61, 7.5b-Sensors12-62, 7.5c-Sensors13-63, 7.5d-Sensors -14-64 ([a] Moisture profiles for sensors 21, 41, 51, 22, 42, 52, 23, 33, 53 24, 44 and 54, omitted for better clarity of plots).

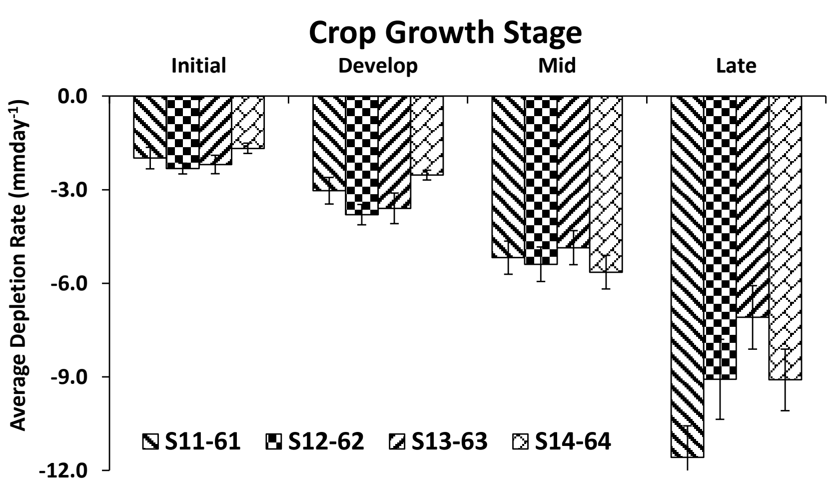


Figure 7.6-Average daily depletion rates for each column of sensor over the growing season

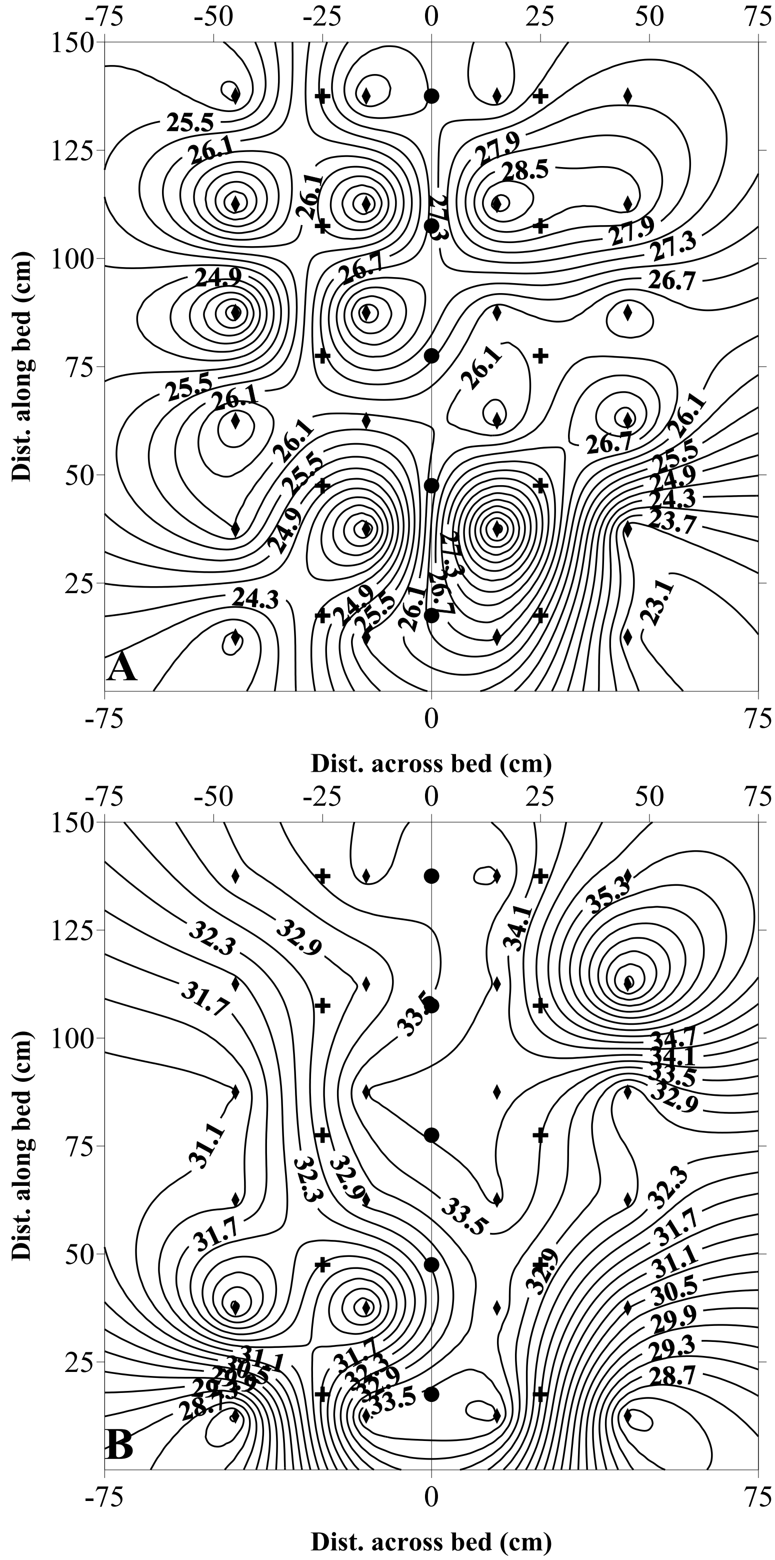


Figure 7.7-Average moisture distribution. 7.7a-at the commencement and 7.7b-at termination of irrigation (● - emitter, ♦ - sensor and + - tomato plant).

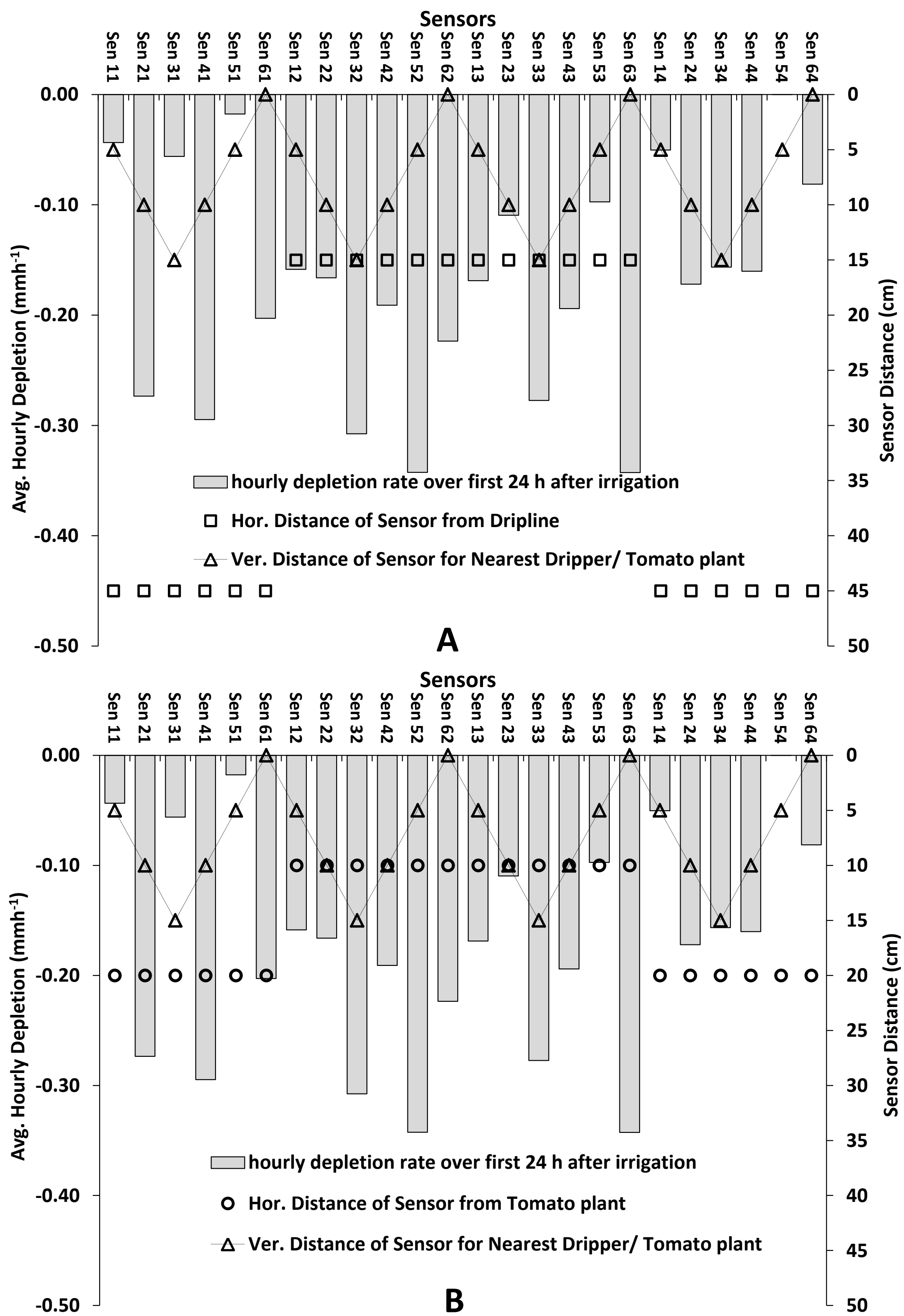


Figure 7.8-Average hourly depletion rate for sensors over the first 24 hours. 7.8a- with horizontal distance from drip line and vertical distance to nearest dripper. 7.8b-with horizontal distance from plant and vertical distance to nearest emitter/plant

Connecting text to Chapter 8

This chapter is a manuscript waiting to be published in 2013. The manuscript is co-authored by my supervisor Dr. C.A Madramootoo. All literature cited in this chapter is listed in the reference section at the end of this thesis.

The majority of agricultural soils in the southwestern Ontario are tile drained and have a high risk of N and P loss due to long-term build up and heavy rainfall which can be leached both through surface and sub-surface runoff. The effects are especially apparent in the Lake Erie region. To this end, chapter 8 addresses objective four in a direct way and investigates the movement of soil nutrients, namely N and P down the soil profile and across the growing season. It was important to ascertain the impact of the irrigation scheduling regime for the different moisture treatments on the movement of nutrients and how that may affect the Lake Erie basin. This is the topic of the following article.

Chapter 8 – Nutrient Dynamics Under Precision Irrigation of Large Scale Processing Tomato Production in Southwestern Ontario

F. Jaria and C.A. Madramootoo

Abstract

A three year field experiment was conducted during 2008 to 2010 to investigate nutrient movement (N and P) in the soil profile, and across the season of a field processing tomato (cultivar H9553) crop in loamy sand under drip irrigation. A split plot randomized complete block design (RCBD) was used in 2008/2010, and a factorial RCBD was used in 2009. Both experimental designs had two factors (irrigation type comprising of buried and surface drip irrigation, and four soil moisture levels) and were replicated four times. Precision irrigation was facilitated through the use of continuous soil moisture sensors. A mixed granular fertilizer was applied prior to and approximately one month after transplanting the tomato seedlings at 400 kg ha^{-1} and 140 kg ha^{-1}, respectively. Soluble calcium nitrate was applied through the irrigation system during the growing season at a rate of 20 kg ha^{-1}. NO_3-N and Olsen P measurements were taken at the pre, mid and end of season at the 0 to 30 cm, 30 to 50 cm and the 50 to 70 cm soil depths. The results showed no significant differences in nutrient content between the moisture treatments. Statistical significance between surface and buried drip irrigation type was obtained 2008 but not in 2009 and 2010. However both NO_3-N and Olsen P soil nutrient content showed statistical significance with depth along the soil profile and across the growing season. There is the potential for leaching of nutrient at each depth during each season.

Keywords: Processing tomatoes, Phosphorus, Nitrogen, soil profile

8.1 Introduction

Optimizing fertilizer management in large scale vegetable production is an urgent priority; in order to conserve natural resources, reduce production costs, minimize negative environmental impacts, and maintain high crop productivity. These goals could be achieved through a combination of improved understanding of crop nutrient uptake, and monitoring soil nutrient status over the growing season, to meet crop needs at appropriate times in requisite quantities.

Disparities between nutrients applied to agricultural soils and removed by harvested crops result in nutrient imbalances that can influence environmental quality and productivity of agricultural systems (Vitousek et al., 2009). Globally, more nutrients including phosphorus (P) and nitrogen (N) are added as fertilizers than are removed by the plant (Carpenter et al., 1998). Between 1950 and 1995, approximately $600*10^6$ Mg and $250*10^6$ Mg of P were added and removed, respectively from the earth's crust to facilitate agricultural production. A further $50*10^6$ Mg was added to croplands as animal manure thus contributing to a net P addition of $400*10^6$ Mg (Brown et al., 1997). In the case of Nitrogen, on the other hand Vitousek et al. (1997) estimate that global industrial N fixation from fertilizers has increased from nearly zero in the 1940s to approximately $80*10^6$ Mg y^{-1}in 1990s. In 1860, natural processes dominated the global input rate of N (≈120 Tg N y^{-1}) while anthropogenic inputs were small (≈$16*10^6$ Mg N yr^{-1}), which was almost entirely from cultivation-induced biological N fixation (BNF). However, by 2005, the reciprocal was true, natural processes had diminished due to land-use change, and anthropogenic processes increased to 210 $*10^6$ Mg N yr^{-1} (Galloway et al., 2004; Galloway et al., 2008). In the US and Europe only 18% of the N input in fertilizer is removed from farms as harvestable biomass. Further, these studies suggest that on average 174 $kg \cdot ha^{-1} \cdot y^{-1}$ of surplus N are left behind in the soil (Isermann, 1991; National Research Council, 1993). The net surplus P and N may remain in the soil profile or exported to surface and groundwater by erosion and leaching, or enters the atmosphere in the case of N (Carpenter et al., 1998; Vitousek et al., 1997). Neilson and MacKenzie (1977) noted that in Quebec between 30% to 60% of N fertilizer applied is lost, making its way to ground water and waterways via leaching and subsurface runoff.

Lake Erie more than any of the Great Lakes, is exposed to the greatest stress from urbanization, industrialization and agriculture. Intensive agricultural development, particularly in Southwest Ontario and Northwest Ohio, contributes huge sediment loads to the lake. Excess P entering the lake primarily from agricultural runoff and point source discharges (Dolan, 1993) plays a major role in the eutrophication of this freshwater system which occurs when surface waters become over-enriched with nutrients such as N and P. This phenomenon stimulates plant and algal growth, which subsequently dies and decomposes; thereby reducing dissolved oxygen concentrations in water columns. Eutrophication of the Great Lakes, particularly Lake Erie is detrimental to aquatic life. The Great Lakes Water Quality Agreement (GLWQA, 1978) is a bilateral program of the governments of Canada and USA. The agreement first signed in 1972, renewed in 1978, expressed the commitment of each country to restore and maintain the chemical, physical, and biological integrity of the Great Lakes Basin Ecosystem. One such initiative undertaken was reduction and control of phosphorus inputs and other nutrients, which reduced P entering the lakes by 11,000 metric tonnes per year (DePinto et al., 1986). However, several natural and anthropogenic factors are responsible for P resurgence (Richards & Baker, 2002).

83% of all of Canada's processing tomatoes are grown in the Ontario counties of Essex and Kent, which drain into Lake Erie (LeBoeuf et al., 2007). The unique combination of climate and lighter soils in those areas, along with the ready market facilitated ongoing production of higher tomato yields. The processing tomato crop has a short season with high nutrient demands. Irrigation and fertilizer application are required to sustain processing tomato economic viability on the world market. Zhang et al. (2009) reported that for yields of 74 to 125 Mg ha^{-1}, processing tomatoes remove 185 to 375 kg N ha^{-1} and 37 to 100 kg P_2O_5 ha^{-1}. This is dependent on soil type, variety and climatic conditions. Davis et al. (2000) found that a decrease in N application rate from 225 to 175 kg ha^{-1} decreased nitrate losses by 48%. Clearly, excessive nutrient supply can negatively impact water quality through surface runoff, leaching, and air quality through gaseous (N_2O) emissions. Tan and Zhang (2011) noted that the majority of soils in the region are tile drained and have a high risk of N and P loss due to long-term build up and leaching through surface and sub-surface runoff to Lake Erie. Additionally, these losses represent an unnecessary economic cost to the farmer, and solutions are needed to support the judicious use of chemical fertilizers, particularly P and N to reduce impacts on the Lake Erie ecosystem.

Accumulation and redistribution of NO_3-N within soil varies depending on management practices, soil characteristics, and growing season precipitation (Gehl et al., 2006). The amount of soil water in the root zone is important because it controls the movement of NO_3-N in the soil profile. Likewise soil P availability and plant P uptake are closely linked to soil water content. Further both the transport of P through surface runoff and vertical movement is controlled by water movement (Bakhsh & Kanwar, 2004; Liu et al., 2011). The long term approach to mitigate nutrient loading into ground water is to more closely mimic crop nutrient uptake with precision application of nutrient volumes, both in terms of timing and placement. This would improve crop nutrient efficiency and minimize leaching losses below the root zone. There is a growing need within Canada for agricultural systems to address the implications of management decisions on nutrient cycling and leaching. There is currently a lack of accurate information on nutrient leaching from intensively cultivated areas to Lake Erie. Lui et al. (2011) identified the need for studies in nutrient management for processing tomatoes under drip irrigation to facilitate agronomic profitability and environmental sustainability. Therefore the primary objective of this research was to study NO_3-N and P concentrations through the soil profile during the pre, mid and end of the growing season for field processing tomatoes grown on sandy loam soils in Southwestern Ontario.

8.2 Materials and Methods

Field experiments were conducted from 2008 to 2010 on a commercial farm in Leamington, Southwestern Ontario, using processing tomato cultivar H9553. The dominant soil within the root zone (0 to 30 cm) was loamy sand (86% sand, 8% silt and 6% clay), with an average bulk density of 1450 kg m^{-3} and pH of 7.1. A subsurface drainage system was installed at 70 cm below the surface. Field soil water capacity (FC) ranged between 0.20-0.24 m^3 m^{-3}. Chemical properties of the soil (0 to 30 cm) are provided in Table 8.1. Due to annual crop rotation, different fields from the same farm were used each year for tomato production.

A split-plot randomized complete block design (RCBD) was used during the 2008 and 2010 seasons, while a (2*4) factorial RCBD design was used in 2009. Both experimental designs consisted of two factors - irrigation types (buried and surface drip irrigation) and four different moisture levels. The experiment had four replicates. For the split plot RCBD, the irrigation type and the moisture treatments were assigned the main and subplot respectively. Table 8.2 summarizes the experimental treatments over the three years. In 2008, blocks were oriented across the beds. Each plot comprised adjacent twin beds (2 beds * 1.5 m * 7.5 m), having an area of 22.5 m^2 per plot and located between guard beds (1.5 m * 7.5 m) on either side. There was a 1.5 m buffer between blocks. In 2009 and 2010, blocks were oriented along the beds. Each of the plots (treatments) per block comprised single beds (1.5 m * 8.0 m), with an area of 12 m^2 per plot and located between guard beds (1.5 m * 8 m) on either side. The guard beds formed the separation between blocks with a 1.5 m buffer between plots in blocks.

Volumetric moisture treatments were expressed as a fraction of field capacity and represented the depletion to which the soil moisture reached, in order to initiate irrigation scheduling. The volumetric moisture treatments were changed from 60%, 70% and 80% of FC to 74%, 82% and 91% of FC respectively, in 2009. This was done to examine the effects of a less stressed irrigation scheduling program. In 2010, moisture treatments were again changed to 55%, 70% and 80% of FC. This change was to increase the range between experimental moisture treatments, to improve monitoring. The change in the experimental design from split-plot RCBD to a factorial design was due to the suitability of fit for both models, and it was opportune to change the model in one of the three years.

Seedlings (42 days old) were transplanted using a mechanical plug transplanter at 42 cm along and 50 cm between rows respectively. Each twin row was centred on a 1.5-m-width raised bed, resulting in a planting density of 31,746 plants per hectare. Transplant dates were 29 May 2008, 25 May 2009 and 15 May 2010. The crop was harvested after 105 days in 2008 (on 10 September), 112 days in 2009 (on 14 September) and 101 days in 2010 (on 24 August).

All agronomic practices, including land preparation, planting; pest management control and fertilization were conducted by the grower. In preparation for each year's growing season, the grower undertakes a range of land preparation activities. During the fall, organic matter in the form of mushroom residue and substrate were incorporated into the soil's top 20 cm. Also applied was Muriate of Potash (KCL) containing approximately 60% potash at around 450 kg ha^{-1}. Rye was used as a cover crop during the winter. Prior to the planting of the tomato seedlings in the spring, a fertilizer mix (Nitrate, Phosphorous, Potassium, Sulphur, Magnesium Calcium and Zinc) was applied at a rate of approximately 400 kg ha^{-1} in the upper 20 cm soil layer, of which 18% and 11% represented NO_3-N and P_2O_5, respectively. All P was applied during the pre-planting stage. Approximately four weeks after planting, a second fertilizer mix was applied as a side dressing at 140 kg ha^{-1}. Liquid calcium nitrate fertilizer with 28% N was also applied at 20 kg ha^{-1} through the irrigation system. All the plots were fertigated simultaneously and for the same duration during each of the three years. Plots were fertigated three times in 2008, 2009, and once in 2010. Table 8.3 provides detail of fertilizer applications over the three years during the pre-planting and side dressing stages.

Soil nutrient samples were taken at the following times and depths: pre-planting, mid-season and end of season (Table 8.4) and at the 0 to 30 cm, 30 to 50 cm and 50 to 70 cm depths. Samples were taken in triplicate (9 samples per plot) for each of the 32 plots. In 2008 and 2009, 864 samples (32 plot * 3 depths * 3 replicates * 3 times) were analyzed. In 2010, the same number of samples was taken but the three samples at each depth were made into a composite sample. Therefore 288 (96*3) composite samples were analyzed. The pre-season nutrient samples were taken just after the pre-planting fertilizer mix was applied in each of the three years. The sodium bicarbonate (Olsen P test) method was used in the determination of P. Olsen P estimated plant available inorganic P levels; but it made no assessment of the organic component of P in the soil, which can be mineralized by the decomposition of organic matter.

Three types of soil moisture sensors were installed in the field for continuous data collection: a time domain reflectometer (TDR) (CS625 water content reflectometer, Campbell Scientific Inc., UT); a frequency domain reflectometer (FDR) (EnviroSMART, Sentek Sensor Technologies, Stepney, Australia) and an electronic tensiometer (Irrolis Sense Tx, Hortau Inc., QC, Canada).

The critical depth at which soil moisture was monitored for the three sensors to effect irrigation scheduling was 0 to 30 cm for the water content reflectometer (5 to 25 cm in 2009), 15 to 25 cm for the frequency domain reflectometer and 15 cm for the tensiometer. The critical lower and upper irrigation thresholds were determined for each of the four moisture treatments and were used to inform irrigation scheduling. Irrigation was triggered when soil moisture from each plot depleted its lower threshold. Irrigation was then applied to bring the plots to field capacity which served as the upper threshold. The equivalent depth at each irrigation event was computed as the quotient of the actual volume of water applied and the effective wetted area.

8.3 Data analysis

Statistical analysis was performed on individual years of data. In both experimental design models, the block was considered a random effect while irrigation type and moisture levels (treatments) were considered fixed effect parameters. Statistical analysis were performed using PROC MIXED procedure of SAS (SAS, 2007) designed to fit mixed effect models. The residual maximum likelihood estimation (REML) approach for repeated measurements of NO_3-N and Olsen P over the growing season was used. Least squares means of fixed effects parameters were pair-wise compared at a P value of 0.05. Model assumptions (normal distribution, and consistent variance of error terms) were verified prior to carrying out the above analysis.

8.4 Results and discussion

8.4.1 Nutrient distribution

Similar trends were obtained each year despite yearly variations in moisture treatments; therefore a general discussion will ensue. Where differences obtained, they are discussed. Neither NO_3-N nor Olsen P was statistically significant among moisture treatments for each of the years. This was attributed to the fact that all nutrient applications in the granular or liquid form were administered to all the plots at the same time and in the same quantities. The results also implied that seasonal irrigation depths applied to the four different moisture treatments did not appear to impact either plant uptake or leaching. However, rainfall depths over the growing seasons would undoubtedly contribute to leaching of nutrients.

Both NO_3-N and Olsen P indicated statistical significance between surface and buried drip irrigation type only in 2008 but not 2009 or 2010. In 2008, buried drip lines were installed at 20 cm below the soil profile, while in the other two years they were raised by 5 cm to a depth of 15 cm. This change was implemented after yields and irrigation depths in 2008 from the surface irrigated plots were significantly higher than those from buried drip irrigated plots. It is believed that the depth of the drip line may have contributed to the statistical difference between irrigation types.

Nutrient content showed a definite decrease in concentration down the three depths and across the season. For the soil depths (0 to 30, 30 to 50 and 50 to 70 cm) and seasons (pre, mid and end) the highest and lowest nutrient content was generally associated with the 0 to 30 cm at the pre-season, and the 50 to 70 cm depths at the end of season, respectively. The gradual decrease in NO_3-N across the season was due to the crop's ability to increase nutrient uptake as the rooting system developed with time. Statistical significance was also obtained across the seasons (pre, mid and end of season) and with depths down the profile (0 to 30, 30 to 50 and 50 to 70 cm). Hartz and Hochmuth (1996) stated that fruiting crops such as tomatoes utilize relatively little nutrition until flowering stages, at which time nutrient uptake accelerates, reaching its peak during fruit set and early fruit bulking. As fruits mature, macronutrient requirement declines. Further, rainfall during the months following transplanting would have contributed to leaching of more mobile NO_3-N. Liu et al. (2011) noted that drip irrigation increased crop uptake and decreased soil P content in the soil profile. Similar decreasing NO_3-N trends were reported by Tan et al. (2003) both along the soil profile and across the seasons for the pre-planting and end of season. Liu et al. (2011) reported end of season Olsen P values greater than 134.4 kg ha^{-1} at the 0 to 20 cm depth under processing tomato cultivation, in Harrow, Ontario.

Since both fixed effect parameters of season and depth indicated significant differences, it is not surprising that their interaction also showed statistical significance for NO_3-N and P in all years. However, all the other two way interactions (irrigation type * moisture treatment, moisture treatment * season, irrigation type * depth and moisture treatment * depth) indicated no significant differences with the exception of the interaction of irrigation type * season, which indicated statistical significance only for N in 2008. The pair-wise comparisons using Bonferroni adjustment among soil depths indicated statistical significance for all the pair-wise comparisons associated with Olsen P for all three years and for NO_3-N in 2008. This implied that the differences in nutrient content along the soil profile were substantial. For NO_3-N, in 2009 and 2010, statistical significance was obtained between the pairs 0 to 30 cm and 30 to 50 cm, and between 0 to 30 cm and 50 to 70 cm depths, respectively, but not between 30 to 50 cm and 50 to 70 cm depths. This was due to the fact that changes over the two depths were relatively small. In relation to the season pair-wise comparisons for NO_3-N, statistical significance was obtained for all pairs except for the mid-season and end of season in 2008, and the pre and mid seasons 2010 respectively, while the P pair-wise comparisons indicated statistical significance for all pairs except for the pre and mid seasons in 2009 and mid and end of seasons in 2010 respectively (Table 8.5). Again the lack of statistical significance was due to the relatively small differences in nutrient contents between the seasons.

Although all P was applied at the pre-season stage, the variation with depth and across the seasons for each year was not as large as the NO_3-N. This may be explained by the larger residual pool of P present in the soil due to previous years of fertilizer application. Further, Grant et al. (2001) alluded to the fact that P is relatively immobile in the soil and so remains near the site of fertilizer placement. The general lower mobility of P by the process of diffusion, particularly during the early season may have been due to some extent as a result of lower soil temperature. Cooper (1973) highlighted that the uptake and translocation of essential nutrients are directly influenced by temperature of the root zone and Grant et al. (2001) reported that temperature also influences the rate of reaction of fertilizer P with soil. Plant availability of P is generally greatest in the pH range of 5.5 to 6.8. When soil pH falls below 5.8, P reacts with Fe and Al to produce insoluble Fe and Al phosphates that are not readily available for plant uptake. At high pH values, P reacts with Ca to form Ca phosphates that are relatively insoluble and have low availability to plants. However, phosphorus solubility and mobilization is greatest in soils with a neutral pH (Grant et al., 2001; Johnston, 2000; McLaughlin et al., 2011).

Figures 8.1 and 8.2 summarize the NO_3-N and Olsen P along the profile and across the season for 2008. In 2008, the 0 to 30 cm depth for the 60% FC treatment increased in NO_3-N content from the mid-season to the end of season by 37.5%, while the 50 to 70 cm depth of the 80% FC treatment for the same period increased by 2.4 kg ha^{-1}.This rise may be due to the combined influence of the nitrogen applied through the fertigation system, and side dressing applied approximately one month after planting, which through capillary rise may have moved away from the active rooting zone. Further, the improved climatic conditions, particularly the favorable temperature and increased organic matter at the end of the season created greater possibility for mineralization to occur. It is estimated that 1 to >3% of the soil organic N mineralizes and becomes available for plant uptake each year (Keeney & Nelson, 1982; Liang et al., 2004).

In 2008, Olsen P at 0 to 30 cm, and 30 to 50 cm depths for all the treatment increased from mid-season to the end season (Fig 8.2). The relatively high organic matter (2.1 to 2.9%) content in the soil may have contributed to the rise in P across the seasons. Studies have shown that soil microbes break down organic P contained in humus through the process of mineralization, to release inorganic phosphate ions. Johnston (2000) stated that the annual turnover of organic P for soils which have been under arable cropping for many years can range from less than 1 to about 10 kg P ha^{-1}. Further, during the earlier part of the season, plant roots were within close proximity to the applied P, thus making root extraction of P easier. However, as the rooting system developed and moved further away from the source of P, the root uptake of P was reduced. Nye and Tinker (1977) noted that due to the low mobility of P relative to N, plant roots have a lower probability

of coming into contact with phosphorous. During active P uptake periods, the plant roots extract most of the P from within 2 mm of the root surface.
Figures 8.3 and 8.4 describe the NO_3-N and P along the profile and across the season for 2009. The 2009 pre-season NO_3-N content at the 0 to 30 cm depth was substantially higher than that of 2008 and 2010. This would undoubtedly be due to the low depth of rainfall during the month of May for 2009 (12.5 mm) as compared to the other two years (66.4 and 114.7 mm, respectively) which may have influenced leaching of N to lower depths. Bakhsh et al. (2010) noted that the dominating factor in the leaching of NO_3–N is soil water movement.

Figures 8.5 and 8.6 summarize the NO_3-N and Olsen P along the profile and across the season for 2010. Two of the four moisture treatments (55% FC and 70% FC) indicated an increase in NO_3-N between the pre and mid seasons but was significantly reduced by the end of the season. This may be due to the influence of the side dressing which would have increased the NO_3-N during the mid-season. The 2010 end of season NO_3-N was the lowest of the three years. This may be attributed to the greater rainfall towards the end of the 2010 growing season (152.4 mm over July and August) compared to the previous two years which may have contributed to greater leaching of NO_3-N. The 2010 Olsen P content over the 0 to 30 cm depth increased from the pre-season to the end of season for all moisture treatments. A combination of factors may have contributed to this increase across seasons. Shenoy and Kalagudi (2005) summarized that the efficiency of applied fertilizer P was approximately 10%. Johnston (2000) stated that plant uptake of P was less than 25% for freshly applied fertilizer and Liu et al. (2011) reported apparent P recovery of 5 to 15%. As a result a large proportion of applied P remains in the soil. Sato et al. (2009) in an irrigated tomato study found that P did not move outside the root zone during the growing season.

Fertilizer P reacts and transforms rapidly when first applied to soil, but continues to transform for months afterward. The transformation is generally to less-soluble forms, with lower temperatures slowing the process. The increased viscosity at low temperatures is known to decrease rates of water uptake by roots and transported within the plant (Wan et al., 2001), and therefore reduces the rate of nutrient transport to the roots in mass flow. Similarly, the transport of nutrient ions from areas of high to low concentration by the process of diffusion is directly influenced by soil temperature (Pregitzer & King, 2005).

8.4.2 Nutrient content under the interaction of season, depth and irrigation type

Figures 8.7, 8.8, and 8.9 summarize the NO_3-N and Olsen P contents in relation to the interactions between depth (0 to 30 cm, 30 to 50 cm and 50 to 70 cm), irrigation type (buried and surface irrigation) and season (pre, mid and end of season) for the three years of the experiment.

Pre-season (0 to 30 cm, 30 to 50 cm and 50 to 70 cm) - 2008 to 2010

The pre-season NO_3-N and Olsen P at the 0 to 30 cm depth for the buried drip irrigated plots indicated higher nutrient content than the surface irrigated drip plots for all three years. A similar trend obtained at the 30 to 50 cm and the 50 to 70 cm depths for 2008 and 2010. In 2009, the reciprocal was true (Fig. 8.7). Under buried drip irrigation, Hartz (2004) noted the surface 10 to 15 cm of soil may (depending on soil characteristics and system depth) often be too dry for active nutrient uptake. Evaporation from the soil surface may move soluble nutrients into this dry zone, beyond the reach of the crop. Evaporation from the soil surface over time can deposit a considerable quantity of NO_3-N in the dry surface soil. Although N may be recovered by a subsequent crop, it may be largely beyond the reach of the current crop. N fertigated early in the cropping cycle is particularly susceptible to this fate, since crop uptake is relatively slow until mid-season, and evaporation is more rapid before the crop canopy shades the soil surface. This accounted for the higher nutrient content in the buried plot than the surface plots over the 0 to 30 cm.

Mid-season (0 to 30 cm, 30 to 50 cm and 50 to 70 cm) - 2008 to 2010

For each of the three years, the change in NO_3-N and P along the profile was substantial. However, the change from the 0 to 30 cm to the 30 to 50 cm depths was greater than the change from the 30 to 50, to the 50 to 70 cm depths. At the mid-season stage, the buried plots indicated lower NO_3-N content than surface plots at the 0 to 30 cm depth, which was the exact opposite at the pre-season for the same depth (Fig. 8.8). By then the crop canopy had fully covered the ground surface and the evaporation from the soil was greatly reduced. Hartz (2004) reported that buried drip line concentrate roots deeper in the soil than conventional surface drip irrigation and therefore would be more effective at nutrient uptake. Gärdenäs et al. (2005) noted that total seasonal leaching of nitrogen was the lowest for subsurface drip in comparison to surface drip for processing tomatoes, and this was attributed to both water and fertilizer being effectively supplied to the rooting system of processing tomatoes. Tan et al. (2003) highlighted that buried drip irrigation produced significantly more N and P removal than surface drip irrigation, regardless of the fertilization method in loamy sand. This may account for the lower NO_3-N from the buried plots than the surface plots at the mid-season stage. However, the P did not exactly follow a similar pattern as the NO_3-N and may be attributed to its lower mobility.

End of season (0 to 30 cm, 30 to 50 cm and 50 to 70 cm) - 2008 to 2010

Similar to the pre-season, P and N at the 0 to 30 cm indicated higher contents in the buried than the surface drip irrigated plots for all three years, except for the P in 2010. The pattern for the mid-season and end of season were similar (Fig. 8.9). Throughout the season P content was always higher than the NO_3-N. Apart for the N being more easily leached, Greenwood et al. (1980) noted that crops extract approximately 5 to 10% of the applied fertilizer in the first year with the remainder coming from existing residual P (Sibbsen & Sharpley, 1997). To this end, a larger residual pool of P must be present in the soil to ensure that the crop's P requirement is adequately met. Uptake of P by the plant is proportional to the root density (Grant et al., 2001); however, drip irrigation tends to limit root development within a narrow range. The root surface should be in contact with soil nutrients to facilitate nutrient uptake by root interception, mass flow, and diffusion (Jungk, 2002). Approximately 1% of nutrients reaching the surface of plant root systems are due to direct interception, while the remainder is transported to the roots by mass flow (for NO_3-N) and diffusion for P (Jungk, 2002).

8.4.3 Soil moisture impact on nutrient content

It was not possible to isolate and measure the sub-surface runoff from the experimental site. Therefore, the leaching effect of the irrigation scheduling and the rainfall over the growing season was not quantifiable. Figure 8.10, depicts the nutrient content (P and N) per treatment at each depth across the seasons, versus the total irrigation depth and effective rainfall (combined) over the growing season for 2008 to 2010. The total irrigation and effective rainfall increased from approximately 302 to 430 mm over the three years. At the 0 to 30 cm depth across the seasons, the P content indicated small variability for 2008 and 2009. However during 2010 there was an increase in the P content, as well as an increase in the combined rainfall and irrigation (Fig. 8.10a). This seemed to suggest that P was not significantly leached with increased soil moisture. This may be attributed to the fact that phosphate anions have the ability to adhere to the surface of the soil particles through specific adsorption reaction thus reducing its ability to be leached down the profile (Evangelou, 1998). Sorption refers to both adsorption on solid surfaces and absorption into solid phases of Al and Fe oxides and other mineral surfaces (Bache, 1964; Rhue & Harris, 1999). At the 30 to 50 cm and the 50 to 70 cm depths, P content across the seasons for each treatment during 2008 and 2009 was again relatively constant. However, during 2010, there was a 17% decrease in the P content across the seasons relative to 2008 and 2009 at both the 30 to 50 cm, and 50 to 70 cm depths, which may be attributed to a measure of leaching due to increased rainfall depth (Fig. 8.10 a and b).

NO_3-N content appeared to be more influenced by soil moisture content. With the increased soil moisture content, there was a corresponding decrease in the NO_3-N content, which seemed to imply that there was some leaching of NO_3-N. This was particularly apparent in 2010 at each of the three depths (Fig. 8.10d to f). Bakhsh et al. (2010) showed that temporal distribution of rainfall over the growing season had a pronounced effect on tile flow and NO_3–N leaching losses and added that rainfall during the early spring months contributed substantially to greater N losses than during the summer months. During the summer months, soil moisture was used beneficially to sustain crop water needs or retained in the soil. Also, crop water requirements are low in early spring and NO_3–N is available for leaching through the soil profile.

8.4.4 Implication of results

The results indicated that there was nutrient leaching throughout the growing season to the lower depths. Of particular interest was the nutrient content across the season and along the soil profile at the end of the season. The residual rates of Olsen P and NO_3-N at particularly the 30 to 50 cm and 50 to 70 cm depth were still high, ranging from 44.0 to 127.5 kg ha^{-1} (19.6 pm to 56.9 ppm) for P and 9.1 to 157.2 kg ha^{-1} (4.0 ppm to 70.0 ppm) for NO_3-N respectively. The fact that the subsurface drainage system was installed at the 70 cm depth would imply that over time these nutrients would be leached out of the soil into the drainage system and eventually into Lake Erie. Olsen P values of 40 and 60 mg P Kg^{-1} (90 to 134 kg ha^{-1}) were proposed as thresholds beyond which significant P losses can result (Fortune et al., 2005; Heckrath et al., 1995). Based on these guidelines, P leaching occurred at each depth and across each of the three seasons. Of significant importance also is the potential for non-growing season losses. Lui et al. (2011) noted that 64% of the annual rainfall occurs during the non-growing season in Ontario. Therefore based on the post-harvest farm management strategy, there is a high potential of nutrient loss through leaching.

Currently, no national environmental quality guidelines exist for phosphorus, although individual provinces in Canada may have guidelines or objectives (Environment Canada, 2004). Alberta uses a maximum concentration of 0.05 mg L^{-1} of phosphorus to control eutrophication in surface water (Alberta Environment, 1999). Ontario Nutrient Management Act (NM Act) was passed in 2002 to establish province-wide standards relating to land applied materials to sustainably manage the water quality and environment. Along with this act, is the Ontario's NMAN nutrient management planning software to facilitate the agrarian community with the development of nutrient management plans (OMAFRA). The United States Environmental Protection Agency (U.S. EPA, 1986) stipulates that phosphorus concentration should not exceed 0.05 mg L^{-1} for streams entering lakes and reservoirs and 0.0025 mg L^{-1} for the lakes and reservoirs themselves. For the prevention of plant nuisances in streams and other flowing water not directly entering lakes and reservoirs, the phosphorus concentration should not exceed 0.10 mg L^{-1} (Daniel et al. 1998).

The percentage recovery (or efficiency) of P is very low, often only 10 to 15% and rarely exceeding 25% (Johnston, 2000; Liu et al., 2011).The present agronomic practice allows for the application of all the P at the pre-planting stage. However, the fact that two batches of granular fertilizers are applied to the crop at the pre-planting stage and approximately one month later as a side dressing may necessitate that P fertilizer be also applied in two batches instead of one, as presently obtains. This may allow for better use of the nutrient by the plants. However the time factor for the breakdown and effective utilization by plants also needs to be taken into consideration. Andersen et al. (1999) and Tremblay et al. (2001) noted that N is difficult to optimize due to its susceptibility to leaching, immobilization, denitrification and volatilization. Therefore, it is possible to reduce the granular application during the two batch applications and increase the frequency of fertigation to better synchronize with crop nutrient uptake. Gärdenäs et al. (2005) recommended that for short fertigation (up to 2 hours) duration, fertigation events should commence near the end of the irrigation cycle as most of the nitrate remains within close proximity to the drip line which corresponds to the zone of maximum root density. While these suggestions may prove workable from an environmental perspective, from the grower's perspective the additional fertilizer cost relative to fruit yields must be evaluated.

8.5 Conclusions

The results indicated statistical variability of soil nutrients (P and NO_3-N) both across the seasons (pre, mid and end of seasons) and along the soil profile as measured at the 0 to 30 cm, 30 to 50 cm and 50-70 cm depths. At the 0-30 cm depth, there was greater variability across the seasons, than observed between the moisture treatments within each season. The general trend showed decreases in NO_3-N from pre-season to end of season. For P, the variability between treatment and across seasons was less than NO_3-N. At the 30-50 cm depth a similar trend obtained for NO_3-N. However, P did not show a consistent trend in one direction across the season. For both NO_3-N and P there were significant decreases down the profile. At the 50 to 70 cm depth there was no consistent trend in 2008 and 2010 across the seasons while in 2009 there was a definite decease in P from pre to end of season for all treatments. The nutrient content indicated a definite decrease in concentration over the three depths with the 50 to 70 cm depth reflecting the lowest amounts of both P and NO_3-N.

In relation to the irrigation type, buried drip irrigated plots generally had higher nutrient content than surface drip irrigated plots. The changes across the seasons were not always consistent in one direction. However both the NO_3-N and P concentration decreased along the profile. There was no statistical difference between the moisture treatment and the irrigation types over the three years, except for the irrigation type in 2008. However, there was statistical difference across the seasons and along depths over the three years.

The end of season residual concentrations of P and NO_3-N particularly at the 30 to 50 cm and 50 to 70 cm depths were high, ranging from 44.0 to 127.5 kg ha^{-1} (19.6 pm to 56.9 ppm) for P and 9.1 to 157.2 kg ha^{-1} (4.0 ppm to 70.0 ppm) for NO_3-N respectively. Based on the Olsen P threshold values, there is the potential for leaching at each depth, and at each season. There is need to examine a more effective nutrient management program in terms of spreading out the fertilizer application over the growing season.

Table 8.1- 2008-2010 pre-planting soil properties at the experimental site over the 0 to 30 cm depth

Soil Parameter	2008	2009	2010
NO_3-N (ppm)	52	101	37
Available P (ppm)	144	121	154
Potassium (ppm)	243	219	191
pH	7.3	7.0	7.0
Organic Matter (%)	2.1	2.9	2.9

Table 8.2– Experimental treatments over the three years (2008-2010)

Year	Experimental Design	Factor 1 – Drip irrigation types		Factor 2 – Moisture treatments			
2008	Split Plot RCBD	Surface	Buried	60% FC	70% FC	80% FC	30kPa
2009	Factorial RCBD	Surface	Buried	74% FC	82% FC	91% FC	30kPa
2010	Split Plot RCBD	Surface	Buried	55% FC	70% FC	85% FC	30kPa

AWC=Available Water Content, FC= Field Capacity, RCBD=Randomized Complete Block Design

Table 8.3-Pre-planting and side dressing fertilizer composition for 2008-2010

Fertilizer Composition	2008				2009				2010			
	Pre-Planting		Side Dressing		Pre-Planting		Side Dressing		Pre-Planting		Side Dressing	
	Qty. (kg ha^{-1})	% of Total	Qty. (kg ha^{-1})	% of Total	Qty. (kg ha^{-1})	% of Total	Qty. (kg ha^{-1})	% of Total	Qty. (kg ha^{-1})	% of Total	Qty. (kg ha^{-1})	% of Total
Nitrogen	173.6	19.9	57.3	17.0	166.1	18.6	55.9	18.8	165.0	17.8	55.0	17.6
Phosphorus	123.7	14.2	-	-	103.5	11.6	-	-	99.2	10.7	-	-
Potassium	33.7	33.7	33.7	10.0	31.2	3.5	26.2	8.8	32.5	3.5	28.7	9.2
Sulphur	47.6	5.5	33.7	10.0	59.8	6.7	23.5	7.9	59.4	6.4	23.1	7.4
Magnesium	16.8	1.9	16.8	5.0	15.6	1.8	10.3	3.5	17.5	1.9	10.1	3.2
Calcium	-	-	-	-	22.1	2.5	5.4	1.8	21.3	2.3	5.3	1.7
Zinc	-	-	-	-	2.6	0.3	-	-	2.5	0.3	-	-
Nitrate N	-	-	-	-	-	-	-	-	64.9	7.0	28.1	9.0
Manganese	1.8	0.2	0.0	-	-	-	-	-	-	-	-	-

Table 8.4-Soil sampling dates over the growing season

Year	Pre-season	Mid-season	End of season
2008	22 May	16 July	14 Sept
2009	24 & 25 May	26 July	07 Sept
2010	17 May	20 July	23 Aug

Table 8.5 -The pair-wise comparisons using the Bonferroni adjustment

Fix Effect Parameter	Pairwise Comparisons	Statistical Results – Adjusted P.					
		2008		2009		2010	
		NO_3_N	P	NO_3_N	P	NO_3_N	P
Depth	00-30 cm & 30-50 cm	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
	30-50 cm & 50-70 cm	<.0001*	<.0001*	0.151**	<.0001*	<.315**	<.0001*
	00-30 cm & 50-70 cm	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Season	Pre-season & Mid-season	<.0001*	<.0001*	<.0001*	0.250**	0.557**	0.0002*
	Mid-season & End of season	1.000**	0.0004*	0.0275*	0.0004*	<.0111*	0.645**
	Pre-season & End of season	<.0001*	<.0111*	<.0001*	0.947**	<.0111*	0.0009*

*, **- Statistically and not statistically significant at α=0.05 respectively.

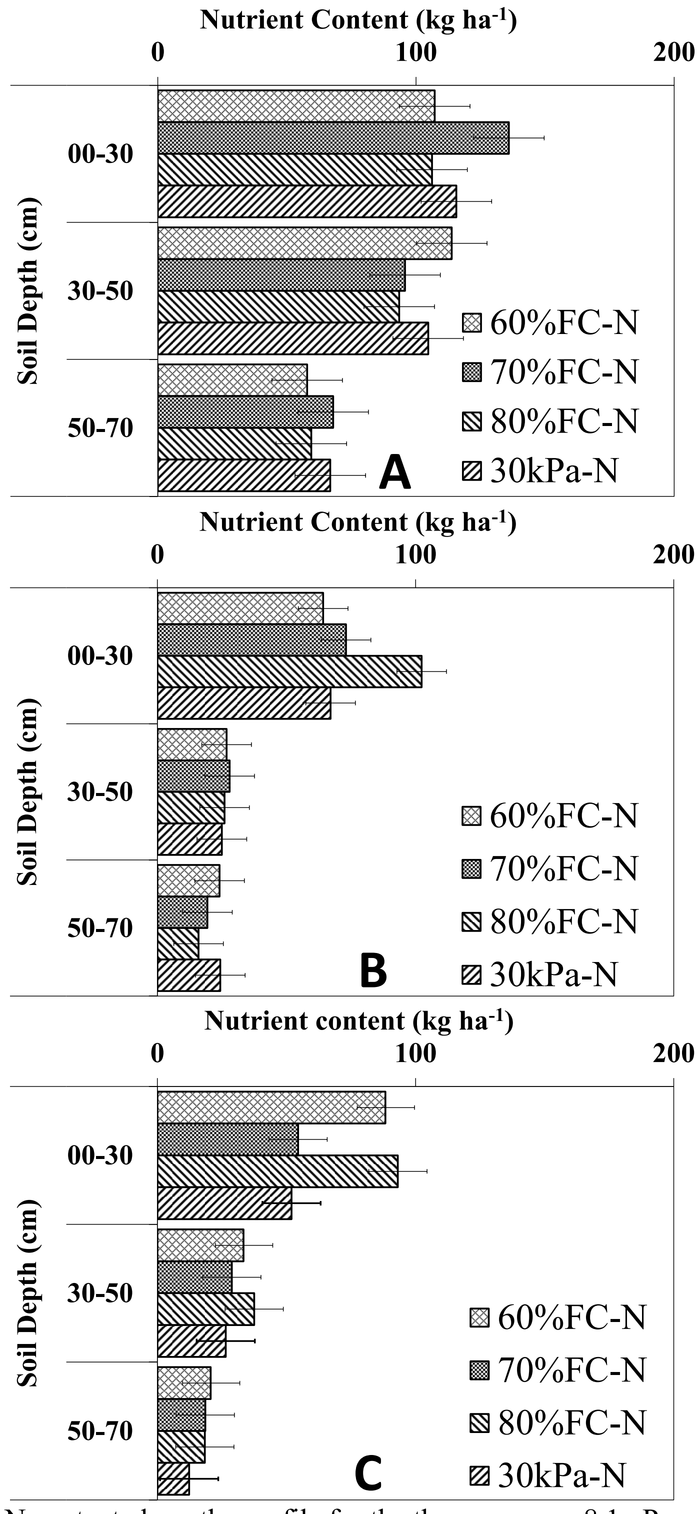


Figure 8.1-2008 N content along the profile for the three seasons. 8.1a-Pre-season, 8.1b-Mid-season, 8.1c-End of season, (60% FC-N represents the Nitrogen content for the 60% field capacity treatment, error bars – standard error of means).

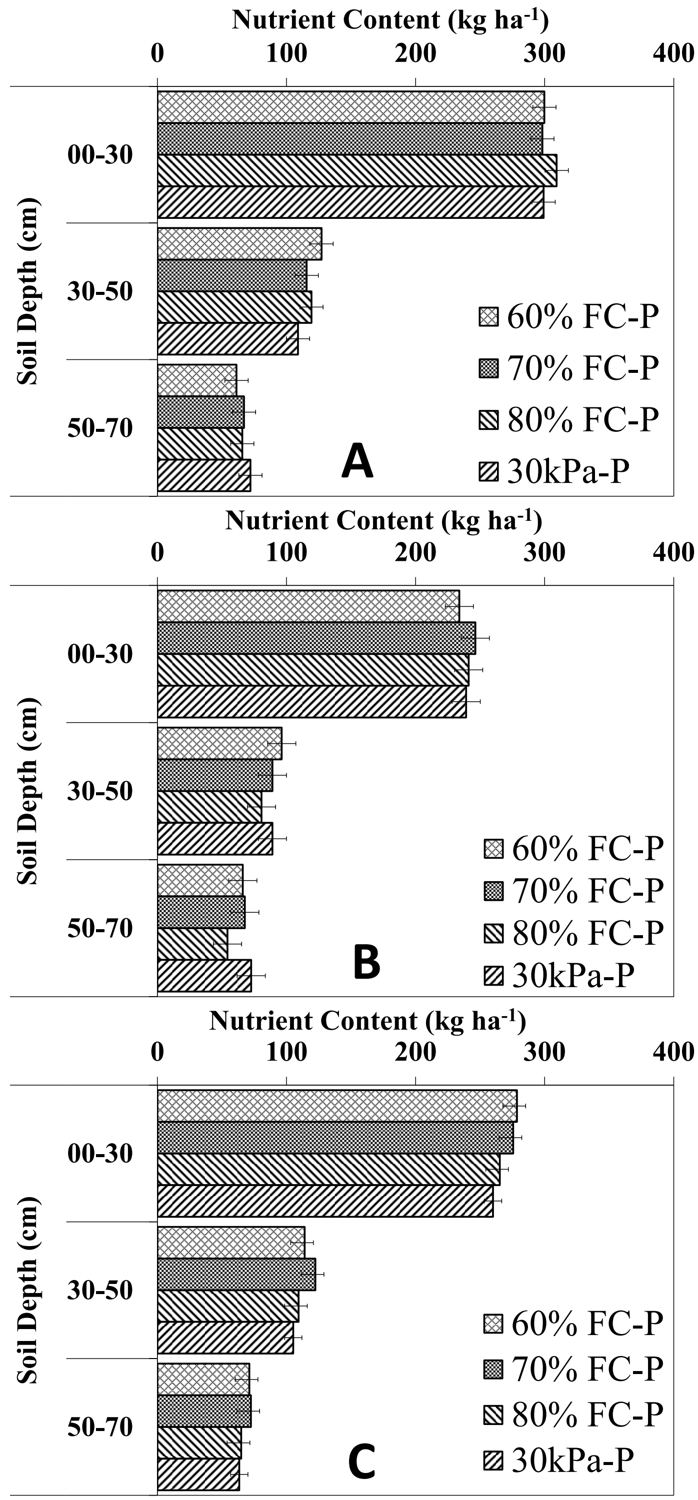


Figure 8.2-2008 P content along the profile for the three seasons. 8.2a-Pre-season, 8.2b-Mid-season, 8.2c-End of season. (60% FC-P represents the P content at the 60% field capacity moisture treatment)

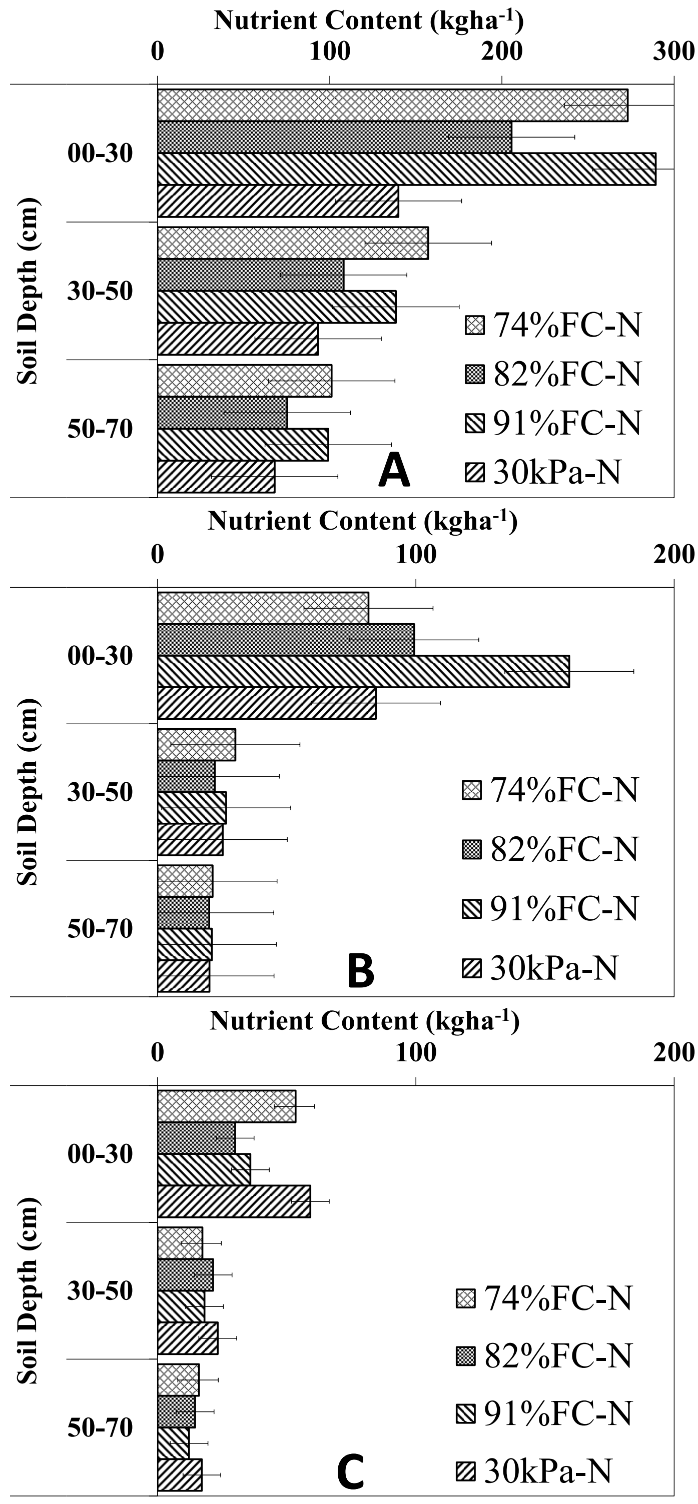


Figure 8.3- 2009 N content along the profile for the three seasons. 8.3a-Pre-season, 8.3b-Mid-season, 8.4c-End of season

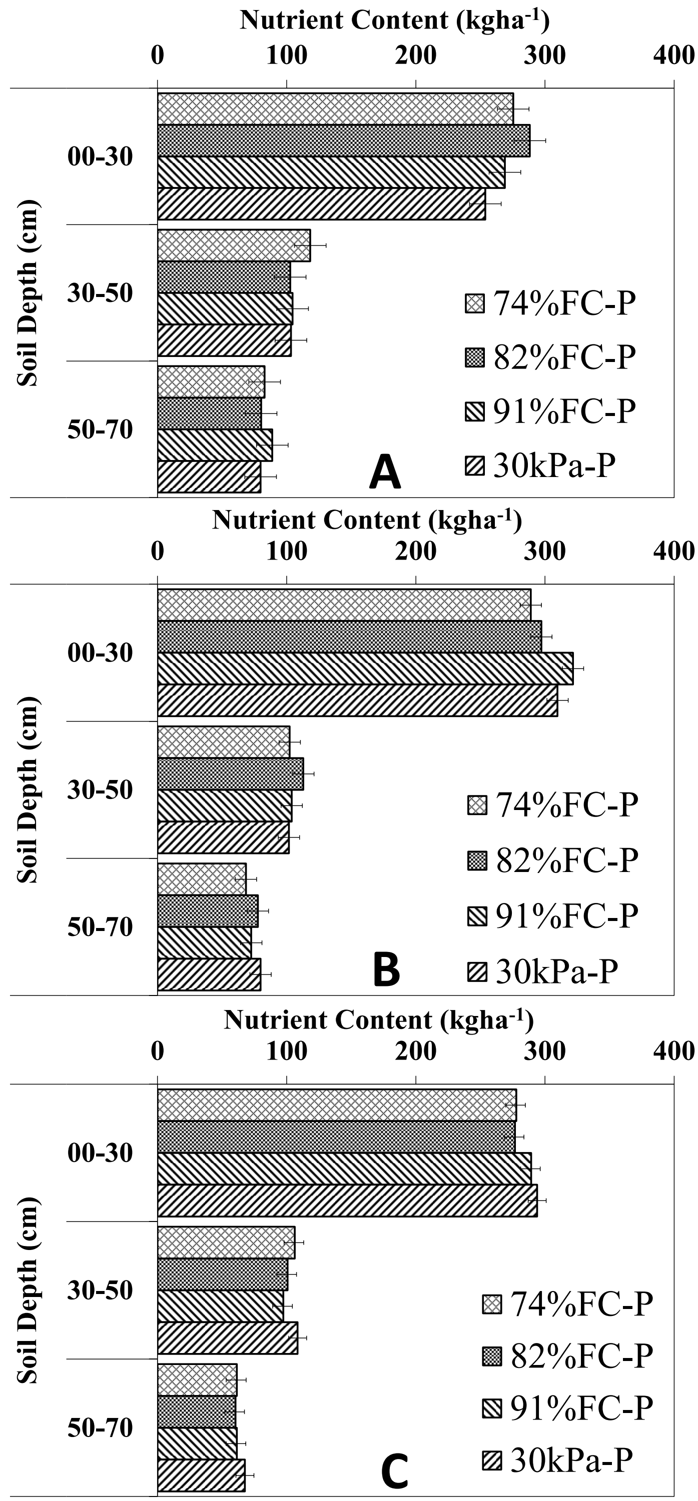


Figure 8.4-2009 P content along the profile for the three seasons. 8.4a-Pre-season, 8.4b-Mid-season, 8.4c-End of season (55% AWC-P represents the P content for the 60% available water content treatment).

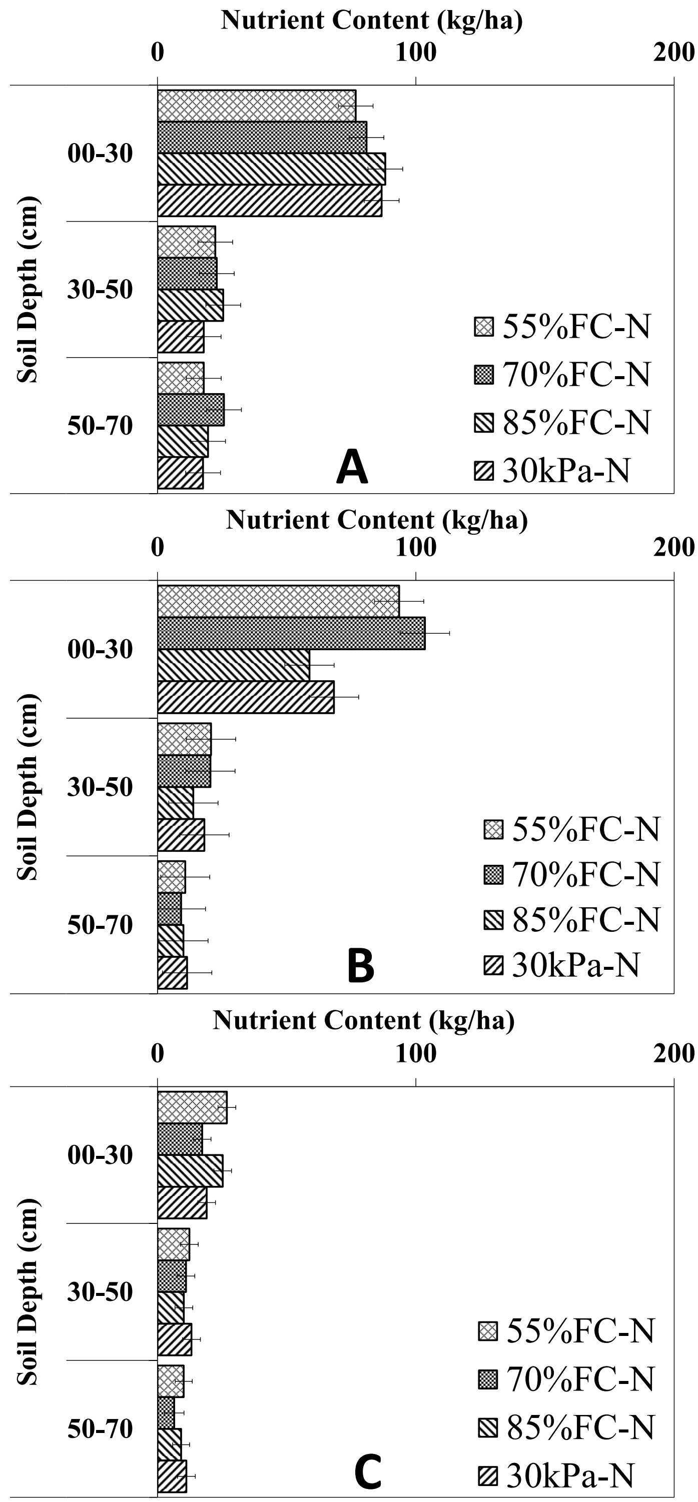


Figure 8.5-2010 N content along the profile for the three seasons. 8.5a-Pre-season, 8.5b-Mid-season, and 8.5c-End of season.

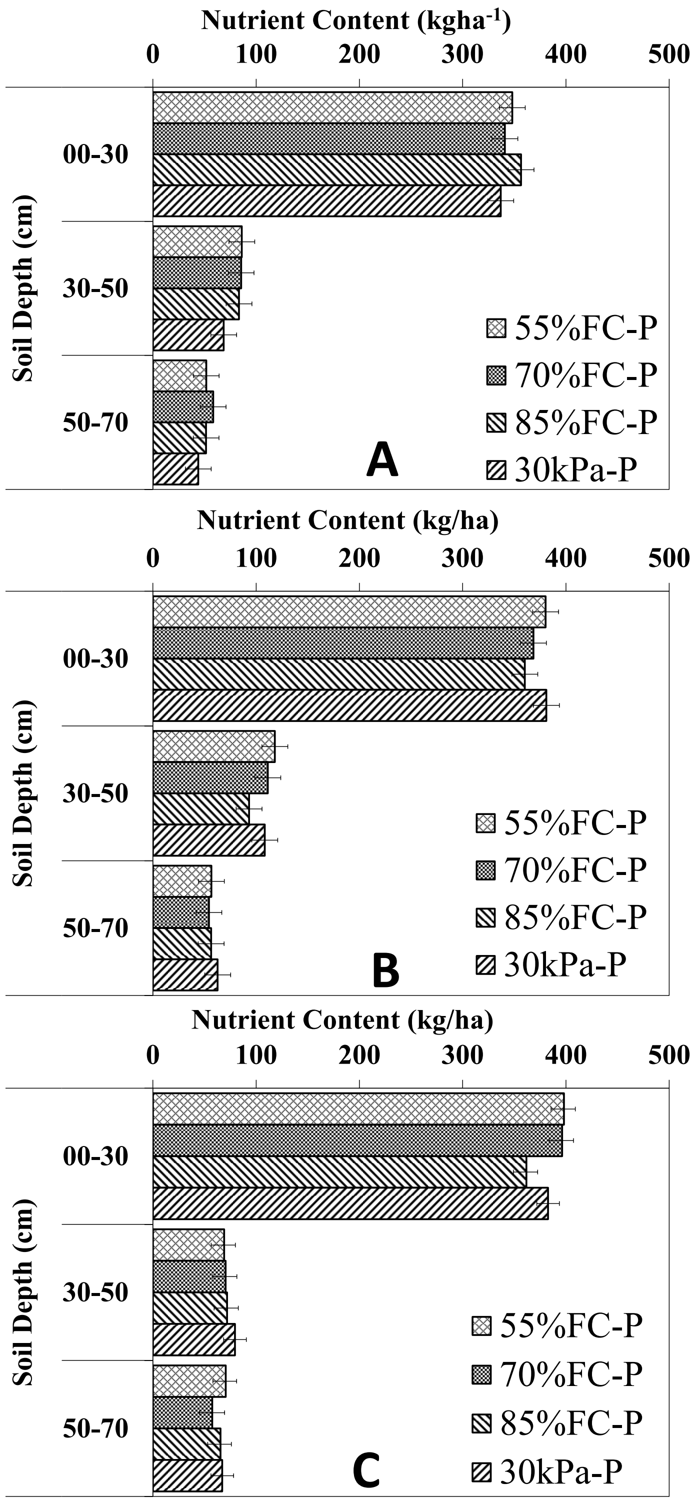
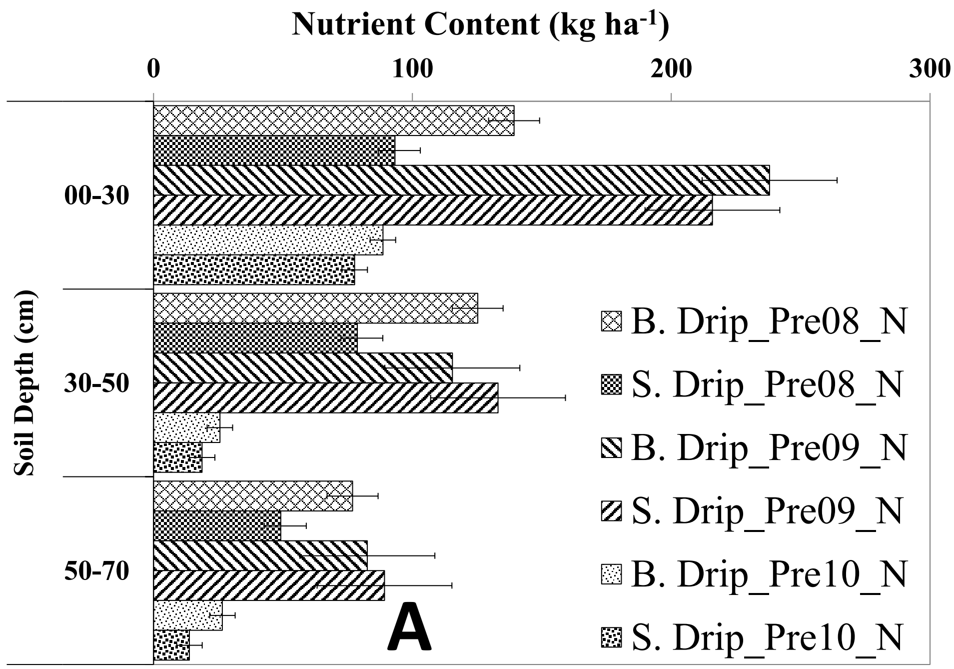


Figure 8.6-2010 P content along the profile for the three seasons. 8.6a-Pre-season, 8.6b-2008 Mid-season, 8.6c-End of season



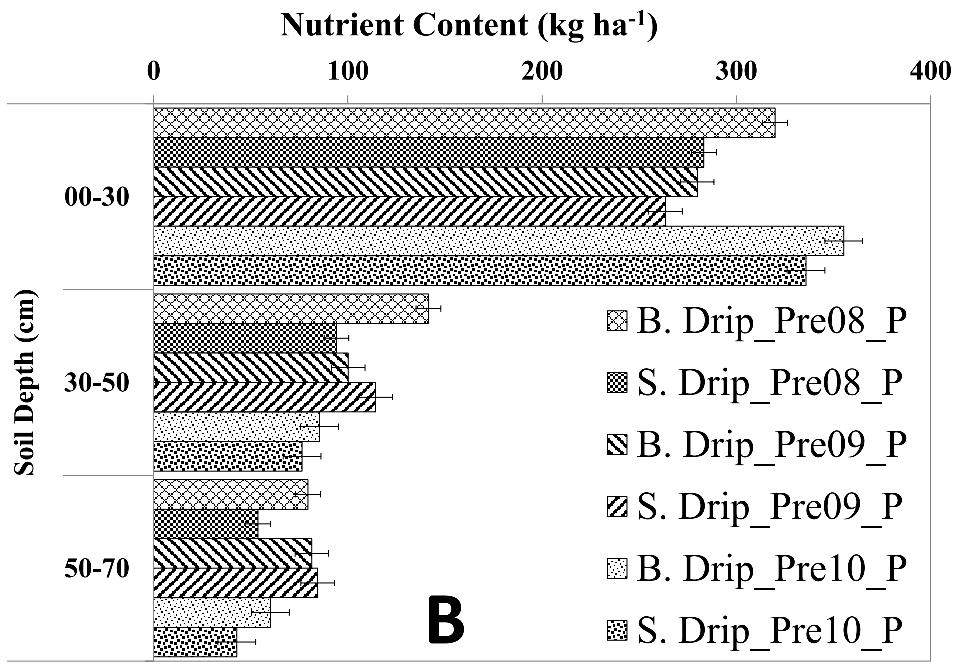


Figure 8.7-Figure 8.7a Pre-season N*Depth*Irrigation Type (2008 to 2010), Figure 8.7b-Pre-season P*depth* irrigation type (2008 to 2010) (B. Drip and S. Drip = Buried and Surface drip irrigation types respectively, Pre08, 09 and 10 = Pre-season for 2008-2010)

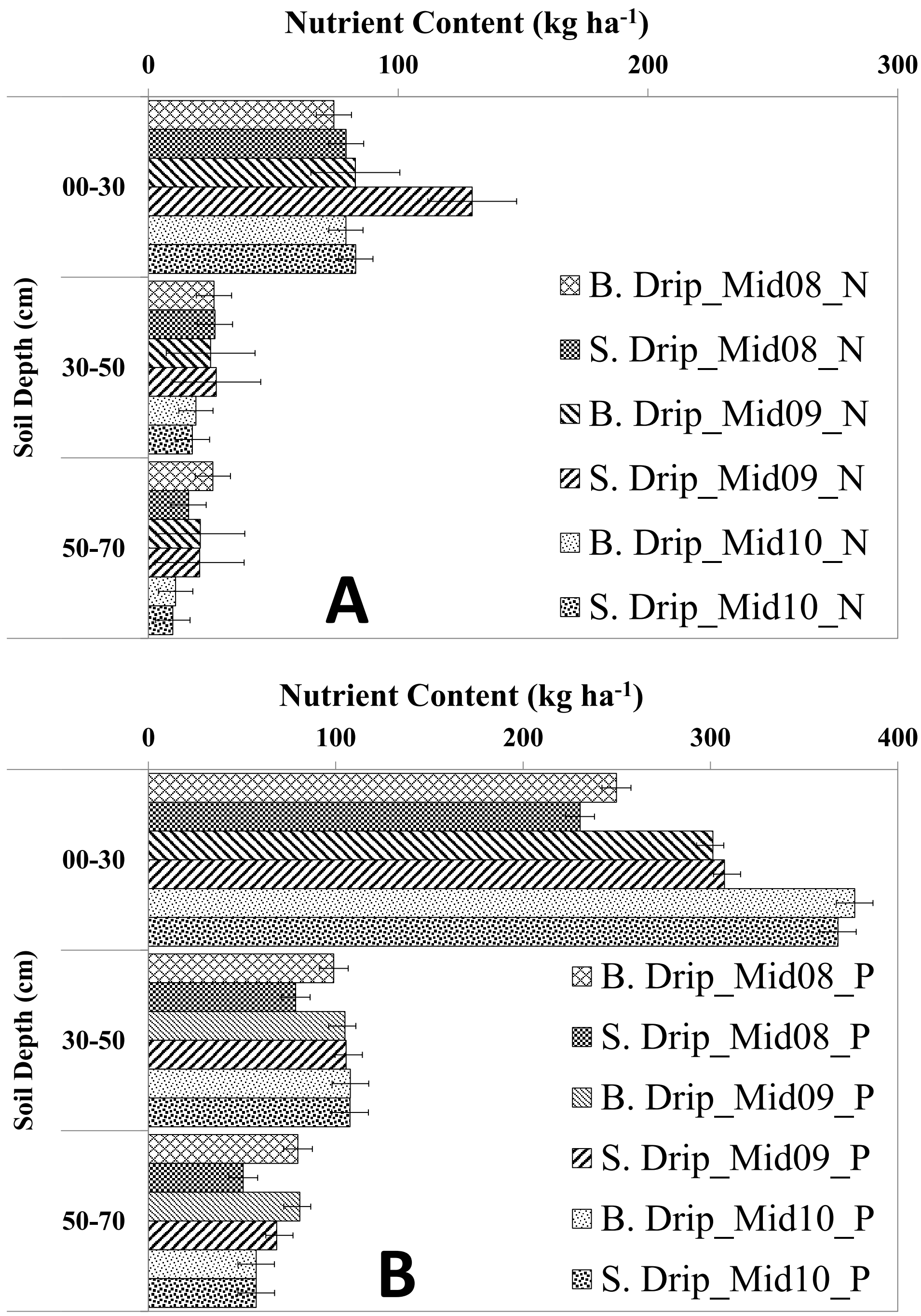


Figure 8.8-Figure 8.8a-Mid-season N*depth*irrigation type (2008 to 2010) Figure 8.8b-Mid-season P *depth * irrigation type (2008 to 2010) (B. Drip and S. Drip = Buried and Surface drip irrigated plots respectively, Mid08, 09 and 10 = Mid-season for 2008-2010)

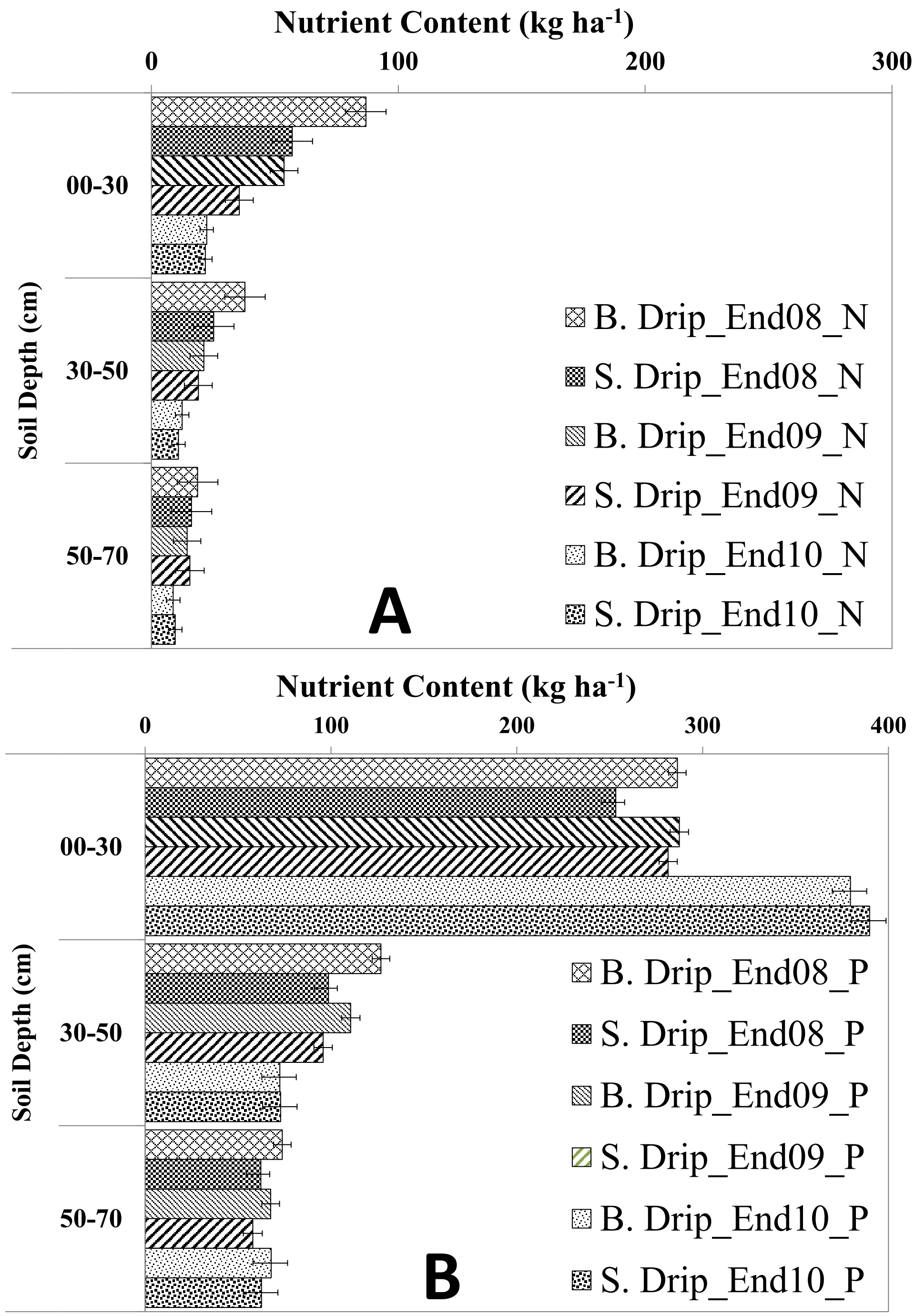
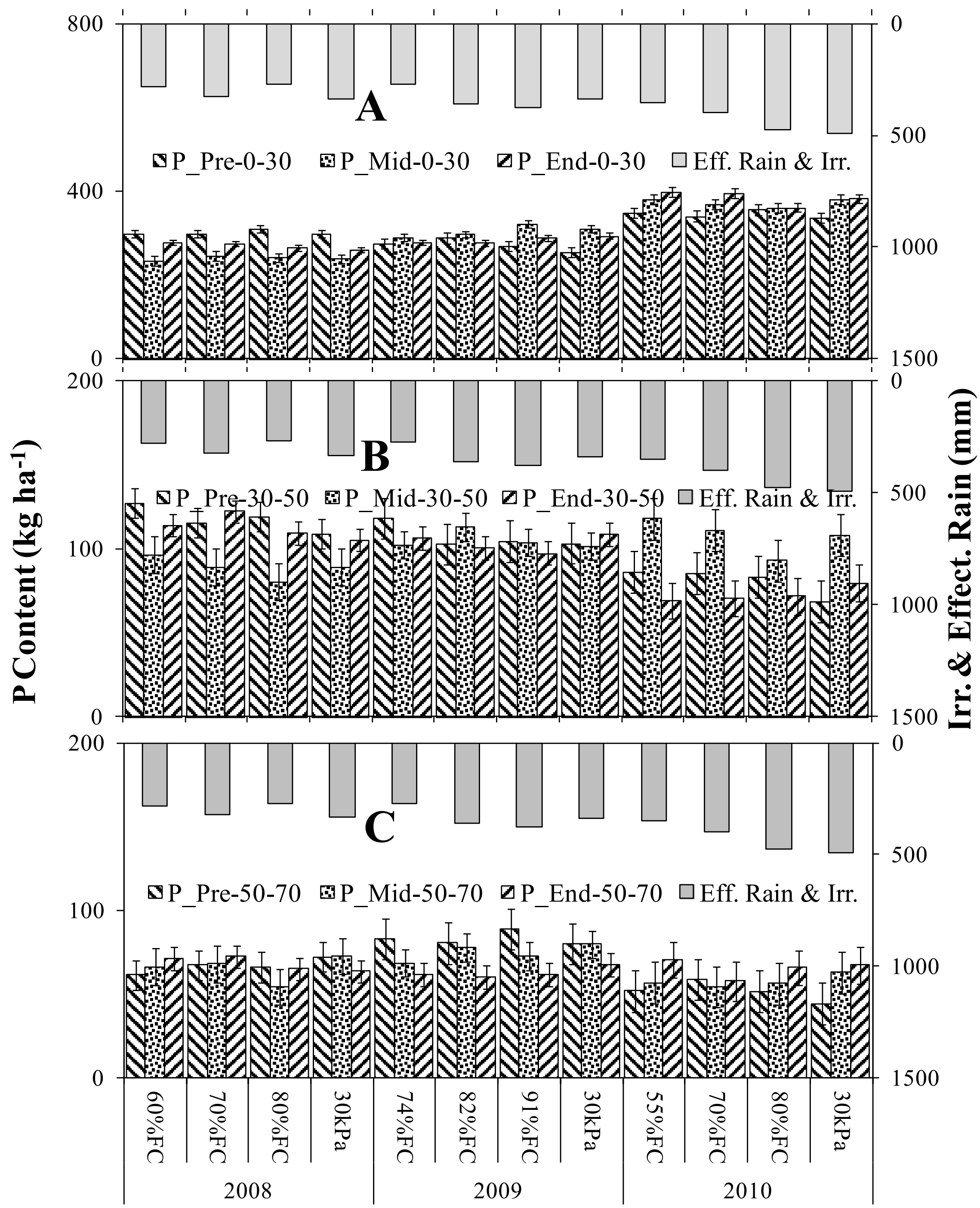


Figure 8.9-Figure 8.9a-End-season N*depth*irrigation type (2008 to 2010), Figure 8.9b.-End-season P *depth * irrigation type (2008 to 2010) (B. Drip and S. Drip = Buried and Surface drip irrigated plots respectively, End08, 09 and 10 = End of season for 2008-2010)



A
P_Pre-0-30
P_Mid-0-30
P_End-0-30
Eff. Rain & Irr.
B
P_Pre-30-50
P_Mid-30-50
P_End-30-50
Eff. Rain & Irr.
C
P_Pre-50-70
P_Mid-50-70
P_End-50-70
Eff. Rain & Irr.
P Content (kg ha^{-1})
Irr. & Effect. Rain (mm)
800
400
0
200
100
0
200
100
0
0
500
1000
1500
0
500
1000
1500
0
500
1000
1500
60%FC
70%FC
80%FC
30kPa
74%FC
82%FC
91%FC
30kPa
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70%FC
80%FC
30kPa
2008
2009
2010

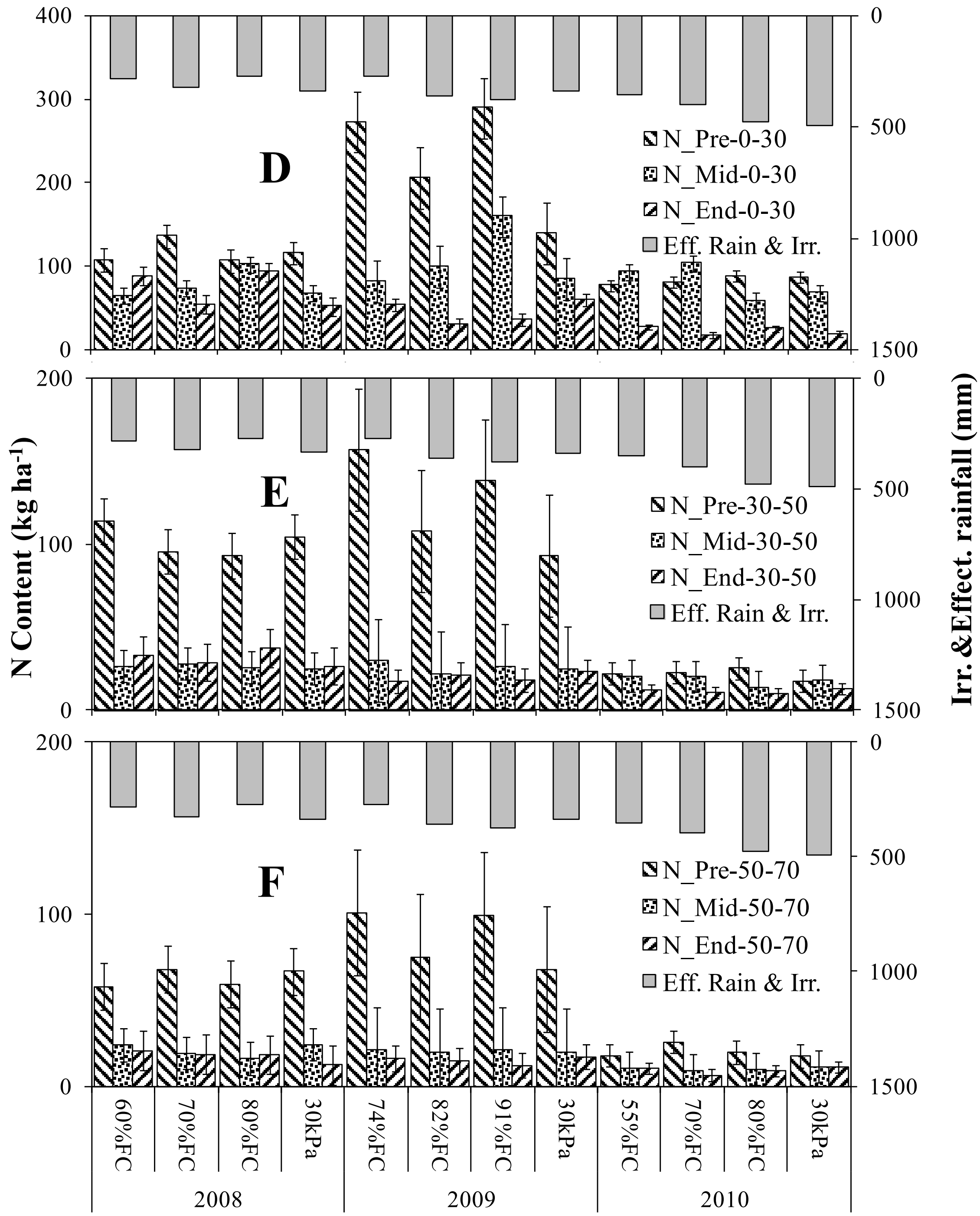

Figure 8.10-Nutrient content per treatment at each depth across each season vs. total irrigation depth and effective rainfall. (8.10a – P at 0-30 cm depth, 8.10b - P at 30-50 cm depth, 8.10c - P at 50-70 cm depth , 8.10d– NO_3-N at 0-30 cm depth, 8.10e - NO_3-N at 30-50 cm depth, 8.10f - NO_3-N at 50-70 cm depth,)

Chapter 9 General Summary and Conclusion

9.1 General summary

Precision irrigation scheduling (PIS) is a combined technical and managerial tool which timely and accurately applies water to the crop and is the key to conserving water, improving irrigation performance and sustainability of irrigated agriculture. Effecting PIS is particularly challenging in the humid region of southwestern Ontario where soil moisture is often influenced by periodic rainfalls. To this end, a three year (2008-2010) field research was undertaken to generate this knowledge. The overall goal of the study was to increase the economic productivity of large scale field processing tomato in Leamington but effectively utilizing the limited water resources through improved irrigation scheduling. This was undertaken with four objectives.

9.2 Conclusions

Objective 1 – To develop an optimum irrigation schedule for intensive cultivation of processing tomatoes by examining different irrigation trigger levels.

Commercial yield was highest for the moisture treatments receiving the highest water applications. In most cases, this also corresponded to the moisture treatments which had a depletion level in soil moisture of ≤ 40% AWC. The tension based treatment (-30 kPa), representing a depletion level of between 20 to 24 % AWC, produced the highest yields in two of three years (2009 and 2010). In 2008, the 70% FC treatment (equivalent to a moisture depletion of 54% AWC) produced the highest yield. This was due to an anomaly with two replicates associated with that treatment. The 2008 results indicated that surface drip irrigation produced significantly higher yields than buried drip irrigation for each of the four moisture treatment. This was attributed to the depth of the buried drip in 2008; however, in the other two years of the project (2009, 2010), there was no statistical significance in yield between the surface drip and buried drip irrigated plots after the buried drip lines were raised from a depth of 20 to 15 cm.

The fruit quality parameters of greatest interests were weight, size, firmness, soluble content and brix yield. The heavier and bigger fruits were associated with the higher moisture treatments. Soluble solids had an inverse relationship with irrigation depth and fruit yields. As a result the most stressed treatment in each year had the highest soluble solids. Brix yield showed statistical significance only between the surface and buried irrigation systems of 2008. This was attributed primarily to difference in yields between the buried and surface drip types. IWUE showed no statistical significance between the moisture treatments, irrigation types or their interaction for each of the three years. However 2010 had the lowest irrigation water use efficiency which was due primarily to the higher rainfall than the previous two years.

Objective 2 – To develop and test a protocol for a real-time soil moisture monitoring for scheduling irrigation and its comparison with an empirical crop water requirement model.

A needs based protocol was developed for accomplishing irrigation scheduling using real time soil moisture sensors, which can be transferable to the agrarian community for implementation. This protocol included field measurements, installation, and data retrieval of soil moisture sensors. Sensors were also calibrated and monitored throughout the growing season. Irrigation scheduling was accomplished based on predetermined lower and upper moisture thresholds. All three sensors used in the experimental research (CS625 water content reflectometer, the EnvroSMART, and the Hortau tensiometer) can be used as standalone instruments for managing irrigation scheduling for large scale field processing tomatoes. However, it was found that the tension based sensor was the most grower friendly sensor. The two volumetric sensors also performed very well but are more geared towards research work. The three different soil moisture sensors were evaluated over a three year period using ten attributes. The final scores were 103, 93 and 71 for the Hortau tensiometer, CS625 Water content reflectometer and EnviroSMART respectively.

The effectiveness of the sensor based irrigation scheduling in satisfying the requisite crop water requirements was evaluated against the Penman-monteith model. The results indicated that standalone soil moisture sensors operating over the range of FC and a soil moisture depletion level of ≤ 40% AWC was adequate in meeting the seasonal crop water requirement. At greater depletion levels, the seasonal crop water requirement was inadequate and resulted in lower crop yields. 2010 was an exceptional year because of the relatively high rainfall over the growing season in which all the treatments surpassed the seasonal crop water requirements. The experiment showed that estimating irrigation water requirement using climatic data is good for planning purposes, while sensor based is excellent for real time application. However a combination of the two approaches to accomplish irrigation scheduling can greatly assist growers to better manage their irrigation water.

Objective 3 - To determine the impact of spatio-temporal variability of soil moisture under drip irrigation for tomato cultivation.

The soil moisture content varied both across and along the plot over the growing season. After an irrigation event, soil moisture was highest near the drip line but gradually decreased away from the drip line. The results indicated that for double row planting of tomatoes with a central drip line, a row spacing of 50 cm was adequate due to the higher soil moisture contents within that zone. After an irrigation event, soil moisture was highest within 25 cm, either side of the centrally aligned drip line but gradually decreased away from the drip line. Maximum soil moisture depletion rates within the first 24 hours after irrigation ranged between 0.27 to 0.34 mmh^{-1} and occurred at a horizontal distance of 15 cm from the drip line and a vertical distance ranging from 0 to 15 cm from the nearest emitter on the drip line. Due to the lack of uniform distribution of moisture in the soil profile, paired sensors (with one either side of the drip line) may provide a better estimate of soil moisture depletion for sensor based irrigation scheduling.

Objective 4 - To determine the nutrient dynamics in the soil profile over the growing season of the crop.

The Olsen P and NO_3-N were statistically significant both across the seasons (pre, mid and end of season) and along the profile (0 to 30, 30 to 50 and 50 to 70 cm). However, there were no statistical differences among the moisture treatments at each of the three seasons or three depths. In relation to the irrigation types, statistical significance occurred between buried and surface drip irrigation for both NO_3-N and Olsen P in 2008 only but not in 2009 or 2010. However, both buried and surface drip irrigation indicated statistical significance across seasons and along the soil profile.

The end of season residual nutrient content for Olsen P and NO_3-N at particularly the 30 to 50 cm and 50 to 70 cm depths were high, ranging from 44.0 to 127.5 kg ha^{-1} (19.6 to 56.9 ppm) for P and 9.1 to 157.2 kg ha^{-1} (4.0 to 70.0 ppm) for NO_3-N respectively. Based on the threshold level of NO_3-N and Olsen P there is the potential for leaching at each depth and across the seasons. There is therefore a need to examine a more effective nutrient management program.

9.3 Recommendations for future research

1. The use of brix yield as a means of water conservation –

From a grower's perspective tomato yield is most important, while from the processor's point of view, soluble solids and brix yields are equally important factors. However, at present, grower's income is contingent on tomato yields and not on brix yields. The brix yield is a function of the total marketable yields and the soluble solid content. A possible water conservation approach is to aim for a threshold brix yield by setting a slightly higher fruit soluble content threshold. To facilitate this goal would inevitably necessitate a reduction in irrigation water application, which would increase soluble solids. While this might lead to a reduction in the fruit yield, financially growers would be compensated by the increased income due to the increase in soluble solids. In the end the environment, grower and processor can all benefit. Further research work is therefore necessary to determine the economically viable brix threshold level to encourage this policy shift.

2. Web based irrigation scheduling decision support system

As an extension to this work, a user friendly and interactive web based irrigation scheduling decision support system can be developed using continuous real time soil moisture and agro meteorological data as inputs into a modular base computer program.

The internet technology provides an easy access to growers to obtain real time data to further enhance their water management strategies.

It is possible that this initiative can pioneer a regional and even a national network of soil moisture monitoring as a part of automated irrigation system that can be accessible to all farmers at the regional or national level.

3 Development of a regional soil moisture monitoring program

A natural progression to this work is to expand the soil moisture monitoring from a field scale to a regional scale. The initial work can be expanded into a regional soil moisture monitoring program that would generate daily soil moisture maps over the growing season. The combined use of satellite, cellular phone and GIS technologies can be used to develop a decision support system which would inform the irrigation scheduling program for a large network of water users.

Microwave satellite can be utilized on a regional scale to monitor soil moisture, due to the strong relationship between dielectric permittivity and soil moisture. Further, microwave remote sensing is not significantly affected by cloud cover and is able to penetrate vegetation and soil while maintaining sensitivity to SWC (Bittelli, 2011).

4. Variable rate irrigation (VIR) for drip system

Precision irrigation is becoming more refined with the advancement in technology and VRI is a possible option. It is a tool of precision agriculture that involves the delivery of irrigation water in amounts that match the needs of individual areas within the fields. This can be a future study to address the heterogeneity with relation to soil moisture.

5. *Buried Drip vs. Surface drip irrigation*.

In the tomato growing areas of southwestern Ontario, farmers continue to use a combination of buried and surface drip irrigation. However, there is a growing trend towards buried drip irrigation. Surface drip lines are used only for one season and are subsequently discarded after the growing season, while the buried drip lines are generally used between 3 to 5 years. The current research indicated that there were significant higher yields from the surface drip plots as compared to the buried drip irrigated plots, with drip lines installed at the 20 cm below the surface. However, when the drip lines were installed at 15 cm, there was no significant difference between the two irrigation types. The literature is conflicting in terms of the yield results from the two irrigation types. There is therefore a need to more conclusively compare the two irrigation types in the tomato growing region of southwestern Ontario with a particular focus on the placement depth for the buried drip lines.

6- Combining nanotechnology and biotechnology

The extended useful life of surface and buried drip irrigation is highly dependent on the irrigation water quality. To this end the possibilities exist in utilizing a combination of nanotechnology and biotechnology in drip irrigation to control water quality and emitter clogging and improve filtration techniques. This however would have to be evaluated both from an environmental and cost perspective.

7. Soil moisture instrument

The majority of soil sensors measure volumetric moisture content within a 5 to 10 cm radius. For some sensors, particularly those requiring access tubes, the volume sensed may be smaller than the representatively elemental volume of soil water content and can be largely within the disturbed zone. The neutron probe volumetric soil moisture sensor is an exception but not particularly safe. To this end, safe, easy to use, soil moisture instruments with a wider measurement sphere (radius ~ 20cm) needs to be developed to provide more accurate soil moisture data.

9.4 Contributions to Knowledge

The following are the contributions to knowledge derived from this research:

1. Irrigation scheduling thresholds for tomatoes

The research identified the critical soil water thresholds for irrigation scheduling of field tomatoes grown on a loamy sand in southern Ontario. Upper and lower trigger points of -10 kPa and -30 kPa were determined, though moisture depletion levels of ≤ 40% AWC were deemed adequate. This would assist producers to schedule irrigation more precisely, in terms of timing and application rates to adequately meet crop water requirements and at the same time increase crop production in an environmentally sustainable manner.

2. **Development of an advanced wireless based irrigation scheduling technology**

A robust and reliable system of irrigation scheduling using automated, real time, advanced soil moisture sensor technology coupled with automated climate measurements, and linked to a root zone soil water balance has been developed for irrigation scheduling. This technology takes into account the complex and dynamic relationships between soil properties, climatic factors, and crop performance during the growing season.

3. Root zone assessment for sensor installation

The success of sensor based irrigation scheduling is dependent on the placement of sensors in the representative rooting zone where the water depletion is reflective of the crop water needs. This experiment was able to identify the active rooting zones of a growing crop, which allows for the proper installation of soil moisture sensors in loamy sand. For tomato crop grown in double rows with a centrally aligned drip line, a horizontal distance of 15 cm from the drip line with distances ranging from 0 to 15 cm from the nearest dripper were identified as zones of highest moisture.

References

AAFC. 2006. Agriculture and Agri-Food Canada-AAFC Science and Innovation Strategy- Available at http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1175602657035#s4, accessed on 18 September 2012.

AAFC. 2008. Agriculture and Agri-Food Canada:An overview of the Canadian agriculture and agri-food system. http://www4.agr.gc.ca/AAFC-AAC/displayafficher.do?id=1228246364385&lang=eng, Cited 22nd August 2011

Abourached, C., Hillyer, C., English, M., J., B. 2007. A Web-Based Advisory Service For Optimum Irrigation Management. ASABE meeting presentation. Paper number:072253. 17-20 June 2007.

Abrahamsen, P., Hansen, S. 2000. Daisy: an open soil-crop-atmosphere system model. *Environmental Modelling & Software*, **15**(3), 313-330.

Ah Koon, P.D., Gregory, P.J., Bell, J.P. 1990. Influence of drip irrigation emission rate on distribution and drainage of water beneath a sugar cane and a fallow plot. *Agric. Water Manage.* , **17**, 267-282.

Ahmed, A.S., Al-Amoud, A.I. 1993. Infrared telemetry for data acquisition and telecontrol in automatic irrigation scheduling. *Computers and Electronics in Agriculture*, **8**(1), 73-85.

Al-Qinna, M., Abu-Awwad, A.M. 2001. Wetting patterns under trickle source in arid soils with surface crust *J. Agric. Engng. Res.*, **80**(3), 301-305.

Alberta Environment. 1999. Surface water quality guidelines for use in Alberta. Environmental Service and Natural Resource Service. Pub. No. T/483.

Ali, M.H. 2006. Deficit irrigation for wheat cultivation under limited water supply condition. in: *Department of Irrigation and Water Management*, Vol. Ph.D. Thesis, Bangladesh Agricultural University. Mymensingh, Bangladesh.

Ali, M.H., Talukder, M.S.U. 2008. Increasing water productivity in crop production—A synthesis. *Agricultural Water Management*, **95**(11), 1201-1213.

Allen, R.G., Huntington, J.L. 2009. Evapotranspiration and Net Irrigation Water Requirements for Nevada. in: *World Environmental and Water Resources Congress 2009*, pp. 1-15.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*. FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Andersen, P., Rhoads, F.M., Olson, S.M., HIll, K.D. 1999. Relationships of nitrogenous compounds in petiole sap of tomato to nitrogen fertilization and the value of these compounds as a predictor of yields. *HortScience*, **34**, 254-258.

Arthur, E., Cornelis, W.M., Vermang, J., De Rocker, E. 2011. Amending a loamy sand with three compost types: impact on soil quality. *Soil Use and Management*, **27**(1), 116-123.

Asgarzadeh, H., Mosaddeghi, M.R., Mahboubi, A.A., Nosrati, A., Dexter, A.R. 2010. Soil water availability for plants as quantified by conventional available water, least limiting water range and integral water capacity.

Assouline, S. 2002. The effects of microdrip and conventional drip irrigation on water distribution and uptake. *Soil Science Society of America Journal*, **66**(5), 1630-1636.

Ayars, J.E., Phene, C.J. 2007. 7. Automation, (Eds.) F.R. Lamm, J.E. Ayars, F.S. Nakayama, Vol. 13, pp. 259-284.

Azhar, A.H., Perera, B.J.C. 2011. Evaluation of Reference Evapotranspiration Estimation Methods under Southeast Australian Conditions. *Journal of Irrigation and Drainage Engineering-Asce*, **137**(5), 268-279.

Bache, B.W. 1964. Aluminium and iron phosphate studies relating to soils II. Reactions between phosphate and hydrous oxides. *Journal of Soil Science*, **15**, 111-116.

Badr, M.A. 2007. Spatial Distribution of water and nutrients in root zone under surface and subsurface drip irrigation and cantaloupe yields. *World Journal of Agricultural Sciences*, **3**(6), 747-756.

Bailey, R.J., Spackman, E. 1996. A model for estimating soil moisture changes as an aid to irrigation scheduling and crop water-use studies: I. Operational details and description. *Soil Use and Management*, **12**(3), 122-128.

Bakhsh, A., Kanwar, R., Baker, J. 2010. N-Application Methods and Precipitation Pattern Effects on Subsurface Drainage Nitrate Losses and Crop Yields. *Water, Air, & Soil Pollution*, **212**(1), 65-76.

Bakhsh, A., Kanwar, R.S. 2004. Using discriminant analysis and GIS to delineate subsurface drainage patterns. *ASAE*, **47**, 689-699.

Baldwin, D.J., Desloges, J.R., Lawrence, E.B. 2000. Physical Geography of Ontario. in: *Ecology of a Managed Terrestrial Landscape-Patterns and process of Forest Landscape in Ontario*, (Eds.) A.H. Perera, D.L. Euler, I.D. Thompson, UBC Press, University of Bristish Colombia. Vancouver, BC.

Bar-Yosef, B. 1999. Advances in fertigation *Advances in Agronomy*, **65**, 1-75.

Barker, R., Molle, F. 2004. Evolution of irrigation in South and Southeast Asia. . *Colombo, Sri Lanka: Comprehensive Assessment Secretariat. (Comprehensive Assessment Research Report 5)*.

Baronti, P., Pillai, P., Chook, V.W.C., Chessa, S., Gotta, A., Hu, Y.F. 2007. Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards. *Comput. Commun.*, **30**, 1655-1695.

Barragan, J., Wu, I.P. 2001. SW--Soil and Water: Optimal Scheduling of a Micro-irrigation System under Deficit Irrigation. *Journal of Agricultural Engineering Research*, **80**(2), 201-208.

Bates, L.M., Hall, A.E. 1981. Stomatal closure with soil water depletion not associated with changes in bulk leaf water status. *Oecologia*, **50**, 62-65.

Battilani, A., Ferreres, E. 1999. The use of decision support systems to manage fertigation and to minimize environmental effects: a challenge for the future. *Acta Hort.* , **487**, 547-556.

Bell, J.P., Dean, T.J., Hodnett, M.G. 1987. Soil moisture measurement by an improved capacitance technique, part II. Field techniques, evaluation and calibration. *Journal of Hydrology*, **93**(1-2), 79-90.

Bellingham, K. 2009. Method for Irrigation Scheduling Based on Soil Moisture Data Acquisition. *Irrigation District Conference*, USA.

Berbel, J., Gómez-Limón, J.A. 2000. The impact of water-pricing policy in Spain: an analysis of three irrigated areas. *Agricultural Water Management*, **43**(2), 219-238.

Bernier, M., Madramootoo, C.A., Mehdi, B.B., Gollamudi, A. 2010. Assessing On-Farm Irrigation Water Use Efficiency in Southern Ontario. *Canadian Water Resources Journal*, **35**(2), 115-130.

Bhatnagar, P.R., Chauhan, H.S. 2008. Soil water movement under a single surface trickle source. *Agricultural Water Management*, **95**(7), 799-808.

Bittelli, M. 2011. Measuring Soil Water Content: A Review. *Horttechnology*, **21**(3), 293-300.

Blackman, P.G., Davies, W.G. 1985. Root To shoot communication in maize plants of the effect of soil drying. *J. Exp. Bot.*, **36**, 39-48.

Blonquist, J.M., Jones, S.B., Robinson, D.A. 2005. Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems. *Vadose Zone Journal* **4**, 1059-1069.

Blonquist Jr, J.M., Jones, S.B., Robinson, D.A. 2006. Precise irrigation scheduling for turfgrass using a subsurface electromagnetic soil moisture sensor. *Agricultural Water Management*, **84**(1-2), 153-165.

Bogena, H., Huisman, J., Oberdörster, C., Vereecken, H. 2007. Evaluation of a low-cost soil water content sensor for wireless network applications. *Journal of Hydrology*, **344**(1), 32-42.

Bos, M.G. 1980. Irrigation efficiencies at crop production level. ICID Bulletin. 29:18-25,60.

Bos, M.G. 1985. Summary of ICID definitions of irrigation efficiency. ICID Bulletin. 34:28-31.

Brady, C.N. 1974. *The nature and properties of soils*. *8 ed*. Macmillan Publishing Co.,Inc. New York, 639 pp.

Brady, N., Weil, R. 2002. *The nature and properties of soils*. *13 ed*, Upper Saddle River, New Jersey, Prentice Hall, 960 pp.

Brandt, A., Bresler, E., Diner, N., Ben-Asher, I., Heller, J., Goldberg, D. 1971. Infiltration from a trickle source. I. Mathematical model. *Soil Sci. Soc. Am. Proc.*, **35**, 675-682.

Bravdo, B.A. 2005. Physiological mechanisms involved in the production of non-hydraulic root signals by partial root zone drying – a review. *Acta Hort.* , **689**, 267–276.

Bresler, E. 1978. Analysis of trickle irrigation with application to design problems. *Irrigation Science*, **1**(1), 3-17.

Bresler, E. 1977. Trickle-drip irrigation: principiles and application to soil-water managment. . *Advances in Agronomy*, **29**, 343-393.

British Columbia Ministry of Agriculture and Food. 1998. Water Conservation factsheet - Irrigation scheduling with tensiometers. Order No. 577.100-2

Brown, D.M., G.A. McKay, G.A., Chapman, L.J. 1968. The Climate of Southern Ontario. Climatological Studies No. 5. Department of Transport, Meteorological Branch, Toronto, ON.

Brown, L.R., Renner, M., Flavin, C. 1997. Vital signs:the environmental signs that are shaping our future, World Watch Institute, Washington, D.C., USA.

Bucks, D.A., Nakayama, F.S., Warrick, A.W. 1982. Principles, practices, and potentialities of trickle (drip) irrigation. in: *Advances in irrigation*, (Ed.) D. Hillel, Vol. 1, Academic Press. New York, pp. 219-298.

Cabelguenne, M., Debaeke, P., Puech, J., Bose, N. 1997. Real time irrigation management using the EPIC-PHASE model and weather forecasts. *Agric. Water Management*, **32**, 227–238.

Cahn, M.D., Herrero, E.V., Snyder, R.L., Hanson, B.R. 2001. Water management strategies for improving fruit quality of drip-irrigated processing tomatoes. *Acta horticulturae*, **542**, 111-116.

Cai, J.B., Liu, Y., Xu, D., Paredes, P., Pereira, L.S. 2009. Simulation of the soil water balance of wheat using daily weather forecast messages to estimate the reference evapotranspiration. *Hydrol. Earth Syst. Sci.*, **13**, 1045–1059.

Calzadilla, A., Rehdanz, K., Tol, R.S.J. 2010. The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *J. Hydrol.*, **384**, 292-305.

Cameron, K.D., Teece, M.A., Smart, L.B. 2006. Increased accumulation of cuticular wax and expression of lipid transfer protein in response to periodic drying events in leaves of tree tobacco. *Plant Physiology* **140**, 176–183.

Camp, C.R. 1998. Subsurface drip irrigation: a review. *Transactions of the ASAE*, **41**(5), 1353-1367.

Campbell, G.S., Campbell, M.D. 1982. Irrigation schedulingusing soil moisture measurements: theory and practice. *Adv. Irrig. Sci.*, **1**, 25–42.

Campbell Scientific Inc. 2006. Instruction Manual - CS616 and CS625 Water Content Reflectometers, Campbell Scientific Canada Corp., 11564 -149 Street, Edmonton, Alberta.

Campbell Scientific Inc. 2006. CS616 and CS625 Water Content Reflectometers. Campbell Scientific, Inc. Edmonton, Alberta.

Cancela, J.J., Cuesta, T.S., Neira, X.X., Pereira, L.S. 2006. Modelling for Improved Irrigation Water Management in a Temperate Region of Northern Spain. *Biosystems Engineering*, **94**(1), 151-163.

CANICID. 1999. Canadian National Committee of ICID. Country Profile - Canada, http://www.icid.org/cp_canada.html#cp, Sourced 28 October 2012.

Canton, Y., Sole-Benet, A., Domingo, F. 2004. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. *Journal of Hydrology*, **285**, 199-214.

Cape, J. 1997. A value selection method for choosing between alternative soil moisture sensors.Project No. AIT2, Land and Water Resources Research and Development Corporation Report. Canberra, ACT.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H. 1998. Nonpoint pollution of surface water with phosphorus and nitrogen. *Ecological Applications*, **8**(3), 559-568.

Cassel, D.K., Klute, A. 1986. Water potential: Tensiometry. 2 ed. in: *Methods of soil analysis. Part 1*, (Ed.) A. Klute, Agron. Monogr. 9, ASA, and SSSA. Madison, WI., pp. 563–596.

Cassel, D.K., Sweeney, M.D. 1974. In Situ woil water holding capacity of selected North Dakotao soils., North Dakota Agricultural Experimental Station Bulletin. No. 495.

Chalmers, D.J., Mitchell, P.D., van Heek, L. 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. *Journal of the American Society of Horticultural Science*, **106**, 307-12.

Chanzy, A., Chadoeuf, J., Gaudu, C., Mohrath, D., Richard, G., Bruckler, L. 1998. Soil Moisture Monitoring at the field scale level using automatic capacitance probe. *European Journal of Soil Science*, **48**, 637-648.

Charlesworth, P., Munro, A. 2005. *Irrigation Insights No.1 Soil Water Monitoring. Eds A. Munro and A. Currey* Canberra, ACT., Land & Water Australia.

Chaves, M.M., T.P, S., Souza, C.R., Ontuno, M.F., M.L., R. 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals Applied Biol.*, **150**, 237-252.

Chavez, J., Neale, C.M.U., Prueger, J.H., Kustas, W.P. 2008. Daily evapotranspiration estimates from extrapolating instantaneous airborne remote sensing ET values. *Irrig. Sci.*, **27**, 67–81.

Chinn, R. 1999. Irrigation: Western Canada Liquid Asset. Statistics Canada. http://www.statcan.gc.ca/kits-trousses/agric/edu04_0094a-eng.htm, sourced 23rd August 2011.

Clothier, B.E. 1984. Solute travel times during trickle irrigation. *Water Resources Research*, **20**(12), 1848-1852.

Coelho, E., Or, D. 1999. Root distribution and water uptake patterns of corn under surface and subsurface drip irrigation. *Plant and Soil*, **206**(2), 123-136.

Coelho, E.F., Or, D. 1996. Flow and uptake patterns affecting soil water sensor placement for drip irrigation management. *Transactions of the American Society of Agricultural Engineers*, **39**(6), 2007-2016.

Coelho, E.F., Santos, D.B.d., Azevedo, C.A.V.d. 2007. Sensor placement for soil water monitoring in lemon irrigated by micro sprinkler. *Revista Brasileira de Engenharia Agrícola e Ambiental*, **11**, 46-52.

Collins, M.J., Fuentes, S., Barlow, E.W.R. 2010. Partial rootzone drying and deficit irrigation increase stomatal sensitivity to vapour pressure deficit in anisohydric grapevines. *Functional Plant Biol.*, **37**, 128-138.

Consoli, S., D'Urso, G., Toscano, A. 2006. Remote sensing to estimateET-fluxes and the performance of an irrigation district in southern Italy. *Agric. Water Manage.*, **81**, 295–314.

Cook, F.J., Thorburn, P.J., Fitch, P., Bristow, K.L. 2003. WetUp: A software tool to display approximate wetting patterns from drippers. *Irrig. Sci.*, **22**, 129-134.

Cook, F.J., Thorburn, P.J., Fitch, P., Charlesworth, P.B., Bristow, K.L. 2006. Modelling trickle irrigation: comparison of analytical and numerical models for estimation of wetting front position with time. *Environ Model Softw*, **21**, 353-1359.

Cooper, A.J. 1973. Root temperature and plant growth.Commonwealth Agric. Bureaux, Farnham Royal, England.

Cosh, M.H., Jackson, T.J., Bindlish, R., Prueger, J.H. 2004. Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates. *Remote Sens. Environ.*, **92**, 427-435.

Costa, M., J, Maria, F., Ortuño, M., Chaves, M. 2007. Deficit Irrigation as a Strategy to Save Water: Physiology and Potential Application to Horticulture. *Journal of Integrative Plant Biology*, **49**(10), 1421-1434.

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irr. Sci.*, **22**, 143-156.

Dalton, F., Herkelrath, W.N., Rawlins, D.S., Rhoades, J.D. 1984. Time-domain reflectometry: simultaneous measurement of soil water content and electrical conductivity with a single probe. *Science*, **224**, 989-990.

Dasberg, S., Dalton, F.N. 1985. Time domain reflectometry field measurements of soil water content and electrical conductivity. *Soil Science Society of America Journal* **49**, 293-297.

Dasberg, S., Or, D. 1999. Drip Irrigation. Springer, Berlin.

Dastane, N.G. 1978. Effective rainfall in irrigated agriculture. FAO, Irrigation and Drainage Paper 25.FAO, Rome, Italy.

Davies, W.J., Zhang, J.H. 1991. Root signals and the regulation of growth and development of plants in drying soil. *Annu. Rev. Plant Phys*, **42**, 55–76.

Davis, D.M., Gowda, P.H., Mulla, D.J., Randall, G.W. 2000. Modeling nitrate nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for southern Minnesota, USA. *J. Environ. Qual.* , **29**, 1568-1581.

Davis, K.R., Phene, C.J., McCormick, R.L., Hutmacher, R.B., Meek, D.W. 1985. Trickle frequency and installation depth effects on tomatoes. Proc. Third Int. Drip/Trickle Irrigation Congress. pp. 896-901. Fresno, CA.

de Loë, R.C., Kreutzwiser, R., Ivey, J. 2001. Agricultural Water Use in Ontario *Canadian Water Resources Journal*, **26**(1), 17-42.

De Wrachien, D. 2003. Global warming and irrigation development- A world-wide view. in: *International Scientific Conference on Agricultral Water Management and Mechanization Factors for sustainable Agriculture*. Sofia,8th – 10th October 2003.

Dean, T.J., Bell, J.P., Baty, A.J.B. 1987. Soil moisture measurement by an improved capacitance technique, Part I. Sensor design and performance. *Journal of Hydrology*, **93**(1-2), 67-78.

Demir, A., Göksoy, A., Büyükcangaz, H., Turan, Z., Köksal, E. 2006. Deficit irrigation of sunflower (Helianthus annuus L.) in a sub-humid climate. *Irrigation Science*, **24**(4), 279-289.

DePinto, J.V., Young, T.C., McIlroy, M. 1986. Great Lakes water quality improvement: the strategy of phosphorus discharge control is evaluated. *Environ. Sci. Technol.*, **20**(8), 752-759.

Devasirvatham, V. 2009. *A Review of Subsurface Drip Irrigation in Vegetable Production. CRC for Irrigation Futures. Irrigation Matters Series No. 03/09*. University of Western Sydney.

Dolan, A.H., Kreutzwiser, R., De Loë, R. 2000. Rural water use and conservation in southwestern Ontario. *Journal of soil and water conservation*, **55**(2), 161-171.

Dolan, D.M. 1993. Point source loadings of phosphorus to Lake Erie: 1986-1990. *J.Great Lakes Res.*, **19**, 212-223.

Donatelli, M., Bellocchi, G., Fontana, F. 2003. RadEst3.00: software to estimate daily radiation data from commonly available meteorological variables. *Eur. J. Agron.*, **18**, 363–367.

Doorenbos, J., Kassam, A.H. 1979. *Yield Response to Water - FAO Irrigation and drainage paper 33*. FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Doorenbos, J., Pruitt, W.O. 1977. *Guidelines for Predicting Crop Water Requirements - FAO Irrigation and drainage paper 24*. FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Dukes, M.D., Zotarelli, L., Morgan, K.T. 2010. Use of irrigation technologies of vegetable crops in Florida. *Horttechnology*, **20(1)**, 133-142. .

Dumas, Y., Leoni, C., Portas, C.A.M., Bièche, B. 1994. Influence of water and nitrogen availability on yield and quality of processing tomato in the european union countries. *Acta horticulturae*, **376**, 185-192.

Elmaloglou, S., Diamantopoulos, E. 2009. Simulation of soil water dynamics under subsurface drip irrigation from line sources. *Agricultural Water Management*, **96**(11), 1587-1595.

Elmaloglou, S., Diamantopoulos, E., Dercas, N. 2010. Comparing soil moisture under trickle irrigation modeled as a point and line source. *Agricultural Water Management*, **97**(3), 426-432.

Encyclopædia Britannica. 2011. Canada. In Encyclopædia Britannica. Available at: http://www.britannica.com/EBchecked/topic/91513/Canada. Accessed 9 May 2012.

Environment Canada. 2004. Canadian guidance framework for the managment of phosphorus in freshwater systems. Scientific Supporting Document. National Guidelines and Standards Office, Water Policy and Coordination Directorate, Environment Canada, Ottawa, ON.

Environment Canada. 1987. Fedral Water Policy, Canada.

Environment Canada. 2007. Municipal Water Use Report: Municipal Water Use 2004 Statistics (Ottawa: Author, 2007), p. 3.

Environment Canada. 1996. The State of Canada's Environment - 1996 SOEM/33. Ottawa: Environment Canada.

Environment Canada. 2011. Water, water use, withdrawal uses. http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=851B096C-1.Internet. Cited 28 August 2011.

Environmental Commissioner of Ontario. 2001. Ontario's Permit To Take Water Program and The Protection Of Ontario's Water Resources.

Evangelou, V.P. 1998. *Environmental Soil and Water Chemistry, Principles and Applications* John Wiley and Sons Inc, New York, NY.

Evans, R., Cassel, D.K., Sneed, R.E. 1996. Soil, water, and crop characteristics important to irrigation scheduling. North Carolina Cooperative Extension Service, Publication Number AG 452-1.

Evett, S. 2007. Soil water and monitoring technology. in: *Irrigation of Agricultural Crops-Agronomy Monograph No 30, Second Edition*, (Eds.) R.J. Lascano, R.E. Sojka, Madison, Wisconsin, USA.

Evett, S., Cepuder, P. 2008. Capacitance sensors for use in access tubes. in: *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology.*, (Eds.) S.R. Evett, L.K. Heng, P. Moutonnet, M.L. Nguyen, IAEA-TCS-30. Intl. Atomic Energy Agency. Vienna, Austria, pp. 123–129.

Evett, S., Schwartz, R., Mazahrih, N.T., Jitan, M., Shaqir, I. 2011a. Soil water sensors for irrigation scheduling: Can they deliver a management allowed depletion? *Acta horticulturae*, **888**, 231-7.

Evett, S.R. 2008. Gravimmetric and volumetric direct measurements of soil water content. in: *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology.*, (Eds.) S.R. Evett, L.K. Heng, P. Moutonnet, M.L. Nguyen, IAEA-TCS-30. Intl. Atomic Energy Agency. Vienna, Austria, pp. 123–129.

Evett, S.R., Heng, L.K. 2008a. Conventional Time Domain Reflectometry systems. in: *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology.*, (Eds.) S.R. Evett, L.K. Heng, P. Moutonnet, M.L. Nguyen, IAEA-TCS-30. Intl. Atomic Energy Agency. Vienna, Austria, pp. 123–129.

Evett, S.R., Heng, L.K. 2008b. Tensiometers. in: *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology.*, (Eds.) S.R. Evett, L.K. Heng, P. Moutonnet, M.L. Nguyen, IAEA-TCS-30. Intl. Atomic Energy Agency. Vienna, Austria, pp. 123–129.

Evett, S.R., Prueger, J.H., Tolk, J.A. 2012a. Water and Energy Balances in the Soil-Plant-Atmosphere Continuum. 2 ed. in: *Handbook of Soil Sciences: Properties and Processes*, (Eds.) P.M. Huang, Y. Li, M.E. Sumner, CRC Press,. Boca Raton, Florida USA,, pp. 6-1–6-44.

Evett, S.R., Schwartz, R.C., Casanova, J.J., Heng, L.K. 2012b. Soil water sensing for water balance, ET and WUE. *Agricultural Water Management*, **104**(0), 1-9.

Evett, S.R., Schwartz, R.C., Mazahrih, N.T., Jitan, M.A., Shaqir, I.M. 2011b. Soil water sensors for irrigation scheduling: Can they deliver a management allowed depletion?, (Eds.) U. Yermiyahu, A. Ben-Gal, A. Dag, Vol. 888, pp. 231-238.

Evett, S.R., Schwartz, R.C., Tolk, J.A., Howell, T.A. 2009. Soil profile water content determination: Spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes. *Vadose Zone J.*, **8**(4), 1-16.

Evett, S.R., Schwatz, R.C., Casanova, J.J., Heng, L.K. 2012c. Soil water sensing for water balance, ET and WUE. *Agricultural Water Management*, **104**, 1-9.

Famiglietti, J.S., Ryu, D., Berg, A., Rodell, M., T.J., J. 2008. Field observations of soil moisture variability across scales. *Water Resour. Res.*, **44 W01423**.

FAO. 2007. Aquastat, http:// www.fao.org/ nr/ water/ www.waterfootprint.org.aquastat/ data/ query/ index.html.

FAO. 2009. CROPWAT 8.0. Food and agriculture Organization of the UN. Water Resources Development and Management Service, Land and Water Development Division, Rome Italy.

FAO. 2003. The Irrigation Challenge, IPTRID Issue Paper 4. , Food and Agricultural Organization of the United Nations. Rome. Italy.

FAO. 2011. *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk,*. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London. .

FAOSTAT Database. 2004. FAOSTAT Database on Agriculture,http://faostat.fao.org/.

Fares, A., Alva, A.K. 2000. Soil Water Components Based on Capacitance Probes in a Sandy Soil. *Soil Sci Soc Am J*, **64**(1), 311-318.

Fares, A., H. , Hamdhani, H., Polyakou, V., Dogan, A., Valenzuela, H. 2006. Real-time soil water monitoring for optimum water management. *Journal of the American Water Resources Association (JAWRA)*, **42**(6), 1527-1535.

Fereres, E., Goldhamer, D.A., Parsons, L.R. 2003. Irrigation Water Management of Horticultural Crops. *HortScience*, **38**(5), 1036-1042.

Fereres, E., Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, **Vol. 58**(No.2), 147-159.

Fernàndez, J.E., Cuevas, M.V. 2010. Irrigation scheduling from stem diameter variations: A review. . *Agr. For. Meteorol*, **150**, 135-151.

Fortune, S., Lu, J., Addiscott, T.M., Brookes, P.C. 2005. Assessment of phosphorus leaching losses from arable land. *Plant Soil :* , **269**, 99-108.

Francesca, V., Osvaldo, F., Stefano, P., Paola, R.P. 2010. Soil moisture measurements: Comparison of instrumentation performances. *Journal of Irrigation and Drainage Engineering*, **136**(2), 81-89.

Gabriel, A.O., Kreutzwiser, R.D. 1993. Drought hazard in Ontario: A review of impacts, 1960-1989 and management implications. . *Canadian Water Resources Journal* **18**(2), 117-132.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vöosmarty, C.J. 2004. Nitrogen Cycles: Past, Present, and Future. *Biogeochemistry*, **70**(2), 153-226.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., L. A. Martinelli, L.A., S. P. Seitzinger, S.P., M. A. Sutton, M.A. 2008. Transformation of the nitrogen cycle: recent trends, questions and potential solutions. *Science* **320**, 889-892.

García-Tejero, I.F., Durán-Zuazo, V.H., Muriel-Fernández, J., Rodríguez-Pleguezuelo, C.R. 2011. *Water and Sustainable Agriculture*. Springer, New York.

Gärdenäs, A.I., Hopmans, J.W., Hanson, B.R., Šimůnek, J. 2005. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water Management* **74**, 219-242.

Gardner, C.M.K., Bell, J.P., Cooper, J.D., Dean, T., J, Hodnett, M.G., Gardner, N. 1991. Soil water content. in: *Soil analysis - Physical methods*, (Eds.) R.A. Smith, C.E. Mullings, Marcel Dekker. New York, NY.

Gardner, W.H. 1986. Water content. in: *Methods of soil analysis. Part 1. Physical and mineralogical methods. Agronomic Series. No. 9. 2nd Ed.*, (Ed.) A. Klute, Amer. Soc. Agron., pp. 493-544.

Gardner, W.H. 1965. Water Content. in: *Methods of Soil Analysis American Society Agronomic Monograph No. 9. Part 1* (Ed.) C.A. Black. Madison.

Gardner, W.H., Israelsen, O.W., Edlefsen, N.E., Clyde, D. 1922. The capillary potential function and its relation to irrigation practice. *Phys. Rev.* , **20**, 196.

Gehl, R.J., Schmidt, J.P., Godsey, C.B., Maddux, L.D., Gordon, W.B. 2006. Post-Harvest Soil Nitrate in Irrigated Corn: Variability Among Eight Field Sites and Multiple Nitrogen Rates. *Soil Sci. Soc. Am. J.* , **70**, 1922-1931.

Gill, G., Humphreys, E., Kukal, S., Walia, U. 2011. Effect of water management on dry seeded and puddled transplanted rice. Part 1: Crop performance. *Field Crops Research*, **120**(1), 112-122.

Gleick, H.P. 2000. The Changing Water Paradigm, A look at twenty-first Century Water Resources Development. International Water Resources Association. *Water International,*, **25,**(1), Pages 127-138, March 2000.

GLWQA. 1978. Great Lakes Water Quality Agreement.

Goldberg, D., Gornat, B., Roimon, D. 1976. Drip irrigation: Principles, Design and Agricultural Practices. Drip Irrigation Science publication;Kfar Shumaryahu, Israel.

Gong, D., Kang, S., Tong, L., Ding, R. 2004. Effects of rootdivided alternative irrigation on soil moisture distribution and root-trunk sap flow dynamics of peach trees. *J Hydraulic Eng*, **10**, 120–127.

Government of Ontario. 2010. Geography of Ontario - It's a Big Place, http://www.ontario.ca/en/about_ontario/EC001032.html?openNav=geography, Sourced January 2012.

Gowing, J.W., Davis, W.J., Jones, H.G. 1990. A positive root-soucred signal as an indicator of soil drying in apples, Malus domestica. Borkh. *Journal of Experimental Botany*, **41**, 1535-1540.

Gowing, J.W., Ejieji, C.J. 2001. Real-time scheduling of supplemental irrigation for potatoes using a decision model and short-term weather forecasts. *Agric. Water Management*, **47**, 137–153.

Grant, C.A., Flaten, D.N., Tomasiewicz, D.J., Sheppard, S.C. 2001. The importance of early season phosphorus nutrition. *Canadian Journal of Plant Science*, **81**(2), 211-224.

Great Lake Commission. 2011. Annual Report of the Great Lakes Regional Water Use Database Representing 2008 Water Use Data. December 2010 Issue No. 17.

Greenwood, D.J., Cleaver, T.J., Turner, M.K., Hunt, J., Neindorf, K.B., Loquens, S.M.H. 1980. Comparison of the effects of phosphate fertilizer on the yield: Phosphate content and quality of 22 different vegetable and agronomic crops. *J. Agric. Sci.* , **95**, 457-469.

Grismer, M., E. 1987. Automated monitoring of remote soil sensors. *Paper No.87-2095 presented at the 1987 summer meeting of the American society of Agricutural Engineers. Baltimore Convention, Baltimore.*

Gu, S., David, Z., Simon, G., Greg, J. 2000. Effect of partial rootzone drying on vine water relations, vegetative growth, mineral nutrition, yield, and fruit quality in field-grown mature sauvignon blanc grapevines. *Research Notes, #000702. California Agricultural Technology Institute, California State University, Fresno*.

Gu, S., Du, G., Zoldoske, D., Hakim, A., Cochran, R., Fugelsang, K., Jordensen, G. 2004. Effect of irrigation amount on water relations, vegetative growth, yield and fruit composition of Sauvignon blanc grapevines under partial rootzone drying and conventional irrigation in the San Joachin Valley of California. *Journal of Horticultural Science & Biotechnology* **79**(1), 26–33.

Haise, H.R., Hagan, R.M. 1967. Soil plant and evaporation measurementas criteria for scheduling irrigation. in: *Irrigation of agriculture land. Agron Monogr 11(30)*, (Eds.) R. Hagan, H. Haise, T. Edminster, Wisconsin. Am Soc Agron, Madison, pp. 577–604.

Hammami, M., Daghari, H., Balti, J., Maalej, M. 2002a. Approach for predicting the wetting front depth beneath a surface point source: Theory and numerical aspect. *Irrig. Drain.* , **51**, 347-360.

Hammami, M., H. Daghari, H., J. Balti, J., Maalej, M. 2002b. Approach for predicting the wetting front depth beneath a surface point source: Theory and numerical aspect. *Irrig. Drain*, **51**, 347-360.

Hankin, L., Sawhney, B. 1978. Soil Moisture Determination Using Microwave Radiation. *Soil Science*, **126**(5), 313-315.

Hanson, B., Schwankl, L., Fulton, A. 2004. Scheduling irrigations: When and How Much Water to Apply. Division of Agriculture and Natural Resources Publication #3396. University of California.

Hanson, B.R., Hutmacher, R.B., May, D.M. 2006. Drip irrigation of tomato and cotton under shallow saline ground water conditions. *Irrig. Drain. Syst.*, **20**, 155-175.

Harker, B., Lebedin, J., Goss, M.J., Madramootoo, C., Neilsen, D., Paterson B, van der Gulik, T. 2008. Threat to water availability in Canada. Environment Canada. http://www.ec.gc.ca/inre-nwri/default.asp?lang=En&n=0CD66675 1&offset=12&toc=show; sourced 23rd August 2010.

Hartz, T., Hanson, B. 2005. Drip irrigation and fertigation management of processing tomato. Vegetable research and information center, University of California, Davis, p 9.

Hartz, T.K. 2004. Drip Irrigation and Soil Fertility Management. in: *2004 Plant & Soil Conference*, California Chapter of the American Society of Agronomy. Visalia, California.

Hartz, T.K., Hochmuth, G.J. 1996. Fertility management of drip-irrigated vegetables. *HortTechnology* **6**, 168-172.

Hartz, T.K., Johnstone, P.R., Francis, D.M., Miyao, E.M. 2005. Processing tomato yield and fruit quality improved with potassium fertigation. *HortScience*, **40**(6), 1862-1867.

Hebrard, O., Voltz, M., Andrieux, P., R., M. 2006. Spatio-temporal distribution of soil surface moisture in a heterogeneously farmed Mediterranean catchment. *Journal of Hydrology* **329**, 110-121.

Heckrath, G., Brookes, P.C., Poulton, P.R., Goulding, K.W.T. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. *J. Environ. Qual.*, **24**, 904-910.

Hendrickx, J.M.H., Wierenga, P.J. 1990. Variability of Soil Water Tension in a Trickle Irrigated Chile Pepper Field. *Irrigation Science* **11**, 23-30.

Herkelrath, W.N., Miller, E.E., Gardner, W.R. 1977. Water uptake by plants: I. Divided root experiments. *Soil Sci. Soc. Am. J.*, **41**, 1033-1038.

Hess, T. 1996. A microcomputer scheduling program for supplementary irrigation. *Computers and Electronics in Agriculture*, **15**(3), 233-243.

Hignett, C., Evett, S.R. 2008. Direct and surrogate measures of soil water content. in: *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology.*, (Eds.) S.R. Evett, L.K. Heng, P. Moutonnet, M.L. Nguyen, IAEA-TCS-30. Intl. Atomic Energy Agency. Vienna, Austria, pp. 123–129.

Hodnett, M.G., Bell, R.J., Koon, A.H. 1990. The control of drip irrigation of sugarcane using index tensiometers: Some comparisons with control by the water budget method. *Agric.Water Management* **17**(3), 189-207.

Hoekstra, T.J., Delaney, A. 1974. Dielectric properties of soils at UHF and microwave frequencies. *J. Geophys. Res.* , **79**, 1699-1708.

Hoffman, G.J., Howell, T.A., Solomon, K.H. 1990. Introduction. In: G.J Hoffman, T.A Howell, K.H. Solomon. editors. Management of Farm Irrigation Systems. ASAE Monograph, American Society of Agricultural Engineering, MI.

Hofmann, N., G, F., Schofield, M. 2005. The loss of Dependable Agricultural Lands in Canada. Statistics Canada. Rural and Small Town Canada Analysis Bulletin 6:1-15.

Holm, R. 2008. rrigation in Alberta. Government of Alberta, Agriculture and Rural Development. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr7197, sourced 23rd August 2011.

Howell, T.A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, **93**(2), 281-289.

Howell, T.A., Meek, D.W., Phene, C.J., Davis, K.R., McCormick, R.L. 1984. Automated weather data collection for research on irrigation scheduling. *Transactions of the ASAE*, **27**(2), 386-391.

Hsiao, T.C., Steduto, P., Fereres, E. 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. *Irr. Sci.* , **25**.

Hubbell, J.M., Sisson, J.B. 2003. Soil water potential measurement by tensiometers. in: *Encycl. of Water Sci*, (Eds.) B.A. Stewart, T.A. Howell, Marcel Dekker. New York, NY, pp. 904-907.

Hudson, B.D. 1994. Soil organic matter and available water capacity. *Journal of soil and water conservation*, **49**(2), 189-194.

Iddo, K. 2008. Yield quality and irrigation with saline water under environmental limitations: The case of processing tomatoes in California. *Agric. Econ.* , **38**, 57-66.

IIda, S., Adunias dos, S.T., Firmino, F.J.C., Olivera, L.R.A. 2005. Development of a Capacitive Sensor for Monitoring Soil Water. ASAE Annual International Meeting, Tampa Convention Center Tampa, Florida, 17-20 July 2005.

Intrigliolo, D.S., Castel, J.R. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. *Irrigation Science*, **23**(2), 93-102.

Irmak, A., Irmak, S., Martin, D.L. 2008. Reference and crop evapotranspiration in south central Nebraska. I: comparison and analysis of grass and alfalfa-reference evapotranspiration. *Journal of Irrigation and Drainage Engineering*, **134**(6), 690–699.

Irmak, S., ., P.O.J., Eisenhauer, E.D., Kranz, L.W., Martin, L.D., Zoubek, L.G., Rees, M.J., VanDe Walle, B., Christiansen, P.A., ., L.D. 2006. Watermark Granular Matrix Sensor to Measure Soil Metric Potential for Irrigation Management. Institute of Agriculture and Natural Resources at the University of Nebraska, Lincoln.

Irmak, S., Irmak, A. 2005. Performance of frequency domain reflectometer, capacitance, and psuedo-transit time-based soil water content probes in four coarse-textured soils. *Appl. Eng. Agric.* , **21**(6), 999-1008.

Isermann, K. 1991. Share of agriculture in nitrogen and phosphorus emissions into the surface waters of Western Europe against the background of their eutrophication. *Fertilizer Research*, **26**, 253–269.

Ismail, S.M., Zin El-Abendin, T.K., Wassif, M.A., El-Nesr, M.N. 2006. Wetting patternsimulation of surface and subsurface drip irrigation systems, II-Model validation and analysis. In: The 14th Annual Conference of Misr Society of Agricultural Engineering **24**(4), 1035-1057.

IWMS. 2002. Irrigation Water Management Study Committee. South Saskatchewan River basin: irrigation in the 21st century. Vol. 1: summary report. Alberta Irrigation Projects Association, Lethbridge, Alberta.

Jabro, J., Evans, R., Kim, Y., Iversen, W. 2009. Estimating in situ soil–water retention and field water capacity in two contrasting soil textures. *Irrigation Science*, **27**(3), 223-229.

Jensen, M. 2007. Beyond irrigation efficiency. *Irrigation Science*, **25**(3), 233-245.

Jensen, M.E., Burman, R.D., Allen, R.G. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70.

Ji, X.-B., Kang, E.-S., Chen, R.-S., Zhao, W.-Z., Zhang, Z.-H., Jin, B.-W. 2007. A mathematical model for simulating water balances in cropped sandy soil with conventional flood irrigation applied. *Agricultural Water Management*, **87**(3), 337-346.

Johnston, A.E. 2000. Soil and Plant Phosphate, International Fertilizer Industry Association. Paris, France.

Johnstone, P.R., Hartz, T.K., LeStrange, M., Nunez, J.J., Miyao, E.M. 2005. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigated processing tomato production. *HortScience*, **40**(6), 1857-1861.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, **55**(407), 2427-2436.

Jones, H.G. 1990. Plant water relations and implication for irrigation scheduling. *Acta Horticulturae*, **287**, 67-76.

Jones Jr, B.J. 2007. *Tomato Plant Culture - In the field, Greenhouse and Home Garden*. CRC Press Taylor and Francis Group, New York.

Jones, S.B., Wraith, J.M., Or, D. 2002. Time domain reflectometry measurement principles and applications. *Hydrological Processes*, **16**, 141-153.

Jungk, A. 2002. Dynamics of nutrient movement at the soil-root interface. 3rd ed. in: *Plant Roots: The Hidden Half* (Eds.) Y. Waisel, A. Eshel, U. Kafkafi, Eds., Marcel Dekker Inc. New York., pp. 587-616.

Jury, W.A., Gardner, W.R., Gardner, W.H. 1991. *Soil Physics, 5th ed.* John Wiley, New York, .

Kandelous, M.M., Liaghat, A., Abbasi, F. 2008. Estimation of soil moisture pattern in subsurface drip irrigation using dimensional analysis method. *J Agri Sci* **39**(2), 371-378.

Kandelous, M.M., Šimůnek, J. 2010. Comparison of numerical, analytical, and empirical models to estimate wetting patterns for surface and subsurface drip irrigation. *Irrig Sci*, **28**, 435-444.

Kandelous, M.M., Šimůnek, J., van Genuchten, M.T., Malek, K. 2011. Soil Water Content Distributions between Two Emitters of a Subsurface Drip Irrigation System. *Soil Sci. Soc. Am. J.* , **75**, 488-497.

Kang, S., Zhang, J. 2004. Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *J. Exp. Bot.*, **55**(407), 2437-2446.

Kang, S., Zhang, J., Liang, Z., Hu, X., Cai, H. 1997. The controlled alternative irrigation: A new approach for water saving regulation in farmland. *Agric Res Arid Areas*, **15**(1), 1–6.

Kang, S.Z., Hu, X., Jerie, P., Zhang, J.H. 2003. The effects of partial rootzone drying on root, trunk sap flow and water balance in an irrigated pear (Pyrus communis L.) orchard. *Jour. of Hydrology*, **280**(192-206).

Karasov, C.G. 1982. Irrigation efficiency in water delivery. *Technology*, **2**, 62-74.

Karoun, M., El-Mourid, M. 2009. Improving water productivity of crops in the Mediterranean region: Case of cereals. Proceedings of the International Agriculture Durable en Region Mediteraneene, May 14-16, 2009, Rabat, Maroc, pp: 123-130.

Keeney, D.R., Nelson, D.W. 1982. Nitrogen - inorganic forms. 2 ed. in: *Methods of soil analysis, part 2. Agron. Monogr. 9*, (Ed.) A.L. Page, ASA and SSSA. Madison, WI., pp. 643-698.

Kirda, C. 2002. *Deficit Irrigation Practices.Water Report Paper No. 22*. FAO, Rome.

Kirda, C., Cetin, M., Dasgan, Y., Topcu, S., Kaman, H., Ekici, B., Derici, M.R., Ozguven, A.I., Management, A.W. 2004. Yield response of greenhouse-grown tomato to partial root drying and conventional deficit irrigation. *69*, 191–201.

Kirda, C., Kanber, R. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. in: *Crop yield response to deficit irrigation*, (Eds.) C. Kirda, P. Moutonnet, C. Hera, D.R. Nielsen, Kluwer Academic Publishers. Dordrecht, The Netherlands.

Kirda, C., Topcu, S., Cetin, M., Dasgan, H.Y., Kaman, H. 2007. Prospects of partial rootzone irrigation for increasing irriation wate use efficiency of major crops in the \mediterranean region. *Ann. Applied Biol.*, **150**(281-291).

Kirkham, M.B. 2005. Principles of soil and plant water relations. Elsevier academic press. Burlington, MA.

Kulkarni, S. 2011. Innovative Technologies for Water Saving in Irrigated Agriculture. *International Journal of Water Resources and Arid Environments* **1**(3), 226-231.

Lazarovitch, N., Warrick, A.W., Furman, A., Simunek, J. 2007. Subsurface Water Distribution from Drip Irrigation Described by Moment Analysis. *Vadose Zone J*, **6**(1), 116-123.

LeBoeuf, J. 2007. Effects of Dry season on the tomato plant. *In Hort Matter*, **7**(20), August 2007.

LeBoeuf, J., Tan, C., Verhallen, A. 2007. Irrigation scheduling for Tomatoes- An Introduction. OMAFRA Factsheet.

Ledieu, J., De Ridder, P., De Clerck, P., Dautrebande, S. 1986. A method of measuring soil moisture by time-domain reflectometry. *J. of Hydrology*, **88**, 319-328.

Leib, B.G., Hattendorf, M., Elliott, T., Matthews, G. 2002. Adoption and adaptation of scientific irrigation scheduling: trends from Washington, USA as of 1998. *Agricultural Water Management*, **55**(2), 105-120.

Leib, B.G., Jabro, J.D., Matthews, G.R. 2003. Field evaluation and performance comparison of soil moisture sensors. *Soil Science*, **168**(6), 396-408.

Levin, I., Sarig, S., Meron, M. 1885. Tensiometers location in controlled automated drip irrigation of cotton. In Proc. of the 3rd International Drip/Trickle Irrigation Congress, 782-785. Fresno, CaUf. St. Joseph, Mich.: ASAE.

Li, F., Liang, J., Kang, S., Zhang, J. 2007. Benefits of alternate partial root-zone irrigation on growth, water and nitrogen use efficiencies modified by fertilization and soil water status in maize. *Plant and Soil*, **295**(1), 279-291.

Liang, B.C., McConkey, B.G., Campbell, C.A., Curtin, D., Lafond, G.P., Brandt, S.A., Moulin, A.P. 2004. Total and labile soil organic nitrogen as influenced by crop rotations and tillage in Canadian prairie soils. *Biology and Fertility of Soils*, **39**(4), 249-257.

Liu, K., Zhang, T.Q., Tan, C.S. 2011. Processing tomato phosphorus utilization and post-harvest soil profile phosphorus as affected by phosphorus and potassium additions and drip irrigation. *Canadian Journal of Soil Science*, **91**(3), 417-425.

Livellara, N., Saavedra, F., Salgado, E. 2011. Plant based indicators for irrigation scheduling in young cherry trees. *Agricultural Water Management*, **98**(4), 684-690.

Livingston, B.E. 1908. A method for controlling plant moisture. *Plant World*, **11**, 39–40.

Loiskandl, W., Stangl, R., Sokol, W. 2003. Comparison of calibration methods for electromagnetic soil water sensors. *5th international conference on electromagnetic wave interaction with water and moist substances*, Rotorua, New Zealand, 23-26 March, 2003. pp. 234-241.

López-Urrea, F., Martín de Santa, F., Fabeiro, C., Moratalla, A. 2006. An evaluation of two hourly reference evapotranspiration equations for semiarid conditions. *Agricultural Water Management*, **86**, 277-282.

Loveys, B.R., Stoll, M., Davies, W.J. 2004. Physiological approaches to enhance water use efficiency in agriculture: exploiting plant signalling in novel irrigation practice. in: *Water use efficiency in plant biology*, (Ed.) A. Bacon M, Lancaster: University of Lancaster, 113–141.

Lubana, P.P.S., Narda, N.K. 1998. Soil water dynamics model for trickle irrigated tomatoes. *Agricultural Water Management*, **37**(2), 145-161.

Lubana, P.P.S., Narda, N.K. 2001. SW--Soil and Water: Modelling Soil Water Dynamics under Trickle Emitters -- a Review. *Journal of Agricultural Engineering Research*, **78**(3), 217-232.

Lukangu, G., Savage, M.J., Johnston, M.A. 1999. Use of sub-hourly soil water content measured with a frequency-domain reflectometer to schedule irrigation of cabbages. *Irrigation Science*, **19**(1), 7-13.

Machado, R.M.A., Oliveira, M.D.R.G. 2005. Tomato root distribution, yield and fruit quality under different subsurface drip irrigation regimes and depths. *Irrigation Science*, **24**(1), 15-24.

Machado, R.M.A., Olivera, L.R.A., Portas, C.A.M. 2000. Effect of drip irrigation and fertilizer on tomato rooting patterns. *Acta Hort.*, **537**, 313-320.

Madramootoo, C., Mehdi, B., Gollamudi, A., Ali, S. 2007. Real time Irrigation Scheduling Using Capacitance and Time Domain Reflectance soil water sensors in Transactions of the Second International Symposium on Soil Water Measurement Using Capacitance, Impedance and Time Domain Transmission. Edited by I.C. Paltineanu. Paltin International Inc. Laurel, Maryland USA.

Mantell, A., Frenkel, H., Meiri, A. 1985. Drip irrigation of cotton with saline-sodic water. *Irrig. Sci.*, **6**, 95–106.

Marouelli, W., Silva, W. 2007. Water tension thresholds for processing tomatoes under drip irrigation in Central Brazil. *Irrigation Science*, **25**(4), 411-418.

Martin, D.L., Stegman, E.C., Fereres, E. 1990. Irrigation scheduling principles. in: *Management of Farm Irrigation Systems*, (Eds.) G.J. Hoffman, K.H. Solomon, ASAE. St. Joseph, Mich, pp. 155-203.

Maton, L., Leenhardt, D., Goulard, M., Bergez, J.E. 2005. Assessing the irrigation strategies over a wide geographical area from structural data about farming systems. *Agricultural systems*, **86**(293-311).

Maxwell, D., Williamson, R. 2012. Wireless temperature monitoring in remote systems. Available online: http://archive.sensorsmag.com/articles/1002/26/main.shtml. (accessed 9th February 2012).

May, D.M., Gonzales, J. 1994. Irrigation and Nitrogen management as they affect Fruit quality and yield of processing tomatoes. *Acta Hort. (ISHS)*, **376**, 227-234.

McCarthy, M.G., Loveys, B.R., Dry, P.R., Stoll, M. 2002. Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. FAO Water Reports 22: 79–87.

McLaughlin, M., McBeath, T., Smernik, R., Stacey, S., Ajiboye, B., Guppy, C. 2011. The chemical nature of P accumulation in agricultural soils—implications for fertiliser management and design: an Australian perspective. *Plant and Soil*, **349**(1), 69-87.

Mehdi, B.B., Madramootoo, C.A., Gollamudi, A., Ali, S., Verhallen, A., Nichols, I., Morrison, W. 2008. A comparison of soil moisture monitoring technologies for irrigation scheduling. Providence, RI. pp. 3415-3439.

Mermoud, A., Tamini, T.D., Yacouba, H. 2005. Impacts of different irrigation schedules on the water balance components of an onion crop in a semi-arid zone. *Agricultural Water Management*, **77**, 282-295.

Michelakis, N., Vougioucalou, E., Clapaki, G. 1993. Water use, wetted soil volume, root distribution and yield of avocado under drip irrigation. *Agric. Water Manage.*, **24**, 119-131.

Miller, G.A. 2012. Sensor based irrigation effects on root distribution and growth of grafted and non-grafted watermelons, CLEMSON UNIVERSITY.

Miyamoto, H., Chikushi, J. 2006. Calibration of Column-Attaching TDR Probe Based on Dielectric Mixing Model, Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 23, 7 p., https://engineering.purdue.edu/TDR/Papers.

Mmolawa, K., Or, D. 2000a. Root zone solute dynamics under drip irrigation: A review. *Plant and Soil*, **222**(1), 163-190.

Mmolawa, K., Or, D. 2000b. Water and solute dynamics under a drip-irrigated crop: Experiments and analytical model. *Transactions of the American Society of Agricultural Engineers*, **43**(6), 1597-1608.

Mohan, S., Arumugam, N. 1996. Comparison of methods for estimating REF-ET discussion. *Journal of Irrigation and Drainage Engineering*, **122**(6), 361-362.

Montoro, A., López-Fuster, P., Fereres, E. 2011. Improving on-farm water management through an irrigation scheduling service. *Irrigation Science*, **29**(4), 311-319.

Morison, J.I., Baker, N.R., Mullineaux, P.M., Davies, W.J. 2008. Improving water use in crop production. *Philo. Trans. R. Soc. London B Biol. Sci.,*, **12**, 639-658.

Mostaghimi, S., Mitchel, J.K., Lembke, W.D. 1981. Effect of discharge rate on distribution of moisture in heavysoils irrigate from a trickle source. American Society of Agricultural Engieers. Paper No 81:2081 American Society of Agricultural Engineers. St. Joseph. MI.

Moutonnet, P. 2000. Yield response factors of field crops to deficit irrigation in Deficit Irrigation Practices. FAO Water Report 22. Rome.

Munoz-Capena, R., Dukes, B.M. 2005. Automatic Irrigation based on soil moisture for vegetable crops. University of Florida IFAS. ADE 356.

Nadler, A., Lapid, Y. 1996. An improved capacitance sensor for in situ monitoring of soil moisture. *Aust. J. Soil Res*, **34**, 361-368.

Nafchi, R.F., Mosavi, F., Parvanak, K. 2011. Experimental study of shape and volume of wetted soil in trickle irrigation method. *African Journal of Agricultural Research*, **6**(2), 458-466.

National Research Council. 1993. *Soil and water quality: an agenda for agriculture*. National Academy Press, Washington, D.C., USA.

Neilson, G.N., MacKenzie, A.F. 1977. Soluble and sediment nitrogen losses as related to land use and type of soil in eastern Canada. *J. Environ. Qual.*, **6**, 318-321.

Nguyen, H.V., Nieber, J.L., Misra, D. 1996. Modeling BMP impacts on ground water quality. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling, San Antonio, TX, USA, 3–6 November 1995, ASAE, pp. 762–768. .

Nielsen, D.R., Th. Van Genuchten, M., Biggar, J.W. 1986. Water flow and solute transport processes in the unsaturated zone. *Water Resour. Res.*, **22**(9S), 89S-108S.

Nye, P., Tinker, P.B. 1977. *Soil Movement in the Soil-Root System Studies in Ecology, Volume 4.* Blackwell Scientific Publications, Oxford.

O'Brain, J., Veldkamp, E. 2000. Calibration of a Frequency Domain Reflectometry Sensor for Humid Tropical Soils of Volcanic Origin. . *Soil Sci. Soc. Am. J.*, **64**, 1549-1553.

OHCRSC. 2006. Ontario Horticultural Crop Research Crop Research and Service Committee Report- 2006, OMAFRA

Oki, L.R., Leith, J.H., Tjosvold, S. 1995. Tensiometer-based irrigation of cut-flower roses. Project report to the Calif. Cutflower Commission.

Olsen, S.R., Cole, C.V., Watannabe, F.S., Dean, L.A. 1954. Estimation of available phosphorus by extraction withsodium bicarbonate, USDA Circ 939. US Gov. Printing Office, Washinton, DC.

OMAFRA. 2004. Best Practices Management Series: Irrigation Management. Revised Edition. Agdex#700. Ontario, Canada.

OMNR. 2009a. Ontario Ministry of Natural Resouces, Water- Importance of Lakes and Rivers. Sourced 28 Oct 2012: http://www.mnr.gov.on.ca/en/Business/Water/2ColumnSubPage/STEL02_163597.html.

OMNR. 2009b. Ontario Ministry of Natural Resources. Water Resources -The nature of Water Resources- Watersheds. http://www.mnr.gov.on.ca/en/Business/Water/2ColumnSubPage/STEL02_163599.html; Cited 4th January 2012.

Ontario Ministry of Environment. 2005. Guide to Permit To Take Water Application Form, Ontario Ministry of the Environment.

Ontario Ministry of Natural Resources, Ontario Ministry of Environment, Ontario Ministry of Agriculture and Food, Ontario Ministry of Municipal Affairs and Housing, Ontario Ministry of Enterprise Opportunity and Innovation, Association of Municipalities of Ontario and Conservation Ontario. 2003. Ontario Low Water Response. Revised Version.

OVPG. 2011. Ontario Processing Vegetable Growers.Crop Information-Tomatoes. in: *http://www.opvg.org/crops/tomatoes/; sited December 2011*.

Paltineanu, I.C., Starr, J.L. 1997. Real-time Soil Water Dynamics Using Multisensor Capacitance Probes: Laboratory Calibration. *Soil Science Society of America Journal*, **61**(6), 1576-1585.

Pardossi, A., Incrocci, L. 2011. Traditional and New Approaches to Irrigation Scheduling in Vegetable Crops. *Horttechnology*, **21**(3), 309-313.

Pardossi, A., Incrocci, L., Incrocci, G., Malorgio, F., Battista, P., Bacci, L., Rapi, B., Marzialetti, P., Hemming, J., Balendonck, J. 2009. Root zone sensors for irrigation management in intensive agriculture. *Sensors (Basel Switzerland)*, **9**, 2809-2835.

Paris, A.T., Zribi, M., Hasenauer, S., Habets, F., Loumagne, C. 2008. Analysis of surface and root-zone soil moisture dynamics with ERS scatterometer and the hydrometeorological model SAFRAN-ISBA-MODCOU at Grand Morin watershed (France). *Hydrol. Earth Syst. Sci.* , **12**, 1415-1424.

Passioura, J. 2006. Increasing crop productivity when water is scarce-from breeding to field management. *Agric. Water Manage.*, **80**, 176-196.

Passioura, J.B. 1988. Root signals control leaf expansion in wheat seedlings growing in drying soil. *Austral. J. Plant Physiol*, **15**, 687-693.

Patanè, C., Cosentino, S.L. 2010. Effects of soil water defi cit on yield and quality of processing tomato under a Mediterranean climate *Agric. Water Manage.*, **97**, 131-138.

Patel, N., Rajput, T.B.S. 2008. Dynamics and modeling of soil water under subsurface drip irrigated onion. *Agricultural Water Management*, **95**(12), 1335-1349.

Patel, N., Rajput, T.B.S. 2004. Fertigation-a technique for efficient use of granular fertilizer through drip irrigation. *Agric Eng* **85**(2), 50-54.

Pereira, A.R., Pruitt, W.O. 2004. Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. . *Agricultural Water Management*, **66**, 251-257.

Peters, D.B. 1965. Water Availability. in: *American Society. Agron. Monograph No. 9. Part 1*, (Ed.) C.A. Black. Madison.

Phene, C., Davis, K., Hutmacher, R., McCormick, R. 1987. Advantages of subsurface irrigation for processing tomatoes. *Acta Horticulturae (ISHS)*, **200**, 101-114.

Phene, C.J. 1999. Efficient Irrigation systems and irrigation scheduling for processing tomatoes: the challenge. *ISHS Acta Horticulturae*, **487**(VI International Symposium on Processing Tomato & Workshop on Irrigation & Fertigation of Processing Tomato).

Phene, C.J., Davis, K.R., Hutchmaker, R.B., Bar-Yosef, B., Meek, D.W., Misaki, J. 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. . *Irrig. Sci.*, **12**, 135–140.

Phene, C.J., Howell, T.A. 1984. Soil sensor control of highfrequency irrigation systems. *Transactions of the ASAE*, **27**(2), 392-396.

Pleban, S., Israeli, I. 1989. Improved approach to irrigation scheduling programs. *J. Irrigation and Drainage. Eng. ASCE*, **115**(4), 577-587.

Pogue, W.R., Pooley, S.G. 1985. Tensiometric management of soil water In Proc. of the Third International Drip/Trickle Irrigation Congress, 761-766, Fresno, Calif St. Joseph, Mich.: ASAE.

Pregitzer, K.S., King, J.S. 2005. Effects of Soil Temperature on Nutrient Uptake. in: *Nutrient Acquisition by Plants: An Ecological Perspective*, (Ed.) H.BassiriRad, Springer-Verlag. Berlin Heidelberg

Prieto, M.H., Lopez, J., Ballesteros, R. 1999. Influence of irrigation system and strategy of the agronomic and quality parameters of the processing tomatoes in Extremadura. *Acta Hort.*, **487**, 575-579.

Quinones, H., Ruelle, P., Nemeth, I. 2003. Comparison of three calibration procedures for TDR soil moisture sensors. *Irrigation and Drainage*, **52**(3), 203-217.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K. 1997. *Water futures: assessment of long-range patterns and problems. Comprehensive assessment of the freshwater resources of the world*. SEI, Stockholm (Sweden).

Ratliff, L.F., Ritchie, J.T., Cassel, D.K. 1983. Field-Measured Limits of Soil Water Availability as Related to Laboratory-Measured Properties. *Soil Sci Soc Am J*, **47**(4), 770-775.

Rattan, L., Uphoff, N., Stewart, B.A., Hansen, D.O. 2005. *Climate Change and Global Food Security*. CRC Press Boca, Raton, FL.

Regalado, C.M., Carpena, R.M., Socorro, A.R., Moreno, J.M.H. 2003. TDR models as a tool to understand the dielectric response of volcanic soils. *Geoderma*, **117:313Y330**.

Renquist, A.R., Reid, J.B. 2001. Processing tomato fruit quality: influence of soil water deficits at flowering and ripening. *Australian Journal of Agricultural Research*, **52**(8), 793-867.

Rhue, R.D., Harris, R.G. 1999. Phosphorus sorption/desorption reactions in soils and sediments. in: *Phosphorus biogeochemistry in subtropical ecosystems*, (Eds.) K.R. Reddy, G.A. O'Connor, C.L. Schleske, Lewis Publishers. Boca Raton, pp. 187-206.

Richards, L.A. 1928. The usefulness of capillary potential to soil moisture and plant investigators. *J. Agric. Res. (Cambridge)* **37**, 719–742.

Richards, R.P., Baker, D.B. 2002. Trends in water quality in LEASEQ rivers and streams,1975-1995. *J. Environ. Qual.*, **31**, 90-96.

Richards, S.K., Marsh, A.W. 1961. Irrigation based on soil suction measurements. *Soil Science Society Proceedings*, **25**, 65–69.

Robinson, D.A., Bell, J.P., Batchelor, C.H. 1994. Influence of iron minerals on the determination of soil water content using dielectric techniques. *Journal of Hydrology*, **161**, 169-180.

Robinson, D.A., Jones, S.B., Wraith, J.M., Or, D., Friedman, S.P. 2003. A Review of Advances in Dielectric and Electrical Conductivity Measurement in Soils Using Time Domain Reflectometry. *Vadose Zone Journal*, **2**(4), 444-475.

Rockstrom, J., Falkenmark, M. 2000. Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. *Crit. Rev. Plant Sci.,* , **19**, 319– 346.

Rolston, D.E., Biggar, J.W., Nighingale, H.I. 1991. Temporal persistence of spatial soilwater patterns under trickle irrigation. *Irr. Sci.*, **12**, 181-186.

Roth, R.L. 1974. Soil moisture distribution and wetting pattern from a point-source. *Proceeding of the second international Drip Irrigation Congress*. pp. 246-253.

Rufat, J., Domingo, X., Arbonés, A., Pascual, M., Villar, J. 2011. Interaction between water and nitrogen management in peaches for processing. *Irrigation Science*, **29**(4), 321-329.

Sabziparvar, A.A., Tabari, H. 2010. Regional Estimation of Reference Evapotranspiration in Arid and Semiarid Regions. *Journal of Irrigation and Drainage Engineering-Asce*, **136**(10), 724-731.

Sammis, T.W., Williams, S., Wu, I.P. 1990. Development of a trickle irrigation scheduling model. *Computers and Electronics in Agriculture*, **5**(3), 187-196.

Santos, C., Lorite, I.J., Tasumi, M., Allen, R.G., Fereres, E. 2008. Integrating satellite-based evapotranspiration with simulation models for irrigation management at the scheme level. *Irrig Sci*, **26**, 27–288.

SAS. 2007. The SAS System for Windows. Release 9. 0. SAS Institute Incorporated, Cary, NC.

Sato, S., Morgan, K.T., Ozores-Hampton, M., Simonne, E.H. 2009. Spatial and temporal distributions in sandy soils with seepage irrigation: II. Phosphorus and potassium. . *Soil Sci. Soc. Am. J.*, **73**, 1053-1060.

Schartzman, M., Zur, B. 1986. Emitter spacing and geometry of the wetted soil volume. *J. Irrig. Drain. Eng.* , **112**, 242-253.

Schwab, G.O., Fangmeier, D.D., Elliot, J.M., Frevert, K.R. 1993. *Soil and water conservation engineering*. *4th ed*. Wiley, New York.

Sentek Sensor Technologies. 2003. Access Tube Installation Guide Version 1.0 for EnvironSCAN, EnviroSMART and Diviner 2000. Sentek Pty Ltd. Stepney, South Australia.

Sezen, S.M., Celikel, G., Yazar, A., Tekin, S., Kapur, B. 2010. Effect of irrigation management on yield and quality of tomatoes grown in different soilless media in a glasshouse. *Scientific Research and Essay*, **5**(1), 041-048,.

Shenoy, V.V., Kalagudi, G.M. 2005. Enhancing plant phosphorus use efficiency for sustainable cropping. *Biotechnol. Adv. Agron.*, **23**, 501-513.

Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *Water International*, **25**(1), 11-32.

Shock, C.C., Feibert, E.B.G., Saunders, L.D., Eldredge, E.P. 2001. Automation of subsurface drip irrigation for crop research. Iguacu Falls, Brazil. American Soc. Agric. Eng. pp. 809-16.

Shock, C.C., Pereira, A., Hanson, B., Cahn , M. 2007. Vegetable irrigation. 2 ed. in: *Irrigation of agricultural crops*, (Eds.) R. Lescano, R. Sojka, Vol. 30, Agron Monogr. ASA, CSSA and SSSA. Madison, pp. 535–606.

Shock, C.C., Wang, F.-X. 2011. Soil Water Tension, a Powerful Measurement for Productivity and Stewardship. *HortScience*, **46**(2), 178-185.

Sibbsen, E., Sharpley, A.N. 1997. Setting and justifying upper critical limits phosphorus in soils. in: *Phosphorus Loss from Soil to Water*, (Eds.) H. Tunney, O.C. Carton, P.C. Brookes, A.E. Johnston, CAB International. New York, pp. 151-176.

Silva, C.R.d., Andrade Júnior, A.S.d., Alves Júnior, J., Souza, A.B.d., Melo, F.d.B., Coelho Filho, M.A. 2007. Calibration of a capacitance probe in a Paleudult. *Scientia Agricola*, **64**, 636-640.

Sims, W.L. 1992. Processing Tomato Production in North America. *Acta Horticulturae*, **301, Processing Tomatoes**.

Simunek, J., M., S., van Genuchten, M.T. 1999. The Hydrus-2D software package for simulating two dimensional movement of water, heat and multiple solutes in variably saturated media., Ver.2.0. Rep IGWMC-TPS-53, Int. Ground Water Model. Cent., Colo. School of Mines, Golden.

Sinclair, T.R., Tanner, C.B., Bennett, J.M. 1984. Water-use efficiency in crop production. *BioSci.*, **34**, 36-40.

Singh, D.K., Rajput, T.B.S., Sikarwar, H.S., Sahoo, R.N., Ahmad, T. 2006. Simulation of soil wetting pattern with subsurface drip irrigation from line source. *Agricultural Water Management*, **83**(1-2), 130-134.

Skaggs, T.H., Trout T.J, Šimůnek, J., Shouse, P.J. 2004. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *J Irrig Drainage Eng*, **130**(4), 304-310.

Smajstrla, A.G., Harrison, D.S., Duran, F.X. 1998. Tensiometers for soil moisture measurement and irrigation scheduling. Ext. Circ. 487. Fla. Coop. Ext. Svc., Univ. Of Fla.,Gainesville.

Smith-Rose, R.L. 1933. The electrical properties of soils for alternating currents at radio frequencies. *Proc. R. Soc. London :*, **140**, 359.

Smith, M., Allen, R., Monteith, J.L., Pereira, L.A., Perrier, A., Segeren, A. 1991. Report on the Expert Consultation for the Revision of FAO Methodologies for Crop Water Requirements, FAO/AGL, Rome 60 pp.

Smith, M., Pereira, L.S., Berengena, J., Itier, B., Goussard, J., Ragab, R., Tollefson, L., P, V.H. 1996. Irrigation scheduling: From theory to practice. Proceedings. in: *Water* *reports 8*, FAO - Food and agriculture Organization of the United Nations, Rome, Italy.

Soler, C.M.T., Hoogenboom, G. 2007. Determining irrigation scheduling for cotton and peanut using cropping system models. Tampa, FL.

Stangl, R., Buchan, G.D., Loiskandl, W. 2009. Field use and calibration of a TDR-based probe for monitoring water content in a high-clay landslide soil in Austria. *Geoderma*, **150**(1-2), 23-31.

Stanley, C.D., Maynard, D.N. 1990. Vegetables. in: *Irrigation of agriculture land. Agron Monogr 30(31)*, (Eds.) B.A. Stewart, D.R. Nielsen, Am Soc Agron, Madison. Wisconsin, pp. 921–950.

Statistics Canada. 2006a. Census of Agriculture 2006, farm data and farm operation data. Cat. No. 95-629-XWE.

Statistics Canada. 2006b. Census of Agriculture 2006. Highlights and Statistics, Provincial trends. http://www.statcan.gc.ca/ca-ra2006/hl-fs-eng.htm, (Accessed December 2011).

Statistics Canada. 2006c. Census of Agriculture 2006. Snapshot of Canada Agricuture-Irrigation. http://www.statcan.gc.ca/ca-ra2006/articles/snapshot-portrait-eng.htm Sourced 13 December 2010.

Statistics Canada. 2011a. *Fruit and Vegetable production, February 2011, Pg 5 Catalogue No 22-003-X Vol. 79, No 2 ISSN 1480-7602.* Statistic Canada.

Statistics Canada. 2011b. *Human Activity and the Environment*. Statistic Canada, R.H. Coats Bldg., 6th Floor, 100 Tunney's Pasture Driveway, Ottawa, ON K1A 0T6.

Stegman, E.C. 1983. Irrigation water management. in: *Design and operation of farm irrigation systems*, (Ed.) M.E. Jensen, American Society of Agricultural Engineers. St. Joseph, pp. 763-816.

Stegman, E.C., Musick, J.R., Stewart, J.I. 1980. Irrigation water management. in: *Design and operation of farm irrigation systems*, (Ed.) M.E. Jensen, Amer. Soc. Agr. Eng. St. Joseph, Mich., pp. 763-816.

Steppe, K., Memeur, R., De Pauw, D.J.W. 2008. A Novel Methodology for Irrigation Scheduling Using Plant-Based measurements and Mathematical Modeling. Proceeding Vth IS On Irrigation of Hort.Crops. Eds: I.Goodwin and M.G.O Connell. *Acta Hort.*, **792, ISHS**

Stieber, T.D., Shock, C.C. 1995. Placement of soil moisture sensors in sprinkler irrigated potatoes. *Amer. Potato J.*, **72**, 533-543.

Stockle, C.O., Kjelgaard, J., Bellocchi, G. 2004. Evaluation of estimated weather data for calculating Penman-Monteith reference evapotranspiration. *Irrigation Science*, **23**, 39–46.

Surfer. 2003. Surface Mapping System. Ver 8.04. Golden Colorado:Golden Softwarer Inc.

Tacker, P., Ashlock, L., Vories, E., Earnest, L., Cingolani, R., Beaty, D., Hayden, C. 1996. Field demonstration of Arkansas irrigation scheduling program. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling, San Antonio, TX, USA, 3–6 November 1995, ASAE, pp. 974–979.

Tan, C., Zhang, T., Reynolds, D., Drury, C. 2003. Farm-Scale Processing Tomato Production Using Surface and Subsurface Drip Irrigation and Fertigation. in: *2003 ASAE Annual International Meeting*, ASABE. Las Vegas, Nevada, USA.

Tan, C.S. 1990. Irrigation scheduling for tomatoes – water budget approach. OMAF, Toronto, ON. Factsheet order no. 90-049.

Tan, C.S., Reynolds, W.D. 2003. Impacts of recent climate trends on Agriculture in Southwestern Ontario. *Water Resouces Journal*, **28**(1), 87-97.

Tasumi, M., Allen, R.G. 2007. Satellite-based ET mapping to assess variation in ET with timing of crop development,. *Agric. Water Management*, **88**(1), 54–62.

Tebal, N. 2011. Growth, yield and water use pattern of chilli pepper under different irrigation scheduling and management. *Asian Journal of Agricultural Research*, **5**(2), 154-163.

Thomas, A.M. 1966. In situ measurement of moisture in soil and similar substances by 'fringe' capacitance. *J. Sci. Instrum.*, **43**, 21-27.

Thompson, R.B., Gallardo, M., Valdez, L.C., Fernandez, M.D. 2007a. Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. *Agricultural Water Management*, **88**(1-3), 147-158.

Thompson, R.B., Gallardo, M., Valdez, L.C., Fernández, M.D. 2007b. Determination of lower limits for irrigation management using in situ assessments of apparent crop water uptake made with volumetric soil water content sensors. *Agricultural Water Management*, **92**(1-2), 13-28.

Thorburn, P., Cook, F., Bristow, K. 2003. Soil-dependent wetting from trickle emitters: implications for system design and management. *Irrigation Science*, **22**(3), 121-127.

Tiessen, H. 1979. Production of Tomatoes for Processing in Canada. ISHS. pp. 37-42.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D. 2001. Forecasting agriculturally driven global climate change. *Science*, **292**, 281–284.

Timlin, D.J., Pachepsky, Y.A. 1996. Comparison of Three Methods to Obtain the Apparent Dielectric Constant from TDR Wave Traces. *Soil Science Society of America Journal*, **60**, 970-977.

Tollefson, C.L., Tomasiewicz, D., Linsley, J., Paterson, B., R., H. 2002. Irrigation Advisory Services (A Canadian Model). ICID/FAO Workshop on Irrigation Advisory Services and Participatory Extension in Irrigation Management. Montreal, Canada.

Tollefson, L.C., Wahab, M.N.J. 2007. Better Research-Extension-Farmer Interaction can Improve the Impact of Irrigation Scheduling Techniques. Agriculture and Food Canada. Canada-Saskatchewan Irrigation Diversification Centre, 901 McKenzie St. S Outlook, Saskatchewan S0L 2N0.

Tomato Processing in Canada. 2006. http://www.wptc.to/pdf/Canada%202006.pdf, sourced 17th August 2011.

Topp, G.C. 1987. The application of time-domain reflectometry (TDR) to soil water content measurement. *Proceedings of International Conference*, Logan, Utah. Utah State University. pp. 85-93.

Topp, G.C. 1993. Soil Water Content. in: *Soil Sampling and Methods of Analysis*, (Ed.) M.R. Carter, Lewis Publ. Boca Raton, FL, pp. 541-557.

Topp, G.C., Davis, J.L. 1985a. Measurement of Soil Water Content using Time-domain Reflectrometry (TDR): A Field Evaluation. *Soil Science Society of America*, **49**(1), 19-24.

Topp, G.C., Davis, J.L. 1985b. Time Domain reflectrometry and its application to irrigation scheduling. *Advanced Irrigation*, **3**, 07-127.

Topp, G.C., Davis, J.L., Annan, A.P. 1980. Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. *Water Resources Research*, **16**, 574-582.

Topp, G.C., Reynolds, W.D. 1998. Time domain reflectometry: A seminal technique formeasuring mass and energy in soil. *Soil Tillage Res.* , **47**(1,2), 125-132.

Toride, N., Leij, F.J., van Genuchten, M.T. 1993. A comprehensive set of analytical solutions for nonequilibrium solute transport with first-order decay and zero-order production. *Water Resour. Res.*, **29**(7), 2167-2182.

Tremblay, N., Scharpf, H., C, Weier, U., Laurence, H., Owen, J. 2001. Nitrongen management in field vegetables: a guide to efficient fertilzation. AAFC, Ottawa, ON. CAT. No. A42-92/2001E.

Tsipori, Y., Shimshi, D. 1979. The Effect of Trickler Line Spacing on Yield of Tomatoes (Lycopersicum esculentum Mill.). *Soil Sci. Soc. Am. J.*, **43**(6).

Turner, N.C. 1986. Adaptation to Water Deficits: a Changing Perspective. *Functional Plant Biology*, **13**(1), 175-190.

U.S. EPA. 1986. Quality Criteria for Water 1986.EPA 440/5-86-001.

Unger, W.P. 2006. *Soil and water conservation handbook*. Haworth Press Inc, Alice Street Binghamton, New York 13904–1580 USA.

USDA. 1967. Irrigation water requirements. *Technical Release No. 21, United States Department of Agricuture, Soil Conservation service, Washington, D.C.*

Vaughan, P.J., Ayars, J.E. 2009. Noise reduction methods for weighing lysimeters. *Journal of Irrigation and Drainage Engineering*, **135**(2), 235–240.

Viets, F.G., 1962... 1962. Fertilizers and the efficient use of water. *Adv. Agron.,* , **14**, 233-264.

Vitousek, P., Naylor, R., Crews, T., David, M., Drinkwater, L., Holland, E., Johnes, P., Katzenberger, J., Martinelli, L., Matson, P. 2009. Nutrient imbalances in agricultural development. *Science*, **324**(5934), 1519.

Vitousek, P.M., Aber, J., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, G.D. 1997. Human alteration of the global nitrogencycle: Causes and consequences. . *Ecological Applications*, **7**, 737–750.

Wallace, J.S., Batchelor, C.H. 1997. Managing water resources for crop production. *Philos. Trans. R. Soc. London Ser.*, **B 352**, 937–947.

Wan, X., Zwiazek, J.J., Lieffers, V.J., Landhausser, M. 2001. Hydraulic conductance in aspen (Populus tremuloides) seedlings exposed to low root temperatures. *Tree Physiol*, **21**, 691-696.

Wang, N., Zhang, N., Wang, M. 2006. Wireless sensors in agriculture and food industry — Recent development and future perspective. *Comp. and Electr. in Agr.*, **50**, 1–14.

Wang, Y., Liu, F., Anderson, M.N., Jensen, C.R. 2010. Improved plant nitrogen nutrition contributes to higher water use efficiency in tomatoes under alternate partial root-zone irrigation. *Functional Plant Biol.*, **37**, 175-182.

Ward, D.A., Trimble, W.S. 2004. *Environmental Hydrology. 2 ed.* Lewis Publishers. A CRC Press Company, Washington, DC.

Warner, J., Tan, C.S., Zhang, T.Q. 2004a. Effect of Regulated Deficit Drip Irrigation on Processing Tomato Fruit Solids and Yield. in: *ASAE Annual International Meeting*, American society of Agricultural Engineers. Ottawa, Canada.

Warner, J., Tan, C.S., Zhang, T.Q. 2007. Water management strategies to enhance fruit soilds and yield of drip irrigated processing tomato. *Canadian Journal of Plant Science*, **87**, 345-353.

Warner, J., Zhang, T.Q., Hao, X. 2004b. Effects of nitrogen fertilization on fruit yield and quality of processing tomatoes. *Canadian Journal of Plant Science*, **84**(3), 865-871.

Weiner, J.J., Peterson, F.C., Volkman, B.F., Cutler, S.R. 2010. Structural and functional insights into core ABA signaling. *Curr. Opin. Plant Biol.* , **13**, 495–502.

Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., Curnow, A. 1993. The Genesis and Collapse of Third Millennium North Mesopotamian Civilization. *Science*, **261**(5124), 995-1004.

Wilks, D.S., Wolfe, D.W. 1998. Optimal use and economic value of weather forecasts for lettuce irrigation in a humid climate. *For. Meteo.*, **89**, 115–129.

Wilson, D.J., Western, A.W., Grayson, R.B. 2005. A terrain and databased method for generating the spatial distribution of soil moisture. *Advances in Water Resources*, **28**, 43-54.

Wraith, J.M., David, A., D.A., R., Jones, B.S., Long, D.S. 2005. Spatially characterizing apparent electrical conductivity and water content of surface soils with time domain reflectometry. *Computers and Electronics in Agriculture* **46**, 239–261.

Wraith, J.M., Or, D. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development. *Water Resources Research*, **35**(2), 361-369.

Yazar, A., Howell, T.A., Busek, D.A., Copeland, K.S. 1999. Evaluation of crop water stress index for LEPA irrigated corn. *Irrig. Sci.*, **18**, 171-180.

Yoder, E.R., Johnson, D.L., Wilkerson, J.B., Yoder, D.C. 1998. Soil Water Sensor Performance. *Applied Engineering in Agriculture*, **Vol. 14**(2), 121-133.

Zazueta, F.S., Xin, J., Smajstrla, A.G., Carrillo, M. 1994. Comparison of soil moisture sensors and rainfall shutoff devices for computer-based irrigation control. Orlando, FL, USA. American Soc. Agric. Eng. pp. 864-9.

Zegbe, J.A., Behboudian, M.H., Clothier, B.E. 2006. Responses of 'Petopride' processing tomato to partial rootzone drying at different phenological stages. *Irrigation Science*, **24**(3), 203-210.

Zhang, T.Q., Tan, C.S., Liu, K., Drury, C.F., Papadopoulos, A.P., Warner, J. 2010. Yield and economic assessments of fertilizer nitrogen and phosphorus for processing tomatoes with drip fertigation. . *Agronomic Journal* **102**, 774-780.

Zhang, T.Q., Tan, C.S., Liu, K., Warner, J.T. 2009. Nitrogen and phosphorus application to processing tomatoes grown with drip fertigation. *Acta Horticulturae (ISHS)*, **823**, 109-113.

Zotarelli, L., Duke, M.D., Scholberg, J.M.S., Femimella, K., Muñoz-Carpena, R. 2011. Irrigation Scheduling for green bell pepers using capacitance soil moisture sensors. *Journal of Irrigation and Drainage Engineering*, **137**(2), 73-81.