ASSESSING ON-FARM WATER USE EFFICIENCY IN SOUTHERN ONTARIO

by

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ABSTRACT

Master of Science **Marie-Hélène Bernier** Bioresource Engineering

Assessing On-Farm Irrigation Water Use Efficiency in Southern Ontario

In southern Ontario, irrigation is essential for high value horticultural crop production to overcome insufficient rainfall and achieve stabilized crop production. In a context where competition for limited water resources intensifies due to the expansion of the agricultural sector, increasing urban development and tourism, and potential climate change impacts, conserving water through efficient irrigation has become a key solution to address this growing challenge. The implementation of advanced soil water monitoring technologies and water budgeting for improved irrigation scheduling is explored to conserve water and thus cope with increasing competing demands for limited water supplies.

Soil moisture was measured by gravimetric sampling in conjunction with several modern soil water sensors over the course of the 2007 growing season at 15 field sites located in southern Ontario where high value horticultural crop production is predominant. Quantities of irrigation water used were measured by flow meters that were installed at three of these sites. In addition, two grower surveys were administered: the first to collect information on current irrigation scheduling practices, and another to determine the appropriateness of the soil moisture monitoring sensors. On-farm irrigation performance was assessed by comparing calculated crop water requirements (using the water budget method) with growers' estimates of irrigation water use with soil moisture measurements taken during the growing season.

In five out of six experimental zones, water was either excessively or insufficiently applied. In addition, the results demonstrated that although there was no "best" soil moisture monitoring sensor – all of them having advantages and drawbacks – growers recognized their usefulness and showed willingness to adopt the technology. Overall, the results of this research proved that by implementing advanced soil moisture monitoring technologies, growers could generally save water and reduce the uncertainty currently involved in their irrigation scheduling practices.

RÉSUMÉ

Maîtrise en Science **Marie-Hélène Bernier** Génie des Bioressources

Évaluation de l'Efficacité d'Utilisation de l'Eau d'Irrigation à l'Échelle de la Ferme dans le Sud de l'Ontario

Dans le sud de l'Ontario, l'irrigation est essentielle à la production de cultures horticoles à haute valeur ajoutée afin de compenser l'insuffisance de précipitations et stabiliser la production de cultures. Dans un contexte où la compétition pour les ressources limitées en eau s'intensifie en réponse à l'expansion du secteur agricole, à la croissance du développement urbain et du tourisme, ainsi qu'aux impacts potentiels des changements climatiques, conserver l'eau grâce à des techniques d'irrigation économes est devenue une solution incontournable pour affronter ce défi grandissant. L'implémentation de technologies avancées de surveillance de la teneur en eau dans le sol et d'un bilan hydrique, pour améliorer les pratiques d'irrigation programmée, est explorée afin de conserver l'eau et ainsi mieux faire face à l'augmentation concurrentielle des demandes pour les ressources limitées en eau.

Au cours de la saison de croissance de 2007, l'humidité du sol a été mesurée avec plusieurs sondes ainsi que par la méthode gravimétrique pour quinze sites situés dans le sud de l'Ontario où la production de cultures à haute valeur ajoutée est prédominante. Les quantités d'eau utilisées pour irriguer étaient mesurées par des compteurs de débit installés dans trois des quatre sites. De plus, les producteurs ont répondus à deux questionnaires: le premier visant à recueillir l'information concernant des pratiques actuelles d'irrigation programmée et le second à déterminer l'utilité des sondes mesurant l'humidité du sol. La performance d'irrigation à l'échelle de la ferme a ensuite été évaluée en comparant les besoins en eau des cultures (calculés à l'aide d'un bilan hydrique) avec la quantité d'eau d'irrigation utilisée telle qu'estimée par les producteurs, ainsi qu'avec les mesures d'humidité du sol prises au cours de la saison de croissance.

Les résultats démontrent que dans cinq des six zones expérimentales, la quantité d'eau appliquée était soit excessive, soit insuffisante. Par ailleurs, bien qu'aucune des sondes ne soit unanimement considérée comme étant le meilleur instrument – chacune ayant ses avantages et inconvénients – les producteurs qui reconnaissent leur utilité, ont exprimé le désir d'adopter la technologie afin de mieux gérer leurs applications d'eau

d'irrigation. Somme toute, les résultats de cette étude montrent qu'en implémentant les technologies avancées de surveillance d'humidité dans le sol, les producteurs pourraient généralement économiser de l'eau en réduisant l'incertitude actuellement imbriquée dans leurs pratiques d'irrigation programmée.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASW: Available Soil Water

ECRD: Effective Crop Rooting Depth

EP: Effective Precipitation

ESR: Environmental Study Report

ET: Evapotranspiration

ET_c: Crop Evapotranspiration

ET_o: Reference Evapotranspiration

FAE: Field Application Efficiency

FAO 56-PM: Food and Agriculture Organization Irrigation and Drainage Paper 56 - Penman-Monteith

FC: Field Capacity

GS: Gravimetric Sampling

IACs: Irrigation Advisory Committees

IRR: Depth of Irrigation Water Applied

IT: Irrigation Trigger

Kc: Crop Coefficient

LADIA: Leamington Area Drip Irrigation Association

MAD: Management Allowable Depletion

MSWD: Maximum Soil Water Deficit

MSWS: Maximum Soil Water Storage

NWSEP: Norfolk Water Supply Expansion Program

OLWRP: Ontario Low Water Response Program

OMAFRA: Ontario Ministry of Agriculture, Food and Rural Affairs

OMOE: Ontario Ministry of the Environment

OMNR: Ontario Ministry of Natural Resources

OWRA: Ontario Water Resources Act

PWP: Permanent Wilting Point

PTTW: Permit to Take Water

PTTWP: Permit to Take Water Program

R: Rainfall

SIS: Scientific Irrigation Scheduling

ΔS: Change in Soil Water Storage

TDR: Time Domain Reflectometry

FC_v: Volumetric Field Capacity

VWC: Volumetric Water Content

WB: Water Budget

WCR: Water Content Reflectometer

WIN: Weather Innovations Incorporated

CHAPTER 1 - INTRODUCTION

1.1. Problem definition

In southern Ontario, high value horticultural production currently faces considerable competition for limited water resources: a condition exacerbated by expansion of the agricultural sector, increasing urban development and tourism as well as potential climate change impacts. As such, efficient irrigation has become a very pertinent practice to stretch limited water supplies and at the same time, meet crop water requirements.

Growers need to have better knowledge about when to start irrigating and what quantity of water to apply. Whereas most growers still rely on intuition or subjective irrigation scheduling techniques, scientific irrigation scheduling (SIS), defined as the use of climate and crop evapotranspiration data and soil moisture sensors to accurately determine when and how much to irrigate, remains mostly unpractised (Leib et al., 2002). Growers schedule irrigation and determine how much water to apply as a result of past experience: observing the condition of their plants, observing and feeling their soil to determine the soil moisture content, and following the weather forecasts. However, even if this subjective method of determining soil moisture levels can become more accurate with experience, UMA Engineering Ltd. (2007) showed that with few exceptions, this technique largely overestimates the crop water needs. The report indicates that in 2007, in Leamington the producers' requested water demand per hectare exceeded the 1:10 year drought risk demand estimated by Weather Innovations Incorporated (WIN). Therefore, techniques such as soil moisture monitoring and crop water budget calculations are crucial.

Although soil moisture sensors have been used for many years in some production systems as well as some research applications, this technology has only recently been applied successfully in a few Canadian regions. Initial attempts were unsuccessful due to the state of the technology, maintenance requirements and cost (Bierman 2005; Van der Gulik 2006). This thesis details one part of such a project in which the overall goal is to undertake a comparison of eight soil moisture monitoring devices in order to determine the amount and timing of irrigation as well as to transfer this information to growers and irrigation stakeholders. The intent of this thesis is to assess on-farm irrigation performance and soil moisture monitoring sensors' usefulness to growers and to determine whether the implementation of scientific irrigation scheduling can successfully help to schedule irrigation water applications and consequently achieve water savings.

1.2. Research objectives

The objectives of this research were as follows:

i. Calculate irrigation water requirements of tomato, bell pepper, strawberry and peach crops of four growers in southern Ontario.
ii. Quantify the amount of irrigation water used by the growers.
iii. Assess on-farm irrigation water performance by comparing calculated crop water requirements using a water budget method with water consumption estimates.
iv. Compare water budget calculations with soil moisture measurements to determine the quantity of water that could be saved through the implementation of scientific irrigation scheduling.
v. Survey growers to establish how useful soil moisture monitoring technologies are and to establish the feasibility of implementation at a larger scale.

1.3. Scope

To conduct this study, 15 agricultural field sites were selected in four counties (Niagara, Haldimand-Norfolk, Chatham-Kent and Essex) in southern Ontario. In each county, one site has been instrumented to continuously monitor soil moisture with several sensors and to obtain climate data (air temperature, rainfall, relative humidity and wind speed). Although the results of this study are limited to the geographic location and climatic conditions studied, they provide a good estimate for locations where similar crop, soil and irrigation system type are found as well as comparable irrigation scheduling practices are followed.

CHAPTER 2 – LITERATURE REVIEW

2.1. Water allocation system

By the *Canadian Constitution Act*, the responsibility of managing the majority of all natural resources including water was granted to the provinces. Notwithstanding, since the statutory law enforcement of the *Ontario Water Resources Act (OWRA)*, was enacted in 1961 and administered by the Ontario Ministry of the Environment (OMOE), numerous water conflicts arose in absence of regulatory control (Kreutzwiser et al., 1999).

2.1.1. Permit to Take Water Program

The Permit to Take Water Program (PTTWP) was established through the OWRA - Section 34 - as the primary water allocating mechanism in Ontario to ensure the conservation, protection, wise use and management of water as well as to act as a dispute resolution mechanism (Ontario Ministry of Environment, 2005). This permitting regime, which requires any water users who extract more than 50 000 litres per day to obtain a permit, has however been severely criticized over the last decade (Environmental Commissioner of Ontario, 2001; Kreutzwiser et al., 2004; Wong and Bellamy, 2005). According to the Environmental Commissioner of Ontario (2001), the administration of the PTTWP is inadequate in that the OMOE threatens ecosystem's protection by issuing new permits without having evaluated accurately how much water is available for abstraction and most importantly, assessed existing water abstractions. Wong and Bellamy (2005) also indicated how derisory reports of water takings are: applicants for a Permit to Take Water (PTTW) must only declare the maximum volume of water they intend to withdraw as opposed to the actual volume withdrawn. Inevitably, the uncertainty associated with the availability of water for consumption and the actual water use patterns, renders the water allocation program unsuitable to find out how much water is withdrawn, when and by whom. Gartner Lee Limited et al. (2002), after having analysed a statistical overview of the permitting process developed by the OMOE, concluded that the dataset was insufficient to explore the consumptive nature of the permits as well as the seasonality of water takings as the dataset was somewhat incomplete and inconsistent. Yet, identifying current water use patterns is an essential step in determining the vulnerability of the irrigated agriculture sector and consequently establishing appropriate adaptation strategies.

2.1.2. Ontario Low Water Response Program

Although Ontario is generally perceived as a water-rich province, it has a long history of drought and water shortages to which the horticultural industry is highly vulnerable. In their review of Ontario's drought history, Gabriel and Kreutzwiser (1993) noted that localized dry spells affecting agriculture occurred almost every year somewhere in the province during 1960-1989. In 1999, during the spring and summer, southwestern Ontario experienced an extended period of low rainfall and high temperatures. These weather conditions resulted in some of the lowest surface water levels and driest soils recorded for several decades. In order to ensure the province is prepared for low water conditions in the future, a response plan was developed (Ontario Ministry of Natural Resources et al., 2003). The Ontario Low Water Response Program (OLWRP) has been developed to complement the PTTWP by providing a framework for water sharing in the event of a drought (Shortt et al., 2006). Based on existing legislations and regulations, the OLWRP, which has been implemented by the Ontario Ministry of Natural Resources (OMNR) under the *Municipal Act*, the *Lakes and Rivers Improvement Act* and the *Ontario Water Resources Act*, was designed to enhance the flexibility of the PTTW program when low water conditions prevail. The end result was to thus mitigate the effects of drought through the implementation of short-term low-water management strategies (Ontario Ministry of Natural Resources et al., 2003). Nevertheless, the OLWRP does not help to clarify the priorities in allocation and water use that were poorly defined by the PTTWP and therefore remains mainly a reactionary approach when low water conditions prevail (Brandes and Mass, 2006). Further steps need to be taken apart from water resource management policies to address this growing challenge.

2.1.3. Local initiatives to manage water resources

Public concern for the environment in conjunction with the weaknesses of Ontario's current water allocation system has motivated a large number of people to take action and to act locally in maintaining and enhancing water supplies.

The Irrigation Advisory Committees (IACs) are one of these local initiatives that emerged in southern Ontario from 1999-2003 to better manage water supplies among irrigators. In Norfolk County, IACs were successfully organized and implemented in four watersheds (Big Creek, Whiteman's Creek, Big Otter and Catfish Creek) where water conflicts among users were frequently occurring. Without any legislative authority, they promoted an informal voluntary community-based mechanism for resolving conflicts related to agricultural production and irrigation practices (Short et al., 2006). In addition to the IACs, the Norfolk Water Supply Enhancement Project (NWSEP) was implemented from 2000 to 2003, by Agriculture and Agri-Food Canada in close collaboration with the local community (Stantec Consulting Ltd., 2005). In response to major concerns about sensitivity of vulnerable groundwater and surface water supply, this water conservation program was developed to establish a reliable alternate water supply; this was accomplished by eliminating water extractions from vulnerable sources and improving the water storage capacity and water use efficiency throughout the overall water supply and usage systems. Since then, it successfully allowed a substantial annual economy of 471 648 m^3 water to be made and thus considerably reduced the pressure on the shallow aquifers.

More recently in 2007, another remarkable local initiative was instigated by a group of farmers in the Essex County whose irrigation was constrained by limited water resources. The emerging Leamington Area Drip Irrigation Association (LADIA) was given the mandate to build up a distribution system that would deliver raw water supply for 1 000 hectares of existing and potential drip irrigated lands. To provide the required volume of 1.4 million m^3 to fulfill the farmers' demands, Lake Erie was selected as the most reliable source. Lake Erie is not considered as an environmentally sensitive source of water and could provide good quality water. Also, water extractions for privately funded irrigation projects are not constrained by regulations once the required permits and an Environmental Study Report (ESR) are provided to the OMOE and the OMNR (Stantec Consulting Ltd., 2005; UMA Engineering Ltd., 2007).

2.2. Water use and trends

According to recent estimates generated by de Loë et al. (2001), the agricultural sector only accounts for 0.6% (168 Mm^3) of total annual withdrawal (28 438 Mm^3) in Ontario. However it is essential to know how much withdrawn water is actually consumed - the difference between withdrawal volumes and subsequent discharges - or not returned to its source but incorporated into products, evaporated or dissipated (Vandierendonck and Mitchell, 1997). In fact, due to its high rate of consumption (commonly cited figure of 78%) the agricultural sector accounts for 20% (13% for irrigation purposes and 7% for stock watering) of total annual consumption (660 Mm^3) in Ontario (de Loë et al., 2001; Marshall Macklin Monaghanm, 2003). The agricultural sector is thus ranked as the third largest water consumer after industrial manufacturing (29%) and municipalities (38%) (de Loë et al., 2001). Table 2.1 displays the relative amount of water withdrawn and consumed in each water use sector.

Table 2.1 Total average daily and annual water withdrawal and consumption by water use sector in Ontario (de Loë et al., 2001)

Water Use Sector	*Water Withdrawal*			*Water Consumption*		
	(m^3/day)	*(Mm^3/yr)*	*(%)*	*(m^3/day)*	*(Mm^3/yr)*	*(%)*
Municipal	4 543 505	1 660	5.8	681 526	249	37.7
Aquaculture	263 288	96	0.3	---	---	---
Industrial Manufacturing	8 630 137	3 152	11.1	511 699	187	28.3
Agriculture	460 274	168	0.6	364 849	133	20.2
Golf Courses	87 671	32	0.1	70 137	26	3.9
Industrial Mining	220 959	81	0.3	61 466	23	3.4
Industrial Thermal Power	63 272 438	23 110	81.3	60 466	22	3.3
Rural Residential	381 600	139	0.5	57 240	21	3.2
Total	***77 859 872***	***28 438***	***100***	***1 807 383***	***660***	***100***

The future expansion of this sector and its increase in water demand as outlined by Miller et al. (2000) emphasize the importance of first identifying the areas of heaviest irrigation water use and then adopting appropriate on-farm water management strategies that will help reduce competition and conflicts over scarce water resources.

2.2.1. Irrigated agriculture sector

Agriculture is the second largest economic sector in Ontario, producing gross annual sales of $6.8 billion (Marshall Macklin Monaghanm, 2003). The high value horticultural production, accounting for 10.5% of the total farm cash revenues, occupies an important part of Ontario's landscape with 25 780 ha under fruit production and 62 967 ha under vegetable production (Statistics Canada, 2006). Irrigated agriculture is geographically concentrated in the southwestern part of the province where the unique blend of climate, geography, and soils allow producers to grow a wide variety of high quality fruits such as peaches, grapes, cherries, and berries as well as vegetables such as sweet corn, beans, tomatoes, and peppers. As a matter of fact, 85% of total irrigation water use in Ontario, corresponding to 53 874 irrigated hectares, is found in this area (Statistics Canada, 2006). Table 2.2 displays the relative amount of irrigated hectares by agricultural regions in Ontario.

Table 2.2 Irrigated land by agricultural region in Ontario (Statistics Canada, 2006)

Agricultural Ontario Region	*Irrigated Area*	
	(ha)	*(%)*
Southern	43 491	68.7
Western	10 383	16.4
Central	5 727	9.1
Eastern	3 122	4.9
Northern	588	0.9
Total	***63 311***	***100***

Figure 2.1 indicates the areas in southwestern Ontario of heavy irrigation water use including the Niagara Peninsula, the Norfolk Sand Plain and surrounding area, and the Essex region around Leamington (de Loë et al., 2001; Marshall Macklin Monaghanm et al., 2003). Most of irrigation water (54%) is consumed during summer months yet, at the same time water demand peaks from the other sectors and low flow conditions prevail; thus, very seasonal and localized competition and conflicts over scarce water resources are expected in these regions (de Loë et al., 2001; Environmental Commissioner of Ontario, 2001).

2.3. Climate change issues for water conservation

Persistent concerns for the availability of water for irrigation are augmented by increasing evidence that climatic conditions are changing in Ontario. Climate also affects irrigation needs through the variation of several climatic parameters including precipitation, air temperature, solar radiation, wind speed and relative humidity.

In southern Ontario, the annual average precipitation ranges between 660-1000 mm (Marshall Macklin Monaghanm et al., 2003). More specific to the growing season, precipitation varies between 300-400 mm whereas crop water requirements average 500-600 mm (OMAFRA, 2004). Over the last 80 years, the climate has changed noticeably in the region (Tan and Reynolds, 2003). The precipitation patterns have significantly fluctuated over this period being at present drier by about 225 mm/yr than in the 1980s. As for temperature, an increase of about 1°C was observed for the last 20 years. The rapid increase in growing season water deficit (currently ranging from 80-275 mm), observed during 1990-2000, is also of particular concern since average yields have declined considerably during this period due to water stress. If the current climate pattern continues and crop productivity is to be maintained to its full potential, water allocated to irrigation might increase significantly over the latter half of this century to cope with augmented crop water deficits that are expected to double in some parts of southwestern Ontario. As a result, on-farm irrigation practices will definitely need to adopt water conservation strategies, such as scientific irrigation scheduling to mitigate negative effects on crop productivity.

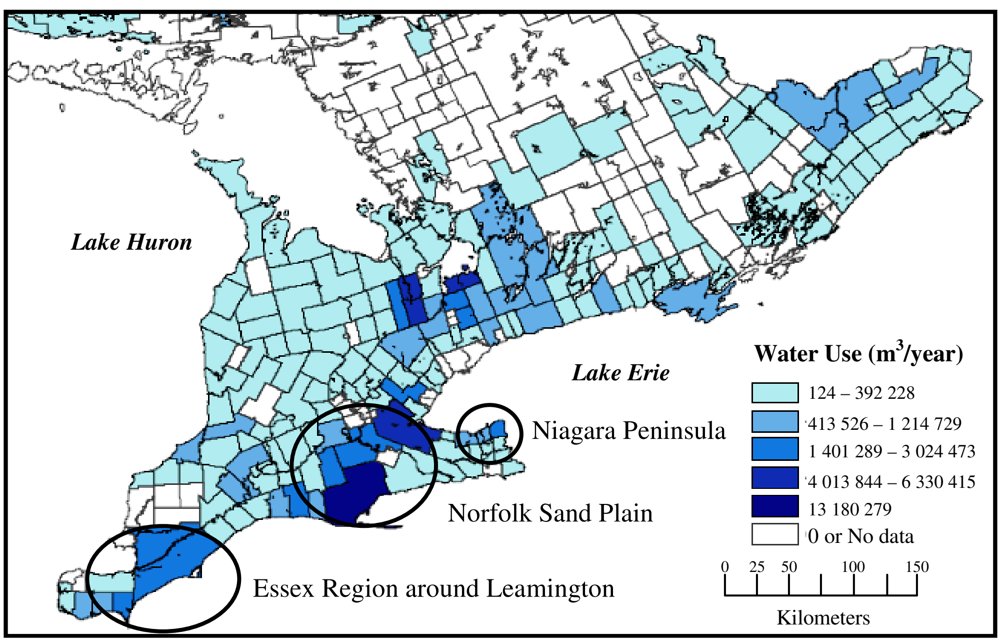


Figure 2.1 Estimated 2001 seasonal irrigation water use in southwestern Ontario de (Loë et al., 2001)

2.4. Irrigation scheduling

Irrigation scheduling is one of the most important tools for developing best irrigation water management practices (Mermoud et al., 2005). Providing plants with a sufficient amount of water at the right time improves irrigation water use efficiency (Cepuder and Nolz, 2007). For the optimization of irrigation management, a sound understanding of soil moisture levels and crop response is a necessary first step.

2.4.1. Available soil water

Water uptake by roots is critical for fruit and vegetable growth. Excessive or insufficient soil water in the root zone is definitely detrimental to crop production. Indeed, when the soil moisture level exceeds the condition known as the “field capacity” (the level of soil water retained after the gravitational water has drained) the soil becomes waterlogged and roots begin to perish due to lack of oxygen (Ley et al., 1994). In contrast, when soil moisture is at or below the “permanent wilting point” (the level at which the roots cannot extract water anymore from the soil because the remaining water is being held too tightly by soil particles), the plants begin to wilt permanently beyond the recovery point. Water that plants can use is known as the available soil water (ASW) and is held in the soil profile between field capacity and permanent wilting point (Figure 2.2) (Werner, 1993). Soil texture (i.e. particle size) and soil structure (i.e. pore spacing and organic matter content) both affect the water storage capacity (Hughes and Evans, 1999). Tables 2.3 and 2.4 clearly show that sandy soils have a poorer capacity to retain water than clay soils. Table 2.5, in which ASW is expressed as a volumetric water content percentage for various textures, also supports this. Well-structured soils with high organic matter content and containing many pores will retain water more effectively. Consequently, it is easier to obtain higher irrigation efficiency on clay soils, which have higher available water-holding capacity (Sammis and Mexal, 1999).

Figure 2.2 Soil moisture profile (Werner, 1993)

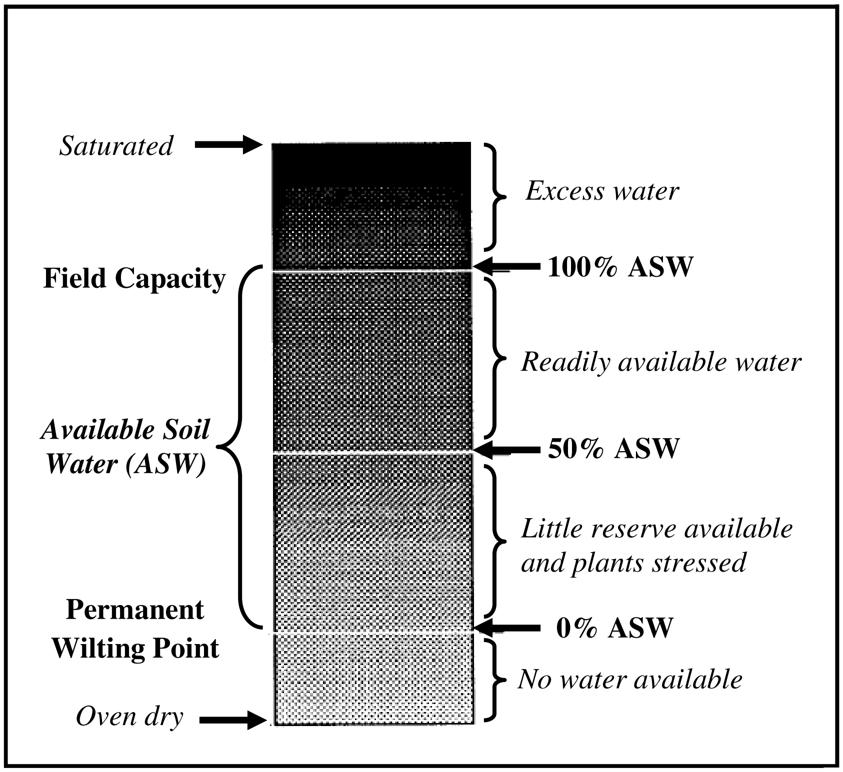


Table 2.3 Available soil water for various soil textures

Soil Texture	*Available Soil Water (mm/cm of soil depth)*									
	Tan (1990)	*Werner (1993)*	*Ley et al. (1994)*	*Nyvall (1998)*	*Nyvall (2002)*	*Dexcel (2006)*	*AgriMet (2007)*	*California University (2007)*	*Leboeuf et al. (2007)*	*Average*
Corse										
Coarse Sand	---	---	---	---	---	---	0.6	---	---	0.6
Sand	---	---	0.4 - 0.7	0.8	0.8	1.5	---	0.7	0.5 - 0.8	0.8
Fine Sand	0.5-0.8	0.6 - 0.8	0.5 - 0.8	---	---	---	0.8	---	---	0.7
Loamy Sand	---	0.8 - 1.3	0.6 - 0.9	0.9	1.0	1.8	---	1.1	0.7 - 1.0	1.0
Gravel/Cobble	---	---	0.5 - 0.7	---	---	---	---	---	---	0.6
Moderately Corse										
Loamy Fine Sand	0.7-1.0	---	0.8 - 1.1	---	---	---	---	---	---	0.9
Sandy Loam	0.9-1.2	1.1 - 1.5	1.0 - 1.3	1.2	1.3	2.3	1.0	1.4	0.9 - 1.2	1.3
Fine Sandy Loam	---	---	1.0 - 1.4	---	1.4	2.2	1.3	---	---	1.5
Medium										
Gravel/Cobble	---	---	0.9 - 1.1	---	---	---	---	---	---	1.0
Very Fine Sandy Loam	---	---	1.3 - 1.8	----	---	---	---	---	---	1.6
Loam	1.3-1.7	1.5 - 2.1	1.3 - 1.9	1.6	1.8	---	1.5	1.8	1.3 - 1.7	1.6
Moderately Fine										
Sandy Clay Loam	---	---	1.4 - 2.0	---	---	---	---	1.3	---	1.4
Silt Loam	1.4-1.7	1.5 - 2.2	1.5 - 2.1	---	2.1	2.2	1.7	1.8	1.4 - 1.7	1.8
Silty Clay Loam	1.5-2.0	---	---	---	---	---	---	1.9	1.5 - 2.0	1.7
Clay Loam	1.5-1.8	1.5 - 2.1	1.5 - 2.1	---	2.0	1.8	1.8	1.6	1.5 - 1.8	1.7
Fine										
Sandy Clay	---	---	1.6 - 2.1	---	---	---	---	1.6	---	1.6
Silty Clay	---	---	1.6 - 2.1	---	---	---	---	2.4	---	1.9
Clay	1.5-1.7	1.5 - 2.0	1.7 - 2.1	---	---	1.8	---	2.2	1.5 - 1.7	1.8
Peats and Mucks										
	---	---	1.7 - 2.5	---	---	2.0 - 2.5	2.0	---	---	2.1

Table 2.4 Field capacity and permanent wilting point values for various soil textures

Soil Textures	*Field Capacity (mm of water / cm of soil depth)*			*Permanent Wilting Point (mm of water / cm of soil depth)*		
	Hanson et al. (2004)	*California University (2007)*	*Average*	*Hanson et al. (2004)*	*California University (2007)*	*Average*
Sand	1.0	1.0	1.0	0.4	0.4	0.4
Loamy Sand	1.4	1.6	1.5	0.6	0.7	0.6
Sandy Loam	1.9	2.1	2.0	0.8	0.9	0.9
Loam	2.7	2.7	2.7	1.2	1.2	1.2
Silt Loam	3.0	3.0	3.0	1.3	1.5	1.4
Sandy Clay Loam	2.5	2.9	2.7	1.5	1.8	1.7
Sandy Clay	2.4	2.8	2.6	1.5	1.5	1.5
Clay Loam	3.2	3.2	3.2	1.9	1.8	1.9
Silty Clay Loam	3.6	3.6	3.6	2.0	2.0	2.0
Silty Clay	4.1	4.0	4.0	2.7	2.0	2.3
Clay	3.9	4.0	4.0	2.6	2.2	2.4

Table 2.5 Volumetric soil moisture content (%) at field capacity, permanent wilting point and available soil water for various soil textures (Hanson et al., 2004)

Soil Texture	*Field Capacity (%)*	*Permanent Wilting Point (%)*	*Available Soil Water (%)*
Sand	10	4	6
Loamy Sand	16	7	9
Sandy Loam	21	9	12
Loam	27	12	15
Silt Loam	30	15	15
Sandy Clay Loam	36	20	16
Sandy Clay	32	18	14
Clay Loam	29	18	11
Silty Clay Loam	28	15	13
Silty Clay	40	20	20
Clay	40	22	18

2.4.2. Management allowable depletion

In the past irrigators used a simple rule-of-thumb: to trigger irrigation when about half of the ASW was depleted (Evans 1996; Hill, 2002). However, recent research has proved this rule to be inadequate for intensively managed high-value crops which are more sensitive to water stress (Home et al, 2002; Kashyap and Panda, 2003). The management allowable depletion (MAD), corresponding to the percentage of ASW which may be safely depleted before yield reducing stress occurs, is now precisely recommended depending of the crop grown, the development stage as well as the irrigation system used (Reddy and Reddy, 1993; Panda et al., 2004). Table 2.6 shows MAD for various crop types.

Table 2.6 Management allowable depletion for various crops

Crop	*MAD (%)*						
	Sanders (1993)	*Ley et al. (1994)*	*Nyvall (2002)*	*Planner (2003)*	*Hanson et al. (2004)*	*AgriMet (2007)*	*Range*
Tomato	50	40-50	40	30-35	40	---	30-50
Bell Pepper	50	---	50	30-35	25	---	30-50
Strawberry	---	50-65	50	---	15	---	50-65
Raspberry	---	50	50	---	---	---	50
Peach	---	50-65	40	50	50	50-65	40-65

The recommended soil moisture depletions are directly related to the crop grown as the rooting depth varies (Sammis and Mexal, 1999). A deep-rooted crop such as peaches will use a greater volume of the soil profile than a shallow-rooted crop such as bell peppers and thus have access to more water in between irrigations (Table 2.7). In the end, the deep-rooted crops will have larger allowable depletions and consequently require less frequent irrigation.

Table 2.7 Published effective rooting depth for several crop types (OMAFRA, 2004)

Crop	*ECRD (cm)*
Tomato	30
Bell Pepper	30
Strawberry	30
Raspberry	60
Peach	60

Plant growth is most sensitive to water stress during the critical growth stages listed in Table 2.8. During these stages, the recommended allowable depletion is smaller since sufficient water has to be available to compensate for the higher crop water use (USDA, 1997). For example, during cell division (30-40 days after bloom) and cell expansion (a few weeks before predicted harvest) peaches should be irrigated when MAD reaches 40-50%, while at other times of the season it can reach 65% before irrigation is triggered (Hanson et al., 2004).

Table 2.8 Critical growth stages for various crops (USDA, 1997; Verhallen and Roddy, 2002; Hanson et al., 2004 and Slingerland, 2005)

Crop	*Critical Growth Stages*
Tomato	Flowering, fruit set & enlargement
Bell Pepper	Flowering, fruit set & enlargement
Strawberry	Fruit development to ripening
Raspberry	Fruit development to ripening
Peach	Flowering, cell division & fruit sizing

The irrigation system used will also influence the MAD. Two primary methods are used in Ontario to apply water to crops: drip irrigation (also known as trickle or micro-irrigation) and sprinkler irrigation (overhead irrigation) including boom, center pivot, lateral move and traveling gun system (OMAFRA, 2004). Drip systems are designed and operated to keep the soil moisture content at a level close to field capacity by irrigating very frequently. As such, they are recommended to have a lower MAD (10-30%). Alternatively, sprinkler irrigation systems are operated to allow soil moisture to reduce to the MAD before replenishing the soil profile to field capacity; consequently these systems are recommended to have a higher MAD (30-50%) (Table 2.9). Finally, climate, which is intimately linked to the crop water use, also has an effect on recommended allowable depletion; some parts of Ontario experience warm and dry growing seasons, in which case MAD should be lower.

Table 2.9 Management allowable depletion for several irrigation systems

Irrigation System	*MAD (%)*				
	Nyvall (2002)	*Nyvall (2005)*	*Bierman (2005)*	*Leboeuf et al. (2007)*	*Range*
Drip, Trickle & Micro-Jet	25	15	10-30	10	10-30
Sprinkler	30	40-50	---	50	30-50

Knowing the factors which affect the ability of the soil to retain water (including soil texture (particle size), soil structure (pore spacing, organic matter content), the rooting depth, the crop type as well as its stage of development) will help growers to better understand how much water is held in the root zone of their soil and how fast the water is being used by the crop; therefore, helping them to make wise irrigation decisions. Overall, by adjusting MAD level, unnecessary irrigation applications can be avoided while increasing yields and conserving water (Upendram and Peterson, 2006).

2.4.3. Irrigation scheduling techniques

Once a basic knowledge of soil moisture levels and crop response is acquired, the next step is to determine when to irrigate and the proper amount of water to apply. Irrigation can be scheduled according to three different techniques: plant monitoring, soil monitoring and water budgeting, as described in the following section.

2.4.3.1. Plant monitoring

Plant monitoring is based on sensing plant responses to soil moisture content, which furthermore is used to indicate soil moisture deficits or over-irrigation (Jones, 2004). Some crucial plant indicators include the leaf temperature (measured using an infrared thermometer), the turgor pressure (turgor pressure sensor), the plant diameter (dendrometer), the flow of water from the soil through the plant (heat pulse sap flow), the water status in plant leaves (pressure bomb) and the stomatal resistance (porometry). Yet, the most obvious and widely used indicator remains the general plant appearance; the retardation of growth stages – foliar growth and fruit development – or visible wilting are excellent indicators of water stress that allow the irrigator to take decisions regarding irrigation (Van der Gulik, 2006). However, these methods are either too crude and subjective, or they call for the use of specialised instrumentation; the major drawback resides in the fact that decisions to irrigate are made after yield-reducing stress has occurred (Singh et al., 1995). It is also relevant to note that irrigation scheduling techniques involving plant measurements give little information on the amount of irrigation water required (Abraha and Savage, 2008).

2.4.3.2. Soil monitoring

Soil monitoring involve determining the current amount of soil water stored in the soil profile, comparing it to the predetermined irrigation trigger, and irrigating to maintain the soil water content to the field capacity. Soil monitoring includes the feel and appearance method and the soil moisture measuring method. The soil moisture measuring method comprises gravimetric and sensor based volumetric soil water content and soil water potential measurements. These indicators are described in the following subsection (Tekinel and Kanber, 2002).

1) Feel and appearance method

The feel and appearance method is a subjective technique commonly used to determine the soil moisture content and schedule irrigation. Cheap and fast, this method consists in taking soil samples with a soil probe, an auger or a core sampler at an appropriate depth relative to the effective crop rooting depth (ECRD) and estimating the soil moisture content by referring to a predetermined guideline (OMAFRA, 2004). Although with practice and diligence this method can become fairly accurate, the development of irrigation scheduling methods that minimize water use – soil moisture monitoring and water budgeting which are more precise and accurate – are gaining importance due to the increasing worldwide shortages of water (Jones, 2004).

2) Soil moisture measuring

By indicating how much soil water is stored in the root zone, soil moisture measuring allows growers to consequently schedule irrigation events when necessary. The two methods to measure soil water are described in the following subsection.

a) Soil water content measurement

The amount of water in the soil, which can be determined by measuring the soil water content, is commonly expressed in two ways as follows:

<u>Gravimetric water content</u>

$$\theta_G = \frac{m_w}{m_s} = \frac{m_{wet} - m_{dry}}{m_{dry}} \qquad \textbf{[2.1]}$$

Where: θ_G = Gravimetric water content [g/g]
m_w = Mass of water [g]
m_s = Mass of soil sample [g]
m_{dry} = Mass of dried soil [g]
m_{wet} = Mass of wet soil [g]

Volumetric water content

$$\theta_v = \frac{V_w}{V_s} = \frac{\frac{m_w}{\rho_w}}{\frac{m_s}{\rho_s}} = \frac{\theta_G \times \rho_s}{\rho_w} \qquad [2.2]$$

Where: θ_v = Volumetric water content[cm^3/cm^3]
V_w = Volume of water in the soil sample [cm^3]
V_s = Volume of soil sample [cm^3]
m_w = Mass of water [g]
m_s = Mass of soil sample [g]
ρ_w = Density of water [g/cm^3]
ρ_s = Soil bulk density [g/cm^3]
θ_G = Gravimetric water content [g/g]

The soil bulk density is calculated with the following formula.

$$\rho_s = \frac{m_s}{V_s} \qquad [2.3]$$

Where: ρ_s = Soil bulk density [g/cm^3]
m_s = Mass of soil sample [g]
V_s = Volume of soil sample [cm^3]

Gravimetric sampling is a direct and absolute method to determine soil water content (Prichard, 2008). The method involves weighing the soil sample, oven drying it (24 hours in the oven at 105˚C) and then reweighing it to determine the mass of water that was contained in the sample when taken (by subtracting the oven-dry weight from the initial field soil weight). Then, by dividing the weight of the water by the oven-dry soil weight, the gravimetric water content (g/g) is obtained.

Although this method is not practical for growers as it is time consuming, labour intensive and does not allow the same site to be monitored over time due to the destructive nature of the measurements, it is commonly used in research to calibrate indirect and non destructive methods which measure soil moisture content on a volume basis (Topp and Davis, 1985; Amer et al., 1994; Nielsen et al., 1995). Indirect methods to measure volumetric soil water content (VWC %) include, time domain reflectometry (TDR), electrical conductivity and capacitance devices.

b) Soil water potential measurement

The second method to determine the amount of water in the soil is to measure the soil water potential, which corresponds to the energy status of the soil water. The total potential in a soil region is actually the sum of gravitational, matric and osmotic potentials as shown below (Campbell, 1988). Note that soil water potentials (suction or tension) are negative pressures commonly measured in kilopascal (kPa).

$$\varphi_t = \varphi_g + \varphi_m + \varphi_o \qquad [2.4]$$

Where: φ_t = Total soil water potential
φ_g = Gravitational potential
φ_m = Matric potential
φ_o = Osmotic Potential

However, since it is the matric potential which generally has the greatest effect on water release from the soil to the plants (Wang et al., 2006; Wang et al., 2007), methods to measure soil water potential - namely tensiometry and electrical resistance blocks - only measure this component and hence provide (arguably) more realistic measures of the actual plant water stress. Table 2.10 shows the tension levels at which irrigation should be triggered.

The major drawback of irrigation scheduling based on soil moisture sensors is that it is limited by the spatial variability of soil water content and the small volume of soil being monitored (Wheaton and Parsons, 2006). This is why, water budgeting which requires only local daily rainfall and ET_o data is a common technique used to complement soil monitoring.

2.4.3.3. Water budgeting

In addition of soil water monitoring, irrigation scheduling is conventionally based on the water budget method (Azhar et al., 1992; Howell, 1996; Allen et al., 1998; Burt et al., 2005; Zhang et al., 2007). Relying on estimated daily crop water use derived from local weather data including air temperature, solar radiation, wind speed and relative humidity, water budgeting, although not very accurate, is adequately applicable over a variety of conditions (Jones, 2004). The principle behind it is straightforward; it relies on keeping track of water additions (i.e. effective precipitation and irrigation water applications) and losses (i.e. crop water use and deep percolation) in the root zone to know exactly how much soil water is stored in the root zone and thus being able to determine with accuracy when irrigation should be triggered before yield-reducing stress occurs (Figure 2.3).

To estimate the rate of evapotranspiration of a specific crop (ET_c) - a measure of the crop water use - the reference evapotranspiration (ET_o) must be calculated. ET_o is defined by Brouwer and Heibloem (1986) as being the rate of evapotranspiration from a large area covered by green grass, 8 to 15 cm tall, grows actively and completely shades the ground, and which is not short of water. During the last fifty years a large number of empirical methods have been developed and used to estimate ET_o including temperature based methods (Thornthwaite, Hamon, Hargreaves-Samini) and radiation based methods (Turc, Priestley-Taylor, Makkink). Their performance is highly variable and depends directly on the climate data quality and availability (Jabloun and Sahli, 2008). ET_c can also be determined by using a Class 'A' evaporation pan or an atmometer which measures evaporation that can be converted to crop water use data by applying a pan crop coefficient (Hess, 1996; Ertek, 2006). However, these methods are very sensitive to the microclimatic conditions under which the pans are operating and the rigour of station maintenance; their performance was generally proved erratic (Allen et al., 1998). As such, if all the required climatic parameters are available - air temperature, relative humidity, wind speed and solar radiation - the Food and Agriculture Organization Penman-Monteith (FAO56-PM) method is universally recommended to calculate ET_c (Allen et al., 1998; Irmak et al., 2003; Irmak et al., 2003; Zhao et al., 2004; Bois et al., 2005).

To determine ET_c, the influence of crop type and growth stage on the calculated ET_o must be considered by applying the proper crop coefficient (K_c) (Howell, 1996; Norman et al., 1998; Burt et al., 2005). In addition, the influence of a greenhouse on ET_c has to be considered. It appears that the requirements are lower in a greenhouse than in the open fields because the micro climate inside the greenhouses has a high relative humidity and less direct sunlight exposure. As well the plants in the greenhouse are less subject to evapotranspiration (ET) losses from wind. The difference of ET would generally be around 70% of that verified outside (Monterro et al., 1985; Rosenberg et al., 1989; Fernandes et al., 2003; Harmanto et al., 2005).

Table 2.10 Tension at which irrigation should be triggered

Reference	*Irrigation System*	*Soil Type*	*Crop Type*	*Irrigation Trigger (kPa)*
Thompson et al. (2007)	---	---	Bell Pepper	58
			Tomato	42-59
Bierman (2005)	---	Most Soils	---	25-30
Nyvall (2005)	Drip	Sand	---	10-15
		Loamy Sand		10-15
		Sandy Loam		15-20
		Loam		25-30
	Sprinkler	Sand	---	20
		Loamy Sand		25
		Sandy Loam		30
		Loam		35
Hanson et al. (2004)	---	---	Peach	50-80
			Strawberry	20-30
			Tomato	60-150
Thomson and Ross (1996)	---	Medium Textured	---	45-70
		Sandy		20-35

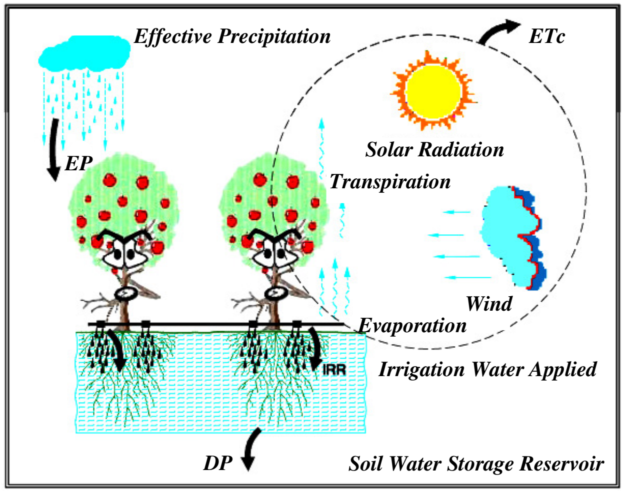


Figure 2.3 Schematic of a water budget (Van der Gulik, 2004)

2.5. Irrigation performance assessment

Increasing water use efficiency is an important tool for the irrigated agriculture sector to address the constraints of current and future disparity between supply and demand for water. To accomplish this task, assessing irrigation performance is a crucial beginning.

Irrigation performance is generally measured through indicators which express a target and an actual value in the form of a ratio (Bos et al., 1994). This enables the user to quickly assess the amount of deviation from a standard and finally to determine whether or not the deviation is acceptable. According to the irrigation system assessment guide of British Columbia, if the deviation exceeds 10% the irrigation system should be reviewed (Nyvall and Tam, 2005). One of the indicators related to water use efficiency that describes performance with respect to the objectives established by this project is the field application efficiency (Bos et al., 1994; Bos et al., 2005; Burt et al., 2005; Skewes et al., 2007). This indicator, defined as the ratio of the amount of irrigation water needed by the plants to the amount of water applied to the field, appears to be the most appropriate for determining if there is over-or under-irrigation (Bos et al., 1994; Stevens, 2007).

$$Field\ Application\ Efficiency = \frac{Crop\ Irrigation\ Water\ Requirement}{Water\ Delivery\ to\ Field} \qquad [\mathbf{2.1}]$$

The amount of water delivered to the field can be calculated according to four different methods: using irrigation system and field information (irrigation system flow rate, number of system operating hours, size of the irrigated zone, etc.), flow meter readings, irrigators' personal water use estimates, or a soil water balance equation (Gardner et al., 1999).

Limitations of the field application efficiency indicator however, primarily reside in the estimation of the amount of water delivered to the field (Skewes et al., 2007). Determining exactly how much water was applied can be complex and inaccurate. Although flow meters can rectify this by providing reliable information, failures to record commonly occur. Data reliability is therefore a major limitation which can have a tremendous effect on irrigation water use calculations. Collected data about the irrigation system, size of the irrigated zone or irrigator's personal water use estimate cannot be verified for each property.

For quantifying the volume of irrigation water required by the crops, a water budget method is commonly used (Fairweather et al., 2003). The elements needed to perform the water budget as well as the soil water balance calculations (crop evapotranspiration, effective precipitation, deep percolation) depend strongly on the spatial extent of the area under study (single field or large irrigation region) and the timeframe (single irrigation application or full irrigation season) over which the performance is assessed. Thus, a clear definition of these two parameters is required (Purcell and Currey, 2003). Indeed, the dimensions over which the performance is reviewed can considerably influence the results; seasonal performance indices often mask individual events.

The aforementioned limitations of this method illustrate why this indicator can only analyse gross irrigation performance and show the sites where excessive over (or under) irrigation take place (Skewes at al., 2007). After detecting excessive water applications, further checks should therefore be performed before concluding that improved irrigation water management through SIS can achieve water savings. This can be done by comparing irrigation water requirements obtained through water budget calculations with soil moisture measurements taken over the course of the growing season.

CHAPTER 3 – MATERIALS AND METHODS

3.1. Overview

In total, 15 field sites were selected within four counties in southern Ontario: Essex, Chatham-Kent, Norfolk-Haldimand and Niagara (Figure 3.1). These counties were chosen based on two criteria: intense areas of irrigated vegetable and fruit production and lack of water constraining irrigation.

Several soil moisture monitoring devices were installed permanently at one site within each county which served as the *hub site*. Soil moisture was additionally measured in situ twice a week by gravimetric sampling and using a portable TDR (FieldScout 300). *Satellite sites* situated in relative proximity to hub sites were set up differently; soil moisture was only measured twice a week by gravimetric sampling and with the portable TDR device. Overall, soil moisture was monitored and measured in nineteen zones; some field sites (1, 2 and 8) had more than one irrigated zone with specificities in terms of irrigation system type, production system (open field, plastic mulch or high tunnel), soil texture or crop grown. Field site summaries reporting information about the size of the irrigated zones, the number of plant rows, the plant row length, the plant spacing length and width, the planting and harvesting dates as well as the crop, soil and irrigation system type are presented in Table 3.1. Figure 3.2 provides a regional map for each county indicating the location of the field sites; hub sites are denoted by an asterisk. Table 3.2 displays the eight devices that were used as part of the broader study to monitor and measure soil moisture over the course of the 2007 growing season. Not all the data sets provided by the sensors were used in the present study as only those indicated by an asterisk were used.

A comprehensive discussion for each study area emphasizing soil, crop and irrigation system types, current irrigation scheduling practices as well as irrigation water constraints is presented in the following section to complement Table 3.1. The portrayal of the aforementioned counties will first be depicted followed by summary descriptions of the hub sites. Due to data availability and quality constraints, the on-farm irrigation performance assessment could only be executed for the hub sites, which explains why the subsection focuses on their specifications.

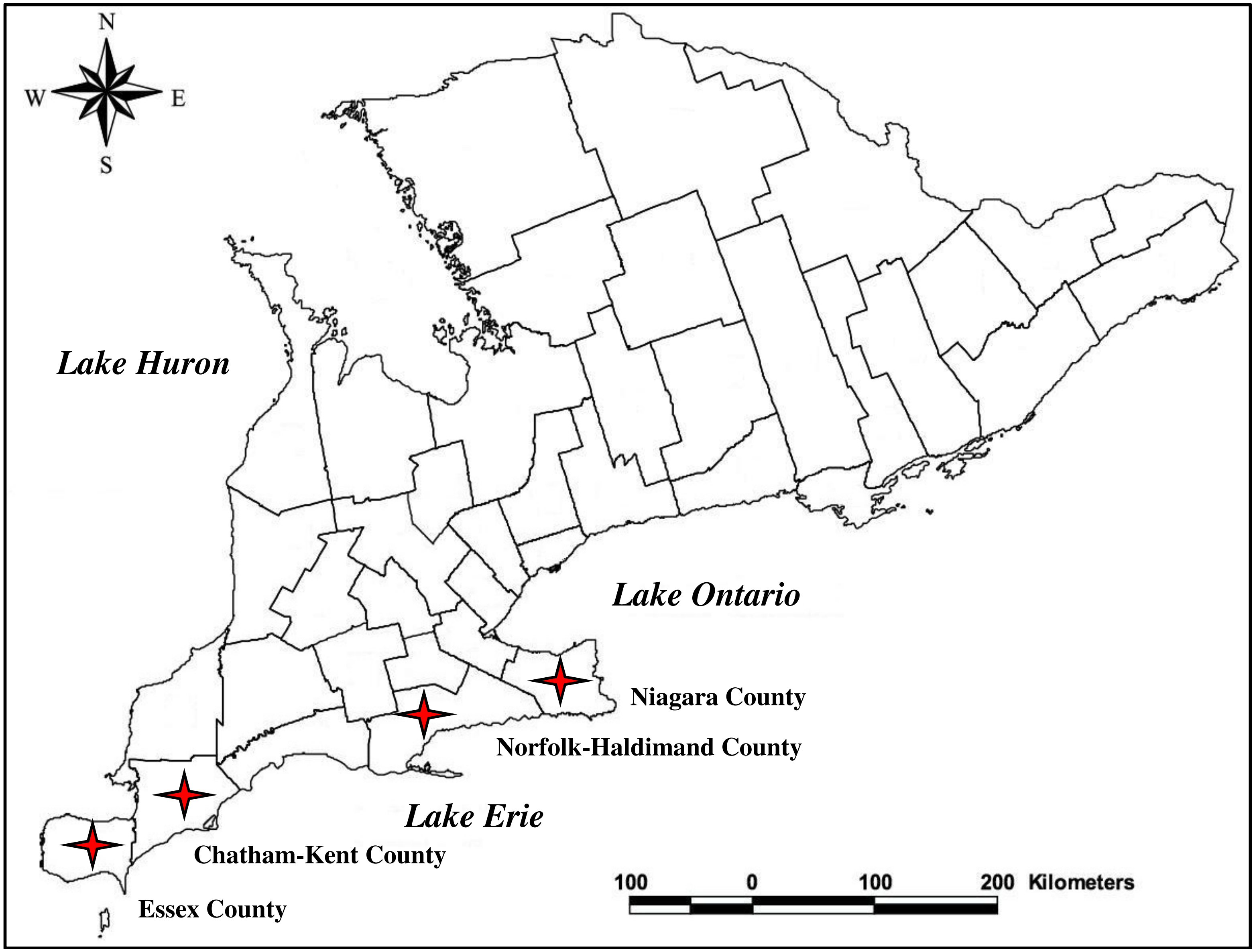


Figure 3.1 Map of the four counties in southern Ontario where field sites were selected

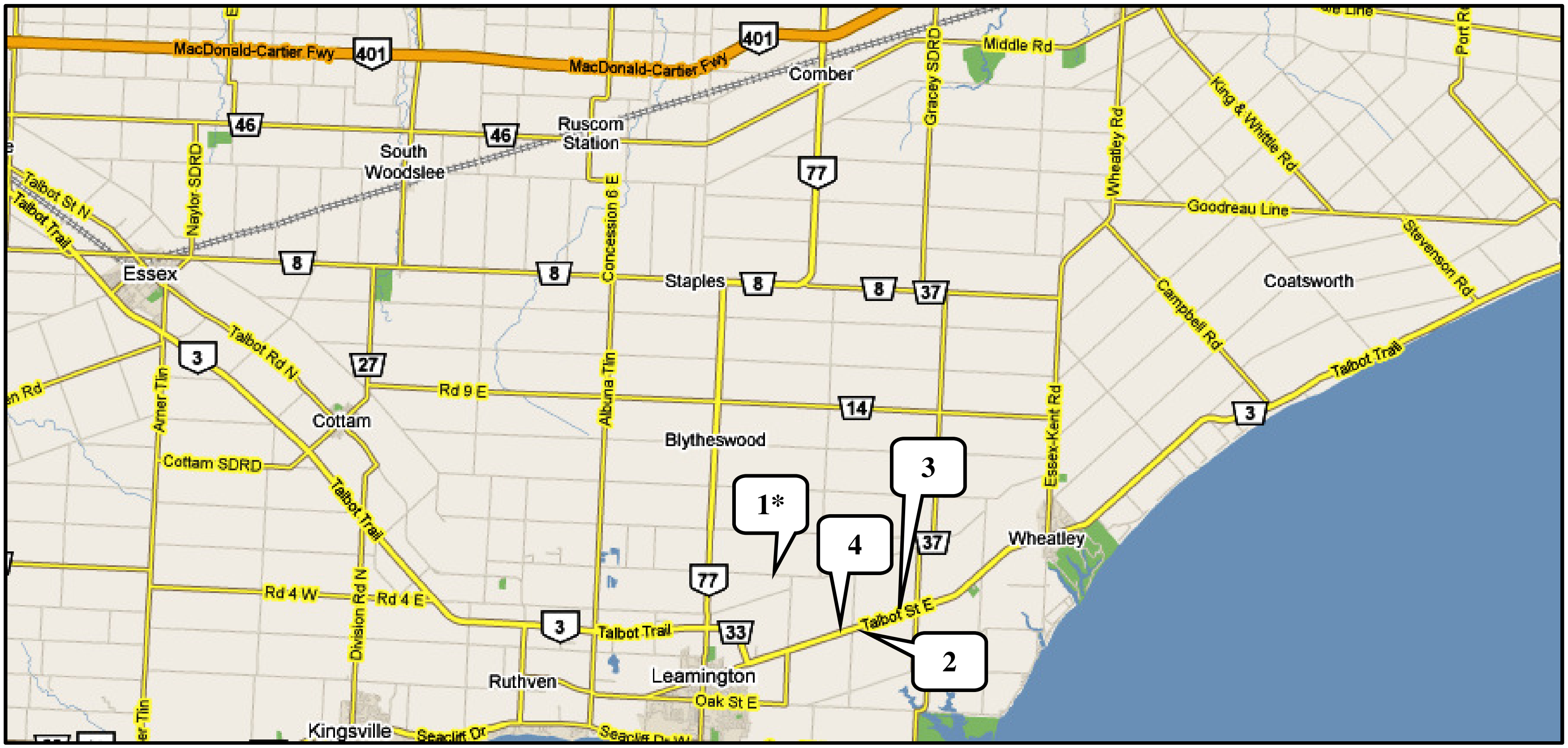
Table 3.1 Field site description summary

County	*Site*	*Zone*	*Crop Type*	*Planting / Harvesting (First & Last Day)*	*Soil Texture*	*Irrigation & Production System Type*	*Irrigated Area (ha)*	*No. of Plant Rows*	*Plant Row Length (m)*	*Plant Spacing*	
										Length (m)	*Width (m)*
Essex	1*	1	Tomato	May 23rd / Sept. 20th	Sand	Surface Drip	1.2	30	335.3	0.4	0.4
		2		May 23rd / Sept. 20th	Sand	Subsurface Drip	1.2	30	335.3	0.4	0.4
	2	3		May 15th / Aug. 31st	Sandy Loam	Surface Drip	8.1	124	365.8	0.4	0.4
		4		June 14th / Sept. 18th	Sand	Surface Drip	9.7	136	396.2	0.4	0.4
	3	5		May 19th / Sept. 19th	Sand	Surface Drip	5.3	121	265.5	0.4	0.5
	4	6		May 25th / Sept. 15th	Sand	Subsurface Drip	3.2	66	335.3	0.4	0.8
Chatham-Kent	5*	7	Bell Pepper	May 21st / Oct. 9th	Loamy Sand	Subsurface Drip	7.7	180	548.6	0.4	0.5
	6	8		May 29th / July 31st	Loam	Subsurface Drip / Plastic Mulch	0.4	13	243.8	0.4	0.3
	7	9		May 29th / Aug. 31st	Loamy Sand	Traveler Boom	4.1	52	975.4	0.4	0.8
Norfolk-Haldimand	8*	10	Strawberry	April 10th / Nov. 5th	Sandy Loam	Surface Drip / Plastic Mulch	0.9	80	213.4	0.3	0.3
		11		April 10th / Nov. 5th	Sandy Loam	Surface Drip / Plastic Mulch, High Tunnel	0.9	80	213.4	0.3	0.3
		12	Raspberry	May 15th / Oct. 21st	Sandy Loam	Surface Drip / Plastic Mulch, High Tunnel	1.5	52	137.2	2.1	0.5
	9	13	Strawberry	May 28th / July 20th	Loam	Solid Set	1.8	78	219.5	0.5	1.2
	10	14		May 1st / June 30th	Loamy Sand	Solid Set	1.2	70	167.6	0.4	1.2
Niagara	11*	15	Peach	April 1st / Aug. 1st	Loamy Sand	Overhead Gun	2.4	27	152.4	5.5	3.1
	12	16		April 1st / Sept. 18th	Sandy Loam	Below Canopy Sprinkler	1.0	80	170.7	3.1	5.8
	13	17		April 1st / July 18th	Sandy Loam	Solid Set	1.2	9	201.2	3.7	6.1
	14	18		April 1st / Sept. 18th	Loamy Sand	Below Canopy Sprinkler	0.4	4	121.9	3.1	5.5
	15	19		April 1st / Sept. 18th	Sandy Loam	Overhead Gun	4.1	17	243.8	4.9	2.1

* Indicates the hub sites.

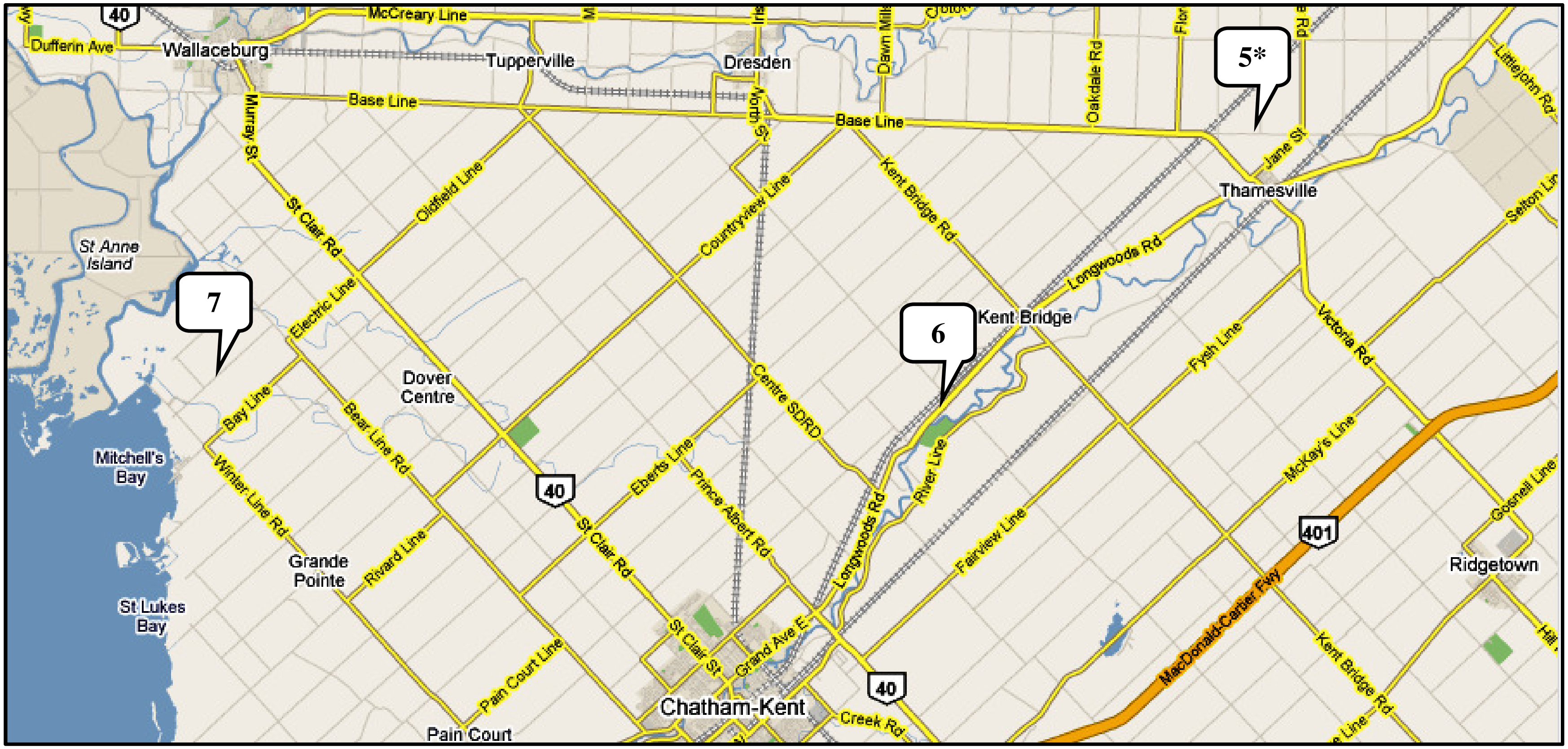
Figure 3.2 Location of the field sites (a) Essex County – Tomato Crop; (b) Chatham-Kent County – Bell Pepper Crop; (c) Norfolk-Haldimand County – Strawberry Crop; (d) Niagara County – Peach Crop

(a) Essex County – Tomato Crop



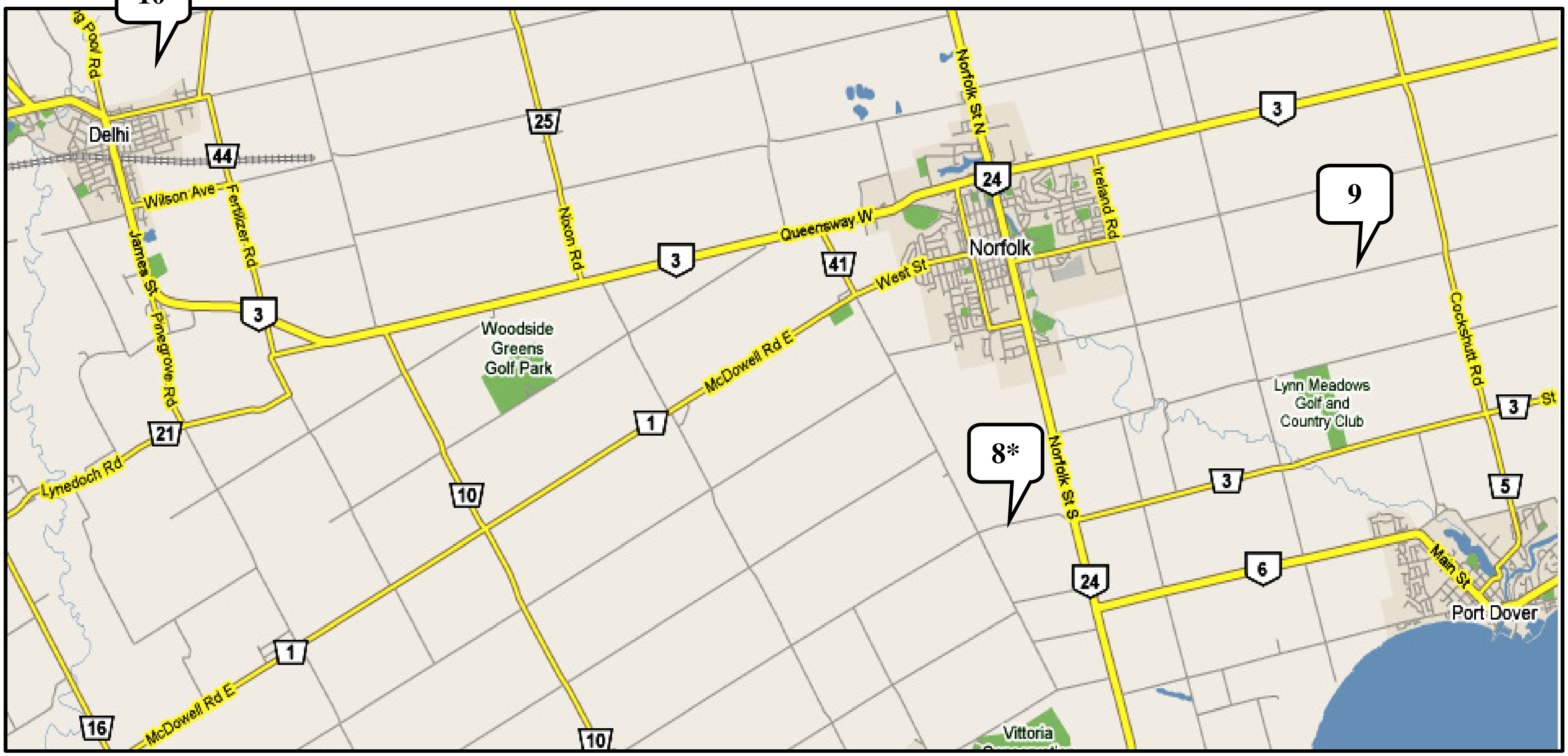
* Indicates the hub site.

(b) Chatham-Kent County – Bell Pepper Crop



* Indicates the hub site.

(c) Norfolk-Haldimand County – Strawberry Crop

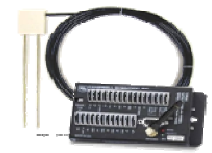


* Indicates the hub site.

(d) Niagara County – Peach Crop

* Indicates the hub site.

Table 3.2 Soil moisture monitoring devices

Output	*Soil Moisture Monitoring Devices*		
	Portable TDR (FieldScout 300)	TDR Sensor (Gro-Point)	Water Content Reflectometer (Campbell C5625) *
Soil Water Content (VWC %)			
	Manual Tensiometer (Irrometer)	Hortau Wireless Tensiometer (Hortimeter-T)	Electrical Resistance Blocks (Watermark)
Soil Water Potential (cbars)			
	Echo-Probe (EC-20 Decagon)	Capacitance Probe (AquaSpy) *	
Soil Water Trend (Volumetric Based)			

* Indicates sensors that provided data used in the present study.

3.2. Study areas

3.2.1. Essex and Chatham-Kent Counties

Essex and Chatham-Kent counties constitute the largest conglomeration of growers dedicated to irrigated vegetable production in Ontario (de Loë et al., 2001). Tomatoes, the main water use crop in the region, are the number one field vegetable in farm value and where 77% of the Canadian tomato crop is produced (Statistics Canada, 2006). The region benefits from a longer growing season than other Ontario regions having rich, relatively light soils and stable soil moisture patterns which are all desirable traits for tomato production. Yet, irrigation activities (mostly performed using a boom cart or a drip irrigation system) are constrained by water availability (UMA Engineering, 2007). Most producers who rely on surface water withdrawn from creeks and rivers passing through their property started to express their concerns in 2007 about this water scarcity. As a solution, the LADIA project proposed an incremental water supply to the irrigators through a water diversion from Lake Erie. Although this project would considerably reduce the current strain on limited water resources by providing an alternative source, it is important to ensure that the irrigators use water resources in the most effective way possible. As such, efficient water use needs to be implemented as part of a routine strategy. Table 3.3 summarizes the information about the growers' source and constraints on irrigation water as well as concerns regarding future water shortages.

At the Essex hub site, processing tomatoes were grown in sandy soil in two separated zones: one irrigated with a surface drip irrigation system and the other with a subsurface drip system buried at a depth of 20 cm below the soil surface. To obtain irrigation water, the producer fills a clay lined pond with water taken from both municipal water and drainage water from a creek. His reservoir which has a capacity of approximately 57 000 m^3 doesn't provide sufficient water to irrigate for the full growing season; he must stretch his water supply by cautiously managing irrigation to ensure his tomatoes will not suffer from yield-reducing stress. As shown in Appendix C, the producer who irrigates almost every day heavily relies on irrigation to produce tomatoes. This information is based on their estimated daily values (growers' personal irrigation records taken from their log books) except for three farms where flow meters were installed (these are indicated as such in Appendix C) which may be more accurate.

Table 3.3 Water constraints on irrigation (based on first survey growers' responses)

County	*Site*	*Irrigation Water Source*	*Reservoir Capacity (m^3)*	*Constraints*	*Anticipated Water Shortages*
Essex	1*	Reservoir/Clay Lined Pond (Municipal Drain & Creek)	57 000	Reservoir too small	Yes, LADIA as a solution
	2	Reservoir (Wilkinson/Shilson Prain Creek)	26 000	Reservoir too small	Yes, more frequent and intense dry years
	3	Reservoir (Lebo Creek)	49 000	No	No
	4	Reservoir (Pelee Drain & Hillman Creek)	28 000	Reservoir too small	Yes, he already runned the pond dry in 2004
Chatham-Kent	5*	Reservoir (Bear Creek)	9 000	Reservoir too small	Yes, adopted drip as a solution
	6	Tam River	NA	No	No
	7	Snye River	NA	No	No
Norfolk-Haldimand	8*	Reservoir (Well)	Unknown	No	No
	9	Lynn River	NA	No	No
	10	Dugout Pond	34 000	No	No
Niagara	11*	Reservoir (Municipal Drainage System)	3 785	No	No
	12	Municipal Drainage System	NA	During peak use	No, municipality will adjust & provide more
	13	Municipal Drainage System	NA	During peak use	No, municipality will adjust & provide more
	14	Municipal Drainage System	NA	During dry year	Yes, based on experienced previous years
	15	Municipal Drainage System	NA	During peak use	No, municipality will adjust & provide more

* Indicates the hub sites.

In Chatham Kent, the crop grown at the hub site was bell peppers and the soil type was loamy sand. The producer, who takes water from the Bear Creek to fill his inadequate reservoir having a capacity of 9 000 m^3, is particularly concerned by his limited water supply (Table 3.3). As such, he chooses the most appropriate irrigation system type – a subsurface drip irrigation system or a traveling overhead gun – depending on how dry the growing season is expected to be; in 2007 drip tape was installed. As shown in Annex C, irrigation was performed only four times during the growing season; the occurrence of significantly frequent rainfall events may explain why.

3.2.2. Norfolk-Haldimand County

The Norfolk-Haldimand County is another pocket of extensive cash cropping including tobacco (the largest water using crop in the area), berries, apples and a large array of market vegetables and canning crops (OMAFRA and University of Guelph, 2005). Agricultural activities take place in the Norfolk Sand Plain where the underlying geology, consisting of glaciolacustrine well-drained sands, forms an important local aquifer with a significant amount of natural recharge. There is also low runoff potential in the area (Wong and Bellamy, 2005). This ground water source, which is easily accessible, is highly vulnerable as it provides most of its water to municipalities, residential, livestock and crop irrigation (65%). Again, better on-farm water management practices could help reduce the vulnerability of this central water supply.

At the hub site in the Norfolk-Haldimand County, strawberries planted in sandy loam soil in 2006 were grown in raised beds covered with plastic mulches in two separated zones: one in a high tunnel and the other in the open field. Both production systems were irrigated with a surface drip system every two to three days (Appendix C). Water used to irrigate was provided from a well and stored in a pond of unknown capacity.

3.2.3. Niagara County

The Niagara Peninsula is unique in its climate from the rest of the region. It has a slightly unique climate due to two natural boundaries: Lake Ontario and the Niagara Escarpment. These features are important in moderating temperature fluctuations; winter temperatures rarely going below -18°C and summer temperatures are seldom greater than 30°C (Gardner et al., 2006). The annual average precipitation is also influenced by the landscape; higher levels are typical of the region (Marshall Macklin Monaghanm et al., 2003). Producers benefit from this favourable microclimate to grow peaches as peaches are temperature sensitive and the most water-intensive crop grown in the area; 66% of irrigation water withdrawn in the region is actually dedicated to peach production (de Loë et al., 2001). The region also profits from well-drained sands and gravel type soils that are suitable for tender fruit production (OMAFRA, 2006).

Almost entirely surrounded by water, Niagara County is also in an enviable position in terms of availability of water resources as there are various reliable irrigation supply sources providing water to the tender fruit and grape industry (Stantec et al., 2005). Although there are significant suitable areas (60%) for the expansion of high value crop production in the region, difficulties in accessing irrigation water may prevent its growth. Currently, irrigation water (13 Mm^3) is mainly provided to growers through the municipal drainage system which occasionally fails to satisfy demand. Yet, irrigation scheduling practices of most producers are executed by a simple "rule of thumb" by which 38-51 mm of water are applied whenever periods without rain extend beyond two consecutive weeks (from early July to mid-September). It therefore appears imperative to revisit these irrigation scheduling practices and move towards more scientifically based methods that will cope with the increasing water demands driven by industry expansion.

At the hub site, the peach orchards were planted in 2002. The soil analysis revealed that the soil type was sand. As shown in Annex C, peaches which were irrigated with an overhead gun were receiving only three water applications during the growing season corresponding to critical growth stages: flowering, cell division and fruit sizing. Water taken from the municipal drain was stored in a pond which had a capacity of 3 785 m^3 (Table 3.3). Although during peak water use this grower does not have enough water to irrigate, he does not feel pressured by upcoming water shortages; he believes that the municipality will adjust to future farmers' water demands and provide more water when needed.

3.3. Data collection

3.3.1. Interview processes

The first survey on irrigation water use was administered to the fifteen growers in July 2007 to obtain baseline information on current irrigation scheduling practices and perceived irrigation water needs[1]. Since the producers were particularly busy during this period of the growing season, the questionnaire was filled out very rapidly in the field with a few exceptions, which were filled out in a grower's residence. The information collected was used to determine whether crop water requirements were being met efficiently while preventing water losses. In addition, the interview process was aimed at gathering information on the extent of guess work currently involved in soil water management.

The type of information collected in the survey was related to the irrigated acreage (crop and soil types; size of irrigated area; number of rows; row length and width; plant spacing; planting and harvesting dates), the irrigation system (system type and brand; number of emitters or sprinklers; emitter and drip line spacing; emitter or nozzle and system flow rate; system pressure; pump brand, model number, flow rate, rpm, impellor size and horsepower), the irrigation scheduling (daily system operating time and amount of water applied), irrigation water (source; reservoir capacity; constraints; anticipation of water shortages), projected expansion of irrigated acreage (size and extra amount of irrigation water required) as well as the cost (capital, maintenance, labour and energy).

In October 2008, once harvesting was completed, a second survey[2] was administered to the growers on usefulness of the soil moisture monitoring sensors that were used in order to collect information addressing the following specific objectives of the project:

i. Determine producers' satisfaction with soil moisture monitoring information.
ii. Find out which devices producers have decided to adopt for future years, if any.
iii. Establish producers' needs regarding irrigation scheduling.

The soil moisture monitoring information include soil moisture data provided to the growers during the growing season through the sensors, face to face meetings with the growers, the handouts distributed during field days and the meeting at the end of the project where the complete data set were presented to the individual growers.

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[1] A copy of the questionnaire given to the growers can be found in Appendix A. The names of the participants have been removed to preserve confidentiality.
[2] A copy of the questionnaire can be found in Appendix B.

3.3.2. Field data collection

Flow meters were installed at three hub sites (Essex, Chatham-Kent and Norfolk-Haldimand) to record the quantity of irrigation water used. They provided more accurate information than the estimated usage provided by the growers via the first survey which was derived from estimations of their irrigation system output capacity.

At each hub site, six soil moisture sensors were installed at the beginning of the growing season. Soil water content was measured continuously over the course of the growing season until harvesting was completed. Soil moisture measurements were also taken with a portable TDR and by gravimetric sampling twice a week at each site. Samples were taken from 0-10 cm and 10-30 cm in the soil profile and were analyzed in the laboratory at the University of Guelph to obtain base-line soil moisture data. The soil moisture measurements were used to determine how much water could be saved or spent by reinforcing the growers' current irrigation scheduling practices. As stated previously, for the purpose of the present study, only soil moisture measurements taken by gravimetric sampling and with the C-probe and the water content reflectometer (WCR) sensors were used.

Soil data were also collected at each site in the beginning of the growing season to determine in laboratory the bulk density, particle size and water retention characteristics (field capacity and permanent wilting point). Samples were taken from 0-5 cm depth at all the sites and additionally at 20-25 cm depth at the hub sites.

In addition, meteorological variables (air temperature, relative humidity, wind speed and rainfall) were collected during the growing season from automated weather stations at each hub site; the data were used to calculate a water budget for these sites.

3.4. Assessing on-farm irrigation performance

Irrigation systems need to be designed and operated efficiently to meet crop water requirements yet at the same time prevent water losses. Assessing irrigation performance is crucial in detecting over- or under-irrigation practices and thus determining how implementing scientific irrigation scheduling may help achieve water savings. This can be done by comparing irrigation water requirements obtained from water budget calculations with growers' estimate of water consumption.

3.4.1. Irrigation water requirements

To calculate irrigation water requirements, water budgeting was used. Once the soil moisture content in the profile has been brought to the field capacity level, which is to say generally two days after a saturating rainfall event or irrigation, the daily budget calculations can begin with the following equation:

$$CSWC = PSWC - ET_c + EP - DP + IRR \qquad [3.1]$$

Where:
CSWC = Current soil water content[mm]
PSWC = Previous soil water storage[mm]
ET_c = Crop evapotranspiration or crop water use[mm]
EP = Effective precipitation[mm]
DP = Deep percolation[mm]
IRR = Irrigation water applied[mm]

The maximum amount of soil water stored in the root zone (MSWS) once the soil profile is brought to field capacity must be determined previous to tracking water additions and losses.

$$MSWS = \frac{FC_v \times ECRD}{100} \qquad [3.2]$$

Where:
MSWS = Maximum soil water storage [mm]
FC_v = Volumetric field capacity [%]
ECRD = Effective crop rooting depth [mm]

To determine what the volumetric field capacity (FC_v) is there are two possibilities: one is to refer to theoretical values which are specific to soil textures (Table 2.5) while the other is to perform laboratory analyses by using a pressure plate apparatus (33 kPa). In the present study, field capacity was determined in the laboratory for accuracy.

$$FC_v = FC_w \times \frac{\rho_s}{\rho_w} \times 100 \qquad [3.3]$$

$$FC_w = \frac{M_w}{M_s} \times 100 \qquad [3.4]$$

Where:
FC_v = Volumetric field capacity [%]
FC_w = Gravimetric field capacity [g water/g soil]
ρ_s = Bulk density of soil [g soil/cm^3 soil]
ρ_w = Density of water [g water/cm^3 water]
FC_w = Gravimetric field capacity [%]
M_w = Mass of water [g]
M_s = Oven dried mass of soil [g]

As the required weather data (air temperature, relative humidity, wind speed and rainfall) were collected at the hub sites from weather stations, the FAO 56-PM method was used to calculate daily ET_o according the procedure established by Allen et al. (1998):

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T + 273}\,u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \qquad [3.5]$$

Where:
ET_o = Reference evapotranspiration [mm/day]
Δ = Slope vapour pressure [kPa/°C]
R_n = Net radiation at the crop surface [MJ/m^2/day]
G = Soil heat flux density [MJ/m^2/day]
γ = Psychometric constant [kPa/°C]
u_2 = wind speed at 2 meter height [m/s]
e_s = Saturation vapour pressure [kPa]
e_a = Actual vapour pressure [kPa]
$e_s - e_a$ = Saturation vapour pressure deficit [kPa]
T = Mean daily air temperature[°C]

A crop coefficient (K_c) specific to southern Ontario was applied on the calculated ET_o for tomato, bell pepper and peach to determine crop water use at particular stages of growth. Strawberry and raspberry ET_c were determined using a crop coefficient specific to the Okanagan Valley in British Columbia where berry production is executed under similar climatic conditions. Table 3.4 displays the crop coefficients used. The growth stages of strawberry and raspberry are defined in Table 3.5.

$$ET_c = ET_o \times K_c \qquad [3.6]$$

Where:
ET_c = Crop evapotranspiration or crop water use [mm]
ET_o = Reference evapotranspiration [mm]
K_c = Crop coefficient

At the hub site in Norfolk-Haldimand County, the influence of the high tunnel on the strawberry water requirements (zone 11) also had to be considered; the difference of ET inside the tunnel was estimated to be lower by 30% than what was calculated for an open field (Monterro et al., 1985; Rosenberg et al., 1989; Fernandes et al., 2003; Harmanto et al., 2005).

Thereafter, effective precipitation (EP) was determined. It is defined as rainfall higher than five millimetres which does not evaporate entirely before infiltrating the soil and thus adds moisture to the soil profile. EP may be determined as follows (Nyvall and Tam, 2005):

$$EP = (R - 5) \times 0.75 \qquad [3.7]$$

Where:
EP = Effective Precipitation [mm]
R = Rainfall [mm]

With the above method, it is suggested to multiply the remaining precipitation (R – 5) by a factor of 0.75 to account for runoff and deep percolation losses. This efficiency factor is also comparable to the one determined by Pitblado et al. (2007) who performed a similar study in Niagara-on-the-Lake; the averaged efficiency for the different soil types in this study was 79%.

Table 3.4 Crop coefficients (Van der Gulik, 2001 and OMAFRA, 2004)

Crop Type	***Growth Stage***	K_c	***Growing Season Dates*** *(Hub Sites' Information)*
Tomato	From seeding to 1st flower	0.4	May 23rd / July 14th
	From 1st flower to maximum row fill	0.7	July 15th / July 31st
	Remainder of crop	1.0	Aug. 1st / Sept. 16th
Bell Pepper	From seeding to 1st flower	0.4	May 21st / May 31st
	From 1st flower to maximum row fill	0.7	July 1st / July 19th
	Remainder of crop	1.0	July 20th / Oct. 23rd
Strawberry	Initial	0.4	April 10th / May 14th
	Mid-season	1.05	May 15th / May 19th
	Late-season	0.7	May 20th / Oct. 31st
Raspberry	Initial	0.4	May 15th / June 19th
	Mid-season	1.2	June 20th / July 9th
	Late-season	0.75	July 10th / Oct. 21st
Peach	May	0.3	May 1st / Aug. 12th
	June (1-15)	0.4	
	June (16-30)	0.6	
	July	1.0	
	August	1.0	

Table 3.5 Strawberry and raspberry growth stages and associated indicators (Van der Gulik, 2001)

Growth Stage	***Indicator***
Initial	Planting date (or start of new leaves to 10% ground cover for perennials)
Mid-season	Effective full cover to maturity (leave drop and yellowing; browning of fruits)
Late-season	Maturity to harvest

For the deep percolation component, defined as water lost beyond the root zone, it is generally assumed to be zero if good irrigation practices are followed. However, in order to validate this assumption, soil moisture measurement data taken with the C-Probe sensor – the only sensor that was measuring deep enough – were used to look at the soil moisture content below the effective rooting depth to make sure that MSWS was never exceeded during the 2007 growing season at each of the hub sites.

Once crop water requirements, effective precipitation and deep percolation were obtained, the next step was to determine the maximum soil water deficit (MSWD): the amount of soil moisture that can be safely depleted before triggering irrigation. Table 3.6 shows the MAD values that were applied.

$$MSWD = \frac{MSWS \times MAD}{100} \quad \mathbf{[3.8]}$$

Where: MSWD = Maximum soil water deficit [mm]
MSWS = Maximum soil water storage [mm]
MAD = Management allowable depletion [%]

Table 3.6 Management allowable depletion values for several crop types[3]

Crop Type	*MAD (%)*
Tomato	25
Bell Pepper	25
Strawberry	25
Raspberry	40
Peach	50

The irrigation trigger (IT) was calculated as the minimum level of water in the soil allowable previous to irrigation. Each time soil moisture was depleted to the irrigation trigger (IT), it was replenished to field capacity.

$$IT = MSWS - MSWD \quad \mathbf{[3.9]}$$

Where: IT = Irrigation trigger[mm]
MSWS = Maximum soil water storage[mm]
MSWD = Maximum soil water deficit[mm]

The depth of irrigation water applied (IRR) must be calculated before continuing to track the soil water additions and losses in the soil profile. Table 3.7 shows application efficiency for several irrigation systems.

$$IRR = \frac{MSWD \times 100}{AE} \quad \mathbf{[3.10]}$$

Where: IRR = Depth of irrigation water applied [mm]
MSWD = Maximum soil water deficit [mm]
AE = Irrigation system application efficiency [%]

[3] For more details on the applied MAD values - derived from the literature - refer to Section 2.4.2.

Table 3.7 Published average irrigation efficiencies (Pitblado et al., 2007)

Type	*Application Efficiency (%)*								
	Solomon (1988)	*Keller & Bliesner (1990)*	*Rogers et al. (1997)*	*Evans et al. (1998)*	*Clemments (2000)*	*Smajstrla et al. (2002)*	*SCC Kansas*	*Edwards Aquifer*	*Avg.*
Solid Set	---	70-85	---	60-75	70-85	70-80	60	---	74
Centre Pivot	75-90	---	65-80	80-85	75-90	70-85	75-95	---	80
Linear Move	75-90	70-85	60-70	65-85	75-90	70-85	75-95	50-60	77
Overhead Gun	65-75	60-75	75-90	55-65	---	60-70	50	50-60	68
Traveler	60-70	70	70-85	60-80	60-75	65-75	55	50-60	68
Surface Drip	75-95	---	75-95	70-95	85-90	70-90	98	90-95	84
Subsurface Drip	---	---	---	---	85-90	70-90	98	90-95	84

3.4.2. Irrigation water used

The quantity of irrigation water used can be calculated using the information collected with the first survey according to three different methods. The first method involves using irrigation system information and system operating time records as follows:

$$Irrigation\ Water\ Use = \frac{System\ Flow\ Rate \times Operating\ Time}{Irrigated\ Area} \times 1000 \qquad [\mathbf{3.11}]$$

Where: Irrigation Water Use = Irrigation water use per growing season [mm]
System Flow Rate = Irrigation system flow rate [m^3/hr] (Values in Table 3.9)
Operating Time = Irrigation system operating time [hrs]
Irrigated Area = Size of the irrigated zone [m^2]

The system flow rates in Table 3.8 were calculated with irrigation system information given by the growers and it must be reiterated that the growers were quite preoccupied and therefore the questionnaires were rushed and not validated.

The second method of determining the amount of irrigation water used is by using the flow meter readings. It is relevant to also consider the irrigators' irrigation records, which are usually based on water use estimations.

In the third method, the quantity of irrigation water used can be calculated using a simple soil water balance equation (Gardner et al., 1999):

$$IWU = ET_c + DP + \Delta S + R - EP \qquad [\mathbf{3.12}]$$

Where: IWU = Irrigation water use [mm]
ET_c = Crop water use [mm]
DP = Deep percolation [mm]
ΔS = Difference in soil moisture storage [mm]
R = Runoff [mm]
EP = Effective precipitation [mm]

The change in soil moisture storage (ΔS) in the soil profile was monitored with different techniques. However as previously mentioned, gravimetric sampling is the only absolute technique used to measure soil moisture content, the data being usually used to calibrate other indirect methods. Gravimetric data sets were therefore given priority to determine ΔS. Nevertheless, the choice of the technique was based on two additional criteria: data quality (depth at which the sensor measured relative to the ECRD; sensor proximity to the emitters) and availability (equipment failures; sample acquisition). As a result, gravimetric data sets were used for every hub site except at Essex (Zone 2) where the data set collected with the WCR sensor was more reliable.

Table 3.8 Irrigation system information (provided by the growers)

County	Site	Zone	Irrigation & Production System Type	No. Emitters		Depth (cm)	Brand	Pressure (psi)	No. Sprinklers	Emitter/Nozzle Flow Rate (L/hr)	System Flow Rate (m3/hr)
				Row	Total						
Essex	1*	1	Surface Drip	1 100	33 000	n/a	Rolldrip	15	n/a	0.4	14
		2	Subsurface Drip	1 100	33 000	20	Rolldrip	15	n/a	0.4	14
	2	3	Surface Drip	1 200	148 800	n/a	Aquatrack	13	n/a	0.3	45
		4	Surface Drip	1 300	176 800	n/a	Netafim	13	n/a	0.3	45
	3	5	Surface Drip	871	105 391	n/a	Netafim	13	n/a	0.6	61
	4	6	Subsurface Drip	1 100	72 600	20	Netafim	11	n/a	0.6	47
Chatham-Kent	5*	7	Subsurface Drip	1 200	216 000	3	Netafim	13	n/a	0.6	131
	6	8	Subsurface Drip / Plastic Mulch	2 400	31 200	8	QueenGill	20	n/a	0.8	26
	7	9	Boom Traveller	n/a	n/a	n/a	n/a	30	29	2 190	64
Norfolk-Haldimand	8*	10	Surface Drip / Plastic Mulch	700	56 000	n/a	Netafim	10	n/a	0.9	51
		11	Surface Drip / Plastic Mulch, High Tunnel	700	56 000	n/a	Netafim	10	n/a	0.9	51
		12	Surface Drip / Plastic Mulch, High Tunnel	450	23 400	n/a	Netafim	10	n/a	0.9	21
	9	13	Solid Set	n/a	n/a	n/a	n/a	100	Unknown	Unknown	82
	10	14	Solid Set	n/a	n/a	n/a	n/a	65	30	3 030	91
Niagara	11*	15	Overhead Gun	n/a	n/a	n/a	n/a	115	1	70 170	70
	12	16	Below Canopy Sprinkler	n/a	n/a	n/a	n/a	50-70	44	820	36
	13	17	Solid Set	n/a	n/a	n/a	n/a	110	20	15 420	308
	14	18	Below Canopy Sprinkler	n/a	n/a	n/a	n/a	Unknown	1	68 130	68
	15	19	Overhead Gun	n/a	n/a	n/a	n/a	Unknown	1	68 130	68

* Indicates hub sites.

Runoff losses, which are already accounted for in the effective precipitation calculation (Equation 3.7) were assumed to be nil for the soil water balance calculations (Equation 3.12).

3.4.3. Assessing on-farm irrigation performance

To determine if water could be saved through the implementation of SIS, on-farm irrigation performance was assessed by comparing irrigation water requirements (Section 3.4.1) with the quantity of irrigation water used (Section 3.4.2) through the field application efficiency indicator (Section 2.5). Before concluding that over- or under-irrigation was performed, an indicator deviation of 10% was considered acceptable as recommended by the Irrigation System Assessment Guide of British Columbia (Nyvall and Tam, 2005). This gross performance assessment was necessary to determine how well crop water needs were met by the current growers' irrigation scheduling practices. Nevertheless, further checks were required before concluding that excessive over- or under-irrigation was performed when the indicator deviation was exceeded. As such, water budget calculations were additionally compared to soil moisture measurements taken over the course of the 2007 growing season.

Before defining this supplementary evaluation, it is important to first define what is considered to be a *potential water saving*. For the purposes of this thesis, a potential water saving is any irrigation water application when the soil profile is already saturated (i.e. at or above field capacity). Because such water application is excessive, and in fact damaging, for crops, to eliminate such water application curbs water expenditure, thus saving water and associated costs.

The following is an explanation of how the aforementioned comparison was performed. Each time an increase of soil moisture content was detected (as measured by gravimetric sampling or the WCR sensor) and at the same time the field capacity of the soil was exceeded, the equivalent depth of water applied was recorded as either precipitation or irrigation. Then, to differentiate the events where soil moisture was replenished by irrigation from those replenished by rainfall, the measured augmentations in soil moisture were compared with those of the water budget; if the measured soil moisture increases were also noticed in the water budget while no irrigation was triggered, the equivalent depth of water added to the soil profile was considered to be due to rainfall and not irrigation. As rainfall is deemed an inherent water addition and must not be "applied" as such, these augmentations were not thought to be potential water savings. Conversely, where measured soil moisture increases were not noticed in the water budget, then the soil moisture increase could be attributed to irrigation, and the equivalent depth of water added to the soil profile can be thought to be a potential water saving. The same procedure was also performed to spot days where soil moisture content was below the irrigation trigger point and in doing so detect under-irrigation practices.

The on-farm irrigation performance assessment was only performed for the hub sites as these are the sites where deep percolation measurements were taken and where the necessary weather data was taken in order to calculate the effective precipitation and crop evapotranspiration as part of the water budget.

3.5. Evaluating usefulness of soil moisture monitoring technologies

In order to establish how useful soil moisture monitoring technologies are to growers, the second survey was the main tool used. The answers were synthesized into three categories: grower's satisfaction with soil moisture monitoring information, anticipated adoption of devices for future years and needs regarding irrigation scheduling. These categories were finally integrated into a comprehensive representation of how feasible the implementation is at a larger scale.

CHAPTER 4 – RESULTS AND DISCUSSION

4.1. Irrigation water requirements and water used

Table 4.1 displays the parameters required to calculate the irrigation water requirements with the water budget method and the quantity of irrigation water used with the soil water balance equation. Table 4.2 shows the calculated irrigation water requirements while Table 4.3 summarizes the quantity of irrigation water used, calculated using the information collected with the first survey according to the four different methods previously described in Section 3.4.2.

By examining Table 4.3, it can be seen that the differences are quite small when considering the water use calculated with irrigation system information provided by the first eight growers in comparison to the data based on flow meter readings. So, it appears that the information provided by the growers is quite accurate as it more or less matches the flow meter data. However, although the annual irrigation water use calculated with the information provided by grower five matches with what was recorded by the flow meter, a discussion with this grower specified that the flow meter was not managed properly nor was the irrigation system information accurate. This table also reveals that some growers personal irrigation water use estimates (growers 9, 11, 13, 14) are not the same as what was calculated with their irrigation system information. The table highlights the extent of the guessing involved in some water management practices; what the water growers perceive as being applied does not match with what the system is actually applying. This in turn questions the reliability of the unverified information provided by the growers which is used to calculate the "Irrigation System Information" column (based on data in Table 3.8). Limitations of the aforementioned comparison were proved to principally reside in estimating the amount of irrigation water delivered to the field (Skewes et al., 2007).

When comparing the water use calculated with information provided by the growers with the soil water balance, the latter appears somewhat more consistent. However, the water balance equation [3.13], which provides average conditions for the growing season, underestimates the water use measured by the flow meters. The equation should therefore be used cautiously when determining seasonal water use since such performance indices often mask individual irrigation applications (Purcell and Currey, 2003).

Table 4.1 Water budget and soil water balance parameters

County	*Site*	*Zone*	*ΔS (mm)*	*ECRD (mm)*	*MAD (%)*	*AE (%)*	*FC_v (%)*	*MSWS (mm)*	*ET_c (mm)*	*EP (mm)*	*DP (mm)*	*MSWD (mm)*	*IT (mm)*	*IRR (mm)*
Essex	1	1	7	300	25	84	13	40	226	109	0	10	30	12
		2	10	300	25	84	11	34	207	107	52	8	25	10
Chatham-Kent	5	7	12	300	25	84	13	38	292	124	0	9	28	11
Norfolk-Haldimand	8	10	10	300	25	84	19	57	464	69	0	14	43	17
		11	19	300	25	84	18	55	325	0	0	14	41	16
Niagara	11	15	68	600	50	68	15	93	251	104	0	46	46	68

Table 4.2 Irrigation water requirements for 2007

County	*Site*	*Zone*	*Crop Type*	*Irrigation & Production System Type*	*Water Budget Dates*	*Irrigation Water Requirements*		
						(mm)	*(m^3)*	*(m^3/ha)*
Essex	1	1	Tomato	Surface Drip	May 24th / Aug. 30th	144	1 748	1 457
		2		Subsurface Drip	June 12th / Sept. 4th	140	1 700	1 416
Chatham-Kent	5	7	Bell Pepper	Subsurface Drip	May 30th / Oct. 9th	165	4 674	607
Norfolk-Haldimand	8	10	Strawberry	Surface Drip / Plastic Mulch	May 23rd / Oct. 12th	384	3 341	3 712
		11		Surface Drip / Plastic Mulch, High Tunnel	May 23rd / Oct. 12th	320	2 823	3 137
Niagara	11	15	Peach	Overhead Gun	May 15th / Aug. 13th	136	3 302	1 376

Table 4.3 Calculated annual irrigation water use for 2007

County	Site	Zone	*Irrigation System Information*		*Flow Meter Readings*		*Grower' Estimate*		*Soil Water Balance Equation*
			Time (hrs)	*Water Use (mm)*	*Time (hrs)*	*Water Use (mm)*	*Time (hrs)*	*Water Use (mm)*	*Water Use (mm)*
Essex	1*	1	177	198	145	191	---	---	110
		2	177	198	145	191	---	---	162
	2	3	66	37	---	---	---	---	---
		4	114	53	---	---	---	---	---
	3	5	140	163	---	---	---	---	---
	4	6	134	193	---	---	---	---	---
Chatham-Kent	5*	7	42	71	---	77	---	---	180
	6	8	98	630	---	---	---	---	---
	7	9	56	88	---	---	---	---	---
Norfolk- Haldimand	8*	10	122	711	---	---	---	---	405
		11	122	701	112	620	---	---	344
		12	156	215	---	---	---	---	---
	9	13	14	63	---	---	14	115	---
	10	14	24	177	---	---	---	---	---
Niagara	11*	15	26	74	---	---	26	114	215
	12	16	15	53	---	---	---	---	---
	13	17	4	Unknown	---	---	4	102	---
	14	18	1	22	---	---	1	51	---
	15	19	126	212	---	---	---	---	---

* Indicates the hub sites.

In the end, the quantity of irrigation water used calculated with flow meter readings was therefore given priority followed by values calculated using irrigation system information and recorded system operating time, the soil water balance equation and lastly, using values based on irrigators' water use estimation (Table 4.4). This order was based on the degree of confidence in the collected data. The information given by the growers about their irrigation system, system operating time records and personal water use estimates which could not be verified was consequently less valued.

4.2. Irrigation performance assessment at the hub sites

Table 4.5 presents the on-farm irrigation performance assessment results where the irrigation water requirements are compared to the amount of irrigation water used at each hub site using the field application efficiency indicator (FAE) (Equation 2.1). Regarding the objectives of the present research, the FAE indicator is the most appropriate to describe irrigation performance in terms of water use efficiency (Bos et al., 1994; Bos et al., 2005; Burt et al., 2005). When the FAE indicator deviation was found exceeding the recommended deviation of 10% by Nyvall and Tam (2005), the irrigation system was considered to be inefficiently meeting crop water requirements as water was either being wasted or insufficiently applied.

By investigating the results in Table 4.5, it can be seen that in 5 out of 6 zones, the FAE indicator deviation was largely exceeding the recommended deviation of 10%. The tomato grower over-irrigated the two zones by about 25 % (50 mm) and the strawberry grower over-irrigated by 48% (330 mm) inside the greenhouse and by 46% (300 mm) in the open field. As for peaches, they appeared to be particularly water stressed compared to other crops; the producer would have needed to apply water almost twice as much as he did (about 65 mm) to meet the crop water requirements. The bell pepper grower is the only one who according to this assessment effectively met his crop water requirements; he slightly over-irrigated by 8% (25 mm).

By examining the basis of how growers currently schedule irrigation, the reason for over- or under-irrigating becomes clearer: almost all growers based their decisions on the plant growth stage and on the weather; few growers used the soil moisture sensors at the time they were interviewed in July (Table 4.6).

Table 4.4 Irrigation water use for 2007

County	*Site*	*Zone*	*Crop Type*	*Data Source*	*Irrigation Water Use* (*mm*)	(*m*^{3})	(*m*^{3}*/ha*)
Essex	1	1	Tomato	Flow Meter	191	2 319	1 932
		2			191	2 319	1 932
Chatham-Kent	5	7	Bell Pepper	Soil Water Balance	180	4 589	596
Norfolk- Haldimand	8	10	Strawberry	Irrigation System Information	711	6 186	6 874
		11		Flow Meter	620	5 470	6 078
Niagara	11	15	Peach	Irrigation System Information	74	1 797	749

Table 4.5 Comparison of irrigation water requirements and water use at the hub sites for 2007

County	*Site*	*Zone*	*Crop Type*	*Field Application Efficiency Indicator (FAE)*	*Deviation (%)*
Essex	1	1	Tomato	0.75	25
		2		0.73	27
Chatham-Kent	5	7	Bell Pepper	0.92	8
Norfolk-Haldimand	8	10	Strawberry	0.54	46
		11		0.52	48
Niagara	11	15	Peach	-0.54	-46

Table 4.6 Factors considered by growers to schedule irrigation: importance scaled from 1 (least) to 5 (most)

County	*Site*	*Growth Stages*	*Weather*	*Energy*	*Soil Moisture Sensors*	*Other Moisture Tests*	*Other*
Essex	1*	5	5	2	4	3	None
	2	5	5	1	1	1	None
	3	5	5	2	1	1	Experience
	4	4	5	1	1	3	None
Chatham-Kent	5*	5	5	3	5	4	None
	6	5	5	2	1	1	None
	7	5	3	3	1	5	Water Supply
Norfolk-Haldimand	8*	5	5	1	1	1	None
	9	3	5	1	1	1	Plant Stress
	10	5	5	1	1	1	Visual Inspection
Niagara	11*	5	4	1	4	3	None
	12	5	5	1	1	1	None
	13	4	5	3	2	1	None
	14	5	5	1	1	1	None
	15	5	5	1	1	1	Weather data

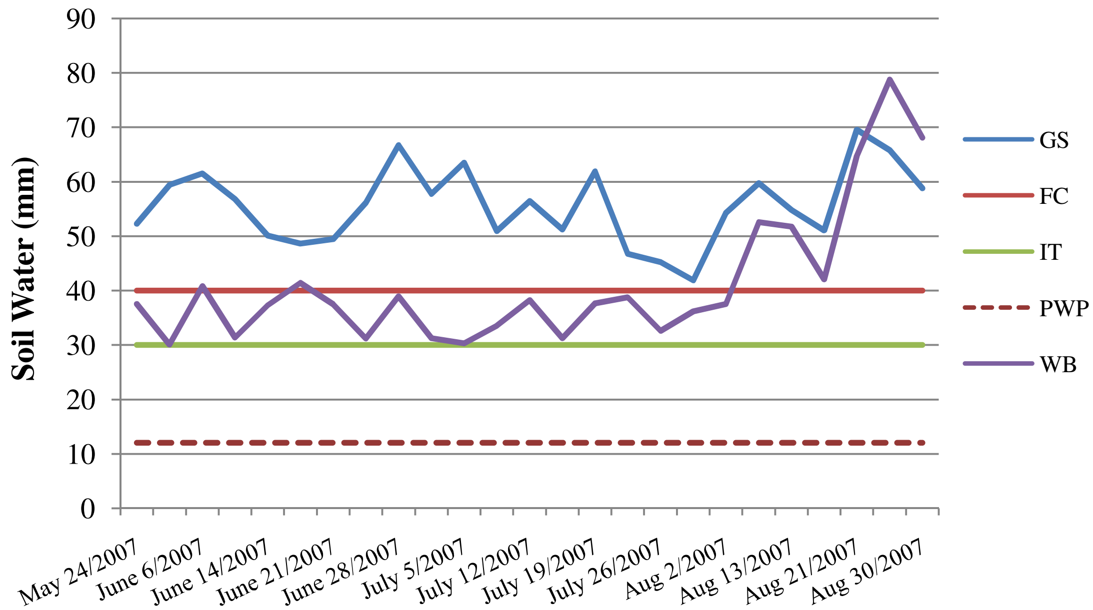
** Indicates the hub sites.*

4.3. On-farm water savings and associated benefits at a larger scale

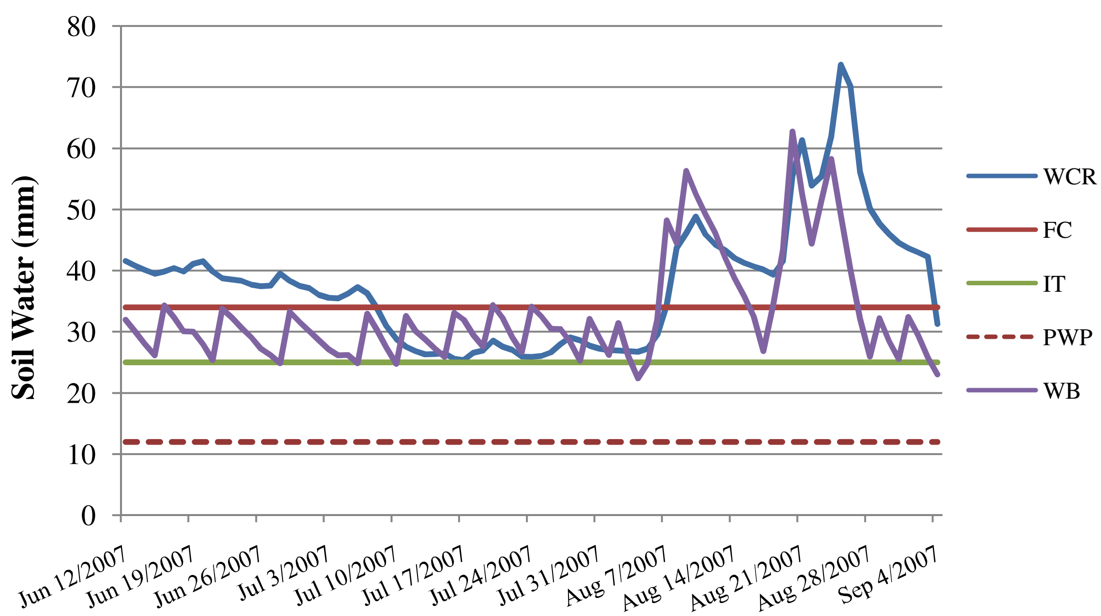
As the first step was to detect over- or under-irrigation practices due to the difference between growers' estimated use and water budget calculations as shown in the previous gross evaluation, the next step was to compare water budget calculations with soil moisture content measurements to determine how much water is excessively or insufficiently applied. Figure 4.1 illustrates how the soil moisture content measurements taken over the course of the 2007 growing season by gravimetric sampling (GS) or with the water content reflectometer (WCR) compares with irrigation water requirements calculated with the water budget method (WB). On each graph, three reference moisture levels are indicated including field capacity (FC), irrigation trigger (IT) and permanent wilting point (PWP). Figure 4.1 supports the findings obtained from the previous comparison of water budget calculations with growers' estimates of water consumption drawn from uncertain information: most growers over-irrigated (some less than others) except the peach grower who under-irrigated critically. The figure shows that the soil moisture content measured by gravimetric sampling or with the water content reflectometer (blue line) at a depth of 0-30 cm was maintained over field capacity for the entire growing season except for the Essex hub site in Zone 2 (Figure 4.1 b)) and the Niagara hub site (Figure 4.1 f)). As shown by Figure 4.1 b), at the Essex hub site the grower maintained the soil moisture content in Zone 2 at a desired level – below field capacity but above the irrigation trigger point – for almost a month. In this case, the extent to which water was excessively applied differs from the previous assessment. According to Table 4.6 which complements Figure 4.1 by providing the actual water saving estimations, crop water requirements were properly met by the Essex hub site grower; only 6 mm were over-applied in Zone 2 compared to 50 mm formerly detected. As for the peach grower, Figure 4.1 f) shows that even though the hub site grower irrigated during flowering, cell division and fruit sizing (critical growth stages during which the crop water needs are higher), the soil moisture content dropped critically close to the permanent wilting point and basically remained below the irrigation trigger point during most of the season. It is clear that this grower needed to irrigate more heavily and more frequently as was indicated by the previous assessment. Contrary to the previous assessment, the Chatham-Kent hub site producer, who was properly meeting his bell pepper water requirements by slightly over-irrigating by 6 mm, now is shown to have over-irrigated by 46 mm (Table 4.7).

Figure 4.1 Comparison of calculated irrigation water requirements with measured soil moisture content at the hub sites for 2007: (a) Essex, Zone 1 – Tomato Crop (b) Essex, Zone 2 – Tomato Crop; (c) Chatham-Kent – Bell Pepper Crop (d) Norfolk-Haldimand, Zone 10 – Strawberry Crop; (e) Norfolk-Haldimand, Zone 11 – Strawberry Crop; (f) Niagara – Peach Crop

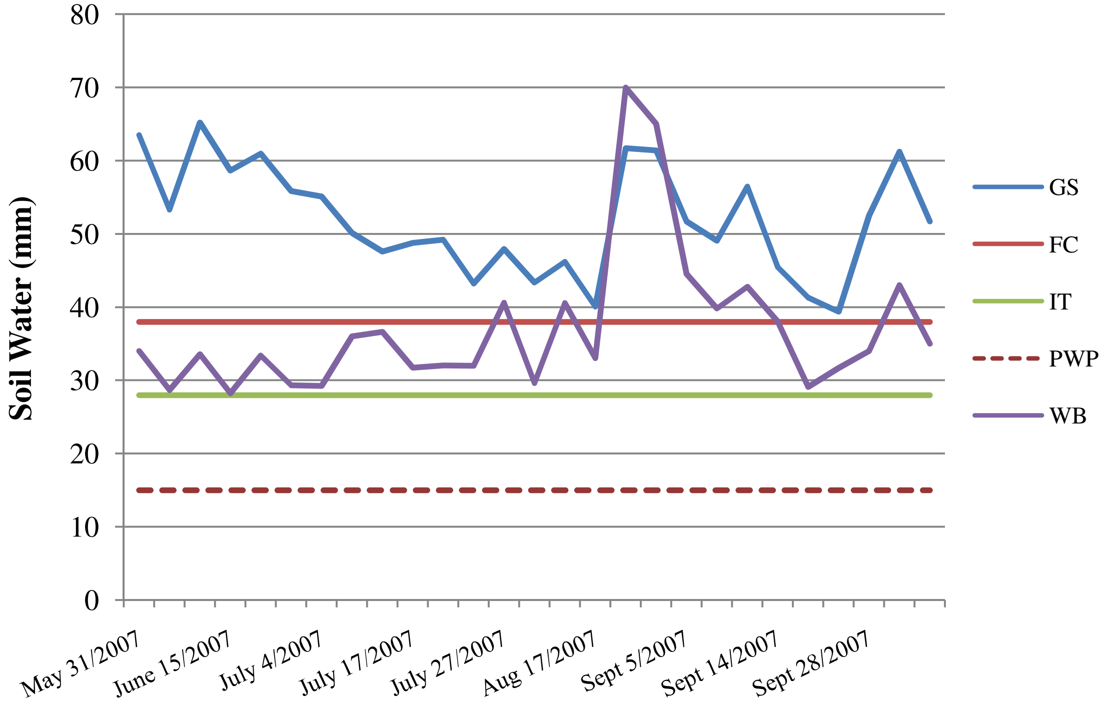
a) Essex, Zone 1 – Tomato Crop



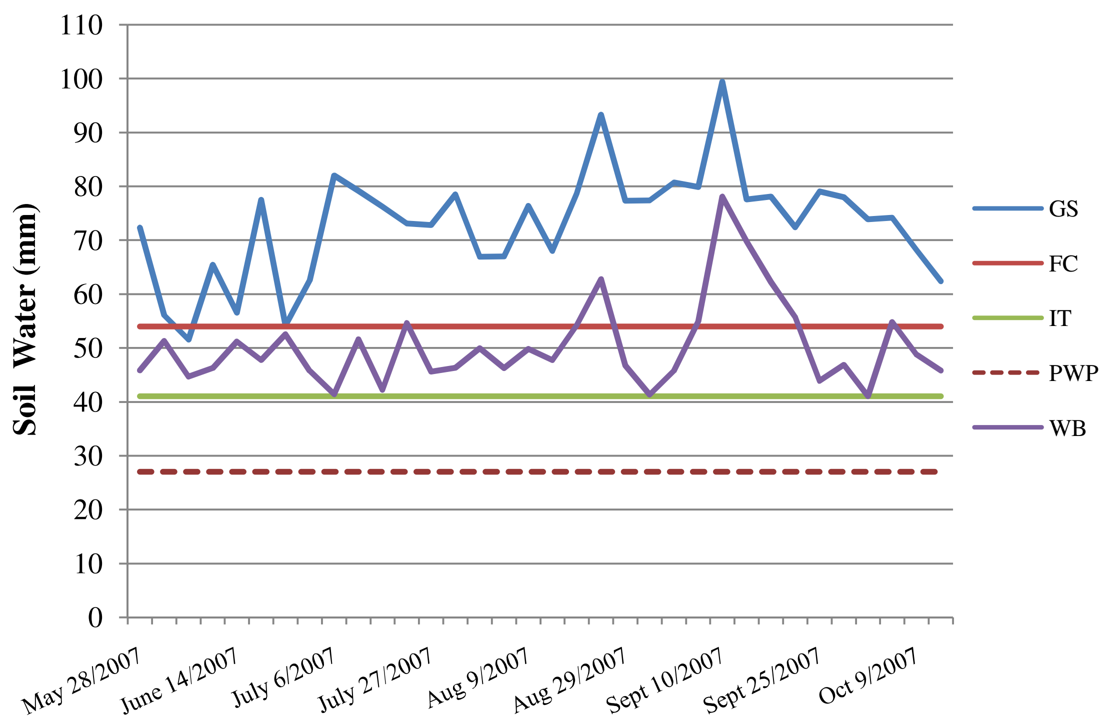
a) Essex, Zone 2 – Tomato Crop



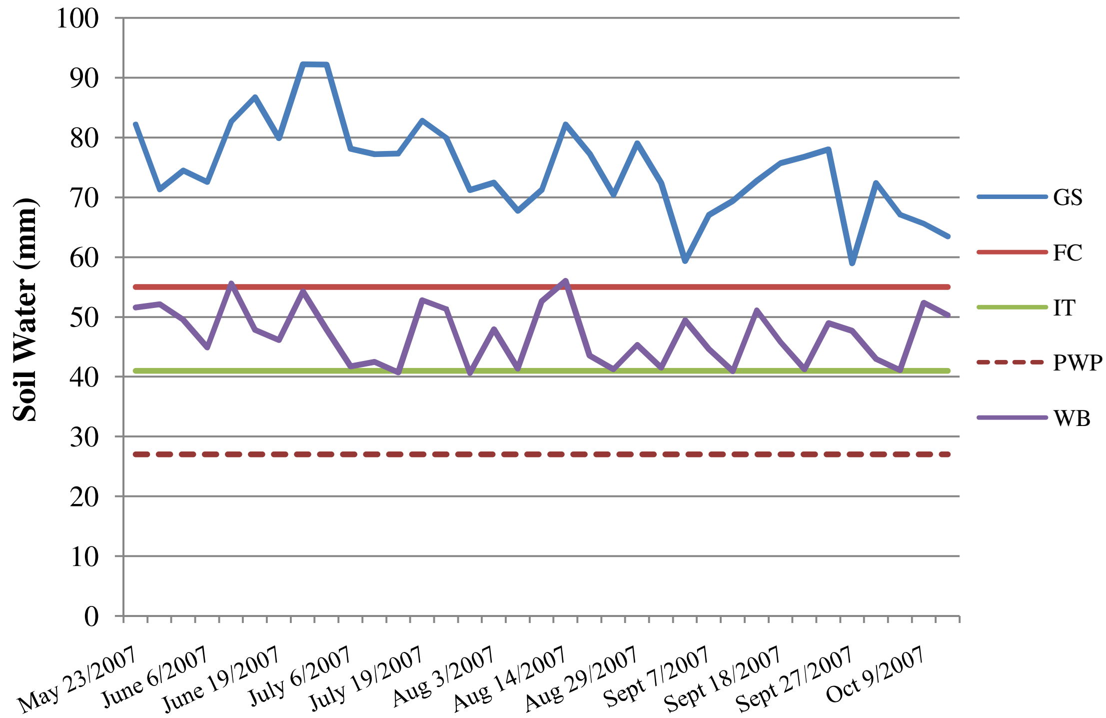
c) Chatham-Kent – Bell Pepper Crop



b) Norfolk-Haldimand, Zone 10 – Strawberry Crop



c) Norfolk-Haldimand, Zone 11 – Strawberry Crop



d) Niagara – Peach Crop

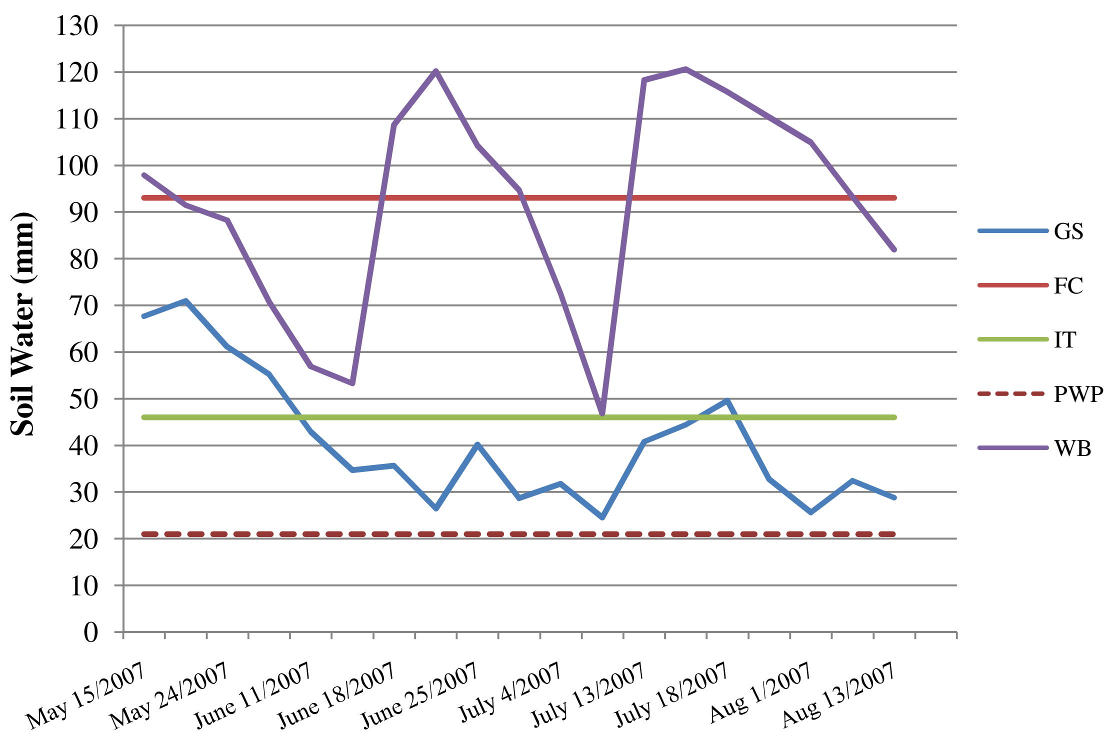


Table 4.7 Potential water savings

County	Site	Zone	Irrigation & Production System Type	Potential Water Saving		
				(mm)	*(m^3)*	*(m^3/ha)*
Essex	1	1	Surface Drip	50	1 416	1 180
		2	Subsurface Drip	6	53	44
Chatham-Kent	5	7	Subsurface Drip	46	1 303	169
Norfolk-Haldimand	8	10	Surface Drip / Plastic Mulch	98	1 190	1 322
		11	Surface Drip / Plastic Mulch, High Tunnel	91	1 105	1 228
Niagara	11	15	Overhead Gun	-75*	-1 821*	-759*

* Negative numbers represent water quantities that would need to be supplemented to the actual amount of irrigation water used to properly meet the crop water needs.

In fact, the potential water saving estimations displayed in Table 4.7, have tremendous implications when applied at the scale of the county in which the hub sites were located. According to Table 4.8, showing information taken from the last Census of Agriculture, in 2006 there were 2617 ha under peach production in the Niagara County (Statistics Canada, 2006). Although no data are available for irrigation water use patterns specific to crop types, the Census of Agriculture estimates that 42.1% of the area under cultivation is irrigated. Assuming that this figure applies to peaches, it is possible to estimate the size of the irrigated area under peach production (1 102 ha). To approximate the extra amount of water that would be required to meet the peach water requirements of the county, it is implicit to assume that all the peach growers in the County follow similar irrigation practices as the hub site grower and thus orchards are commonly prone to water stress in the region. However, it remains a very large assumption that all growers can be represented by the hub site grower. As a result, the calculated extra amount of irrigation water (836 000 m^3) that would be required to properly meet peach water requirements in Niagara provides only a rough estimate (Table 4.8).

Table 4.8 Potential water savings per county[4]

County	*Site*	*Zone*	*Crop Type*	*Irrigation& Production System Type*	*Area (ha)*	*Irrigated (%)*	*Irrigated Area (ha)*	*Water Saving*	
								(× 1 000 m^3)	*(m^3/ha)*
Essex	1	1	Tomato	Surface Drip	2 320	11.8	274	323	5.2
		2		Subsurface Drip	2 320	11.8	274	12	0.2
Chatham-Kent	5	7	Bell Pepper	Subsurface Drip	560	16.1	90	15	14.5
Haldimand-Norfolk	8	10	Strawberry	Surface Drip / Plastic Mulch	223	6.7	154	204	7.7
		11		Surface Drip / Plastic Mulch, High Tunnel	223	6.7	27	189	7.2
Niagara	11	15	Peach	Overhead Gun	2 617	42.1	1 102	-836*	-1.7*

* Negative numbers represent water quantities that would need to be supplemented to the actual amount of irrigation water used to properly meet the crop water needs.

[4] The data regarding both the size of the area under tomato, bell pepper, strawberry, and peach crops production and the percentage of the area under production being irrigated were taken from the last Census of Agriculture (Statistics Canada, 2006).

Even though it is hard to quantify with accuracy what the extra needed amount of irrigation water would be, it can be assumed that the implementation of soil moisture monitoring in the region will boost the irrigation water demand from the peach growers. This could have an impact on the future design of the municipal irrigation system of the Town of Niagara-on-the-Lake for example. Indeed, since the system, which currently has a capacity of 81 800 m^3/day, occasionally failed in the past to satisfy demand, the Town is considering to add an additional capacity of 43 600 m^3/day to avoid future water shortages (Stantec Consulting Ltd., 2005). Such modification to the current infrastructure might not be sufficient to prevent upcoming water shortages considering the possible augmented water demand from the peach producers.

The same pattern also applies in Essex County with the LADIA project. Assuming that most producers irrigate their crop with a surface drip system operated similarly to the hub site tomato grower, reinforcing the tomato growers' current irrigation scheduling practices in the region could potentially save up to 323 000 m^3. This would largely reduce the demand and stress on existing groundwater resources and treated water. This review of the grower's water demand could facilitate the build up of the distribution system and reduce the associated costs.

Again, these findings also have implications for the Haldimand-Norfolk County. The estimated water savings of 189 000 to 204 000 m^3 (depending if the production is in a greenhouse or an open field) of water that can potentially be saved by implementing SIS would help the county to adapt to increasing competition for limited water supplies mainly taken from the shallow aquifers.

4.4. Usefulness of advanced soil moisture monitoring technologies

The following section summarizes and discusses the growers' answers to the second survey's questions, organized by category of question asked.

The findings showed that the growers were satisfied with the equipment and that the growers consulted at least one specific piece of equipment (if not two) regularly during the season. All equipment was useful and generally performed well; there is no "best" piece of equipment for monitoring soil moisture; all have their own positive aspects as well as drawbacks, and a lot of these depend on growers' preference.

4.4.1. Usefulness of soil moisture monitoring information

Growers seemed to prefer the sensors which displayed information on their computer in near-real time, as this eliminated the need to download any data. They also stressed the importance of being able to read the sensors when they walk their fields. At the onset of the project, all of the hub growers were shown the weather station, and informed as to how to obtain actual weather readings from the displays. They were also shown how to read the displays of the sensors that were installed in their fields (if the sensors had displays to read). However, it is difficult to be certain how often these sensors were consulted. From discussions with the growers, it was clear that due to the myriad of sensors installed on the hub sites, they were not always able to distinguish one sensor from the other. As well, some of the sensor displays were located at a distance from where the sensor was buried, and this led to some confusion. In the field, the growers tended to favour sensors which were visible (i.e. sticking out of the soil) and which had dials or displays directly on them.

Survey results to the questions confirmed the difficulty experienced delivering on-time soil moisture data to every grower regularly during the growing season. Indeed, as mentioned previously, the project was very ambitious; there was too much data to compile and distribute for the resources allotted to this task. As a result, many satellite site growers, who did not receive data during the growing season, were unable to answer some of the questions (n/a).

In Table 4.9, grower satisfaction with soil moisture monitoring information they received is shown. The participants were asked to rate from 1 (poor) to 5 (very good) several criteria. Overall, the data showed that when the frequency of data delivery was on-time, the information received was considered very useful, fairly clear and user friendly. On the contrary, the criteria with which growers were less satisfied, was the time required to assimilate and understand the data. Since the growers are extremely busy during the growing season, they would appreciate to minimize the amount of time spent on irrigation scheduling by implementing techniques which are not time consuming.

Table 4.9 Satisfaction with soil moisture information received

Criterion	*Average Growers' Satisfaction*
Usefulness	4.4
Clarity	4.0
User friendliness	4.0
Time required to assimilate and understand the data	3.8
Frequency of data delivery	3.4

4.4.1.1. Using soil moisture monitoring to facilitate current irrigation scheduling and improve irrigation water use efficiency

The usefulness criterion was then further investigated to determine if the soil moisture monitoring data facilitated growers' irrigation scheduling and helped them irrigate more efficiently. The results, in Table 4.10, show that five (33%) growers have decided to modify their current irrigation scheduling practices in response to the data they received and thus the data facilitated their irrigation scheduling, while four (27%) estimated it helped them to irrigate more efficiently. According to the growers, because they were better informed to make decisions regarding the timing and amount of water to apply, they improved their irrigation efficiency. In contrast, a grower in Niagara County, where water is delivered to the irrigators through a municipal drainage system, explained that although he believes the soil moisture monitoring data facilitated his irrigation scheduling by guiding his decisions, he was not able to adjust his irrigation timing. The non-flexibility of his system was a limiting factor to improving his irrigation efficiency. Interestingly, this grower who was part of the satellite farm participants met with the field technicians frequently to get readings with the portable TDR. This explains why, contrary to other satellite site growers, he had access to soil moisture data during the growing season and used it to guide his decisions.

Table 4.10 Usefulness of soil moisture monitoring information

	Usefulness	*No. of Growers*
Improve Irrigation Efficiency	Yes	4
	No	1
	n/a	10
Modify Current Irrigation Scheduling Practices (Facilitate)	Yes	5
	No	0
	n/a	10

4.4.1.2. Saving water by using soil moisture sensors

For the remaining growers who answered that they improved their irrigation efficiency, it is all the more relevant in the framework of this project to determine whether they considered having saved or spent water as a result of using the soil moisture monitoring data. Water economies have been realized according to two out of the four hub site growers. Although one grower professing water economies was not able to express his water savings as a percentage, he affirmed that the soil moisture monitoring information has allowed him to shorten his irrigation runs. The other grower estimated he saved 25-30% by using the monitoring information. On the other hand, one of the growers claimed that he spent 30% more water and suspected that his increase in water use might be better explained by the fairly hot and dry summer experienced rather than because he used the soil moisture data to guide his decisions. Finally, the last grower said that he used more water because he realized he was not irrigating deep enough into the soil profile as indicated by the soil moisture monitoring data set. In this sense, he estimated he would have used 30-50% more water than if the sensors had been in place earlier by irrigating four times per growing season instead of three and much heavier. All growers agreed however, that the quantity of water saved or augmented during the growing season was worth the investment in soil moisture monitoring sensors since these management tools help to obtain better quality crops. This shows the importance of the growers being able to access near real-time information in order to adjust their irrigation amounts.

4.4.1.3. Usefulness of soil moisture monitoring devices

Once the growers' satisfaction with soil moisture monitoring information was assessed, it was determined which of the sensors on the four hub sites were useful and further, which was the most helpful. Here, it is important to note that one grower was not able to tell the difference between sensors and therefore could not distinguish from which sensor the data was coming from; it must be mentioned that the data he was looking at on Internet was considered very useful to him. As this one grower was not able to rate any other devices, the results show an average of the scores that were allotted by the three other participants. The same goes for the flow meters as they were installed only on three of the four hub sites.

Table 4.11 shows usefulness scores of each sensor according to the growers. From the results, the C-probe received the highest score. However, it is important to note that at the start of the project trial, the data from the C-probe and manual tensiometer was the main data provided to the producers in order to not overwhelm them with data, which may have influenced their preferences by sheer familiarity. By mid-season, all data outputs were provided; therefore, this may have influenced the results. However it may not be the sensor but the availability of the information which is preferred as the C-probe has real-time capability, which other sensors could do if equipped to do so. The growers' preference is detailed in the last section where the growers' needs regarding irrigation scheduling are explained.

According to the survey results, only one grower was totally unsatisfied with the sensors which he stated as too complicated and too detailed. His opinion was shared by another grower who appreciated the manual tensiometer because it was not complex and easy to read but found that the other devices were not user friendly and as such, not useful. On the other hand, the two other growers, for whom the data proved to be useful, claimed that it certainly helped them to reduce guessing in terms of irrigation timing and amounts of water to apply.

4.4.1.4. Growers estimates of yield and irrigation water requirements

All growers involved were asked to estimate how their yields would have fared without irrigation and how their yields and irrigation water requirements were this year compared to other years. Generally, yields are a good indicator of how successfully growers provided on-time and sufficient water to their crops to replenish moisture before yield-reducing stress occurred. Furthermore, knowing how irrigation water requirements were different this year from other years due to climate variance may explain why water use of some growers was augmented, even though the soil moisture sensors were used to guide decisions.

Table 4.11 Averaged usefulness score for each device installed on the four hub sites

Equipment	*Averaged Usefulness Score**
Manual Tensiometer (Irrometer)	3.3
Portable TDR (FieldScout 300)	2.5
Echo Probe (EC-20 Decagon)	3.2
Capacitance Probe (AquaSpy)	4.3
TDR Sensor (Gro-Point)	3.2
Electrical Resistance Blocks (Watermark)	2.8
Water Content Reflectometer (Campbell C5625)	2.3
Hortau Wireless Tensiometer (Hortimeter-T)	3.3
Flow Meter	4.0

* Rated from 1 (poor) to 5 (very good).

Table 4.12 shows, not surprisingly, that irrigation is essential to high value horticultural production in southern Ontario. Indeed, the growers estimate that their yields would have been ranging from average to very low in the case where they would not have irrigated. The importance of irrigation is further illustrated by this grower statement: "I would never have grown strawberries without irrigation."

From these results, four (21%) of the growers estimated that their yields in the experimental irrigated area were below average this year compared to other years. However, it is impossible to determine whether it was due to inappropriate irrigation scheduling practices or to the very hot and dry summer that the region experienced. Fourteen growers mentioned that they irrigated more frequently and much heavier this year in comparison to other years to compensate for the hotter and drier summer weather. The degree to which irrigation needs were higher varied from grower to grower. For one grower, the irrigation need was one of the highest it has ever been since he began irrigating five years ago; for another who cultivates bell peppers on raised beds covered with plastic mulch, the crop water requirements which are similar from year to year needed just a bit more water this year. In the case where the grower affirmed he had the same irrigation need, he justified it by the fact that he has to deal with a very limited water supply; he cannot irrigate more if crop water needs increase. He has to stretch his supply to ensure that he will not run the pond dry and thus that he has enough water to finish the growing season. Again it can be seen that it is important for the growers to be able to know how much water they will be requiring for irrigation purposes in a typical growing season.

Table 4.12 Perceived comparison of 2007 yields with: a) yields expected for 2007 without irrigation; b) yields in previous years

County	*Site*	*Zone*	*Yields*[5]									
			a) Expected 2007 Yield Without Irrigation					***b) Previous Years***				
			Excellent	***Good***	***Average***	***Poor***	***Very Low***	***Excellent***	***Good***	***Average***	***Poor***	***Very Low***
Essex	1*	1				X			X			
		2				X			X			
	2	3					X		X			
		4					X		X			
	3	5				X				X		
	4	6					X				X	
Chatham-Kent	5*	7			X			X				
	6	8			X				X			
	7	9			X			X				
Norfolk-Haldimand	8*	10					X					X
		11					X					X
		12					X				X	
	9	13				X		X				
	10	14				X			X			
Niagara	11*	15				X			X			
	12	16			X				X			
	13	17				X				X		
	14	18				X				X		
	15	19				X				X		
Total			***0***	***0***	***21% (4/19)***	***47% (9/19)***	***32% (6/19)***	***15% (3/19)***	***42% (8/19)***	***21% (4/19)***	***11% (2/19)***	***11% (2/19)***

* Indicates the hub sites.

[5] Excellent (much better than expected); Good (above average); Average (normal); Poor (below average); Very Low (much below what was expected)

4.2.1.5. Improving overall understanding of soil moisture levels and crop responses to irrigation scheduling

Finally, as a result of this project, 14 (93%) growers found that their overall understanding of soil moisture levels and crop response and irrigation scheduling has improved. Aside from the fact that the knowledge facilitated irrigation scheduling, it showed them what is going on in the soil profile: how the soil dries out and how soil water holding capacity varies with soil texture. They also mentioned that their understanding of concepts such as field capacity, permanent wilting point and irrigation trigger point improved. In the end, they estimated it helped them to better understand how to irrigate. However, when the growers were asked what their field capacity value was only 3 (20%) growers were able to answer of which only one answered correctly. The score was higher for knowing the irrigation trigger point. Out of the 8 (53%) growers who answered, only one did so incorrectly and another grower, who did not know the exact figure off the top of his head, stated it was around 50% of his field capacity value.

4.4.2. Sensors that growers have decided to adopt for future years

The second part of the survey determined which sensors (if any) growers have decided to adopt for future years. Table 4.13 shows that seven (47%) growers have decided to adopt a sensor, three (20%) have estimated it was not necessary and five (33%) were interested but have not decided as yet which one they would like to install on their farm. Again, the C-Probe appears to be the growers' preferred device so far (though it is not possible to distinguish the reason).

In reference to the growers that considered the instruments to be unnecessary, two of the growers decided not to adopt a device because they estimate that their current irrigation scheduling practices are satisfactory. They believe that by feeling and observing the soil to determine the soil moisture content and by examining plant conditions and weather forecasts, they can adjust irrigation to meet the crop water requirements fairly well while preventing water losses. The third one found that each device has its own specific problems related to its usage, and that although the C-Probe appeared to be the best device, it is too expensive to install, especially since the results showed him that he was irrigating efficiently.

Table 4.13 Growers willingness to adopt a soil moisture monitoring technology

Yes	*No*	*Undecided*	*Sensor*	*Grower's Explanation*
X			C-Probe	The C-probe is more practical. It is very useful - due to time constraints - to have access to soil moisture trends at anytime on Internet (i.e. during lunch times and evenings).
		X	Hortau Wireless Tensiometer or Portable TDR	Not fixed yet but interested by the portable TDR or the Hortau wireless tensiometer; must evaluate if it is cost effective to use/install the devices.
		X	Hortau Wireless Tensiometer or C-Probe	Interested in the C-probe and the Hortau wireless tensiometer; they are fairly easy to use, have low maintenance and are not intrusive. The data can also be downloaded easily on a computer.
	X		None	Will continue using the ET model and adjusting irrigation to weather and crop stage with in-field monitoring to make sure the water being applied is sufficient and not excessive. Soil moisture monitoring devices could facilitate it.
X			Manual Tensiometer	The tensiometers are easy to read, very simple and cost effective.
X			Flow Meter	Would install a flow meter to know exactly how much water is applied.
X			Portable TDR	Since many fields must be irrigated, the portable TDR is more practical than the C-probe. Although the C-probe is preferred, it has to be cost effective; money is a crucial issue.
		X	C-Probe	C-probe data on the Internet are very useful. No decision was taken yet concerning the adoption of an advanced soil moisture monitoring technology.
	X		None	None of these equipments are useful.
		X	Manual Tensiometer or C-Probe	The manual tensiometer is preferred; it is portable and relatively inexpensive. Depending on the budget (i.e. acres/cost) it is preferable to invest in a C-probe sensor.
X			C-Probe	The C-probe is the more user friendly tool.
	X		None	The usage of each device comes with specific problems. The C-probe is the best choice but is too expensive, especially when crop water needs are properly met.
X			C-Probe	The C-probe is interesting; it is easy to access the data and it works better than other devices.
		X	Not Sure Which Device	Not sure which one could be adopted.
X			C-Probe	Interested in a C-probe network where soil moisture trends could be shared and accessed on Internet.
47% (7/15)	**20% (3/15)**	**33% (5/15)**		

4.4.3. Growers' irrigation scheduling needs

4.4.3.1. Preferences in soil moisture data delivery method

Most of the growers surveyed preferred to obtain the results from the Internet or their personal computer (Table 4.14). This may help to explain why the C-probe was one of the most preferred instruments. Otherwise, they preferred to get the information directly from the field. This does not mean that both are mutually exclusive as some growers prefer both (however, in the survey they were only allowed one choice). The survey further revealed that those who were comfortable with computers found that the C-probe was handier and fairly user friendly. One grower mentioned that the Internet was allowing him to access the soil moisture levels at anytime he needed - whether it was during lunch times or evenings. On the other hand, one grower who was not familiar with computers preferred to access the soil moisture monitoring data directly in the field with equipment such as a manual tensiometer, which he qualified as easy to read.

Table 4.14 Growers' preference to accessing soil moisture sensor data

Means to Access Data	***No. of Growers***
Directly in the field	5
Fax	0
Internet	6
Irrigation consultant	0
E-mail	1
Directly in the field or E-mail	1
Internet or E-mail	1
Fax or E-mail	1

4.4.3.2. Willingness to invest money and time in the sensors

Sensor cost was also an important issue regarding the choice of equipment; a few growers chose non-permanently installed equipment, such as the portable TDR or the manual tensiometer over the C-probe because they are relatively inexpensive. One of the growers has to irrigate many stations; thus, the portable TDR would be more cost effective than adopting a C-probe. The peach growers in Niagara County mentioned they would be interested to be part of a C-probe network which would allow them to access the moisture trends of various regional soil profiles without having to install their own equipment.

All participants mentioned that while they do not have extra time, they are extremely busy during the whole growing season, and most of them consider that irrigation scheduling is important and it is worthwhile to spend extra time on it (Table 4.15). In this sense, one grower said: "These sensors are management tools which help to get better quality crops, I don't mind to spend extra time on it due to the benefits I get." Some consider it as part of their job and they will spend the time it requires to get it done, while most prefer to spend as little as time as possible on it.

Table 4.15 Growers' willingness to spend extra time on irrigation scheduling

Extra Time	*No. of Growers*
Whatever	4
Some daily	1
50% more	1
A bit more	1
10 minutes/day	3
10-15 minutes/day	1
20 minutes/day	1
1 hr/week	1
1-1.5 hr/week	1
None	1

4.4.3.3. Readiness to improve irrigation water use efficiency

The interviewed growers established that irrigation is essential to high value horticultural production in southern Ontario. Table 4.16 shows that all growers would not anticipate reducing their irrigation water use in the future even though energy prices were to continue rising considerably. Although two of them would try to receive a better price (10% and 30% more respectively) from their crops if energy was to rise, they would not consider reducing their irrigation water use as being an alternative to lessening energy costs. Another grower answered he would prefer reducing the size of his irrigated acreage if energy prices were to rise by more than 30% rather than moderating irrigation.

In addition, Table 4.16 reveals that most growers (80%) could be convinced to improve their existing irrigation equipment. An increase of 10% in crop price and even no increase at all would be sufficient to convince 47% and 44% of growers respectively; some of them are very concerned about their limited water supply. When growers were asked what would be the minimum increase in crop price necessary to convince them to replace their irrigation equipment, the answers were more moderated; 40% would not substitute their irrigation system for a more efficient system before they received an increase of 30% or more in crop price. This shows that although most growers are willing to improve their irrigation efficiency with little or no monetary incentives through energy savings, replacing the existing irrigation equipment for more efficient equipment is not unanimous.

Given the growers' positive feedbacks about the usefulness of soil moisture monitoring sensors and willingness to adopt several devices (depending on their personal preferences), implementing scientific irrigation scheduling seems to be a prospective solution to improve irrigation efficiency without replacing the system in place.

4.4.3.4. Intentions of using soil moisture information in the future

When the growers were asked how they intend to use the soil moisture monitoring equipment, most of them (33%) answered they would use it to schedule irrigation; they would adjust their irrigation timing and amount (Table 4.17). They would use the information to decide when to trigger irrigation and how much water to apply to maintain soil moisture at the right level. Two growers further mentioned that irrigation scheduling using soil moisture monitoring information would allow them to avoid over- and under-irrigation. In addition, two growers confident on the amount of water applied intend to use the information to adjust their irrigation frequency by better determining when to water. In contrast, a peach grower who cannot be flexible in terms of irrigation timing intended to use the information to better determine the amount of water applied he should apply. Indeed, he is aware of the two critical development stages when peaches need a boost of water (i.e. cell division and fruit sizing before harvest), but he is limited by his irrigation system. Even if he recognizes the perfect timing for irrigating it takes 7-10 days to irrigate the whole field with his overhead gun. The soil moisture monitoring information would in this case allow the adjustment of the amount of water applied, as the timing remains inflexible. Furthermore, three growers who were using the results presented to them at the end of the season stated they would use the data to continue irrigating in their way and validate their decisions with the sensors. One grower specified he would use the data to look at the trends in the soil profile to see if water reaches the root zone deep enough and to see if the crops need water sooner than what he expects from his observations of the plant conditions and the feel and appearance of the soil.

Another grower clearly stated he was intending to use the soil moisture monitoring information to improve his on-farm water use efficiency. Only one grower has not been involved enough in the project to know about the kind of information he was able to obtain with the different sensors.

Table 4.16 Importance of irrigation and willingness to improve irrigation efficiency

Question Asked	*Growers' Answers*	*No. of Growers (%)*
Energy prices have risen considerably recently. If energy prices were to rise would you anticipate ***reducing*** your irrigation water use? If so, by how much?	No	12 (80)
	No, if energy rises by 10% he will try to sell crops at a higher price.	1 (7)
	No, if energy rises by 30% he will try to sell crops at a higher price.	1 (7)
	No, if energy rises by >30% he will reduce irrigated acreage.	1 (7)
What would be the minimum increase in crop price necessary to convince you to ***improve*** your existing irrigation equipment?	None	5 (33)
	10%	7 (47)
	20%	2 (13)
	30%	1 (7)
What would be the minimum increase in crop price necessary to convince you to ***replace*** your existing irrigation equipment?	None	6 (40)
	10%	2 (13)
	20%	1 (7)
	30%	3 (20)
	>30%	1 (7)
	50%	2 (13)

Table 4.17 Details on how the growers intend to use the soil moisture information

Intention to Use Soil Moisture Monitoring Information	*No. of Growers*
Adjust Irrigation Timing & Amount	6
Adjust Irrigation Timing & Amount to Avoid Over/Under Irrigation	2
Adjust the Amount	1
Adjust the Timing	2
Validate Current Irrigation Scheduling Practices	2
Improve On-Farm Water Use Efficiency	1
None	1

CHAPTER 5 – CONCLUSIONS

To lessen the impact of increasing competition and conflicts over scarce water resources, the horticultural industry needs to adopt on-farm water management practices that will allow improving water use efficiency. Therefore the principal aim of this research was to assess on-farm irrigation performance to determine when scientific irrigation scheduling could help irrigate more efficiently and in the end, achieve water savings and enhanced water resource management. This chapter summarizes the key findings of this study.

5.1. Potential water savings

The comparison of water budget calculations with growers' irrigation water use estimates established that current irrigation scheduling practices of most hub site growers should be reviewed; water was either wasted or insufficiently applied in 5 out of 6 irrigated zones. The Essex hub site grower over-irrigated his tomatoes in both zones by 50 mm per year; the Norfolk-Haldimand grower over-irrigated his strawberries by 330 mm inside the greenhouse and by 300 mm in the open field and the Niagara hub site grower under-irrigated his peaches by about 65 mm. Only the Chatham-Kent hub site grower, who slightly over-irrigated his bell peppers by 25 mm, properly met his crop water requirements. Not surprisingly, at the time they were interviewed most growers stated their decisions regarding irrigation were based on plant growth stages and weather forecasts rather than the information that the soil moisture sensors were providing.

The over- or under-irrigation patterns detected with the first assessment drawn on uncertain data were validated by the comparison of water budget calculations with soil moisture measurements taken over the course of the 2007 growing season. The extent to which they over- or under-irrigated was different in this evaluation; the Essex hub site grower over irrigated his tomatoes in Zone 2 only by 6 mm instead of 50 mm whereas the Chatham-Kent hub site grower who previously was properly meeting his bell peppers water requirements slightly over-irrigated by 25 mm was now over-irrigating by 46 mm. This highlights the guess work that is crucially involved in the growers' current irrigation system layout and output capacity. Water applications based on irrigation system setup and operation do not correspond to how crop water needs are gauged by the growers.

Given similar climatic conditions, implementation of SIS in the Essex hub site could have potentially saved 1 180 m^3 of water per hectare for irrigated tomatoes with a surface drip system and 44 m^3 per hectare with a subsurface drip system. Similarly, the Chatham-Kent hub site grower could have saved 169 m^3 of water per hectare and the Norfolk-Haldimand grower 1 322 m^3 per hectare for strawberries grown in an open field and 1 228 m^3 per hectare in a greenhouse. As for the Niagara hub site grower, he would have needed to supplement 759 m^3 of water per hectare to better meet his peach water requirements. More importantly, at a larger scale such water economies could have considerable impact on the planned modification of the municipal irrigation system in Niagara County, the depletion of the central water supply (shallow aquifers) in Norfolk-Haldimand County or on the LADIA project in Essex County.

Overall, scientific irrigation scheduling is an important tool to address the constraints of current and future mismatch between supply and demand for water. By achieving water savings through increasing water use efficiency, growers could better cope with increasing competition for scarce water resources. However, conversion from less efficient to more efficient irrigation scheduling practices does not always result in decreased water consumption as it was revealed by the results of this study; the Niagara hub site grower is indeed expected to irrigate more frequently and more heavily in the coming years to better meet his peaches water requirements.

5.2. Implementing scientific irrigation scheduling at a larger scale

Almost all the growers recognized the usefulness of the soil moisture monitoring sensors; the hub site growers used at least one piece of equipment to adjust and validate their irrigation decisions over the course of the 2007 growing season. There is no “best” piece of equipment for monitoring soil moisture; all of them have advantages and drawbacks. The choice of a device depends on grower preference in terms of equipment cost, time required to gather the data from the device, data delivery method (Internet, directly in the field, etc.) and real-time capability versus occasional verification of soil moisture content.

Soil moisture monitoring sensors were new technology to the growers. Most of them continued to base their irrigation decisions on weather forecasts, visual inspection of plants and a subjective soil moisture examination instead of adopting the technology. As a result, no considerable water savings were realized this year. Due to the difficulty experienced in delivering on-time soil moisture data to every grower regularly during the growing season, it is only at the end of the growing season, when the growers were shown the complete soil moisture data set, that they realized how inefficiently they were meeting their crop water requirements. As a result, most of them showed increased willingness to adopt the sensor technology to better manage their irrigation water applications. Some of them would be interested in setting up a soil moisture monitoring network the next season using C-probes; this demonstrates that they recognized the benefits of the technology. The importance of the training aspect for the growers on how to use the technology has also been brought to the forefront by the survey responses; better results would have been achieved if explanations of how the different sensors worked and of how to access the data had been given earlier.

Given the growers' positive feedback about the usefulness of the soil moisture monitoring sensors and their willingness to adopt several devices, scientific irrigation scheduling does emerge as a promising solution which will allow the agricultural sector to adapt to increasing competition for limited water resources. The industry could potentially benefit from less conflicts arising due to the water consumption reduction amongst those who adopt the technology.

CHAPTER 6 – FUTURE RESEARCH OPPORTUNITIES

Throughout the duration of this research, a number of areas for fruitful irrigation scheduling research and technology transfer were identified, were there to be funding available in the future.

i. It would be interesting to perform this study another year by providing the data in a timelier manner during the growing season. This would allow adjusting irrigation water applications in order to better meet crop water requirements. More specifically, the study could be retried with the growers' preferred sensors or with a C-Probe network. A follow up project lasting a few years would further help determining the extent to which growers improved their understanding of advanced soil moisture monitoring technologies as tools to manage irrigation more efficiently.
ii. Future research should be made to provide irrigation management tools that are more practical, user friendly and cost effective. Such tools would give on-site data showing whether the soil moisture is above or below the irrigation trigger level.
iii. The limits of this research are emphasized by the fact that the reliability of the data used to calculate the annual current irrigation water use (irrigation system information provided by the growers, flow meter readings and growers' water use estimates) could not be validated. Installing flow meters at every hub site and ensuring their proper management would be valuable. Survey forms should also be filled at the beginning of the growing season when growers are not busy and the information they provide should be validated by any means possible such as looking at the irrigation system manuals for example.
iv. Lifestyle patterns, personal philosophy, and social status of the grower within the community of growers can influence how SIS is adopted. It would therefore be potentially fruitful to investigate these aspects in order to facilitate the technology transfer. Farm characteristics (i.e. the size of the farm, whether it is owned or leased), economic constraints, education, experience with previous water shortages and anticipation of future shortages are all important attributes that should be closely examined.

REFERENCES

Abraha, M.G. and Savage, M.J. 2008. The soil water balance of rainfed and irrigated oats, Italian rye grass and rye using the CropSyst model. Irrigation Science, 26 (3): 203–212.

AgriMet. 2007. Managing Water in the West. The Pacific Northwest Cooperative Agricultural Weather Network. US Department of the Interior.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper No. 56, 300 pp.

Amer, S.A., Keefer, T.O., Weltz, M.A., Goodrich, D.C. and Bach, L.B. 1994. Soil moisture sensors for continuous monitoring. Water Resources Bulletin, 30 (1): 69-83.

Azhar, A.H., Murty, V.V.N. and Phien, H.N. 1992. Modeling Irrigation Scheduling for Lowland Rice With Stochastic Rainfall. Journal of Irrigation and Drainage Engineering, 118 (1): 36-55.

Bierman, P. 2005. Managing Irrigation for High-Value Crops. University of Alaska Fairbanks Cooperative Extension Service. FGV-00649.

Bois, B., Pier, P., Van Leeuwen, C. and Gaudillère, J-P. 2005. Sensitivity analysis of the Penman-Monteith evapotranspiration formula and comparison of empirical methods used in viticulture soil water balance. Institut National de la Recherche Agronomique de France.

Bos, M.G., Murray-Rust, D.H., Merrey, D.J., Johnson, H.G. and Snellen, W.B. 1994. Methodologies for assessing performance of irrigation and drainage management. Irrigation and Drainage Systems, 7: 231-261.

Bos, M.G., Burton, M.A. and Molden, D.J. 2005. Irrigation and Drainage Performance Assessment: Practical Guidelines

Brandes, O.M. and Mass, T. 2006. What we govern and what governs us: Developing sustainability in Canadian water management. Canadian Water Resources Association 59th Annual Conference: Working from the source towards sustainable management. Toronto, Ontario.

Brouwer, C. and Heibloem, M. 1986. Irrigation Water Management: Irrigation Water Needs. Food and Agriculture Organization of the United Nations (FAO). Retrieved December 5th, 2007, from http://www.fao.org/

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Members ASCE and Eisenhauer, D.E. 1997. Irrigation Performance Measures: Efficiency and Uniformity. Journal of Irrigation and Drainage Engineering, 123 (6): 423-442.

Burt, C.M., Mutziger, A.J., Allen, R.G., Howell, T.A. 2005. Evaporation Research: Review and Interpretation. Journal of Irrigation and Drainage Engineering, 131 (1): 37-58.

California University. 2007. Section C. Measuring Water Sources. Retrieved December 3rd 2007, from http://cesanjoaquin.ucdavis.edu/

Campbell, G.S. 1988. Soil Water Potential: An Overview. Irrigation Science, 9: 265-273.

Cepuder, P. and Nolz, R. 2007. Irrigation Management by Means of Soil Moisture Sensor Technologies. Journal of Water and Land Development, 11: 79-90.

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

Doorenbos, J. and Pruitt, W.O. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper No. 24. Food and Agriculture Organization of the United Nations.

Ertek, A., Şensoy, A., Gedik, İ. and Küçükyumuk, C. 2006. Irrigation scheduling based on pan evaporation values for cucumber (Cucumis sativus L.) grown under field conditions. Agricultural Water Management, 81: 159-172.

Environment Canada. 2004. Canadian Climate Normals 1971-2000. Retrieved June 4th, 2008, from http://www.climate.weatheroffice.ec.gc.ca/

Environmental Commissioner of Ontario. 2001. Ontario's Permit To Take Water Program And The Protection Of Ontario's Water Resources.

Evans, R., Cassel, D.K. and Sneed, R.E. 1996. Soil, Water, and Crop Characteristics Important to Irrigation Scheduling. North Carolina Cooperative Extension Service. Publication Number: AG 452-1.

Fairweather, H., Austin, N. and Hope, M. 2003. Water Use Efficiency – Terms and Definitions. Canberra: Land and Water Australia, Chapter 2, pp.7-14.

Fernandes, C., Corá, J.E. and Campos de Araújo, J.A. 2003. Reference Evapotranspiration Estimation Inside Greenhouses. Scientia Agricola, 60 (3).

Gabriel, A. and Kreutzwiser, K. 1993. The Ontario drought hazard: a review of impacts, 1960-1989, and management implications. Canadian Water Resources Journal, 18: 17-132.

Gardner, C.M.K., Laryea, K.B. and Unger, P.W. 1999. Soil Physical Constraints to Plant Growth and Crop Production. Land and Water Development Division. Food and Agriculture Organization of the United Nations.

Gardner, J., Slingerland, K. and Fisher, P. 2006. What You Should Know About Fruit Production In Ontario. Ontario Ministry of Agriculture, Food and Rural Affairs. Agdex # 206/11. Retrieved November 9th, 2007, from http://www.omafra.gov.on.ca/

Gartner Lee Limited, Ogilvie, Ogilvie and Company and Huber Environmental Consulting. 2002. Best Practices for Assessing Water Taking Proposals.

Hanson, B., Schwankl, L. and Fulton, A. 2004. Scheduling Irrigations: When and How Much Water to Apply. Department of Land, Air and Water Resources, University of California. Water Management Series publication number 3396. Davis, California.

Hess, T.M. 1996. Evapotranspiration estimates for water balance scheduling in the UK. Irrigation News, 25: 31-36.

Hill, R.W. 2002. Using Evapotranspiration Data to Schedule Irrigation of Forages. Proceedings of 2002 Western Alfalfa and Forage Conference. Sparks, Nevada. Davis 95616.

Harmanto, V.M., Salokhe, M.S. and Tantau, H.J. 2005. Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. Agricultural Water Management, 71: 225-242.

Home, P.G., Panda, R.K. and Kar, S. (2002). Effect of method and scheduling of irrigation on water and nitrogen use efficiencies of Okra (Abelmoschus esculentus). Agricultural and Water Management, 55: 159-170.

Howell, T.A. 1996. Irrigation Scheduling Research and its Impact on Water Use. In Camp, C.R., Sadler, E.J., Yoder, R.E (eds.) Evapotranspiration and Irrigation Scheduling, Proceedings of the International Conference, San Antonio, TX, American Society of Agricultural Engineers, St. Joseph, MI.

Hughes, J.D. and Evans, L. H. 1999. SOILpak for Southern Irrigators, Chapter E7 Irrigation Scheduling. New South Wales Agriculture, Australia.

Irmak, S., Allen, R.G. and Whitty, E.B. 2003. Daily Grass and Alfalfa-Reference Evapotranspiration Estimates and Alfalfa-to-Grass Evapotranspiration Ratios in Florida. Journal of Irrigation and Drainage Engineering, 129 (5): 360-370.

Irmak, S., Irmak, A., Allen, R.G. and Jones, J.W. 2003. Solar and Net Radiation-Based Equations to Estimate Reference Evapotranspiration in Humid Climates. Journal of Irrigation and Drainage Engineering, 129 (5): 336-347.

Jabloun, M. and Sahli, A. 2008. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data Application to Tunisia. Agricultural Water Management, 95: 707-715.

Jones, H.G. 2004. Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods. Journal of Experimental Botany, 55 (407): 2427-2436.

Kashyap, P.S. and Panda, R.K. 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. Agricultural Water Management, 59 (1): 49-66.

Kreutzweiser, R., de Loë, R. and Benninghoff, B.D. 1999. Agricultural and Rural Water Allocation in Ontario. Agricultural Council under the National Soil and Water Conservation Program.

Kreutzweiser, R., de Loë, R., Durley, J. and Priddle, C. 2004. Water Allocation and the PTTW Program in Ontario: Challenges and Opportunities. Canadian Water Resources Journal, 29(2): 135-146.

LeBoeuf, J., Shortt, R., Tan, C. and Verhallen, A. 2007. Irrigation Scheduling for Tomatoes - An Introduction. Ministry of Agriculture, Food and Rural Affairs (OMAFRA).

Leib, B.G., Hattendorf, M., Elliott, T. and Mattews, G. 2002. Adoption and adaptation of scientific irrigation scheduling: Trends from Washington, USA as of 1998. Agricultural Water Management, 55: 105-120.

Ley, T.W., Stevens, R.G., Topielec, R.R. and Neibling, W.H. 1994. Soil Water Monitoring and Measurement. Paper PNW0475. Pacific Northwest Cooperative Extension Publication.

Marshall Macklin Monaghan. 2003. Analysis of Agricultural Water Supply Issues. National Water Supply Expansion Program, Province of Ontario. Final Report presented to Agriculture and Agri-Food Canada (AAFC-PFRA).

Mermoud, A., Tamini, T.D. and 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.

Miller, J.J., Bolton, K.F.S.L., de Loë, R.C., Fairchild, G.L., Gregorich, L.J., Kreutzwiser, R.D., MacAlpine, N.D., Ring, L. and Veeman T.S. 2000. Limits on rural growth related to water. Chapter 11, pp. 131– 138 in Coote, D.R. and Gregorich, L.J. (eds.) The health of our water - toward sustainable agriculture in Canada. Research Planning and Coordination Directorate, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ontario.

Monterro, J.I, Castilla, N., Gutierrez de Rave, E. and Bretones, F. 1985. Climate Under Plastic in Almeria. ACTA, 170: 227-234.

Nielsen, D.C., Lagae, H.J. and Anderson, R.L. 1995. Time-Domain Reflectometry Measurements of Surface Soil Water Content. Soil Science Society of America Journal, 59: 103-105.

Norman, W.R., Shayya, W.H., Al-Ghafri, A.S. and McCann, I.R. 1998. Aflaj irrigation and on-farm water management in northern Oman. Irrigation and Drainage Systems, 12: 35-48.

Nyvall, J. 1998. Irrigation Scheduling with Tensiometers. Water Conservation Factsheet, Ministry of Agriculture and Food of British Columbia. No. 577.100-2.

Nyvall, J. 2002. Soil water storage capacity and available soil moisture. Food and Fisheries of British Columbia. Ministry of Agriculture. Agdex 550.

Nyvall, J. and Tam, S. 2005. Irrigation System Assessment Guide. Food and Fisheries Resource Management Branch. British Columbia Agriculture Council. British Columbia Ministry of Agriculture.

OMAFRA. 2004. Best Practices Management Series: Irrigation Management. Revised Edition. Agdex#700.

OMAFRA. 2006. What you should know about fruit production in Ontario. Revised Edition. Agdex 206-11.

OMAFRA and University of Guelph. 2005. Tree and Small Fruit Open House and Equipment Display – Simcoe Experiment Station.

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.

Panda, R.K., Behera, S.K. and Kashyap, P.S. 2004. Effective management of irrigation water for maize under stressed condition. Agricultural Water Management, 66 (3): 181-203.

Pitblado, R., Drewitt, G., Nichols, I., Danford, R., Heinen, W. and Rowlandson, T. 2007. Raw Water for Agricultural Irrigation Study Phase 2. Technical Advisory Committee, Stantec Consulting Ltd.

Planner, B. 2003. Furrow Irrigation Management Plan. Natural Resources Conservation Service, United States Department of Agriculture.

Prichard, T.L. 2008. Soil Moisture Measurement Technology. Agriculture Publications. University of California Cooperative Extension. Davis, CA.

Purcell, J. and Currey, A. 2003. Gaining Acceptance of Water Use Efficiency, Framework, Terms and Definitions. National Program for Sustainable Irrigation. Final Report - Stage 2, AQC1.

Reddy C.R. and Reddy, S.R. 1993. Scheduling irrigation for peanuts with variable amounts of available water. Agricultural Water Management, 23: 1-9.

Rosenberg, N.J., McKennedy, M.S and Martin, P. 1989. Evapotranspiration in greenhouse-warmed world: a review and a simulation. Agricultural and Forest Meteorology, 47: 303-320.

Sammis, T.W. and Mexal, J.G. 1999. Irrigation Water Management to Sustain Agriculture in the Desert. New Mexico Journal of Science, 39: 301-309.

Sanders, D.C. 1993. Vegetable Crop Irrigation. North Carolina Cooperative Extension Service. Retrieved December 10th, 2007, from http://www.ces.ncsu.edu/

Shortt, R., Caldwell, W.J., Ball, J. and Agnew, P. 2006. A Participatory Approach to Water Management: Irrigation Advisory Committees in Southern Ontario. Canadian Water Resources Journal, 31(1): 13-24.

Singh, B., Boivin, J., Kirkpatrick, G. and Hunn, B. 1995. Automatic Irrigation Scheduling System (AISSUM): Principles and Applications. Journal of Irrigation and Drainage Engineering, 121 (1): 43-56.

Skewes, M., Meissner, T., Herbert, T., Newman, B. and Smith, K. 2007. Assessment of Irrigation Performance at Regional and Property Scale. Government of South Australia. Retrieved October 24th, 2007, from http://www.sardi.sa.gov.au/

Slingerland, K. 2005. The Tender Fruit Grape Vine, A Newsletter for Commercial Fruit Growers. Ministry of Agriculture, Food and Rural Affairs (OMAFRA).

Stantec Consulting Ltd., J. Kinkead Consulting and KCMS Applied Research and Consulting Inc. 2005. Feasibility Study - Raw water for agricultural irrigation purposes. Project Report (Draft).

Statistics Canada. 2006. 2006 Census of Agriculture. Retrieved June 5th, 2008, from http://estat.statcan.ca/

Stevens, J.B. 2007. Adoption of irrigation scheduling methods in South Africa. Doctoral Thesis. University of Pretoria, Department of Agricultural Economics, Extension and Rural Development. South Africa.

Tan, C.S. and Reynolds, W.D. 2003. Impact of recent climate trends on agriculture in Southwestern Ontario. Canadian Water Resources Journal, 28: 87-97.

Tan, C.S. 1990. Irrigation scheduling for tomatoes - Water budget approach. Agdex 257/560. Ontario Ministry of Agriculture, Food and Rural Affairs.

Tekinel, O. and Kanber, R. 2002. Trickle Irrigation Experiments in Turkey. Chapter 2, pp. 27-72 in Mehmet, Ö. and Biçal, A.H. (eds.) Modern and Traditional Irrigation Technologies in Eastern Mediterranean. International Development Research Center, Ottawa, Ontario.

Thompson, R.B., Gallardo, M., Valdez, L.C. and Fernández, M.D. 2007. Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. Agricultural Water Management, 88: 147-158.

Thomson, S.J. and Ross, B.B. 1996. Using Soil Moisture Sensors for Making Irrigation Management Decisions in Virginia. Virginia Polytechnic Institute and State University. Retrieved December 2nd, 2007, from http://www.ext.vt.edu/

Topp, G.C. and Davis, J.L. 1985. Measurement of Soil Water Content using Time-Domain Reflectometry (TDR): A Field Evaluation. Soil Science Society American Journal, 49: 19-24.

UMA Engineering Ltd. 2007. Leamington Area Drip Irrigation Association, Pre-Design of Leamington Area Drip Irrigation Project Report. RPT-099-07.

Upendram, S. and Peterson, J. 2006. Optimal irrigation schedules and estimation of corn yield under varying well capacities and soil moisture levels in Western Kansas. Selected Paper prepared for presentation at the Southern Agricultural Economics Association Annual Meetings. Orlando, Florida.

United States Department of Agriculture (USDA). 1997. Irrigation Guide - National Engineering Handbook Series. Part 652.

Van der Gulik, T. 2001. Crop Coefficients for Use in Irrigation Scheduling. Ministry of Agriculture, Food and Fisheries of British Columbia. Agdex 561.

Van der Gulik, T. 2004. Trickle Irrigation Scheduling Using Evapotranspiration Data. Ministry of Agriculture, Food and Fisheries of British Columbia. Agdex 561.

Van der Gulik, T. 2006. Irrigation Scheduling Techniques. Ministry of Agriculture and Lands of British Columbia, Resource Management Branch.

Vandierendonck, M. and Mitchell, B. 1997. Water Use Information for Sustainable Water Management: Building Blocks and the Ontario Situation. Canadian Water Resources Journal, 22: 395-415.

Verhallen, A. and Roddy, E. 2002. Irrigating Vegetable Crops. Ministry of Agriculture, Food and Rural Affairs (OMAFRA).

Wang, D., Kang, Y. and Wan, S. 2006. Effect of soil matric potential on tomato yield and water use under drip irrigation condition. Agricultural Water Management, 87: 180-186.

Wang, F-X., Kang, Y., Liu, S-P. and Hou, X-Y. 2007. Effects of soil matric potential on potato growth under drip irrigation in the North China Plain. Agricultural Water Management, 88: 24-42.

Werner, H. 1993. Checkbook Irrigation Scheduling, Irrigation Management Manual for South Dakota. Cooperative Extension Service, South Dakota State University, US Department of Agriculture.

Wheaton, T.A. and Parsons, L.R. 2006. Simulating Irrigation Requirement for Citrus on Excessively Drained Soils. Hortscience, 41 (6): 1487-1492.

Wong, A. and Bellamy, S. 2005. Water Use in the Long Point Region Conservation Authority. Grand River Conservation Authority.

Zhao, C., Feng, Z. and Chen, G. 2004. Soil water balance simulation of alfalfa (*Medicago sativa* L.) in the semiarid Chinese Loess Plateau. Agricultural Water Management, 69: 101-114.

Zhang, B.Z., Kang, S.Z., Zhang, L., Du, T.S., Li, S.E. and Yang, X.Y. 2007. Estimation of Seasonal Crop Water Consumption in a Vineyard Using Bowen Ratio-Energy Balance Method. Hydrological Processes, 21: 3635-3641.

APPENDIX A

First survey on irrigation water use

GENERAL

- Name of grower:____
- Age: ____
- Educational level: ____________________________________
- Are you owner or operator?: ______________________________
- Is it an intergenerational farm? If yes, which generation?:______
- For how many years have you been farming?: _______________
- Is the farm your primary income source?: __________________

GROWING SEASON

- How long is the growing season? (days): _________
  -Planting date: _________
  -Harvesting date: _________

IRRIGATED ACREAGE: ZONE SPECIFICATIONS

Zone	*Irrigated Area (acres)*	*Crop Type*	*Soil Type*	*No. Rows*	*Row Width (ft)*	*Row Length (ft)*	*Plant Spacing (ft × ft)*	*No. Plants per Row*
1								
2								

IRRIGATION SYSTEM

1) Drip Irrigation System

Zone	*Type*	*No. Emitters*	*Emitter Flow Rate*	*Emitter Brand*	*Depth (in)*	*Pressure (psi)*	*Drip Line Spacing (in)*	*System Operating Time (hr/day)*
1								
2								

2) Sprinkler Irrigation System

Zone	*Type*	*No. Sprinklers*	*Sprinkler Flow Rate*	*No. Nozzles*	*Nozzle Flow Rate*	*Nozzle Size (in)*	*System Operating Time (hr/day)*
1							
2							

3) Irrigation System Operating Time

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
May																															
Time (hrs) Water (mm)																															
June																															
Time (hrs) Water (mm)																															
July																															
Time (hrs) Water (mm)																															
August																															
Time (hrs) Water (mm)																															
September																															
Time (hrs) Water (mm)																															
October Time (hrs) Water (mm)																															

PUMP SPECIFICATIONS

- Brand: _____________
- Model number: _____________
- Horsepower: _____________
- Impellor size: _____________
- Revolution per minute (rpm): _____________
- Flow rate: _____________
- Energy consumption (kWh/year, electricity bill or gallons of fuel): _____________

IRRIGATION SCHEDULING

- When do you irrigate (time of day)?: ____________
- How much water is used for each irrigation water application? (mm/day & mm/acre): ____________
- For how many years have you been irrigating?: ____________
- Based on which information do you determine the amount of water that should be applied and when to irrigate?:

  -Please rank the importance of each of the following (scale from 1: least to 5: most):

  Crop growth stage ____________
  Weather ____________
  Energy cost ____________
  Data from moisture sensors ____________
  Outcome of other moisture tests ____________

  Other (specify) _________________________

IRRIGATION WATER

- What is the source of irrigation water (i.e. municipal drainage system, well, stream, etc.)?: ____________
- What is the capacity of your on-farm pond/reservoir?: ____________
- On what type of irrigation water delivery system are you relying to deliver water from the municipal drainage system/well/stream to the field (i.e. natural stream, pipes, man-made canals, etc.)?: ____________
- What are the dimensions of the natural stream/pipe/man-made canal delivering water?: ____________
- Is the irrigation water quantity/flow rate measured by any device?: ____________

  If yes, indicate:

  -Metered flow rate: ____________
  -Meter reading at start of year: ____________
  -Meter reading at end of year: ____________

- In what year did you install (1) and upgrade the equipment (2)?: (1) ____________
  (2) ____________
- Do you have a Permit To Take Water (PTTW)?: ____________

  -What is the annual water withdrawal stated on water license?: ____________
  -What is the peak flow rate allowed by the water license?: ____________

- Does water availability constrain your irrigation? When? How?

  Details:

- Do you anticipate any water shortages? When? How?

  Details:

- Do you have a tile drainage system installation? What kind?: ____________
- Do you recapture and reuse runoff? Volume?: ____________
- Are you aware of or participating in water conservation programs?

  Details:

PROJECTED EXPANSION OF IRRIGATED ACREAGE

- How many additional acres are you planning to irrigate? (acres): ____________
- What kind of crops do you plan to grow in the future?: ____________
- In what time frame? (i.e. 2, 5, … years from now?): ____________
- From which source will the extra irrigation water required be withdrawn?: ____________
- What would be the additional irrigation water quantity required?: ____________
- Approximately how much will you invest? ($/acre): ____________
- What is the expected income? ($/acre): ___________
- Will this expansion require a PTTW?: ____________
- If yes, what will be the amount of water licensed?: ____________

COST

- How much did you invest for the technical equipment (irrigation system, water meter, men-made canals, pumps, etc.)?

  Details:

- What is the cost of maintenance of the irrigation equipment? ($): ____________
- What is the cost associated with additional labor requirement? ($): ____________
- What is the cost associated with irrigation water use (municipal tax)? ($/irrigated acre): ____________
- Did you have to pay a "catch-up" payment? (Any new participant in the system has to pay a cumulative capital contribution made over the years by the original participants)? If yes, how much? ($): ____________
- What is the energy cost associated to irrigation (electricity bill)? ($): ____________
- Is there a cost for the permit and how much is it?: ____________

- Do you have any annual permit or license fees?: ____________

- Energy prices have risen considerably recently. If energy prices were to rise at rates as suggested below, would you anticipate reducing your irrigation water use and, if so, by how much (as a percentage)?

  10 percent ____________
  20 percent ____________
  30 percent ____________
  More than 30 percent ____________

- Please consider the price you have received for your principal crops in the last 2-3 years. What would the minimum increase in price be necessary to convince you to improve your existing irrigation equipment?

  10% increase
  20%increase
  30% increase
  >30% increase (specify)

- Please consider the price you have received for your principal crops in the last 2-3 years. What would the minimum increase in price would be necessary to convince you to replace your existing irrigation equipment?

  10% increase
  20%increase
  30% increase
  >30% increase (specify)

APPENDIX B

Second survey on usefulness of soil moisture monitoring sensors

GROWERS' SATISFACTION

🏳 ***Questions that are preceded by this flag only apply to hub site growers.***

1. Please rate from 1 (poor) to 5 (great) your satisfaction with the irrigation scheduling information you received.
   - Usefulness of data
   - Clarity of data
   - User friendliness of data
   - Time required to assimilate and understand the data
   - Frequency of data delivery
   - Not applicable, the irrigation scheduling information was not received

2. Would you say that the soil moisture information has helped you to irrigate more efficiently?

   Yes ❑ No ❑ Not Applicable ❑

   If yes, please give some examples?

3. How has the information modified your current irrigation scheduling practices? Has it facilitated your irrigation scheduling?

4. Has your understanding of soil moisture and irrigation scheduling improved as a result of this project?

   Yes ❑ No ❑

   If yes, please give some examples?

5. Do you know what your field capacity value is? If yes, what is it?

6. Do you know what your trigger point for irrigation is? If yes, what is it?

🏳 7. Was the data provided by the soil moisture monitoring equipment useful? If so, in what way?

   Please give some examples.

8. How were your yields in the experimental area this year, compared to other years?

- Excellent (much better than expected)
- Good (above average)
- Average (normal)
- Poor (below average)
- Very low (much below what was expected)

9. What would your yields have been without irrigation?

- Excellent (much better than expected)
- Good (above average)
- Average (normal)
- Poor (below average)
- Very low (much below what was expected)

10. How was your irrigation need this year compared to other years? Please explain how the irrigation frequency and the amount of water applied were different from other years (if different).

11. Approximately how much water have you saved or spent as a result of using the soil moisture data equipment?

GROWERS' NEEDS REGARDING IRRIGATION SCHEDULING

1. Please rate the usefulness from 1(poor) to 5(great) for each of the equipment installed on your farm.

- Manual Tensiometer
- Manual Portable FieldScout TDR
- Echo Probe
- C-Probe
- Gro-Point TDR
- Watermark (Watchdogs)
- Campbell Water Content Reflectometer TDR
- Hortau
- Flow Meter

2. By which means would you prefer to access soil moisture monitoring data? What would be most convenient for you (i.e. directly in the field, fax, Internet, consultant, e-mail)?

3. How do you intend to use the soil moisture information?

4. Which irrigation scheduling techniques have you decided to adopt for future years (if any)?

   Please explain why.

5. Do you consider the quantity of water saved (or spent) during the growing season worth the investment into future soil moisture monitoring equipment?

6. How much extra time would you be willing to spend on irrigation scheduling?

7. If funding is available to continue the project in the future, do you have any recommendations to improve it?

8. Do you have any other comments?

APPENDIX C

Irrigation records based on growers' log book & flow meter readings

1) Essex hub site – Zone 1 & 2 (Flow meter)

June	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)																					6	12			6	3	4		3	4	
W (mm)																					10	16			9	5	6		5	6	
July	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)		4	4	4	4	4	4		4	4	4	3	4	3		3	3	2	2	2	2		3	3	4	4		3	4	2	2
W (mm)		6	6	6	2	2	4		6	6	6	5	6	4		5	5	3	3	3	3		5	4	7	6		1	1	3	3
August	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	4	3	2	3											0	4	2														
W (mm)	6	4	3	4											0	6	3														

2) Essex hub site – Zone 1 & 2 (Grower's log book)

June	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)																		4	4	4	4	4	4		4	4	4	4	4	4	
W (mm)																		5	5	5	5	5	5		5	5	5	5	5	5	
July	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
W (mm)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
August	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	3	3	3	3	3	3	3	3	3																						
W (mm)	3	3	3	3	3	3	3	3	3																						

3) Chatham-Kent hub site – Zone 7 (Flow meter)

July	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)						12								9																	
W (mm)						55								42																	
August	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	7																														
W (mm)	32																														
Sept.	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)							7																7								
W (mm)							32																32								

4) Norfolk-Haldimand hub site – Zone 10 (Grower's log book)

May	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)												3			3			3			2			2				2			2
W (mm)												17			17			17			2			12				12			12
June	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	
T (hrs)				2			2		2		2		2		2			2		2					2		2		2		
W (mm)				12			12		12		12		12		12			12		12					9		9		9		
July	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)	2		2		2		2		2		2		2		2			2		2		2		2		2		2		2	
W (mm)	12		12		12		12		2		12		12		12			12		12		12		12		12		12		12	
August	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)	2		2		2		2		2			2		2		2	2	2				2		2		2		2		2	2
W (mm)	12		12		12		12		12			12		12		12	12	2				12		12		12		12		12	2
Sept.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	
T (hrs)	2		2		2		2			2		2		2			2		2		2					2					
W (mm)	12		12		12		12			12		12		12			12		12		2					12					

5) Norfolk-Haldimand hub site – Zone 11 (Grower's log book)

May	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)												3			3			3			2			2				2			2
W (mm)												18			18			18			12			12				12			12
June	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	
T (hrs)				2			2		2		2		2		2			2		2					2		2		2		
W (mm)				12			12		12		12		12		12			12		12					9		9		9		
July	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)	2		2		2		2		2		2		2		2			2		2		2		2		2		2		2	
W (mm)	12		12		12		12		12		12		12		12			12		12		12		12		12		12		12	
August	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
T (hrs)	2		2		2		2		2			2		2		2	2	2				2		2		2		2		2	2
W (mm)	12		12		12		12		12			12		12		12	12	12				12		12		12		12		12	12
Sept.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	
T (hrs)	2		2		2		2			2		2		2			2		2		2					2					
W (mm)	12		12		12		12			12		12		12			12		12		12					12					

6) Norfolk-Haldimand hub site – Zone 11 (Grower's log book)

June	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)													1	2	2	2		4	2	3	2	3	3		1		3		3		
W (mm)													4	12	15	10		22	8	14	10	15	19		10		15		17		
July	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	3		2		2		2		2		3		4		2			1		2		2		2		2		3		2	
W (mm)	13		9		11		14		12		13		19		8			5		8		12		11		12		14		12	
August	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	2		2		2		2		2			1		2		1		1				2		2		2		2		2	
W (mm)	11		14		9		12		7			5		12		8		6				9		8		7				8	
Sept.	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)	2		2		2		2			2		2		2			2		1		2			2					2		
W (mm)	11		12		12		13			11		10		15			13		7		11			9					9		
October	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)	1																						2								
W (mm)	9																						10								

7) Niagara hub site – Zone 15 (Grower's log book)

June	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	
T (hrs)																				9											
W (mm)																				38											
July	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***
T (hrs)										9																	9				
W (mm)										38																	38				