

Decision support system for irrigation water management

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To Babajide, Teju and Chandra

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Contribution of Authors

All the manuscripts in this thesis were authored by Olanike Aladenola (first author) and Prof Chandra Madramootoo. Olanike Aladenola conducted the field and greenhouse experiments, developed the model with guidance from some matlab experts and wrote all the manuscripts. Prof Chandra Madramootoo, is the research supervisor and co-author, he supervised and funded the research project, provided guidance on various aspects of experimental design, reviewed all the manuscripts and provided constructive recommendations.

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Abstract

Variability in seasonal precipitation, potential climate change impacts, competition for water among users, rising population and increasing food demands are putting pressure on agricultural water demands. For irrigated agriculture in Canada to play a major role in addressing current and future global food supply problems, more innovative and sustainable irrigation management approaches are required. In this context a decision support system that ensured more effective irrigation water allocation, application and optimisation was developed.

Crop water requirements and irrigation schedules for bell pepper (*Capsicum annuum* L.) were obtained from greenhouse and field studies. Greenhouse experiments were conducted to determine appropriate irrigation water applications, agronomic and physiological response to water stress for peppers grown on clay and loamy sand soils. These studies involved four irrigation levels — 120% (T_{120}), 100% (T_{100}), 80% (T_{80}) and 40% (T_{40}) of pan evaporation (E_{pan}). The results showed that highest yields and water use efficiency were obtained with 120% E_{pan} on loamy sand compared to clay soil. The corresponding crop water stress index (*CWSI*) at T_{120} was 0.18 to 0.20 on clay, and 0.09 to 0.11 on loamy sand. The *CWSI* determined is valuable for determining when to irrigate. The fruit total soluble solids content was highest in the T_{40} , and least in the T_{120} treatments.

Given that the greenhouse results were obtained under controlled conditions, it was necessary to extend the research in the field. Experiments were conducted to determine the level of available soil water (threshold) at which irrigation should be applied to prevent water stress and yield loss for peppers on a clay soil. Four irrigation thresholds, as a percentage of available soil water content, were investigated. These were: 85% (T_1), 75% (T_2), 50% (T_3), and 25% (T_4) available soil water content. A control of no irrigation (T_5) was implemented. The crop water stress index (*CWSI*) and effects of elevated CO_2 on the stomatal conductance and water applied were also investigated. The three CO_2 levels studied were: ambient CO_2 (~400 ppm), predicted CO_2 for the year 2050 (550

ppm), and predicted CO_2 for the year 2100 (750 ppm) simulated by changing the CO_2 concentration in the LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA). Optimum marketable yields were achieved when 50% (T_3) of the available soil water content had been depleted with a corresponding $CWSI$ of 0.3 to 0.4. Irrigating at 50% resulted in consistently higher yields, better fruit quality and average 50% savings in water. A decrease in stomatal conductance with increasing CO_2 was observed. Irrigation water requirements decreased by 6-42% under elevated CO_2 of 550 ppm, and 28-58% for elevated CO_2 of 750 ppm. This assessment was independent of other climatic parameters that could affect IWR because neither bell pepper plant nor the growing environment was injected with CO_2 .

An integrated agricultural water demand model (IAWDM) was developed using a graphical user interface (GUI) in Matlab to estimate irrigation water requirements (IWR). A pre-requisite for the model development was to ensure that solar radiation (R_s) input data were of good quality. The suitability of nine (R_s) estimation methods, and their effects on reference evapotranspiration (ET_o) were evaluated using data from eight weather stations across Canada. Based on Root mean square error (RMSE) of 0.86 to 1.44 MJ m⁻² d⁻¹, the Hargreaves and Samani (H-S) method gave best results for locations that did not have reliable, long term, observed R_s and sunshine duration data.

Output from the IAWDM was compared with CROPWAT simulations, and metered irrigation water-use. IWR from IAWDM deviated from field data by 7 to 28%, while CROPWAT deviated by 7 to 42%. Future IWR was estimated using Agriculture and Agri-food Canada (AAFC) generated climate change data for 2040 to 2069. Results showed that IWR of bell peppers will increase by 19 to 27% in the future. A sensitivity analysis showed that IWR is most sensitive to air temperature, reference evapotranspiration (ET_o), and crop coefficients, followed by solar radiation and precipitation. Overall the findings from this study led to a more sustainable greenhouse and field production of vegetable. The improved management practices increased irrigation water use efficiency thereby leading to a more beneficial use of agricultural water.

Résumé

L'imprévisibilité des présentes précipitations saisonnières et des répercussions potentielles du changement climatique, ainsi que les besoins alimentaires grandissants d'une population croissante, mènent à une compétition plus acharnée entre les utilisateurs des ressources en eau, imposant ainsi d'importantes pressions sur la demande en eau à fins agricoles. Pour que l'agriculture irriguée au Canada puisse contribuer de façon significative à la résolution de présents et futures problèmes d'approvisionnement alimentaire mondial, des modes de gestion d'irrigation plus innovateurs et durables sont nécessaires. Dans ce contexte, un système d'aide à la décision assurant une plus grande efficacité d'allocation, d'application et d'optimisation des eaux d'irrigation fut conçue.

Des études en serre et en champ déterminèrent les exigences en eau et les programmes d'irrigation nécessaires à la culture des poivrons (*Capsicum annuum* L.). Les études en serre établirent un régime d'irrigation approprié pour les poivrons et notèrent leurs réponses agronomiques et physiologiques à des stress hydriques lorsque cultivés sur un sol argileux ou un sable loameux. Quatre niveaux d'irrigation furent évalués, soit 120% (T_{120}), 100% (T_{100}), 80% (T_{80}) ou 40% (T_{40}) de l'évaporation bac (E_{bac}). Un réapprovisionnement à 120% E_{bac} entraîna un rendement et une efficacité d'utilisation de l'eau plus élevés sur le sable loameux que sur le sol argileux. L'indice de stress hydrique (ISH) de la culture soumise au taux de réapprovisionnement de 120% fut de 0.18 à 0.20 sur le sol argileux, et de 0.09 à 0.11 sur le sable loameux. L'ISH est particulièrement utile pour déterminer quand irriguer. La teneur totale en matières sèches solubles des fruits de poivron fut à son maximum pour le taux de réapprovisionnement de 40%, et à son minimum pour le taux de 120%.

Comme les résultats en serre furent obtenus sous des conditions hautement contrôlées, il fut nécessaire d'étendre la recherche à une culture en champ. Une étude fut entreprise sur un sol argileux pour déterminer quel seuil de pourcentage d'eau disponible dans le sol (85%, 75%, 50%, ou 25%) devrait entraîner une irrigation visant à prévenir un stress hydrique du plant de poivron et la perte de rendement qui en suivrait. Un étalon n'ayant reçu aucune irrigation fut également inclus. L'indice de stress hydrique (ISH) fut suivi et

l'effet de teneurs élevées en CO_2 sur la conductance stomatique et la quantité d'eau devant être appliqué furent également étudiés. Les trois teneurs en CO_2 évalués furent celles de l'air ambiant présent (~400 ppm), et les teneurs prédites pour 2050 et 2100 (550 et 750 ppm, respectivement), simulées en fixant la concentration en CO_2 à ces niveaux dans un système photosynthétique portatif LI-6400 (LI-COR Inc., Nébraska, É.U.). Un rendement commercialisable optimal fut obtenu avec un seuil d'irrigation représentant à une carence de 50% en eau disponible du sol, ce qui correspond à un indice de stress hydrique de 0.3 à 0.4. Irriguer à ce seuil de carence donna systématiquement de meilleurs rendements, une plus grande qualité des fruits et épargne, en moyenne, 50% de l'eau d'irrigation. La conductance stomatique diminua avec l'augmentation de la teneur en CO_2 . Par rapport aux besoins en irrigation sous la présente teneur en CO_2 de l'air ambiant, ces besoins diminuèrent de 6 à 42% sous une teneur en CO_2 de 550 ppm, et de 28 à 58% sous une teneur en CO_2 de 750 ppm. Ce bilan s'avère indépendant des autres paramètres climatiques pouvant influencer les besoins en eau d'irrigation, puisque ni les plantes de poivron ni l'environnement dans laquelle elles croissaient n'avaient reçu d'apport en CO_2 .

Un modèle intégré de demande en eau pour fins agricoles (MIDEFA) permettant l'estimation des besoins en eau d'irrigation (BEI) fut élaboré en utilisant l'interface graphique de Matlab. L'élaboration du modèle nécessita des données d'entrée de radiation solaire (R_s) de haute qualité. Laquelle de neuf méthodes permettant d'estimer R_s conviendrait le mieux, et quel serait l'effet de chacune de ces méthodes sur le calcul de l'évapotranspiration de référence (ET_o) fut évalué en utilisant des données parvenant de huit stations météorologiques canadiennes. Avec une erreur quadratique moyenne de 1 à 6%, la méthode Hargreaves et Samani (H-S) donna les meilleurs résultats pour les endroits n'ayant pas d'observations de R_s ou de la durée de l'ensoleillement fiables à long terme.

Les données tirées du MIDEFA furent comparées à celles tirées de simulations avec CROPWAT, et aux données provenant d'un compteur d'eau utilisée à fins d'irrigation. Les différences entre le BEI mesuré au champ et ceux calculés par MIDEFA et

CROPWAT furent de 7 à 28% et 7 à 42%, respectivement. De futures BEI furent estimés en utilisant des données fournies par Agriculture et Agroalimentaire Canada (AAC), reflétant le changement de climat prévu pour 2040 et 2069. Selon cette analyse, le BEI pour les poivrons augmenterait de 19 à 27% dans l'avenir. Une analyse de sensibilité indiqua que les BEI étaient plus sensibles aux variations dans la température de l'air, l'évapotranspiration de référence (ET_o), et les coefficients cultureux, suivi de la radiation solaire et de la précipitation.

Dans l'ensemble les constats de notre étude ont mené à une production de légumes plus durable à la fois en serre et au champ. Un mode de gestion améliorée a augmenté l'efficacité d'utilisation des eaux d'irrigation, menant à une utilisation plus bénéfique des eaux servant à des fins agricoles.

Abbreviations and acronyms

AAFC	Agriculture and Agri-Food Canada
AET	Actual Evapotranspiration (mm period^{-1})
AIMM	Alberta Irrigation Management Model
A-P	Angstrom-Prescott
ASCE	American Society of Civil Engineers
ASW	Available Soil Water
AWCt	Available Water Content Threshold
AWDM	Okanagan Irrigation Water Demand Model
CR	Capillary Rise
CRCM	Canadian Regional Climate Change Model
CROPWAT	A Computer Program for Irrigation Planning and Management
CWSI	Crop Water Stress Index
CWR	Crop Water Requirements (mm period^{-1})
DOY	Day of the year
DP	Deep Percolation
e_a	Actual Vapour Pressure (kPa)
e_s	Saturation Vapour Pressure (kPa)
$e_s - e_a$	Saturation Vapour Pressure Deficit (kPa)
E_p	Evaporation from a standard pan (mm)
ET	Evapotranspiration
ET_c	Crop Evapotranspiration (mm day^{-1})
ET_o	Reference Evapotranspiration (mm day^{-1})
FAO	Food and Agriculture Organization
FAO 56-PM	Food and Agriculture Organization Irrigation and Drainage Paper 56 - Penman-Monteith
FAOSTAT	Food and Agriculture Organization Statistical Database
FC	Field Capacity
FDR	Frequency Domain Reflectometry
G	Soil Heat Flux Density ($\text{MJ m}^{-2}\text{day}^{-1}$)

GCM	General Circulation Model
GDP	Gross Domestic Product
HADCM	Hadley Climate Model
IPCC	Intergovernmental Panel on Climate Change
I	Irrigation
ISAREG	irrigation scheduling simulation model
IRT	Infrared Thermometer
IT	Irrigation Trigger
IWUE	Irrigation Water Use Efficiency ($\text{kg ha}^{-1}\text{mm}^{-1}$)
IWR	Irrigation Water Requirement
IAWDM	Integrated Agricultural Water Demand Model
K_c	Crop Coefficient
K_{cp}	Crop-Pan Coefficients
LAI	Leaf Area Index
LAI_{active}	Sunlit Leaf Area Index
MAD	Management Allowable Depletion
MBE	Mean Bias Error
n	Average Daily Sunshine Duration (hrs)
N	Maximum Possible Sunshine Duration
NRCS	Natural resources Conservation Service
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
P_e	Effective Rainfall (mm)
PET	Potential Evapotranspiration (mm day^{-1})
P	Atmospheric pressure (kPa)
p	Precipitation
PRIDE	Program for Regional Irrigation Demand Estimation
PWP	Permanent Wilting Point
PTTW	Permit to Take Water
PTTWP	Permit to Take Water Program
R	Rainfall (mm)

R^2	Coefficient of determination
R_a	Extraterrestrial Radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
RDI	Regulated Deficit Irrigation
RMSE	Root Mean Square Error
R_n	Net Radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$)
r_a	Aerodynamic Resistance (s m^{-1})
R_s	Solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
r_s	(Bulk) Surface Aerodynamic Resistance (s m^{-1})
RO	Surface Runoff
SIMETAW	Simulation of Evapotranspiration of Applied Water application program
SIS	Scientific Irrigation Scheduling
SRES	Special Report on Emission Scenario
T	Mean Daily Air Temperature ($^{\circ}\text{C}$)
T_a	Air temperature ($^{\circ}\text{C}$)
T_c	Canopy Temperature ($^{\circ}\text{C}$)
$T_c - T_a$	Difference between Air and Canopy Temperature ($^{\circ}\text{C}$)
T_{dry}	Temperature of a non-transpiring (dry) leaf/canopy ($^{\circ}\text{C}$)
T_{nws}	Temperature of a non-water stressed leaf/canopy ($^{\circ}\text{C}$)
TDR	Time Domain Reflectometry
u_2	Wind Speed at 2 m height (ms^{-1})
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
VPD	Vapour Pressure Deficit (kPa)
VWC	Volumetric Water Content
WASIM	WATER SIMulation
WUE	Water Use Efficiency
WCR	Water Content Reflectometer
θ_v	Volumetric Water Content
γ	Psychrometric Constant ($\text{kPa } ^{\circ}\text{C}^{-1}$)
z_{oh}	Roughness length governing heat and vapour transfer (m)

z_{om}	Roughness length governing momentum transfer (m)
ε	Emissivity
Δ	Slope of saturation vapour pressure curve (kPa °C ⁻¹)
ΔS	Change in soil water storage

Chapter 1 General introduction

1.1 Challenges of agricultural production

The main factors influencing the future of the agricultural sector include population growth (FAO, 2009), changes in incomes and diets (Kearney, 2010). It is estimated that the world population will exceed 10 billion by 2100 (United Nations, 2011), an increase of 30% from today's population. This will place significant pressures on world agriculture to satisfy food demand. In order to meet this demand, global agricultural production must increase and become more efficient to sustain the population, despite intensifying competition for water resources (de Fraiture and Wichelns, 2010) in the future and a changing climate.

Irrigation is a vital component of world's agriculture. Irrigated agriculture is practiced worldwide on approximately 260 million hectares of land (Morison et al., 2008). Although this represents only 17% of the world's cultivated area, irrigated agricultural land provides 40-45% of the world's food supply (Evans and Sadler, 2008), twice the yield of that obtained from rainfed agriculture. Irrigated agriculture is, nevertheless, the major consumer of available fresh water worldwide, accounting for 70% of the total freshwater use (Evans and Sadler, 2008). The pressure posed by agricultural water consumption through irrigation is a global concern. Even countries that are relatively richly endowed with water may have to address regional or temporary water scarcity. Canada, for example, which is richly endowed with 20% of the world's total fresh water, suffers from uneven distribution. There is strong competition for available water resources. These include irrigation, potable water, power generation, industrial production, environmental services and recreation. This often makes the water allocation process complex for water managers. There are a variety of mechanisms for allocating water resources, including administrative allocation, water markets and user based allocation (Dinar et al., 1997). In Canada, water allocation mechanisms vary across provinces and there is a lack of a Canada-wide water strategy to facilitate stronger and more effective water management (de Loe et al., 2007).

1.2 Agricultural water management

Ward et al., (2006) described the urgency to recognize agricultural water management as a key mechanism for solving water resources problems. Agricultural water management includes all issues affecting water use at the farm and regional level. It is composed of two sectors: agricultural water supply and agricultural water demand. Water supply is generally fixed, or reduced, in response to competing needs while agricultural water demand can be manipulated and effectively managed. There is a general perception that agricultural water use is often wasteful and highly inefficient (Hsiao et al., 2007). The challenge now is for the agricultural sector to maximize the economical return per unit of water (water productivity). This will involve more efficient water management techniques (Molden, 2007; Rockstrom et al., 2007; Fraiture et al., 2010) such as appropriate water allocation to the agricultural sector as well as efficient water applications using the knowledge of crop water requirements.

Canada is expected to play a prominent role in meeting future food demands with its available freshwater resources and agricultural technology. In fact, there is a great potential for increased food production in Canada. However, irrigated agriculture faces competition for water resources from other users as well as seasonal shortages, water allocation issues and poor conservation methods. The general belief is that Canada has an abundance of water (Sprague, 2007). Seasonal precipitation variability and the flow of the major waters away from areas where water is needed reduce access to, and availability of, water for consumption (Kreutzwiser and de Loë, 2010). Within the past few years, nearly a third of Canadian communities have faced threats to the security of the quantity or quality of their water supply (Environment Canada, 2004). Many important agricultural regions in Canada, including parts of the Prairies and portions of British Columbia, are already water-stressed, and there are mounting concerns about water quality throughout most of Canada's agricultural lands (Stewart et al., 2011). Therefore, there is a need for more insight into the efficiency of irrigated agriculture; this calls for the development of a robust framework for estimating irrigation water demand

and scheduling water use under varying weather conditions, crop management options and irrigation technologies.

Improved irrigation water management can be achieved through accurate determination of crop water requirements (CWR) and appropriate scheduling of irrigation. It is important for growers to know the environmental demands for surface water, which occurs primarily through evapotranspiration (ET). ET is the amount of water returned to the atmosphere through evaporation and transpiration. The ET rate is a function of such factors as temperature, solar radiation, humidity, wind, and the characteristics of the specific vegetation that is transpiring, which may vary significantly between vegetation types (Allen et al., 1998). Of these factors, solar radiation (R_s) is not available at many weather stations in Canada and worldwide (Liu and Scott, 2001; Abraha and Savage 2008). A modification of the ET concept is reference evapotranspiration (ET_o) that provides a standard crop such as a short, clipped grass or tall grass (alfafa) with an unlimited water supply so that a user can calculate the maximum evaporative demand from that surface for any given day. This value, adjusted for a particular crop, is the consumptive use (or demand). A deficit represents that component of the consumptive use that goes unfilled, either by precipitation or by soil-moisture use, during the given time period. This deficit value is the amount of water that must be supplied through irrigation to meet the water demand of the crop (Allen et al., 1998). Therefore, reliable estimates of ET , along with the knowledge of precipitation totals and soil moisture storage capacity will lead to higher irrigation water use efficiency, which will be beneficial for the production of high value crops in Canada.

1.3 Problem statement

The challenge facing irrigated agriculture is to utilize limited water resources more sustainably, given variability in seasonal precipitation, potential climate change impacts and competition for water among users. To improve agricultural water use in Canada, more accurate methods for estimating irrigation water demands across Canada's diverse regions are necessary. Also, a comprehensive assessment of the yield, water use efficiency and physiological response of the test crop (bell peppers) in particular soil

types, using a particular production system and irrigation regime is needed. Bell pepper is a valuable and water sensitive crop grown in the greenhouse and field in Canada. Furthermore, the irrigation water demand model is better developed with local data and its irrigation scheduling process is improved by incorporating plant water status indicators into the model.

1.4 Research objectives

The goal of the research was to develop irrigation management protocols that will lead to improved irrigation decisions (allocation, application and optimisation). This study is expected to provide a decision tool that will assist irrigators and water managers in determining reference evapotranspiration (ET_o), crop water requirement (CWR), irrigation water requirement (IWR) and irrigation scheduling for more effective water allocation and application.

The goal of the study was achieved through the following specific objectives:

1. Evaluate the suitability of solar radiation (R_s) estimation methods and their effect on ET_o estimation in Canada,
2. Investigate the effects of irrigation levels and soil types on yield and water use efficiency of greenhouse grown bell peppers and establish their crop water stress index baselines,
3. Determine available soil water content thresholds and crop water stress index baselines for timing irrigation in the field grown bell pepper,
4. Evaluate the effect of fixed, varied surface resistance and elevated CO_2 , on bell pepper water requirements,
5. Develop and evaluate an integrated climatic/plant physiological based irrigation management model for water allocation/application.

1.5 Scope

This study involved greenhouse and field experiments, estimation of solar radiation (R_s) and reference evapotranspiration (ET_o) using locally calibrated coefficients and of

irrigation water requirements for the purpose of improving water use efficiency in irrigated agriculture. R_s and reference evapotranspiration (ET_o) components were developed, tested and evaluated with weather stations in Quebec, Ontario, Manitoba, Alberta, Saskatchewan and British Columbia. The greenhouse and field experiments, and irrigation water requirements studies are crop and location specific. The study provided information on irrigation management protocols for the optimal production of bell peppers in southern Quebec. The protocols are transferable to different locations; however, it is important to note that irrigation scheduling decisions are local and therefore, local crop coefficients, soil and climate must be taken into consideration before it can be adopted in other locations.

1.6 Thesis organisation

This thesis has been developed as a collection of manuscripts (Chapters 3,4,5,6,7,8).

This thesis is presented in 9 chapters:

- Chapter 1 General introduction, problem statement and objectives.
- Chapter 2 Literature review of irrigated agriculture in Canada, vegetable production with emphasis on bell pepper, irrigation water demand estimation and irrigation scheduling. A review of crop water demand estimation methods and inputs (solar radiation estimation, reference evapotranspiration and effective precipitation estimation methods) were discussed. The impacts of climate change on irrigation requirements were discussed. Also reviewed were the agricultural water demand models.
- Chapter 3 Evaluation of solar radiation estimation methods and their effect on ET_o estimation in Canada.
- Chapter 4 Response of greenhouse grown bell pepper to variable irrigation
- Chapter 5 Effects of irrigation levels and soils on yield and physiological response of bell pepper.
- Chapter 6 Available soil water content thresholds and crop water stress index for field grown bell pepper was determined

- Chapter 7 The effects of fixed and varied canopy resistance and elevated CO_2 on bell pepper requirements were discussed.
- Chapter 8 This chapter presented the development of an integrated agricultural water demand model (IAWDM). The validation and accuracy of the model with field data and the CROPWAT model were presented.
- Chapter 9 Contains summary and conclusions from this research. The contributions to knowledge and recommendations for future research are also presented.

Chapter 2 Literature review

2.1 Irrigated agriculture in Canada

In 2006, agriculture and the agri-food system contributed \$87.9 billion to Canada's Gross Domestic Product (GDP), representing 8% of the Canadian economy and employed 2.1 million people (AAFC, 2008), making it one of the largest economic sectors in the country. Of Canada's 67.5 million ha of agricultural land, 36.4 million ha is cropland, but only 858 020 ha (representing 2.5% of the total cropped lands) are irrigated (Table 2.1). In 2010, gross farm receipts for irrigated agriculture were \$51.1billion (Statistics Canada, 2011). About 15% of this irrigated land area was dedicated solely to field vegetable production. Cropping patterns and irrigation needs differ among the various regions of Canada. Whereas British Columbia has 14.5% of its cropland area irrigated, Alberta has the largest irrigated area, representing 67% of the national total of irrigated area (AAFC, 2011c; Statistics Canada, 2011) (Figure 2.1). About 75% of all agricultural water withdrawals in Canada take place on the Prairies, mainly for irrigation (Harker et al., 2008). The largest estimated amount of water used for irrigation is in Alberta (59% of the national total in 2010), followed by British Columbia (28%), Saskatchewan (5.4%), Manitoba (2.9%), and Ontario (2.4%). Other provinces use 2% or less of the national total. In 2010, most irrigation water volume in Canada (52%) went to field crops and tame forages (including barley and potatoes), followed by hay (31%), fruit and vegetables (9.3%), and pasture (7.3%) (Council of Canadian Academies, 2013). Irrigation in the Prairie provinces is mostly used for field crops, hay, and pasture, while in British Columbia and Ontario, it is mainly used for high value horticultural crops (fruit and vegetables) (Statistics Canada, 2011b).

Irrigation water demand is relatively low in eastern Canada in comparison to the western provinces (Figure 2.2) (Statistics Canada, 2011). This may be attributed to the smaller irrigated land base (approximately 100,000 ha) and the region's high annual precipitation rates (700-900 mm) which exceed evapotranspiration (500-600 mm) (OMAFRA, 2004). Total water demand for agricultural production in Quebec is estimated at 174.1million m³ per year. Aquaculture accounts for the largest component (42%), followed by the

livestock sector (32%) and crop production (26%) (AAFC, 2003). In Ontario and Quebec, water for agriculture comes from a combination of surface water and groundwater sources (de Loë and Moraru, 2004). Certain parts of both provinces have experienced constraints on water supply from competing uses as well as issues with water quality related to agricultural production (AAFC, 2003a; de Loë and Moraru, 2004). The variability of rainfall events requires the application of supplemental irrigation to meet crop water demands.

2.2 Vegetable production

Vegetables make a significant contribution to the dietary needs of the world's population, because they provide good sources of protein, vitamins and minerals (Peet and Wolfe, 2000). Sweet peppers have become extremely popular for their high antioxidant content (Deepa et al., 2007). The annual worldwide production of peppers in 2010 has been estimated at 27.5 million tonnes with a total production area of about 1.7 million ha (FAOSTAT, 2012).

Vegetable crops are an important component of Canada's agricultural industry. In 2012, the farm gate value for field vegetable production in Canada which takes place on 101 489 ha was \$800 million. Greenhouse vegetables occupy about 1255 ha and accounts for a farm gate value of about \$1041 million (Statistics Canada, 2014). Of this production, bell peppers (*Capsicum annuum* L.) cover 1875 ha of field and have a value of \$33.4 million. Ontario and Quebec account for 83.2% of the total vegetable area in Canada. Ontario ranked first with 48% of the total vegetable farms in Canada, followed by Quebec (35%) and British Columbia (6%) (Table 2.2). Ontario has the largest number of greenhouse vegetable farms, accounting for 64% of all greenhouse vegetable farms in Canada, followed by British Columbia(23%), Quebec (7%), and Alberta (5%) because these provinces are close to the US market and have good climate (Agrifood-Canada, 2001). Vegetable sales in Canada amounted to \$847 million in 2012, representing an 8.5% increase from 2011. Most of Canada's vegetable production is marketed domestically as fresh produce, with a smaller proportion sold as processed products.

Vegetable production in the province of Quebec occupied 27 872 ha, about 13 705 ha of which was dedicated to irrigated vegetable crops concentrated mostly in the Montérégie and Lanaudière regions. About five hundred thousand metric tonnes of vegetables, with a farm gate value of \$252 million, were produced in Quebec in 2010 (Statistics Canada, 2011). Of this, 13 779 tonnes were peppers produced on 493 ha with a farm gate value of \$13.5 million. Bell peppers (*Capsicum annuum* L.) are a major greenhouse and field vegetable grown for the fresh and processing markets, accounting for 37% of the Canadian greenhouse vegetable exports (Statistics Canada, 2011). Field grown bell peppers are produced in warm summers in southern regions of Ontario, Quebec and British Columbia. In 2002, Canada was second to Mexico in volume (17.1%) and value (\$71,417 million) of bell peppers sold to the United States (Jovicich et al., 2005).

Bell pepper (*Capsicum annuum* L.) was chosen as the test crop in this study because of its high market value and susceptibility to water stress (Bosland and Votava, 1999). Many studies have reported a reduction in yield of bell peppers as a result of water stress (Delfine et al., 2001; Antony and Singandhupe, 2004). Warmer temperatures cause more evaporation, thereby, affecting the time of day irrigation water is applied, the soil moisture status and consequently, plant physiological processes (Russo, 2011). Adequate information on the effects of irrigation applications on bell pepper production will help growers improve efficiency and profitability.

2.2.1 Bell pepper production

High value vegetables grown in Canada require irrigation to meet evapotranspiration demands (Bernier et al., 2010). The bell pepper plant is highly sensitive to water stress and performs well with adequate supplies of water during its growth cycle (Gonzalez-Dugo et al., 2007; Ferrara et al., 2011; Zotarelli et al., 2011; Yildirim et al., 2012). Higher yields are obtained under rainfed conditions with rainfall ranging from 600 to 1250 mm and well distributed over the growing season. Heavy rainfall cause flower shedding and poor fruit setting during the flowering period and blossom end rot (BER) during the ripening period (Doorenbos and Kassam, 1979). Excessive nitrogen fertilization leads to rapid shoot growth. If rapid shoot growth is occurring simultaneously with fruit set and

growth, then BER could result, because Calcium (Ca) is preferentially moved to the growing leaves as opposed to the fruits. Inadequate irrigation could predispose the fruits to Ca deficiency and BER. The management of irrigation for bell pepper plants differs with respect to pepper varieties, length of growing cycle, soil type, environment, climatic region, irrigation type and irrigation scheduling (Dalla Costa and Gianquinto, 2002; Sezen et al., 2006; Ezzo et al., 2010). Therefore, there is a need for a comprehensive assessment of the yield, water use efficiency and physiological response of the plant to a particular soil type, production system and irrigation regime. The information from this assessment will be integrated and used to develop an irrigation water management model.

2.2.2 General characteristics of bell peppers

Bell pepper is the common name for a cultivar group of the species *Capsicum annuum*, widely cultivated for its edible, bell-shaped fruits. It belongs to the family of Solanaceae (also known as the nightshade family) and genus *Capsicum*. Pepper plants demand warm weather, sunshine and water because of their extreme sensitivity to water stress. Bell peppers are one of the most widely eaten vegetables in the world because they can be eaten fresh or in multiple processed forms and they are an excellent source of nutrients and antioxidants (Table 2.3). Several cultivars are grown in the greenhouse or in the field. Fresh-market varieties grown in greenhouses are generally indeterminate (continuous fruiting over growth season) while most of the varieties grown in the field are determinate (fruiting all at once). The plant reaches 0.5–1.5 m (Allen et al., 1998) depending on the cultivar. Single white flowers bear fruits which are green when unripe, changing principally to red but also orange, yellow or purple on ripening.

Sweet peppers are plump, bell-shaped vegetables having three to five lobes. The size usually ranges from 5 to 13 centimetres in diameter, and 5 to 16 centimetres in length. Inside the thick flesh is an inner cavity with edible bitter seeds and a white spongy core. Bell peppers are valued for their nutritional value, (vitamin C and natural antioxidants) taste and decorative colours (Perez-Lopez et al., 2007). Bell peppers are one of the vegetables that has a high Vitamin A content due to its high β -carotene and β -cryptoxanthin concentrations (Stahl and Sies 2003). The level of ascorbic acid in peppers

can vary according to cultivar, stage of maturity, growing conditions (Perez-Lopez et al., 2007; Serrano et al., 2010) and postharvest handling (Sakaldas and Kaynas, 2010). These antioxidants work together to effectively neutralize free radicals, which can travel through the body causing damage to cells (Knekt et al., 2002). Red bell peppers are a good source of lycopene, a carotenoid whose consumption has been inversely correlated with the incidence of gastric and esophageal cancer (Mateljan, 2007).

Kader (1999) defined fruit quality as a combination of attributes, properties, or characteristics that give each commodity value in terms of human food. Determinants of bell pepper quality include the characteristic parameters of colour (related to chlorophyll and carotenoid content), firmness, soluble solid, dry matter, and vitamin C content. The relative importance of each quality component depends upon the commodity and its intended use either as fresh or processed, and varies among producers, handlers, and consumers. To producers, a given commodity must have high yield and good appearance, must be easy to harvest, and must withstand long-distance shipping to markets, while the appearance, firmness, and shelf-life are most important from the point of view of wholesalers and retailers. Consumers, on the other hand, judge quality on the basis of appearance, freshness and firmness; hence, the consumer's satisfaction depends on previous experience of flavour during consumption. Consumers are also concerned about the nutritional quality; they want a good source of energy, vitamins, minerals, dietary fibres and bioactive compounds that enhance human health.

2.2.3 Bell pepper's climatic and water requirements

Peppers are warm-season crops, sensitive to frost and cold weather and as such, they are generally not transplanted until mid-June. Bell peppers are tolerant of a wide range of temperatures. The minimum soil temperature for seed germination is 15°C with a maximum of 35°C (optimum range of 18 to 35°C). Best growth and quality occurs at an optimal temperature range of 21 to 24°C (minimum of 18°C and a maximum of 26°C) (Garton and Bodnar, 1991). Higher yields are obtained when daily air temperature ranges between 18 and 32 °C during fruit setting (Bosland and Votava, 1999). Persistent, high

relative humidity and temperatures above 35°C result in reduced fruit setting and excessive blossom drop.

Bell peppers are shallow to medium rooted crops and are very sensitive to variations in soil moisture; the extent depends on the type of soil. Field moisture has to be carefully monitored throughout the crop growth to prevent excess soil moisture; this might lead to oxygen deprivation and/or moisture deficit, which might result in blossom end rot and possibly, fruit abortion. Capsicums extract 70–80% of water used from a depth of 0–30 cm (Dimitrov and Ovtcharova, 1995) because most of the roots are concentrated within this depth. Bell peppers, like other high value horticultural crops in Canada, rely on supplemental irrigation to sustain their cultivation and to improve yield (Madramootoo et al., 2006). However, the depth of irrigation depends upon the soil type and stage of crop growth. In clay soil, the depth of irrigation may be 6-8 cm while in sandy soil; it may be 4-5 cm. At the peak period of irrigation (90-120 days after transplanting), the evapotranspirative demands are higher; during this period, plants require more water. A general rule is that vegetables need about 2.5 cm of water per week from rain and/or supplemental irrigation in order to grow vigorously. DeWitt and Bosland (1993) indicated that, in the southern United States, peppers require 2.5 to 3.8 cm of water weekly.

2.3 Irrigation water demands and scheduling

Irrigation scheduling ascertains when to irrigate the crop and how much water (time and quantity) to apply (Thompson et al., 2007). Several irrigation scheduling models using soil water balance calculation/meteorological approach, (Allen et al., 1998), evaporation pan measurements (Doorenbos and Pruitt, 1975), soil moisture measurements (Dane and Topp, 2000), or crop water stress index irrigation (*CWSI*) (Cremona et al., 2004) are available. Presently, irrigation scheduling using plant water indicators is limited.

Good irrigation scheduling involves applying water at the right time and in the right quantity in order to optimise production and minimise adverse environmental impacts. FAO-56 defines the irrigation water requirement for a well watered crop as the depth of water needed to meet water loss through evapotranspiration of a disease-free crop under

non limiting soil conditions (Allen et al., 1998). Bad irrigation scheduling, on the contrary, involves a situation whereby enough water is either not applied or is applied at the wrong time, thereby, resulting in under-watering, or too much is applied which results in over-watering (Andales et al., 2011). Under-watering can lead to a reduction in yield and quality due to water stress while over-watering can reduce yield and quantity due to an increase in vegetative growth and leaching of nutrients away from the root zone.

Appropriate methods of irrigation scheduling are necessary to improve water use efficiency, especially when faced with rising competition between the environment and the various end-users of water resources (Jones, 2004b). Generally, irrigation scheduling techniques are divided into four categories: a soil moisture based approach involving direct measurements of soil moisture (e.g. with neutron probes, capacitive or TDR-type sensors, tensiometers; Smith and Mullins, 2001), soil water balance calculated from meteorological data (Allen et al., 1998), direct measurement of plant water status (Jones, 2004a) or remotely sensed data obtained using passive and active microwave, or radar techniques (Gardner et al., 2001).

2.3.1 Soil water balance approach

With the water balance approach to irrigation scheduling, the soil water deficit is tracked by accounting for all water additions (inputs) and subtractions (outputs) from the soil root zone. Major inputs are precipitation (p) and irrigation (I). Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone (Allen et al., 1998). Outputs include any form of water removal with the major removal being crop water consumption or crop evapotranspiration (ET_c) (Figure 2.3). Portions of p and I might be lost by surface runoff (RO) and by deep percolation (DP). DP losses increase depletion although this will eventually recharge the water table. The soil water balance approach is based on conservation of mass which states that the change in soil water storage (ΔS) of the root zone of a crop is equal to the difference between the amount of water added to the root zone (Q_i), and the amount of water withdrawn (Q_o) (Hillel, 1998) in a given time interval. This process is expressed in Eq. (2.1). Irrigation is required when ET_c exceeds the supply of water from both soil water and precipitation. The logic behind

the water balance method is to apply irrigation with a net amount equivalent to the accumulated ET losses since the last irrigation. This method can be used if initial soil water content in the root zone, ET_c , precipitation, and the available water capacity (AWC) of the soil are known. ET_c is often determined as the product of reference evapotranspiration (ET_o) and crop factor (K_c) with the ET_o calculated from climatic parameters. The initial soil water content can be assessed after a thorough wetting of the soil by irrigation or snow melts at the beginning of the growing season although only a percentage of this moisture content can be readily available to plants.

The soil in the root zone has an upper and a lower limit for storing water that can be used by crops. The upper limit is called the field capacity (FC), which is the amount of water that can be held by the soil against gravity after the excess water has been drained. This is typically attained after 1 day of rain or irrigation for sandy soils and from two to three days for heavier-textured soils that contain more silt and clay (Andales et al., 2011). The lower limit is called the permanent wilting point (PWP), which is the soil moisture level at which plants can no longer absorb water from the soil. The available soil water content (AWC), or total available water, of the soil is the amount of water between these two limits ($AWC = FC - PWP$). An irrigator usually will set a management allowable depletion level (MAD), which is used as a trigger to irrigate and prevents soil from reaching the yield threshold depletion level. This may be based on a percentage of available water.

$$\Delta S = Q_i - Q_o \quad [2.1]$$

Expanding Eq 2.1 becomes

$$SW_2 = SW_1 + I + R - ET_c - DP \quad [2.2]$$

Where Q_i : inflow, Q_o : outflow, SW_1 and SW_2 : beginning and ending total available soil water contents (mm), respectively, I : irrigation (mm), R is the effective rainfall or precipitation since yesterday (mm), ET_c : calculated crop water use, or evapotranspiration (mm d^{-1}) and DP : deep percolation or drainage out of the root zone (mm).

2.3.2 Soil moisture measurements

Measuring soil water is very important for determining the amount of water required to bring the soil water in the crop root zone to field capacity for an irrigation scheduling regime. Soil water content measurement methods include the gravimetric and indirect (instrumental) methods (Charlesworth, 2005). The indirect methods measure other properties of the soil that vary with water content and relate it to the soil water content through calibration. There are various indirect soil-water measurement tools available, most of which must be calibrated for the soil in which they are used. In this study, the method of determining soil moisture content by the different techniques is described with attention given to the gravimetric, time-domain reflectometry (*TDR*) and frequency domain (Capacitance) techniques, in particular.

2.3.2.1 Gravimetric method

This is the oldest; most widely adopted and frequently used direct method of soil moisture measurement (Charlesworth, 2005). The gravimetric method is the most satisfactory method for many problems requiring onetime moisture-content data and for calibrating the equipment to be used in the other methods (Johnson, 1962). These methods often serve as references rather than a means for irrigation scheduling. The gravimetric method involves collecting a soil sample, weighing the sample before and after oven drying (for 24 hours), and calculating its original moisture content. This moisture content is usually expressed as the ratio of the mass of water present in the soil sample to the dry weight of the soil sample, or on a volume basis, as the ratio of the volume of water in the sample to the total volume of the soil sample (Hillel, 1982).

The measurement of the gravimetric soil moisture content by weight (g water per 100 g soil) only requires auger sampling while volumetric soil moisture content (cm^3 water per 100 cm^3 soil) requires the use of sampling cylinders of known volume to calculate soil bulk density (g cm^{-3}). This method, which involves sampling (especially from depths greater than a few cm), transporting and repeated weighing, is laborious and time consuming. The accuracy of this method depends on the accuracy of sampling and

drying. Errors might be introduced as the soil corers tend to compress the soil to some extent resulting in incorrect volumetric water content calculations (Bell, 1987). Variations in moisture content can be observed as soils are normally variable within an experimental area and two samples cannot be collected from the same point. The oven drying process is arbitrary as some clay may retain appreciable water at 105°C. Also, some organic matter oxidizes and decomposes at this temperature and, therefore, the weight loss may not be entirely due to the evaporation of water. Generally, errors can be minimised by increasing the size and number of samples. However, the sampling procedure occasionally alters the area of the experiment as a result of trampling of the vegetation or by making numerous holes. Many researchers prefer indirect methods, which once installed and calibrated (using the gravimetric method as a reference), permit repeated or continuous measurements of soil water content at the same points with minimal time and labour inputs and little soil disturbance (Hillel, 1998).

2.3.2.2 Indirect methods

Indirect water content measurement requires the installation of instrumentation and soil moisture based sensors in the soil profile. These measurement methods can be broadly categorized into two measurement systems: one that measures soil suction (i.e., soil matric potential, ψ_m) and the one that measures volumetric water content (θ_v) (Charlesworth, 2005). Tensiometers and resistance blocks measure the energy status (water potential) of the soil water, indicating its availability for plant uptake, while instruments such as the neutron probe and dielectric sensors including the time domain reflectometry (*TDR*) and frequency domain reflectometry (*FDR* or capacitance) measure the volumetric soil moisture content (Jones, 2008). Soil moisture sensors that provide volumetric information are useful in most irrigation scheduling applications when the objective is to apply a volume of water that returns the soil moisture content to its original well-watered state (Jones, 2008). The water content reflectometer (Campbell Scientific Inc., UT) was used in this study. Some of the indirect soil moisture measurement methods are discussed below.

a) Tension measurement systems

Tensiometers

The tensiometer consists of a porous ceramic cup, connected through a transparent tube to a pressure-measuring device. The tube is filled with water and it is air tight; the water moves through the porous cup to equilibrate with the moisture in the surrounding soil. As the soil dries, the water is lost from the tensiometer via the ceramic cup and creates tension that is reported as a pressure reading. Water, on the contrary, returns to the cup as the soil becomes wetter resulting in less tension and a drop in the pressure reading. To determine the moisture content with a tensiometer, the relation between moisture tension and moisture content must be known. The tensiometer can be replaced, or reset, by refilling the tube. During installation, it is important for the soil to be thoroughly saturated before sealing the tube and placing it in the soil (Prichard et al., 2004). Water flows in and out of the tensiometer if only the porous crop is saturated with water, if the cup desaturates little or no flow occurs, and air enters the tensiometer. The tensiometer stops operating. This method is most useful for measuring the moisture content of tensions of 0-75 kPa.

Electrical resistance

Another indirect way to measure tension is by measuring the soil's electrical resistance. The electrical-resistance "blocks" operate on the principle that resistance to the passage of an electrical current between two electrodes buried in the soil will depend upon the moisture content of the soil. Compared to tensiometers, resistance blocks have a wider working range (0 to 200 kPa), i.e., they can operate in soils that are far drier (Thompson et al., 2006). When buried in the soil, the porous material of the block readily absorbs or releases moisture so that the moisture content of the block tends to stay in equilibrium with the moisture content of the soil. These moisture-content changes cause a change in electrical resistance which is measured by a meter at the surface. The resistance read on the meter is converted to moisture-content values by means of a calibration chart which is a chart prepared by the correlation of gravimetric moisture-content values and resistance readings for the soil in which the blocks are buried. Laboratory calibration consists of

drying and intermittently weighing soil cores in which the blocks have been inserted. Field calibration consists of taking gravimetric samples as close as possible to blocks that have been buried in the field, and relating the moisture content of the sample to the measured resistance.

b) Soil dielectric systems

The dielectric constant is a measure of the capacity of a non-conducting material to transmit electromagnetic waves or pulses. The dielectric of dry soil is much lower than that of water, and small changes in the quantity of free water in the soil have considerable effect on the electromagnetic properties of the soil water media. Time domain reflectometry (*TDR*) and frequency domain reflectometry (*FDR*) are two approaches developed for measuring the dielectric constant of the soil water media and consequently, the soil water content.

Time domain reflectometry (TDR)

This instrument determines the apparent dielectric (K_a) of the soil matrix and empirically relates it to the volumetric soil moisture content. The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. Time domain reflectometry (*TDR*) instruments, such as TRASE and Campbell, send a signal down steel probes, called wave guides, buried in the soil. The signal reaches the end of the probes and is reflected back to the *TDR* control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe. *TDR* is the most widely accepted dielectric technique for measuring volumetric water content (*VWC*) (Cassel et al., 1994; Jones et al., 2002) because of its performance in mineral soils (Topp et al., 1980) and its ability to measure both water content and bulk electrical conductivity (*EC*) in the same soil volume (Nadler et al., 1991; Castiglione and Shouse, 2003).

Water content reflectometer

The water content reflectometer (*WCR*) employs the principles of time domain reflectometry to calculate moisture within the soil (Campbell Scientific., 2006). However, the measurement frequency for the *WCR* is generally between 15 and 45 MHz (Seyfried

and Murdock, 2001), whereas the effective measurement frequency for *TDR* is up to about 1 GHz (Or and Wraith, 1999). The probe consists of two 30 cm long stainless steel rods forming an open-ended transmission line. A differential oscillator circuit is connected to the rods, with an oscillator state change triggered by the return of a reflected signal from one of the rods. The two-way travel time of the electromagnetic waves that are induced by the oscillator on the rod varies with changing dielectric permittivity. Water is the main contributor to the bulk dielectric permittivity of the soil or porous media, so the travel time of the reflected wave increases with increasing water content and decreases with decreasing water content. The probe rods can be inserted from the surface or the probe can be buried at any orientation to the surface.

Frequency domain reflectometry

Frequency domain reflectometry (*FDR*) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. This explains the term ‘capacitance’, which is commonly used to describe what these instruments measure. When a voltage is applied to the electric plates a frequency can be measured. This frequency varies with the soil dielectric. The probes usually consist of two or more electrodes (i.e., plates, rods, or metal rings around a cylinder) that are inserted into the soil. On the ring configuration, the probe is introduced into an access tube installed in the field. Thus, when an electrical field is applied, the soil around the electrodes (or around the tube) forms the dielectric of the capacitor that completes the oscillating circuit. Changes in soil moisture can be detected by changes in the circuit operating frequency. The use of an access tube allows for deployment of multiple sensors to take measurements at different depths.

2.3.3 Plant-based irrigation scheduling

Proper monitoring of plant water stress is required for efficient scheduling of irrigation (Yazar et al., 1996). By measuring the appropriate plant parameters, one can evaluate a plant's general health and use that information to make a decision about when to irrigate (Reginato and Howe, 1985). Neither soil water status nor the atmospheric demand accurately represents the plant water status as well as the plant itself. However, plant

methods typically indicate only when to irrigate, implying that soil moisture measurements or other estimation procedures must be used to determine how much water to apply to optimize crop water use (Nielsen, 1990; Stockle and Dugas, 1992). The response of a plant to the combined effects of soil moisture availability, evaporative demand, internal hydraulic resistance and resistance/uptake capacity of the plant/root interface is principally measured in terms of the plant water status. These methods measure water loss either from a whole single plant or from a small group of plants. The plant water status can be determined by measuring either the tissue water status (i.e. potential or content) or the plant's response to a change in tissue water status (White and Raine, 2008). Plant based sensing is classified based on what the sensors are measuring; they may measure a direct physiological indicator (e.g. plant water status) or an indirect physiological plant response induced by changes in plant water status (e.g. leaf temperature, plant organ diameter or growth) (Remorini and Massai 2003).

Direct physiological indicators express relative water content (Bennett, 1990) or leaf water potential (Scholander et al., 1965; Meyer and Green 1980). Direct measurements of the plant's water status would appear to be superior to soil and meteorological methods as the plant responds to both its aerial and soil environments (Jones 2008; Wanjura et al., 2006). Measurement of plant water status is generally done with a pressure chamber. There are also a variety of sensors which indirectly measure the plant water status by measuring the tissue water content of the plant (leaf, fruit or stem). Tissue water content sensors measure changes in the structure of a particular plant component. Sensors include dendrometers (Sheriff, 1976), stem micro-variation (diameter) sensors (Molz and Klepper, 1973), linear variable differential transformer gauges (Higgs and Jones, 1984), beta gauges (Klepper et al., 1971), and leaf thickness sensors (White and Raine, 2008).

Indirect physiological indicators describe the processes induced by changes in plant water status, including variations in stomatal conductance, leaf temperature, and plant organ diameter. Plant response sensors include those which measure a change in the plant that is related to a change in water status and include tools such as sap-flow sensors, porometers (ie. measures stomatal conductance) and thermal infrared guns (i.e. measures canopy

temperature). One method of assessing crop water stress conditions is the use of canopy temperature (T_c) that has been shown to reflect subtle changes in physiological processes such as cell growth and biochemical reactions associated with the damaging effects of super-optimal temperature (Conaty, 2010).

2.3.3.1 Canopy temperature (T_c)

Widmoser (2010) observed that the difference between canopy surface temperature and air temperature ($T_c - T_a$) is in some way related to plant water stress. The $T_c - T_a$ was first studied by Ehrler (1973), who investigated the possibility of using $T_c - T_a$ as a guide for irrigation scheduling. He found that the canopy-air temperature decreased after irrigation, reaching a minimum several days following irrigation, and then increased as soil water became increasingly depleted. The linear relationship between $T_c - T_a$ and vapour pressure deficit (VPD) led Ehrler (1973) to conclude that $T_c - T_a$ has potential as an irrigation scheduling tools. Idso et al., (1981a) further observed a linear relationship between canopy temperatures (measured using infrared thermometer (IRT)) and air temperature and vapour pressure deficit (VPD), which they used to develop an empirical method for quantifying crop water stress. Jackson et al., (1981) also conducted a theoretical research to develop a crop water stress index ($CWSI$). Jones (2004) confirmed that irrigation scheduling can be improved by monitoring crop canopy temperature using IRT . The availability of precise, handheld IRT allow rapid monitoring of canopy temperature to identify crop water stress (Colaizzi et al., 2003; Peters and Evett, 2007) for irrigation timing and automatic scheduling (Irmak et al., 2000).

Crop water stress index ($CWSI$)

$CWSI$ is calculated from plant canopy temperature (T_c), air temperature (T_a) and atmospheric vapor pressure deficit. This approach is based on the principle that transpiration cools the leaf surface and as water becomes limited, stomatal conductance and transpiration decrease, leading to increases in leaf temperature. However, given that ambient conditions can have a large influence on canopy temperatures, canopy temperatures are in fact a reflection of both plant and environmental factors (Jones, 2008; Conaty, 2010). Empirical (Idso et al., 1986) and theoretical (Jackson et al., 1988) $CWSI$

approaches have been proposed to estimate the lower limiting canopy temperature (T_c). The empirical CWSI uses two baselines (non-water stressed and water stressed). The lower baseline represents canopy temperature (T_c) - air temperature (T_a) (denoted as $T_c - T_a$) of a well-watered crop transpiring at the maximum potential rate while the upper baseline represents $T_c - T_a$ of a non-transpiring crop. The plot of ($T_c - T_a$) and air vapour pressure deficit (VPD) under fully watered and water stressed crop that was used to determine the non-water stressed and maximum stressed baselines respectively is used to quantify crop water stress (Figure 2.4). The empirical CWSI does not account for net radiation and wind speed whereas the theoretical method is estimated based on net radiation and the aerodynamics resistance factor. O'Toole et al., (1984) conducted a study to assess eight different methods, namely, leaf water potential, leaf diffusive resistance, transpiration rate, photosynthesis rate, canopy temperature, canopy-air temperature, CWSI and leaf rolling score for assessing plant water status and concluded that CWSI was the best technique. Yuan et al., (2004) also stated that the CWSI is the most frequently used index to quantify crop water stress based on the canopy surface temperature. CWSI is a sensitive plant water stress index. It is a valuable tool for making irrigation decisions along with soil water measurements

CWSI has been widely used as a tool to indicate plant water status and for scheduling irrigation in many crops (Cremona et al., 2004; Erdem et al., 2010; Yildirim, 2012). Nonetheless, for CWSI to be an effective tool for scheduling irrigation predicting yield, it has to be determined for particular crops in specific climates, given that crop response to water stress depends on local environmental conditions (Orta et al., 2003). The application of CWSI in irrigation scheduling has been evaluated for different crops, including vegetables (Erdem et al., 2006; Köksal, 2008; Erdem et al., 2010). The physiological responses of plants to water stress and their relative importance for crop productivity vary with species, soil type, nutrients and climate (Orta et al., 2003; Akıncı and Lösel, 2012). Greater understanding of the interactions between CWSI, water applied, yield and stomatal conductance would be beneficial for irrigation scheduling.

$$CWSI = \frac{[(T_c - T_a) - (T_{nws} - T_a)]}{[(T_{dry} - T_a) - (T_{nws} - T_a)]} \quad [2.3]$$

Where T_c : canopy temperature ($^{\circ}\text{C}$), T_a : air temperature ($^{\circ}\text{C}$), T_{nws} : non-water stressed canopy temperature ($^{\circ}\text{C}$), T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$).

$$T_{nws} = \text{Intercept} + \text{Slope}(\text{VPD}) \quad [2.4]$$

$$T_{dry} = \text{Intercept} + \text{Slope}(VP_{sat}(T_a) - VP_{sat}(T_a + \text{Intercept})) \quad [2.5]$$

Where VPD: vapour pressure deficit (kPa), $VP_{sat}(T_a)$: saturation vapour pressure at air temperature (kPa), T_{nws} : non-water stressed canopy temperature ($^{\circ}\text{C}$), T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$) (terms are shown in Figure 2.4).

2.3.3.2 Advancements in CWSI applications

Phene et al., (1990) predicted that sensors placed in the soil, or on plants, could provide information to determine precisely when to irrigate. According to these researchers, connecting these sensors to computers, will not only lead to the calculation of an index of stress, but also automatic activation of the irrigation system to apply the correct amount of water and fertilizer to high-value crops where water costs are high and supplies are limited. Irrigation scheduling has advanced considerably in the past 20-30 years with improved technology to measure soil or plant water status, including the utilization of remote sensing tools within the past 10-15 years (Howell et al., 2009). Howell et al., (2009) stated that some of the approaches that have great potential for commercial application include:

- (a) Scheduling irrigation with a fixed amount of water whenever a threshold criterion (trigger point) is generated by a CWSI estimated using the remotely sensed crop canopy temperature (T_c) and local weather data.
- (b) Scheduling irrigation with a fixed amount of water whenever a threshold criterion is determined by the time-temperature threshold index ($TTTI$) reaching a crop and region-specific value. The $TTTI$ is calculated using crop canopy temperatures (T_c).

Stomatal conductance

Stomatal conductance (the speed or rate at which water vapor exits through the stomata of a leaf) regulates many plant processes (carbon dioxide assimilation, respiration, transpiration); like *CWSI*, it may be used to determine bell pepper water use, water status and response to growth environment. Stomata conductance is directly related to stomata opening and plant water status. Stomatal conductance of plants experiencing water stress can be correlated with changes in soil water in some plants, especially in isohydric crops such as *Capsicum annum L.* (cultivar Vau Maor) (Yao et al., 2001) but not in others. Isohydric characteristics are exhibited when plants have tight and continuous control of leaf water potential by root-to-shoot signalling of hydraulic and chemical interactions, thus, managing water loss through the stomata, particularly during the initial onset of water stress (Limpus, 2009). Jones (2008a) stated that measurements of stomatal conductance are sensitive to declining soil water and thus, water stress. The size of the stomata aperture is also sensitive to other environmental factors such as radiation, air temperature, wind velocity as well as leaf size (Jones et al., 2009; Scherrer et al., 2011).

2.4 Crop water demand estimation

Crop water requirements vary during the growing period, mainly due to crop growth, climatic conditions and irrigation methods. Water requirements for a given crop are the same as crop evapotranspiration (ET_c) because most of the water uptake by plants from soil is lost through evaporation from the soil and transpiration from the plants. In order to avoid the underestimation or overestimation of crop water consumption, knowledge of the exact water loss through actual ET is necessary for sustainable and environmentally sound water management.

ET_c quantification needs to be preceded by the determination of reference evapotranspiration (ET_o) (Lopez–Urrea et al., 2006). ET_o is computed for a grass or alfalfa reference crop which is then multiplied by a crop-specific coefficient with the objective of estimating ET_c for different crops relative to this reference rate (ET_o). The accuracy of computed ET_o is greatly influenced by weather parameters which may be

lacking, or vary as a result of natural process/greenhouse gas emissions or are inaccurate (data errors). The use of inaccurate ET_o for crop water requirements and irrigation demand estimation will result in misapplication of water (Amayreh and Al-Abed 2005; Coolong et al., 2012). Also, the economic value associated with applying the proper amount of water at the right time is worthy of consideration. For instance, a 1 mm loss of water through ET across 1 ha is equivalent to 10 m^3 (268,000 gallons) of water (Allen et al., 1998). Thus, if the grower overestimates the actual ET value by 1 mm, the farmer will have to pay needlessly for 268 000 gallons of water, and the groundwater will have wasted 268 000 gallons of water (in the case of groundwater abstraction). Increasing the efficiency of agricultural water management through optimization of irrigation scheduling is dependent on an accurate assessment of ET (Allen et al., 1998). The use of *FAO 56* and American Society of Civil Engineers Penman-Monteith (*ASCE PM*) equations for ET_o is restricted by the lack of input variables. In these cases, when data are missing, the option is to calculate ET_o by the *FAO PM* method using estimated input variables from other available meteorological data as detailed in the *FAO-56* report (Allen et al., 1998). Despite the robustness of this equation, errors can be introduced if the available data are of poor quality and the variables are approximated from a limited set of observations.

2.4.1 Solar radiation estimation methods

Solar radiation (R_s) is a key component of photosynthesis, evapotranspiration and an essential input variable to crop water requirements and irrigation scheduling, hydrological cycles and crop growth simulation models (Stöckle et al., 2003; Yang et al, 2006). R_s , air temperature, humidity and wind speed are the major parameters used for estimating ET_o . According to Samani (2000), more than 80% of ET_o can be explained by temperature and R_s . However, unlike air temperature and precipitation data, R_s data is not readily available (Liu and Scott, 2001; Weiss and Hays, 2004). The number of meteorological stations where solar radiation is observed is limited in many areas of the globe (Abraha and Savage, 2008; Droogers and Allen, 2002; Liu and Scott 2001). The number of stations where reliable R_s data exist is even smaller (Nonhebel, 1993; Hunt et al., 1998).

In Canada, for instance, R_s data is available in 10 out of the 301 stations in British Columbia, 3 of the 150 stations in Saskatchewan, 4 of the 110 stations in Manitoba, 4 of the 147 stations in Alberta, 9 of the 246 stations in Ontario and 9 of the 276 stations in Quebec. Moreover, the stations with long-term R_s records in Canada have gaps from several days to several months; that might be due to equipment failure or cloud cover.

There are also concerns about the accuracy of the measured R_s data (Droogers and Allen, 2002) because the pyranometer (the instruments for measuring R_s) is often subjected to stability errors. Samani (2000), for example, observed a drift of as much as 10% in R_s measurements with pyranometers. The non-availability and occasional questionable reliability of measured R_s data has been a concern prompting the development of several approaches for estimating R_s , such as, satellite-based methods (Pinker et al., 1994, 1995), single-layer and multi-layer radiative transfer models (Gueymard, 2001; Pawlak et al., 2004), artificial neural network (ANN) methods (Tymvios et al., 2005; Lam et al., 2008), interpolation (Elizondo et al., 1994; Reddy and Ranjan, 2003) and empirical models based on measured meteorological data (Ångström, 1924; Hargreaves et al., 1985; Hunt et al., 1998; Thornton and Running, 1999; Liu and Scott, 2001; Mahmood and Hubbard, 2002), whose accuracy still needs to be tested (Bandyopadhyay et al., 2008).

The empirical methods are the most popular in hydrological and agricultural studies, because of their low computational cost and accessible inputs (Liu et al., 2009). Essentially, two methods are widely adopted, namely: the sunshine based method (Allen, 1998; Iziomon and Mayer, 2002; Trnka et al., 2005) and temperature based methods (Hargreaves and Samani, 1982, 1985). In this study, the sunshine based (Ångström-Prescott, 1924) and temperature based (Hargreaves and Samani, 1982) methods were selected.

2.4.1.1 Sunshine based solar radiation model

A common feature of these models is the inclusion of the extraterrestrial radiation (R_a) term which accounts for latitude, solar declination, elevation, day length and atmospheric

transmissivity. Although the sunshine-based method is generally more accurate (Iziomon and Mayer, 2002; Trnka et al., 2005), it is often limited by the lack of sunshine records.

Ångström-Prescott

The most widely used sunshine based radiation method is the Ångström-Prescott method. Ångström (1924) proposed a linear relation between the ratio of average daily global irradiance to the corresponding value on a clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration. In 1940, Prescott suggested using extraterrestrial irradiance (R_a) to replace clear sky radiation (R_s) data, hence, the Ångström –Prescott equation (Eq. 2.6)

$$R_s = \left(a + b \frac{n}{N} \right) R_a \quad [2.6]$$

Where, R_s : global solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), a and b : Ångström -Prescott coefficients, n : average daily sunshine duration, N : maximum possible sunshine duration and R_a : extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

Martinez-Lozano et al., (1984) interpreted coefficient “ a ” as the fraction of R_a during a completely cloudy day (when $n = 0$), and “ b ” as the rate of increase of R_s/R_a with n/N , both vary from 0 to 1. This equation is recommended by Allen et al., (1998) and Doorenbos and Pruitt, (1977) to estimate R_s . The values $a = 0.25$ and $b = 0.50$ are recommended when these fractions are not calibrated using the location’s climatic data.

2.4.1.2 Temperature based solar radiation models

In order to resolve the problem of availability of sunshine data, Hargreaves (1981) and Hargreaves and Samani (1982) proposed the R_s equation (eq. 2.7, Table 2.4) using daily maximum (T_{max}) and minimum (T_{min}) temperatures. This model has undergone significant modifications by many researchers. Annandale et al., (2002), for example, introduced the effect of altitude (eq. 2.8, Table 2.4) in a multiplicative form of the model, which was applied by Fletcher and Moot (2007); this resulted in an accurate prediction of R_s . De Jong and Stewart (1993) (eq. 2.9, Table 2.4) introduced the effect of precipitation in a multiplicative form that was found to perform better than a model based on stochastic

weather generation (Hayhoe, 1998) but rated poorly by Liu and Scott (2001). Hunt et al., (1998) modified equation 2.4 by introducing precipitation and $T_{\max}$ in an additive form (eq. 2.10, Table 2.4). In spite of the various modifications and recommendations, the Hargreaves and Samani method continues to be the most widely used because of its relative accuracy and fewer data and coefficients requirements.

Hargreaves and Samani

This methodology was based on the assumption that the difference in maximum and minimum temperatures ($T_{\max}-T_{\min}$) is directly related to the fraction of extraterrestrial radiation (R_a) received at the ground level (Hargreaves and Samani, 1982) (eq. 2.11, Table 2.4). This assumption could lead to a significant underestimation of R_s because other factors such as latitude, elevation/topography, storm patterns and proximity to a large body of water can influence the difference in maximum and minimum temperatures in a given location (Jagtap, 1991). Thus, there is a need to calibrate the K_{RS} coefficient (eq. 2.11) in order to minimise errors. Hargreaves and Samani (1985) suggested a value of 0.17 from 8 years of weighing lysimeter data from Davis, California. Hargreaves (1994) recommended K_{RS} values of 0.162 for interior regions and 0.19 for coastal regions. This approach is currently recommended by the Food and Agriculture Organization (FAO) for estimating R_s using the Hargreaves and Samani equation (Allen et al., 1998). Allen (1995) recommended a correction factor for K_{RS} considering the ratio of mean monthly atmospheric pressure to mean monthly atmospheric pressure at sea level (eq. 2.12, Table 2.4).

2.4.2 Evapotranspiration (ET)

Evapotranspiration (ET) also known as consumptive use, or actual evapotranspiration (AET), (Watson and Burnett, 1995) of a crop indicates the simultaneous process of transfer of water to the atmosphere by evaporation (E) from the soil surface and transpiration (T) from the crop. The evaporation component of ET is comprised of the water returned back to the atmosphere through direct evaporative loss from the soil surface, standing water (depression storage), and water on surfaces (intercepted water) such as leaves or roots (Hansen et al., 1980). The evaporation process is affected by the

shading of the crop canopy, irrigation management or the amount of water available at the evaporating surface. Transpired water is the water that enters the plant through the root zone, used for various biological functions including photosynthesis, and then leaves the plant through the leaf stomatal to the atmosphere (Hansen et al., 1980). Transpiration depends on radiation, air temperature, air humidity, wind terms, salinity and crop characteristics. Transpiration will stop if the vegetation becomes stressed to the wilting point, also known as the point at which there is insufficient water left in the soil for a plant to transpire (Watson and Burnett, 1995).

A related concept is that of potential evapotranspiration (*PET*), defined simply as the amount of water that would be lost from the surface to *ET* if the soil/vegetation mass had an unlimited supply of water available (Hansen et al., 1980, Dingman 1994, Watson and Burnett 1995). Since *PET* assumes that water availability is not an issue, vegetation would never reach the wilting point (Fontenot, 2004). Based on this, the only limit to the transpiration rate of the plant is the physiological state of the plant and not as the result of any atmospheric or soil moisture restrictions (Watson and Burnett 1995). Therefore, *PET* is considered the maximum *ET* rate possible with a given set of meteorological and physical parameters (Dingman 1994). This implies that applying water above *PET* will lead to waste.

ET is a required parameter for hydrological and agricultural projects (Maulé et al., 2006). In agricultural regions, efficient irrigation water management/practices require a good quantification of crop evapotranspiration (ET_c). Plant growth and productivity are directly related to the availability of water (Rosenberg et al., 1983). Weather parameters, crop characteristics, management and environmental aspects are factors affecting evaporation and transpiration. It is important to recognize the difference between potential evapotranspiration and reference evapotranspiration. Potential *ET* (ET_p) is the *ET* considered from a wet surface that is non-specific as to crop type while reference *ET* (ET_o) refers to the *ET* from a reference surface of a well watered crop with specific characteristics (Allen et al., 1998). *ET* (either *PET* or ET_o), being the most important hydrological variable, will reflect the effect of climate change (Cannarozzo et al., 2006;

Xu et al., 2006a) and can be measured directly, using weighing lysimeters or the eddy correlation technique, or indirectly, from changes in soil water or via the surface energy budget, using the conservation of mass and energy. However, this procedure is laborious, time-consuming, costly and involves complex instrumentation (Vaughan and Ayars, 2009; Brimelow et al., 2010); thus, many empirical methods continue to be used to estimate ET (Liu et al., 2009).

2.4.3 Reference evapotranspiration (ET_o)

PET is the ET that will occur if there is no deficiency in the water in the soil for use by vegetation. However, PET depends on vegetation-specific and not solely meteorological variables; thereby, a reference surface that is independent of vegetation and soil characteristics is needed (Jensen et al., 1990; Allen et al., 1998). This reference surface would allow for the analysis of the “evaporative demand of the atmosphere”, thus, leaving only meteorological factors to be considered (Jensen et al., 1990, Allen et al., 1998). This would simplify the calculation of ET by creating a single surface against which different vegetation types can be compared and eliminate the requirement to vary the ET equation at different stages of vegetative growth (Allen et al., 1998). This new form of ET is known as reference evapotranspiration (ET_o). ASCE-EWRI (2005) defined the ET_o as the rate of ET from a uniform surface of dense, actively growing vegetation having a specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of fetch distance. Other researchers (Doorenbos and Pruitt, 1977; Allen et al., 1998) defined reference evapotranspiration as the rate of evapotranspiration from an extensive grassed area of 8-15 cm tall, uniform, actively growing, completely shading the ground and with adequate water with a fixed surface resistance of 70 s m^{-1} and albedo of 0.23 (Figure 2.5). ET_o expresses the evaporative demand of the atmosphere independent of crop type, crop stage and management practices (Sentelhas et al., 2010).

Numerous ET_o equations have been developed and published (Dodds et al., 2005), which have created some confusion for practitioners regarding which equation to use. In May 1999, the Irrigation Association requested the ASCE Evapotranspiration Task Committee

(*ASCE-ET*) to define a benchmark ET_o equation (Walter et al., 2000; ASCE-EWRI 2005). The need for standardised methods to estimate evapotranspiration for a range of vegetated surfaces led the ASCE-ET task committee (TC) to establish a standard equation in order to bring commonality to the various ET equations and crop coefficients (K_c) by simplifying several terms within that equation. This was intended to establish uniform evapotranspiration (ET) estimates and transferable K_c . Two standardized reference surfaces were recommended: (1) a short crop (similar to grass) (ET_o) and (2) a tall crop (similar to alfalfa) (ET_r), based upon comparisons to lysimeter data and calculated reference evapotranspiration using 1982 Kimberly Penman, FAO-56 Penman, and ASCE Penman Monteith equations. This committee evaluated the performance of 12 ET equations using grass (short crop) as a reference crop (ET_o) and 8 ET equations having alfalfa (tall crop) as the reference crop (ET_r).

ASCE-ET found the equations (FAO-56 Penman Monteith with grass as a reference crop and ASCE Penman Monteith with alfalfa as a reference crop) to be sufficiently accurate (ASCE committee, 2000). FAO recommended grass as the primary reference surface for international use (Pereira et al., 1999) since there is more experimental data on grass, despite the fact that alfalfa has bulk stomatal resistance and exchange values that are similar to many agricultural crops. Currently, the standardized reference evapotranspiration equations have been recommended for use by the American Society of Civil Engineers (ASCE, 2005). This method is a variation of the Penman Monteith (PM) method and attempts to standardize the use of one method. The equation provides a recommended determination of reference ET for a well-watered short (ET_o), or tall (ET_r), grass surface.

2.4.4 Evapotranspiration (ET) models description

Evapotranspiration (ET) models have become essential tools in areas such as climate modelling, weather forecasting, crop yield forecasting and irrigation planning. Some of these models were based on temperature alone (Thornthwaite, 1948; Blaney and Criddle, 1950), pan evaporation (Christiansen, 1968), radiation and temperature (Jensen and Haise, 1963; Priestley and Taylor, 1972; Hargreaves and Samani, 1985), or a

combination theory-energy balance and aerodynamic transport of water vapor (Penman, 1948, 1963; Monteith, 1965; Allen et al., 1994 and 1998; Walter et al., 2000) (Table 2.5). Some of these equations are still in general use, though with modifications to suit different environments and data. In this mix, the equation of Penman (1948, 1963) was undoubtedly a benchmark (Farahani et al., 2007). Penman derived the “combination equation” by combining two terms, one of which accounted for the energy required to maintain evaporation, an “available energy” term, and the second for the atmosphere's ability to remove water vapor, an “aerodynamic” or “sink” term. A well-recognized simplification of Penman's equation was later introduced by Priestley and Taylor (1972) for humid environments, in which the aerodynamic term was set as equal to a fixed fraction (0.26) of the energy term. The significance of Penman's basic concept gained momentum in the 1960s when Monteith (1965) extended it to plant communities by explicitly recognizing the dependence of transpiration on canopy controls. Rearranging Monteith's original equation results in the formulation that has become known as the *PM-ET* equation or the Priestley-Taylor equation (Jury and Tanner, 1975).

In this study, *ET* estimates were made using weather data and the following methods:

- Modified Penman Monteith (short reference) method (*FAO-56 PM*):
- *ASCE* (tall reference) method;
- Hargreaves method and
- Turc method.

(a) *FAO-56 PM method*

The Penman Monteith equation was modified by FAO and hereafter referred to as the FAO-56 Penman Monteith (*FAO-56 PM*) equation. This method uses the concept of a reference surface/combination approach to calculate ET_o (Eq. 2.13). ET_o is determined for a hypothetical reference crop which closely resembles an actively growing grass surface of uniform height with adequate water and completely shading the ground. The surface has an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Figure 2.5) (Allen et al., 1998; Droogers and Allen 2002).

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} u_2\right)} \quad [2.13]$$

Where, ET_o : reference evapotranspiration (mm d^{-1}), R_n : net radiation at the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$), G : soil heat flux density (taken as zero for daily calculations) ($\text{MJ m}^{-2} \text{d}^{-1}$), T : mean daily air temperature at 2m height ($^{\circ}\text{C}$), u_2 : wind speed at 2 m height (m s^{-1}), r_s , r_a : (bulk) surface and aerodynamic resistances (s m^{-1}), e_s : saturation vapour pressure (kPa), e_a : actual vapour pressure (kPa), $e_s - e_a$: saturation vapour deficit (kPa), Δ : slope vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ : psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

The slope vapour pressure curve and the psychrometric constant are calculated following the method and procedure outlined in chapter 3 of *FAO-56* publication (Allen et al., 1998).

$$\Delta = \frac{4098 * \left(0.6108 * \exp\left(\frac{17.27 * T}{T+273.3}\right)\right)}{(T+273.3)^2} \quad [2.14]$$

$$\gamma = 0.000665 * P \quad [2.15]$$

Where P , the atmospheric pressure is calculated thus:

$$P = 101.3 * \left(\frac{293 - 0.0065 * z}{293}\right)^{5.26} \quad [2.16]$$

Where, z is elevation in metres.

Aerodynamic resistance (r_a)

Aerodynamic resistance (r_a) is the transfer of heat and water vapour from the evaporating surface to the air above the canopy (Allen et al., 1998). The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly irrigation frequency.

$$r_a = \frac{\ln \frac{z_m - d}{z_{om}} \ln \frac{z_h - d}{z_{oh}}}{k^2 u_z} \quad [2.17]$$

Where, r_a : aerodynamic resistance (sm^{-1}), z_m : height of wind measurements (m), z_h : height of humidity measurements (m), d : zero plane displacement height (m), z_{om} : roughness length governing momentum transfer (m), z_{oh} : roughness length governing transfer of heat and vapour (m), k : von Karman's constant, 0.41 (-), u_z : wind speed at height z (ms^{-1}).

The zero plane displacement height d and the roughness length governing momentum transfer, z_{om} can be estimated from the crop height h for a wide range of crops using:

$$d = \frac{2}{3} h \quad [2.18]$$

$$z_{om} = 0.123h \quad [2.19]$$

The roughness length governing transfer of heat and vapour, z_{oh} can be approximated by:

$$z_{oh} = 0.1z_{om} \quad [2.20]$$

(Bulk) surface resistance (r_s)

The 'bulk' surface resistance (r_s) describes the resistance of vapour flow through the transpiring crop and evaporating soil surface (Allen et al., 1998). An acceptable approximation to a much more complex relation of the surface resistance of dense full cover vegetation is given as:

$$r_s = r_1 / \text{LAI}_{\text{active}} \quad [2.21]$$

Where, r_s : (bulk) surface resistance (sm^{-1}), r_1 : is bulk stomatal resistance of a well-illuminated leaf (s m^{-1}), $\text{LAI}_{\text{active}}$: active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)].

Using the assumption of a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m ($z_m = z_h = 2$ m) in FAO-56

Penman Monteith equation in eq. 2.13, , the aerodynamic resistance r_a for the grass reference surface became;

$$r_a = \frac{208}{u_2} \quad [2.22]$$

Assuming that the stomatal resistance, r_s , of a single leaf has a value of about 100 s m^{-1} under well-watered conditions. By assuming a crop height of 0.12 m, the surface resistance, r_s for the grass reference surface became:

$$r_s = 70 \text{ sm}^{-1}. \quad [2.23]$$

From the original Penman-Monteith equation (Eq. 2.13) and the equations of r_a (Eq. 2.17) and r_s (Eq. 2.15), the modified *FAO-56* Penman Monteith equation is:

$$ET_o = \frac{0.408*\Delta*(R_n - G) + \gamma*\frac{900}{T+273}*u_2*(e_s - e_a)}{\Delta + \gamma(1+0.34*u_2)} \quad [2.24]$$

(b) ASCE (tall reference) method (ASCE Penman Monteith equations)

This method was developed by defining ET_o as the rate of ET from a uniform surface of dense, actively growing vegetation that is not short of water and represents an expanse of at least 100 m (ASCE 2005). This equation is physically based and provides a consistent and standardized definition of reference evapotranspiration for a tall reference surface.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{1600}{T + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.38u_2)} \quad [2.25]$$

Where the parameters are as defined in *FAO-56* equation (Eq. 2.13).

(c) Hargreaves and Samani equation

A major limitation to the use of *FAO 56* and *ASCE PM* equations is the requirement for detailed climatic data, some of which are estimated from other measured climatic parameters which might be of questionable quality. The desirability for an ET_o equation

with few and frequently measured input data led to Hargreaves equation in 1975. Using Alta fescue grass evapotranspiration data from a precision lysimeter and 8 years of weather data from Davis, California, Hargreaves performed regressions and observed, that for five-day time steps, 94% of the variance in measured ET could be explained through average temperature and R_s . This led him to propose Eq. 2.26. Hargreaves and Samani (1982) proved that the fraction of extraterrestrial radiation (R_a) that actually passes through the clouds and reaches the earth surface is the main energy source for ET and could be estimated by the difference between the maximum and minimum daily temperatures (Eq. 2.27). Based on Eqs. 2.26 and 2.27, Hargreaves and Samani (1985) developed a modified equation (Eq. 2.28), which is now commonly used. This model was adopted by *FAO* based on previous studies that assessed the performance of ET temperature methods (Jensen et al., 1990). The result of the assessment showed that ET_o can be estimated using the empirical Hargreaves–Samani (*H-S*) equation in areas where R_s or sunshine hours is not available (Allen et al., 1998, Hargreaves and Allen 2003).

$$ET_o = 0.0135R_s(T_{mean} + 17.8) \quad [2.26]$$

$$R_s/R_a = K_{RS}(T_{max} - T_{min})^{0.5} \quad [2.27]$$

$$ET_o = 0.408 * 0.0135K_T(T_{max} - T_{min})^{0.5}(T_{mean} + 17.8)R_a \quad [2.28]$$

Where, R_a : extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), T_{mean} : mean temperature calculated, T_{min} : minimum temperature, T_{max} : maximum temperature, Coefficient 0.408 converts from $\text{MJ m}^{-2} \text{ day}^{-1}$ to mm day^{-1} , K_{RS} : empirical coefficient.

(d) Turc method

The Turc model (1961) was developed in the Netherlands and has been used to some extent in the United States (e.g., Amatya et al., 1995; Irmak et al., 2003b). The equation has been found to compare well with *FAO-56* in humid areas, although it does not consider the effect of wind speed (Amayta et al., 1995; George et al., 2002; Irmak et al., 2003b; Nandagiri and Kovoov, 2006). The model calculates ET_o with air temperature,

relative humidity and solar radiation. Turc's equation was defined for use by Allen (2003) as:

$$ET_o = a_T 0.0133 \left(\frac{T_{mean}}{T_{mean} + 15} \right) 23.886 R_s \quad [2.29a]$$

Where, ET_o : reference crop evapotranspiration (mm day^{-1}), T_{mean} : mean air temperature ($^{\circ}\text{C}$), R_s : solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$).

The coefficient a_T is a humidity-based value. If the mean daily relative humidity (RH_{mean}) is greater than or equal to 50%, then $a_T = 1.0$. If the RH_{mean} is less than 50%, then a_T has the value:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \quad [2.29b]$$

2.4.5 Crop coefficient (K_c)

The concept of K_c was introduced by Jensen (1968) and further developed by other researchers (Doorenbos and Pruitt, 1977; Burman et al., 1980a, 1980b; Allen et al., 1998). The ratio of ET_c to the ET_o for a reference crop (short grass or alfalfa) is called crop coefficient (K_c) (Jensen, 1968). K_c relates crop water use at a particular development stage to the amount of ET calculated from weather data. The K_c methodology was adopted by the United Nations Food and Agriculture Organization (FAO) in the 1970s (Doorenbos and Pruitt, 1977). The use of ET_o (estimated using local climate data) and the associated K_c have since become an accepted way to estimate ET_c for well watered crops. K_c integrates the effects of characteristics that distinguish field crops from grass, such as crop type, height, stage of crop growth and climate.

K_c can be calculated in two forms, namely, as single K_c or as dual K_c . In the single K_c approach, a single crop factor is used for the crop transpiration rate and soil evaporation together. This approach expresses only the time-averaged effects of crop evapotranspiration (Eq. 2.30a). In the dual K_c approach, the effect of specific wetting events on the value of K_c and ET_c is determined by splitting K_c into two: basal crop

coefficient (K_{cb}) representing the transpiration of the crop and the soil water evaporation coefficient (K_e) which describes the evaporation component from the soil surface (Eq. 2.30b). In this approach, the single K_c coefficient is taken as the algebraic sum of K_{cb} and K_e . In both approaches, K_{cb} or K_c is multiplied by a coefficient K_s (range 0 to 1) to account for water stress. When there is adequate soil water available, i.e., no stress is imposed in plants, $K_s = 1$. K_s declines linearly to zero when all the available water in the rooting zone has been used. The basal crop coefficient, K_{cb} , is defined as the ratio of ET_c and ET_o when soil water evaporation is minimal, but soil water availability remains non-limiting to plant transpiration. As the K_c values include averaged effects of evaporation from the soil surface, the K_{cb} values are below the K_c values (Lazzara and Rana, 2010). K_c takes into account the differences in crop canopy and aerodynamic resistance relative to the reference surface, while the K_s takes into account the reduction of ET as a consequence of actual soil moisture.

The crop coefficients for both approaches are defined for different stages of growth (initial ($K_{c\ ini}$), crop development ($K_{c\ dev}$), mid season ($K_{c\ mid}$) and late season ($K_{c\ late}$) (Doorenbos and Kassam, 1979; Allen et al., 1998). The different growth stages are defined as follows:

- Initial (establishment): from sowing to 10% ground cover
- Crop development : from 10 to 70% ground cover
- Mid-season (fruit formation): including flowering and fruit set or yield formation
- Late-season: including ripening and harvest.

The single K_c approach is recommended for irrigation practice while the dual approach is recommended for research work (Allen et al., 1998). FAO-56 (Allen et al., 1998) presents a procedure to calculate ET_c using three K_c values ($K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ late}$) that are appropriate for the four general growth stages.

The values for $K_{c\ ini}$ in FAO-56 Table 12 (Doorenbos and Kassam, 1979)) are approximations that should only be used for estimating ET_c for planning purposes. $K_{c\ ini}$

accounts for management practices such as the time interval between wetting events, evaporation power of the atmosphere and magnitude of the wetting event. Allen et al., (1998) recommended using Figures 29 and 30 which provide estimates for $K_{c\ ini}$ as a function of the factors stated above for more accurate K_c estimates. Likewise, the values for $K_{c\ mid}$ and $K_{c\ end}$ in the FAO-56 report represent those for a sub-humid climate with an average daytime minimum relative humidity (RH_{min}) of about 45% and calm to moderate wind speeds, averaging $2\ ms^{-1}$. Allen et al., (1998) recommended a modification of the K_c for other climatic conditions using Eqs. 2.19.

$$ET_c = ET_o * (K_s * K_c) \quad [2.30a]$$

$$ET_c = ET_o * (K_{cb} K_s * K_e) \quad [2.30b]$$

Where, ET_c : crop actual ET ($mm\ d^{-1}$), ET_o : reference ET ($mm\ d^{-1}$), K_s : water stress coefficient, K_{cb} : the basal crop coefficient, K_e : soil water evaporation coefficient, K_c : crop coefficients.

$$K_{c,stage} = K_{c,stage(tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad [2.31]$$

Where, $K_{c\ stage}$ is the adjusted K_c for either the mid-season or late season, $K_{c\ stage(tab)}$ is the K_c for different growth stages (taken from FAO-56 table 12), u_2 is the wind speed taken at 2 m height (ms^{-1}), RH_{min} is the minimum relative humidity and h is the height of the crop.

2.5 Effective precipitation (rainfall)

A precise estimate of the quantity of rainfall that is useful over a period of time is essential for planning its full utilization as a supplement to irrigation (Mohan et al., 1996). Precipitation stored in the crop root zone can be effectively used for crop evapotranspiration and thereby, meet part of the crop's irrigation requirement (Dastane, 1978). However, not all of the rain that falls infiltrates the soil and becomes useful to crops. Many authors have defined effective rainfall in the past (Hershfield, 1964; USDA SCS, 1967; Jensen, 1990; NRCS, 1993). According to Dastane (1974), effective rainfall

(precipitation) (P_e) is defined as that portion of rainfall (precipitation) which is useful directly and/or indirectly for crop production at the site where it falls.

Numerous methods for estimating effective rainfall have been proposed in the past including: direct measurement techniques, empirical methods and soil water balance methods. All effective rainfall estimation methods are based on representations and varying degrees of simplification of the hydrologic cycle (Patwardhan et al., 1990). The processes involved are shown in Figure 2.6. Some of the methods used to estimate effective rainfall are:

Real-time method

In this method, the amount of effective rainfall is estimated using the soil water balance approach (Obreza and Pitts, 2002). The amount of deep percolation and runoff must be estimated. The runoff can be predicted using the USDA-SCS curve number method applied to the specific site.

$$P_e = P - RO_r - D_p \quad [2.32]$$

Where, P_e : effective rainfall (mm), RO_r : runoff from rainfall (mm), D_p : deep percolation from rainfall (mm).

Renfro equation

Renfro, as quoted by Chow (1964), suggested the following equation for estimating effective rainfall:

$$P_e = E * R_g + A \quad [2.33]$$

Where, P_e : effective rainfall, R_g : growing season rainfall, A : average irrigation application, E : ratio of consumptive use of water (CU) to rainfall during the growing season (Table 2.6). The E value implies the degree of rain that is likely to be utilized in meeting consumptive water needs. The greater the E value, the higher the value of P_e .

Soil conservation service (SCS)

The U.S. Department of Agriculture's Soil Conservation Service (USDA-SCS) scientists analyzed 50 years of rainfall records at 22 locations throughout the United States to develop a technique to predict effective precipitation. This method was developed with water balance. However, the soil infiltration rate and rainfall intensity were not considered in the procedure for developing this method (Dastane, 1974). The accuracy of this method depends on the availability of reliable daily climate data (temperature, R_s , wind and relative humidity) used to calculate ET . It is important to know that the procedures were designed only for a monthly time step.

$$P_e = SF \left(0.70917 * \left(\frac{P_m}{25.4} \right)^{0.82416} - 0.11556 \right) 0.82416 (10^{0.000955ET_c}) \quad [2.34]$$

Where, P_e : effective rainfall (mm), P_m : average monthly precipitation (mm), ET_c : average monthly crop evapotranspiration (mm), SF : soil water storage factor.

The soil water storage factor was defined by:

$$SF = \left(0.53175 + 0.2952 \left(\frac{D}{25.4} \right) - 0.0577 \left(\frac{D}{25.4} \right)^2 + 0.003804 \left(\frac{D}{25.4} \right)^3 \right) \quad [2.35]$$

Where, D : usable soil water storage (mm), calculated as 40 to 60 percent of the available soil water capacity in the crop root zone, depending on the irrigation management practices used.

Percentage method

A simplified daily or monthly method for determining effective precipitation is to multiply the rainfall (precipitation) by a user-specified percentage. Kruse and Haise (1974) conducted a lysimeter experiment in the vicinity of Gunnison, Colorado in 1969 and 1970 to investigate the effectiveness of precipitation. The effectiveness of the precipitation was calculated as the measured difference in irrigation water demand divided by the measured total precipitation at the lysimeter site. Kruse and Haise (1974) concluded that the effectiveness of all rainfall received during the growing season was 75 percent. In a similar manner, Smith (1988) suggested a fixed percentage of 80 percent.

The U.S. bureau of reclamation

The United States Bureau of Reclamation recommends the following formula to calculate the effective rainfall (Smith, 1992).

$$P_e = P_{tot} (125 - 0.2P_{tot})/125 \quad \text{for } P_{tot} \leq 250 \text{ mm} \quad [2.36]$$

$$P_e = 0.1 * P_{tot} + 125 \quad \text{for } P_{tot} > 250 \text{ mm} \quad [2.37]$$

where: P_e : effective rainfall (mm), P_{tot} : total monthly precipitation (mm).

Nyvall and Tam

Effective rainfall as used in this study 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 (Nyvall and Tam, 2005). It was assumed by the author that any rainfall less than five millimetres will be intercepted by vegetation and quickly evaporate. This contrasts with the conventional hydrologic definition where effective precipitation means that part of the total precipitation that contributes to runoff. It is suggested the remaining precipitation ($R - 5$) should be multiplied by a factor of 0.75 to account for runoff and deep percolation losses.

$$P_e = (R - 5) * 0.75 \quad [2.38]$$

Where, P_e : effective rainfall (mm), R : rainfall (mm).

2.6 Available soil water (ASW)

Soil water availability refers to the capacity of soil to retain water available to plants (Allen et al. 1998). After a heavy rainfall or irrigation, the soil will drain until field capacity is reached. Field capacity is the amount of water that a well-drained soil should hold against gravitational forces. In the absence of water supply, the water content in the root zone decreases as a result of water uptake by the crop. As water uptake progresses, water becomes more strongly bound to the soil matrix and it is more difficult for the plant to extract. Eventually, a point is reached where the crop can no longer extract the remaining water and the plants die; this point is the wilting point. The fraction of total

available water that a crop can extract from the root zone without suffering water stress is the readily available soil water (Allen et al., 1998).

Management allowable depletion (MAD)

Producing optimal yield requires that the soil-water content be maintained between an upper limit at which leaching becomes excessive and a lower point at which crops are stressed (NRCS, 1993). As water is removed from the soil through *ET*, there is a point below which the plant experiences increasing water stress. This point is known as the management allowable depletion (*MAD*). Depletion below this point is detrimental to maximum crop growth. *MAD*, corresponding to the percentage of *ASW* which may be safely depleted before yield reducing stress occurs, depends on the crop grown and may be influenced by the development stage as well as the irrigation system used (Panda et al., 2004).

There have been studies on bell peppers recommending different *MAD* values. Allen et al., (1998) stated that the bell pepper may begin to exhibit symptoms of moisture stress when 30% of the available soil water content (*AWC*) has been used. Doorenbos and Pruitt (1977) and Hanson et al., (2004) recommended a *MAD* of 25%, while Planner (2003) showed that the bell pepper can tolerate depletion levels of 30 to 35% in *AWC* in the active root zone with no yield loss. The varying *MAD* values obtained by these studies revealed that it is not advisable to use a fixed *MAD* value and that irrigation thresholds using *MAD* should be determined for site specific conditions since climate, soil conditions, soil type, cultivars and the irrigation system might play a prominent role.

2.7 Impact of climate change on irrigation

Climate change is expected to alter the hydrological cycle resulting in the large-scale impact on water availability (Hagemann et al., 2012). Researchers, through the use of general circulation models (GCMs) and other methods, develop "scenarios" of possible future climates of a region. These scenarios are then applied to the ecosystem or the economic region to determine how it would be affected by climate change. Impacts of climate change are expected to be greater in some regions than in others. The IPCCs

Special Report on Emissions Scenarios (*SRES*) contains projections of future greenhouse gas emissions starting with a “storyline”, describing the way world population, economies, political structure and lifestyles may evolve over the next few decades (IPCC, 2000). The storylines were grouped into four scenario families (Table 2.7) and led ultimately to the construction of six *SRES* marker scenarios: *A1* has three marker scenarios, *A2*, *B1* and *B2* each has one (Arnell, 2004). The *A1* scenario family develops into groups that describe alternative directions of technological change in the energy system: *A1FI*-Fossil fuel intensive, *A1T*-Technologically advanced (non-fossil fuel) and *A1B*- Balanced (mix of fossil and non-fossil fuel).

The amount of irrigation water needed depends on climatic conditions and socio-economic factors (e.g. amount of crop production and technology) (Schaldach et al., 2012). Agriculture may be particularly vulnerable to climate change due to its dependence on natural weather patterns and climate cycles for its productivity. Climate change is projected to have a major impact on water availability for agriculture in most, if not all parts, of Canada, but these impacts will vary with local climatic, geographic, and agricultural conditions in response to a number of interacting factors (Council of Canadian Academies, 2013). Changes to climate variables (e.g. temperature, precipitation, and CO_2 levels), increased occurrence of extreme events (e.g., floods, droughts, and heat waves), and other indirect effects (e.g., the spread of pests and diseases) will impact agriculture and water in the future. However, the extent of these changes is uncertain, particularly with respect to local and regional precipitation (Kundzewicz et al., 2007).

Climate change has already resulted in an increase in mean temperature in Canada and is likely to affect local precipitation patterns (Zhang et al., 2011). For example, already relatively dry areas of the Canadian Prairies may become more so as the temperature increases (Kulshreshtha, 2011). In Canada, a lengthening of the growing season due to an earlier start and a later end has been shown in studies by Qian et al., (2010b; 2012). Overall, in southern Quebec, daily temperature increases of 0.2 to 0.4°C per decade are observed (Yagouti et al., 2008). According to the Ouranos, Consortium on Regional

Climatology and Adaptation to Climate Change, temperatures are projected to rise in Quebec by 2050. The expected temperature increase in the summer would be around 1.9 to 3.0°C in southern Quebec with no projected change in precipitation during the warm season.

2.8 Modelling Approach

The power of models consists of their capacity to describe complex, interrelated relationships and to handle large quantities of data (Alkan Olsson, 2003; Kasemir et al., 2003). It should be pointed out that the availability of data often determines the choice of model. Models are classified as either deterministic or stochastic according to the way in which processes are described in the model. Singh (1995) described variants of these as quasi-stochastic, quasi-deterministic and hybrid model or stochastic-deterministic depending upon the respective mixture of deterministic and stochastic component. A stochastic model can be used when there is no a priori information available and deterministic models are used where all or most of the necessary information is available.

Stochastic

A stochastic model has one or more variables that are randomly distributed in probability (Clarke, 1973; Woolhiser and Brakensiek, 1982). An example of a stochastic model is the neurofuzzy computing technique. This neural approach was used for water demand prediction in irrigation delivery systems (Pulido-Calvo et al., 2003a; 2007). The adaptive neurofuzzy inference system (ANFIS) (Jang, 1993), is a universal approximator and as such is capable of approximating any real continuous function on a compact set to any degree of accuracy (Jang et al., 1997). The ANFIS model using solar radiation, temperature, relative humidity and wind speed inputs estimated FAO-56 PM ETo better than the other neurofuzzy, ANN and empirical models (Kisi et al., 2007).

Deterministic

A deterministic model is one whose variables are generally free from random variation (Clarke, 1973; Woolhiser and Brakensiek, 1982). The set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables.

Most agricultural water models are deterministic (process or empirical), the models primarily used for irrigation water demand estimation are simple and empirical. The process-based approach focuses on simulating detailed physical or biological processes that explicitly describe system behavior, while the empirical approach relies on correlative relationships in line with mechanistic understanding, but without fully describing system behaviors and interactions (Korzukhin et al., 1996; Adams et al., 2013). Relative differences in the characteristics of process-based and empirical modelling approaches are presented in Table 2.8.

2.9 Agricultural water demand models

The complexity and magnitude of water resource problems require the use of computer models in order to obtain reliable, quantifiable and timely solutions (George et al., 2007). Computer models provide a means to improve the understanding of the interaction of water demand and supply, to predict the effects of climate change and population growth and to compare management alternatives. The agricultural water demand model will be beneficial for crop production in Canada and in similar environments.

There is no universal agriculture or irrigation water demand model, hence, the need to adapt a model to specific environments or to new problems (Van Ittersum et al., 2003). Similar models for the same region might produce consistent estimates; however, each region requires its own model that has to be updated regularly. The models are often more accurate at the local or regional scale, provided they have been extensively calibrated and validated using local data

2.10 Summary of literature review

The variability of rainfall events requires the application of supplemental irrigation to meet crop water demands in Canada; irrigation needs vary by location and type of crop. Irrigation is mainly used for high value horticultural crops in Ontario, Quebec and British Columbia. These three provinces are the highest producers of field grown vegetables. The test crop, bell pepper (*Capsicum annuum* L), is a major greenhouse and field vegetable grown for the fresh and processing markets and sensitive to water stress.

Determining appropriate irrigation strategies for optimising bell pepper production is necessary to increase yield, quality and water use efficiency. Information about irrigation management strategies, crop production systems, ET_o , soil, climate variability and change and their interaction with crops can be simulated with a computer based irrigation management model. Most models require local data to be accurate because irrigation decisions are made at the local level. In general, the available irrigation management models are more empirical and use water balance methods. Table 2.9 summarises the agricultural models developed primarily for crop water requirement and irrigation water demand estimation. None of the models reviewed included the use of plant water status monitoring i.e crop water stress index (*CWSI*). *CWSI* is a plant water status indicator that has been tested in a number of crops. However, climate, soil and crop cultivar could influence the *CWSI*. *CWSI* and soil water sensors have thresholds for scheduling. This threshold has to be established for crops before it can be included into an integrated irrigation management model.

Irrigation scheduling methods are based on soil moisture measurements, soil water balance calculations/meteorological approaches (Allen et al., 1998), plant water status monitoring (Jones, 2004a; Cifre et al., 2005), or computer simulation. Several irrigation scheduling models using soil water balance calculation/meteorological approach, (Allen et al., 1998), evaporation pan measurements (Pruitt, 1966; Doorenbos and Pruitt, 1975), soil measurements (Smith and Mullins, 2000; Dane and Topp, 2000) are available. Other studies have also determined the potential use of crop water stress index (*CWSI*) for irrigation timing (Erdem et al., 2010), however, irrigation scheduling using plant water indicators are limited (Cremona et al., 2004).

Effective irrigation requires management decisions that ensure an accurate estimation of crop and irrigation water requirements as well as an allocation irrespective of the irrigation scheduling methods. Accurate *ET* estimates are important in determining crop water requirements for appropriate irrigation scheduling. Field measurement of evapotranspiration is rarely available and actual crop evapotranspiration (ET_c) is usually calculated using estimated ET_o and crop coefficient (K_c). Several methods have been

developed, revised, and recommended for the estimation of ET_o for different types of weather data and climatic conditions (Yoder et al., 2005). ET_o estimation is influenced by the reliability and suitability of the method used. Numerous studies have shown that the Penman-Monteith equation (combination based method) is the most reliable method, but this method requires many input data, some of which are difficult and expensive to obtain. In such circumstances, methods based on either radiation or on maximum and minimum temperature as suggested by Hargreaves and Samani (1985), Thornthwaite (1948) method or Turc (1961) are often used to estimate ET_o . Solar radiation (R_s) is the most significant parameter for all combination and radiation-based ET_o methods but R_s data is not available in many weather stations in Canada and in the rest of the world. It is often computed using methods and coefficients that have to be evaluated for suitability and calibrated for the area of application for better accuracy (Amatya et al., 1995). However, there are only a limited number of studies that have tested the reliability of the coefficients used in these different R_s estimation methods.

Table 2.1: 2006 crop and irrigated lands in Canada

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

Source: 2006 Census of Agriculture

Table 2.2: Area of field and greenhouse vegetable farms by province

Province	Field (Ha)	Greenhouse (Ha)	Greenhouse and field (Ha)	Percentage (%)
Ontario	52445	800.9	53245.9	48.6
Newfoundland and Labrador	359	0.3	359.3	0.3
Quebec	37657	96.4	37753.4	34.5
British Columbia	6591	284.6	6875.6	6.3
Manitoba	2092	2.1	2094.1	1.9
Alberta	4337	58.4	4395.4	4.0
Saskatchewan	310	2.5	312.5	0.3
Prince Edward Island	1014	0.7	1014.7	0.9
Nova Scotia	2739	7.0	2746.0	2.5
New Brunswick	778	1.8	779.8	0.7
Total	108322	1254.8	109576.8	100.0

Source: Statistics Canada, 2011

Table 2.3: Nutritional values per 100 g of red, raw, bell pepper (*Capsicum annuum* L).

Principle	Nutrient Value	Percentage of RDA
Energy	31 Kcal	1.50%
Carbohydrates	6.03 g	4%
Protein	0.99 g	2%
Total Fat	0.30 g	1%
Cholesterol	0 mg	0%
Dietary Fiber	2.1 g	5.50%
Vitamins		
Folates	46 µg	12%
Niacin	0.979 mg	6%
Pyridoxine	0.291 mg	22%
Riboflavin	0.085 mg	6.50%
Thiamin	0.054 mg	4.50%
Vitamin A	3131 IU	101%
Vitamin C	127.7 mg	213%
Vitamin E	1.58 mg	11%
Vitamin K	4.9 µg	4%
Electrolytes		
Sodium	4 mg	<1%
Potassium	211 mg	4.50%
Minerals		
Calcium	7 mg	1%
Copper	0.017 mg	2%
Iron	0.43 mg	5%
Magnesium	12 mg	3%
Manganese	0.112 mg	5%
Phosphorus	26 mg	4%
Selenium	0.1 µg	<1%
Zinc	0.25 mg	2%
Phyto-nutrients		
Carotene-β	1624 µg	--
Carotene-?	20 µg	--
Cryptoxanthin-β	490 µg	--
Lutein-zeaxanthin	51 µg	--

Source: USDA National Nutrient data base, Release 26

Table 2.4: Selected temperature based solar radiation estimation methods

Eq. No	Methods	Equations
2.8	Hargreaves and Samani (1982)	$R_s = K_{RS}(T_{max} - T_{min})R_a$
2.9	Annandale et al., (2002)	$K'_{RS} = (1 + 2.7 * 10^{-5}Z)K_{RS}$
2.10	De Jong and Stewart (1993)	$\zeta = R_s/R_{so} = a(\Delta T)^b(1 + cP + dP^2)$
2.11	Hunt et al., (1998)	$R_s = a_0R_{so}(T_{max} - T_{min})^{0.5} + a_1T_{max} + a_2P + a_3P^2 + a_4$
2.12	Allen (1995)	$K_{RS} = K_{ra} * (P/P_o)^{0.5}$, K_{ra} =0.17 and 0.20 for inland and coastal regions respectively
		Where R_s: solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), K_{RS}: an empirical radiation adjustment coefficient, R_a: extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), T_{max}: maximum temperature ($^{\circ}\text{C}$), T_{min}: minimum temperature ($^{\circ}\text{C}$), P: mean atmospheric pressure (kPa), P_o: are mean atmospheric pressure at sea level (kPa), a, b, c and d:empirical coefficients (vary with time of year) ΔT: ($T_{max}-T_{min}$), ζ: solar transmissivity a_0, a_1, a_2, a_3 and a_4: correlation coefficients, P: daily precipitation (mm), R_{so} the daily solar radiation above the atmosphere ($\text{MJ m}^{-2} \text{ day}^{-1}$)

Table 2.5: Evapotranspiration models and parameters required

Methods	Main parameters needed	Equations
Combination theory-energy balance		
FAO-56 Penman Monteith (Allen et al., 1998)	$T_{\max}$, $T_{\min}$, R_a , RH, R_n , e_s , e_a , u , γ , G , aerodynamic and bulk surface resistance	$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{900}{T + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma(1 + 0.34 * u_2)}$ $\Delta = \frac{4098 * \left(0.6108 * \exp\left(\frac{17.27 * T}{T + 273.3}\right)\right)}{(T + 273.3)^2} \quad [a]$ $\gamma = 0.000665 * P \quad [b]$ Where P, the atmospheric pressure is calculated thus: $P = 101.3 * \left(\frac{293 - 0.0065 * z}{293}\right)^{5.26} \quad [c]$ Parameters defined in Eq. 2.13 in text
ASCE, 2005	$T_{\max}$, $T_{\min}$, R_a , RH, R_n , e_s , e_a , u , γ , G , aerodynamic and bulk surface resistance	$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{1600}{T + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma(1 + 0.38 * u_2)}$ Parameters defined in Eq. 2.13 in the text.
Penman, 1948	R_n , e_s , e_a , u , γ , G	$E_p = R_n \Delta / (\Delta + \gamma) + E_a \gamma / \Delta + \gamma$ $E_a = 0.35(0.5 + 0.0062u)(e_s - e)$

Radiation and temperature based		
Hargreaves-Samani, 1985	$T_{\max}, T_{\min}, R_a$	$ET_o = 0.0135R_s(T_{mean} + 17.8) \quad [a]$ $R_s/R_a = K_{RS}(T_{max} - T_{min})^{0.5} \quad [b]$ $ET_o = 0.408 * 0.0135K_T(T_{max} - T_{min})^{0.5}(T_{mean} + 17.8)R_a \quad [c]$
Jensen and Haise, 1963	T, R_s	$\lambda ET_o = C_t(T - T_x)R_s$ Where ET_o : Reference evapotranspiration (mm d^{-1}), R_s : solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), C_t : temperature constant (0.025), and $T_x = -3$ when T is in degrees Celsius. These coefficients were considered to be constant for a given area.
Turc 1961	R_s, RH_{mean}	$ET = 0.013 \left(\frac{T}{T + 15} \right) (R_s + 50) \left(1 + \frac{50 - RH}{70} \right) \text{ for } RH < 50\%$ $ET = 0.013 \left(\frac{T}{T + 15} \right) (R_s + 50) \text{ for } RH \geq 50\%$ Parameters defined in Eq. 2.29 in the text
Priestley-Taylor, 1972	T_{mean}, R_n derived from R_s and R_a	$\lambda PET = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G)$ where ET_o : Evapotranspiration (mm d^{-1}), λ : is the latent heat of vaporization (MJ kg^{-1}), R_n : is the net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G : the soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$), Δ : slope of the saturation vapour pressure-temperature relationship ($\text{kPa } ^\circ\text{C}^{-1}$), γ : psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), α : Priestley-Taylor coefficient.

Temperature based		
Thornthwaite, 1948	$T_{\max}, T_{\min}$	$ET = 1.6(L/12)(N/30)(10T/I)^a$ $I = \sum_1^{12} (T/5)^{1.514}$ $a = (0.675I^3 - 77.11I^2 + 492\,390)10^{-6}$ where $E T$: Potential evapotranspiration (mm d^{-1}) L:actual day length (hours), N: number of days in the month, T:mean monthly air temperature($^{\circ}\text{C}$), a: parameter.

Table 2.6: Ratio E for use in estimating effective rainfall in Renfro Equation

CU/R _g	E	CU/R _g	E	CU/R _g	E
0	0	1.6	0.57	3.5	0.84
0.2	0.1	1.8	0.61	4.0	0.88
0.4	0.19	2.0	0.65	4.5	0.91
0.6	0.27	2.2	0.69	5.0	0.93
0.8	0.35	2.4	0.72	6.0	0.96
1.0	0.41	2.6	0.75	7.0	0.98
1.2	0.47	2.8	0.77	9.0	0.99
1.4	0.52	3.0	0.8	/	/

Source: Allen et al., (1998)

Table 2.7: The main characteristics of the four Special Report on Emission Scenarios (SRES) storylines scenario families

	More economic focus	More environmental focus
Globalization	A1 - o Rapid economic growth - o Global population that peaks in mid-century and declines thereafter - o Rapid introduction of new and more efficient technologies - o Substantial reduction in regional differences in per capita income	B1 - o Convergent world - o Global population that peaks in mid-century and declines thereafter - o Economic development shifts towards service and information economy - o Introduction of clean and more efficient technologies
Regionalization	A2 - o Heterogeneous world and self reliance - o Continuously increasing population - o Economic development is primarily regionally oriented - o Economic development and technological change is slower than other storylines	B2 - o Emphasis on local solutions to social, economic, and environmental sustainability - o Continuously increasing population at a lower rate than A2 - o Intermediate levels of economic development - o Less rapid and more diverse technological change than in B1 and A2 storylines

Source: IPCC, 2000.

Table 2.8: Relative differences in the characteristics of process-based and empirical modelling approaches.

Characteristics	Process-based	Empirical
Relationship type	Causal	Correlative
Relative comprehensiveness	More comprehensive	Less comprehensive
Incorporation of mechanism	Explicit	Implicit
Primary source of error	Unknown parameters and processes	Extrapolation
Model uncertainty	Higher	Lower
Data requirements	Higher	Lower
Spatial scale for calibration	Smaller	Smaller to larger
Spatial scaling of prediction	Smaller to Larger	Best at scale of calibration

Source: Adams et al., 2013

Table 2.9: Agricultural models developed for crop water requirement and/or irrigation water estimation.

MODEL CHARACTERISTICS	MODEL NAMES							
Model structure	PRIDE	CROPWAT	ISAREG	WaterGAP	WASIM	SIMETAW	AIMM	AWDM
Process based/mechanistic			X					
Empirical	X	X		X		X	X	X
Scale								
Field		X			X	X	X	X
Regional	X		X					
Global				X				
Mode of operation								
User interface	X	X	X		X		X	X
Command line								
Spreadsheet based								
Primary purpose								
Yield prediction								X
Crop water requirement		X			X	X	X	X
Irrigation water requirement	X	X		X			X	
Irrigation scheduling		X	X			X	X	
Irrigation scheduling approaches								
Water balance		X	X			X	X	
Soil moisture monitoring								
Plant water status monitoring								

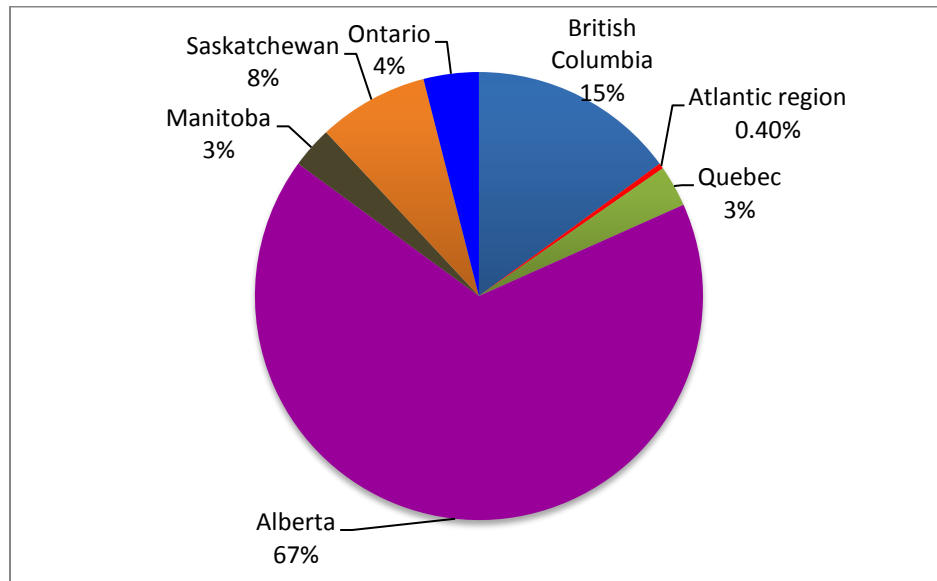


Figure 2.1: Percentage of total irrigated area by province or region, 2010
(excludes Yukon, the Northwest Territories and Nunavut)

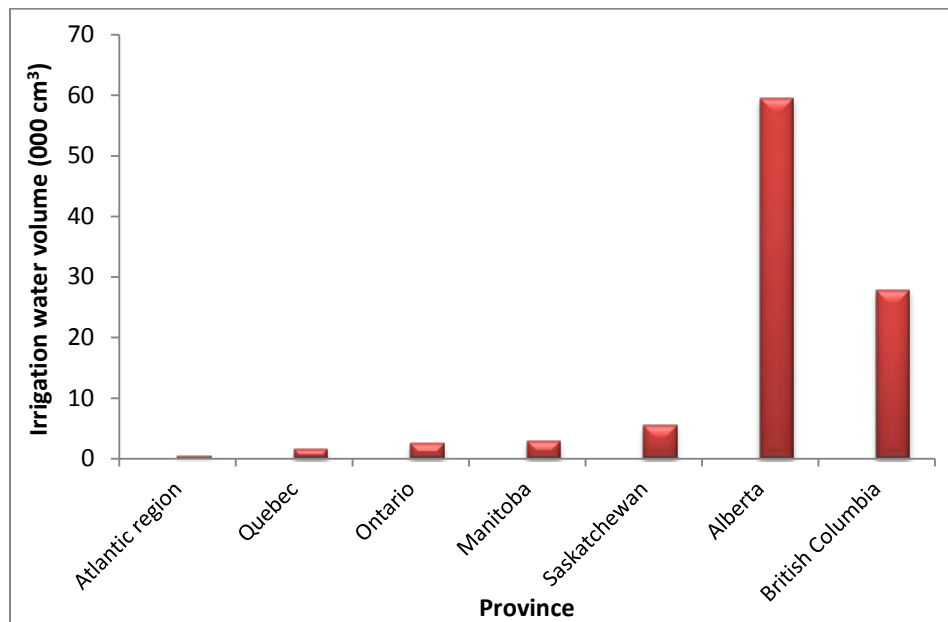


Figure 2.2: Irrigation volume by month, 2010

Source: Statistics Canada, 2011

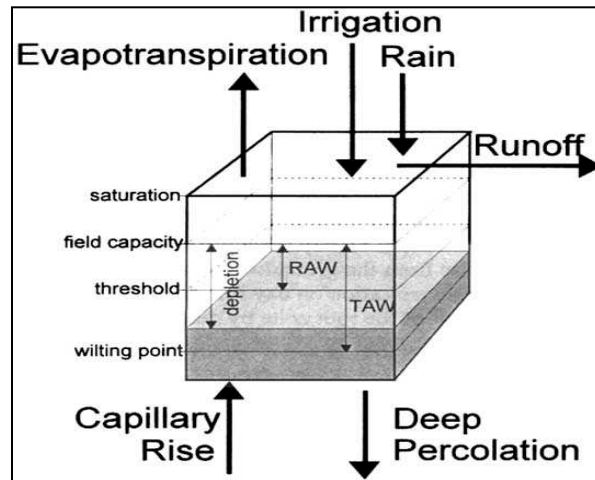


Figure 2.3: Schematic presentation of the water balance of the root zone

Source : Allen et al., (1998)

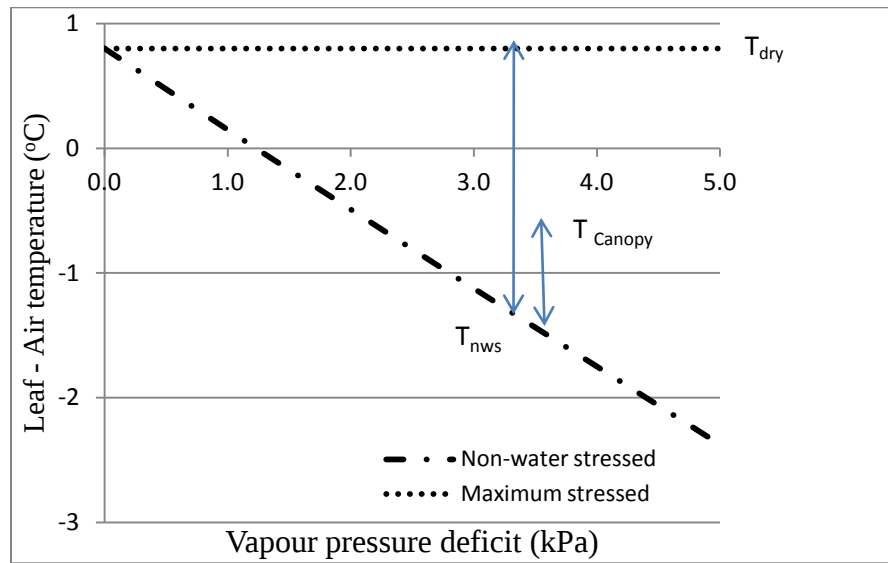


Figure 2.4: Leaf-Air temperature vs vapour pressure deficit

$$T_{nws} = \text{Intercept} + \text{Slope}(\text{VPD})$$

$$T_{dry} = \text{Intercept} + \text{Slope}(\text{VP}_{sat}(T_a) - \text{VP}_{sat}(T_a + \text{Intercept}))$$

Where VPD: vapour pressure deficit (kPa), $\text{VP}_{sat}(T_a)$: saturation vapour pressure at air temperature (kPa), T_{nws} : non-water stressed canopy temperature ($^{\circ}\text{C}$), T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$).

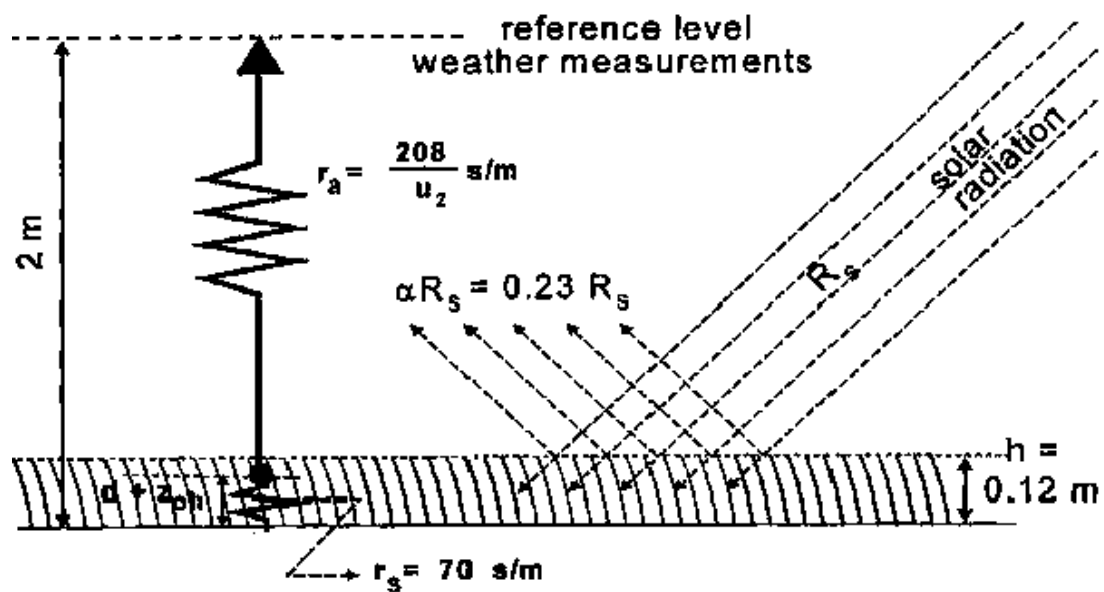


Figure 2.5: Characteristics of hypothetical reference crop

Source: Allen et al., (1998)

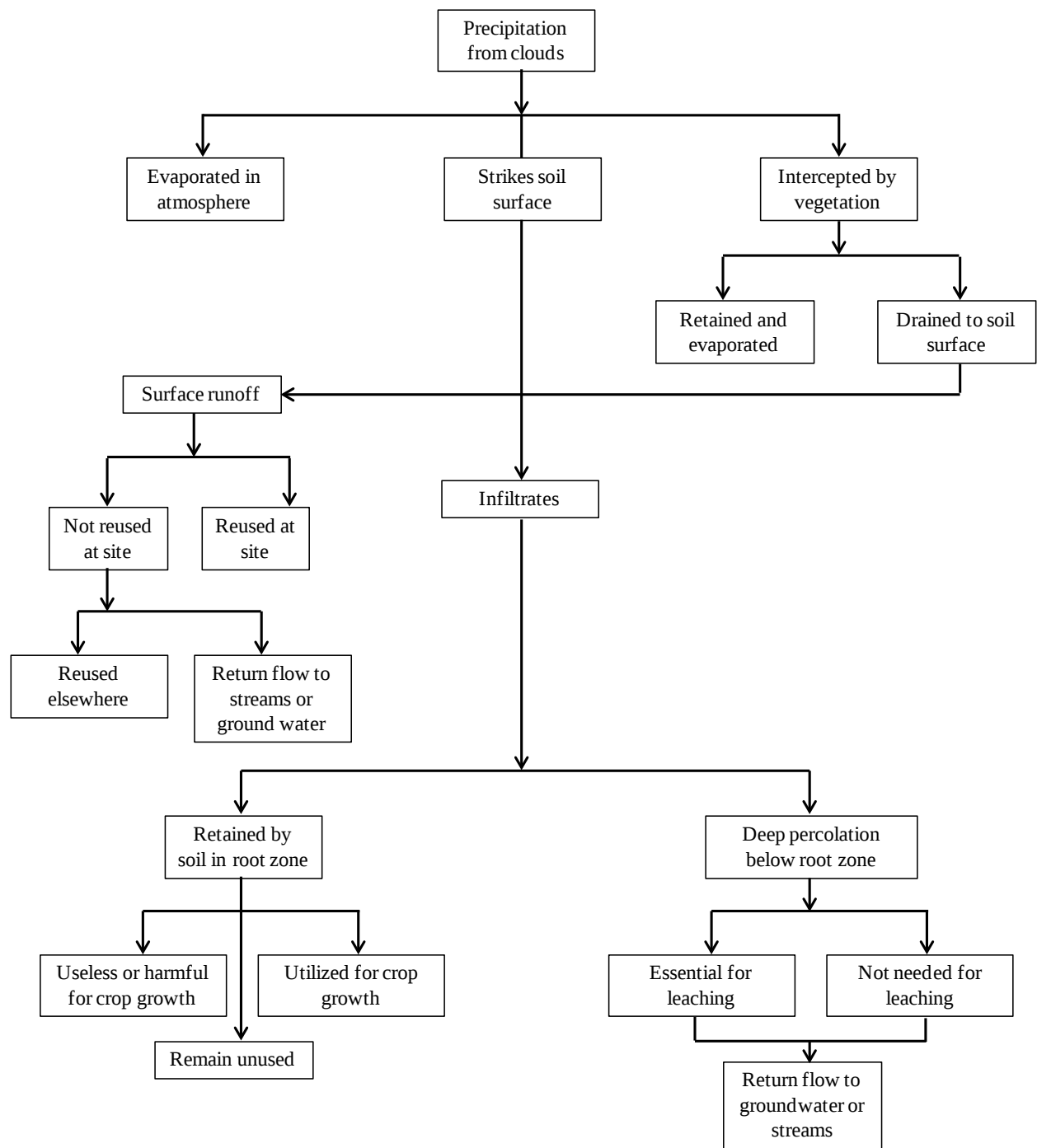


Figure 2.6: Precipitation pathways
(adapted from Dastane 1974)

Connecting text to Chapter 3

Chapter 3 covers the theoretical evaluation of the suitability of empirical solar radiation estimation methods for use in Canada. This assessment is a key process for improving the accuracy of reference evapotranspiration (ET_o), crop water requirement (CWR) estimation and irrigation water management models. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis. This chapter was accepted for publication in December, 2013 in Theoretical and Applied Climatology, Manuscript ID: TAAC-D-13-00102R1.

Chapter 3 Evaluation of solar radiation estimation methods for reference evapotranspiration estimation in Canada

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Abstract

The accuracy of nine solar radiation (R_s) estimation models and their effects on reference evapotranspiration (ET_o) were evaluated using data from eight meteorological stations in Canada. The R_s estimation models were FAO recommended Angstrom-Prescott (A-P) coefficients, locally calibrated A-P coefficients, Hargreaves and Samani (H-S) (1982), Annandale et al., (2002), Allen (1995), Self-Calibrating (S-C, Allen, 1997), Samani (2000), Mahmood and Hubbard (M-H) (2002), and Bristow and Campbell (B-C) (1984). The estimated R_s values were then compared to measured R_s to check the appropriateness of these models at the study locations. Based on root mean square error ($RMSE$), mean bias error (MBE) and modelling efficiency (ME) ranking, calibrated A-P coefficients performed better than all other methods. The calibrated H-S method (using K_{RS} 0.15) estimated R_s more accurately than FAO-56 recommended A-P in Elora, and Winnipeg. The $RMSE$ of the calibrated H-S method ranged between 0.81 to 1.44 MJ m⁻² d⁻¹ and the $RMSE$ of the calibrated and FAO recommended Angstrom-Prescott (A-P) methods ranged between 0.35 to 2.12 MJ m⁻² d⁻¹. The models with the least accuracy at the eight locations are the Mahmood & Hubbard (2002) and Self-Calibrating models. The percent deviation in ET_o calculated with estimated R_s was reduced by about 50% as compared to deviation in measured versus estimated R_s .

Keywords: Empirical models; FAO-56 Penman-Monteith; model evaluation; reference evapotranspiration; solar radiation.

3.1 Introduction

Solar radiation (R_s) is a key driver of photosynthesis, evapotranspiration and an essential input to irrigation scheduling, the hydrologic cycle, and crop growth simulation models (Stöckle et al., 2003; Yang et al., 2006). Solar radiation is also one of the key parameters for estimating reference evapotranspiration (ET_o). Other inputs used to estimate ET_o are temperature, humidity and wind speed. Solar radiation data are not available at many weather stations worldwide (Liu and Scott 2001; Abraha and Savage 2008). In Canada, solar radiation data is available only at a few weather stations: for example, 10 out of 301 stations in British Columbia, 3 out of 150 stations in Saskatchewan, 4 out of 110 stations in Manitoba, 4 out of 147 stations in Alberta, 9 out of 246 stations in Ontario, and 9 out of 276 stations in Quebec. In the absence of measurements, R_s may often be estimated from empirical models using other available meteorological data. The empirical models are attractive because of their low computational cost and accessible inputs.

Accurate estimates of R_s and crop water requirements are required to guarantee sufficient and timely quantities of water for horticultural crops under intensive production in Ontario, Quebec, and British Columbia. Also the semi arid prairies of Canada requires accurate estimation of R_s and crop water requirements to address the problems of limited access to water supplies and water allocations, seasonal shortages, allocation/regulatory/licensing issues, poor water quality, competition for water, and limited water conservation (Agriculture and Agri-food Canada, 2003; Corkal and Adkins, 2008). There is no recent literature about the suitability of R_s estimation models in Canada and specific studies about the effect of calibration on the performance of Food and Agriculture Organisation (FAO) recommended Angstrom-Prescott coefficients (Allen et al., 1998), and other temperature based equations in Canada. The focus of this study was to determine the accuracy and suitability of these R_s estimation models in diverse Canadian agricultural regions: (1) the semi-arid prairies of Saskatchewan, Alberta and Manitoba which are noted for grain production; (2) British Columbia for its fruit and greenhouse production of tomatoes and sweet bell pepper, and (3) Ontario and Quebec with a humid continental climate and warm summers.

The most widely adopted solar radiation estimation model is sunshine based (Allen et al., 1998; Iziomon and Mayer, 2002 and Trnka et al., 2005), but the use of this model is often limited by the lack of available sunshine records. Temperature-based models such as the Hargreaves, Bristow and Campbell equations and their modified forms have been used in the absence of sunshine records (Bristow and Campbell 1984; Hargreaves and Samani, 1982; Allen et al., 1998). Other studies have also used precipitation (Hunt et al., 1998; Almorox 2011; Woli and Paz, 2011) and cloud cover (Barker, 1992; Supit and van Kappel, 1998) for estimation of R_s . Several studies have suggested that empirical coefficients used for estimation of R_s should have site or region specific values for sunshine based (Almorox et al., 2008; Liu et al., 2009), temperature based (Ball et al., 2004; Thepadia and Martinez, 2012) and precipitation based (Hunt et al., 1998; Woli and Paz, 2011).

Researchers have evaluated the suitability and accuracy of a limited number of R_s estimation models in Canada. Boisvert et al., (1990) examined the suitability, under Canadian conditions, of an equation valid for a range of seasons and station locations, where sunshine duration but no global radiation data are available. The result of the study indicated the spatial and temporal variations of the Angstrom-Prescott (a and b) coefficients. De Jong and Stewart (1993) related daily global R_s to maximum and minimum air temperatures and precipitation for a number of locations in the wheat growing areas of western Canada. The accuracy of temperature and/or precipitation based solar radiation estimation methods varied with locations, their variability R^2 explained was 57% in Canada (De Jong and Stewart, 1993), 79% in Australia (Liu and Scott, 2001) and 81-85% in Austria and Czech Republic (Trnka et al., 2005). Hunt et al., (1998) stated that a newly developed formula that included the maximum temperature, the difference between maximum and minimum temperature, precipitation, and precipitation squared, provided estimates with less error than models by Hargreaves et al., (1985), Bristow and Campbell, (1984) and Reddy, (1987). The Hargreaves coefficients used was not stated in Hunt et al., (1998) and other studies that had reported the performance of $H-S$. The precipitation and cloud cover based R_s estimation methods require some complex coefficients and/or detailed hourly cloud cover observations which are either too complex to determine or not available. These models are not considered as best alternatives for estimating daily solar radiation and are not tested in this study. This study therefore evaluated (1) the accuracy of nine R_s estimation models, namely FAO

recommended Angstrom-Prescott (FAO A-P hereafter); Hargreaves and Samani, (1982); Bristow and Campbell, (1984) and their modified forms under Canadian conditions, and (2) effect of the estimated R_s on reference evapotranspiration computed by the FAO-56 Penman Monteith equation.

3.1.1 Sunshine and temperature based R_s models

The widely adopted R_s estimation models are based on sunshine and temperature. The models described in this study were chosen as representative models that utilize temperature, readily available weather data, and extraterrestrial irradiation.

3.1.2 Temperature based models

3.1.2.1 Hargreaves and Samani, 1982 (H-S)

Hargreaves and Samani (1982) assumed that the atmospheric transmissivity on a given day is proportional to the square root of the difference between the maximum (T_{max}) and minimum (T_{min}) air temperatures (°C) and developed the following empirical model:

$$R_s = K_{RS}(\sqrt{T_{max} - T_{min}})R_a \quad [3.1]$$

Where, R_s is the solar radiation, ($\text{MJ m}^{-2} \text{ d}^{-1}$), K_{RS} is the empirical coefficient, T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature (°C) for weekly or monthly periods; R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), estimated using the procedure by with Allen et al., 1998.

Hargreaves and Samani (1985) recommended a value of 0.17 for K_{RS} from 8 years of weighing lysimeter data from Davis, California. Hargreaves and Samani (1982) recommended values of 0.16 and 0.19 for inland and coastal regions, respectively. This approach is currently recommended by the FAO for estimating R_s from a temperature difference (Allen et al., 1998; Thepadia and Martinez, 2012).

3. 1.2.2 Allen 1995

Allen (1995) proposed estimating K_{RS} as a function of elevation to account for effect of elevation on the volumetric heat capacity of the atmosphere by using:

$$K_{RS} = K_{ra} * \left(\frac{P}{P_o}\right)^{0.5} \quad [3.2]$$

where K_{ra} is the empirical coefficient having a value of 0.17 for interior regions and 0.20 for coastal regions; P is the mean atmospheric pressure at the site (kPa), which can be estimated from the elevation of the site (Burman et al., 1987) and P_o is the mean atmospheric pressure at sea level (which is 101.3 kPa).

3.1.2.3 Self calibration (S-C)

Allen (1997) reported that fixed calibration coefficients are inaccurate and proposed a self calibrating procedure that is constrained by computed clear-sky radiation curves. The procedure involves calculation of R_s by Eq. (3.1) with an initial guess of K_{RS} and plotting them with clear-sky short wave radiation (R_{so}) against time. The value of K_{RS} is varied until the highest estimates of R_s contact the R_{so} envelope, which is the expected R_s when the sky is free of clouds. R_{so} is calculated using the following equation:

$$R_{so} = (a + b + 2 * 10^{-5}Z)R_a \quad [3.3]$$

Where a and b are Angstrom coefficients taken as $a = 0.25$ and $b = 0.50$, respectively when a and b are not locally calibrated.

3.1.2.4 Samani

Samani modified Equation 1, which uses maximum and minimum temperature to estimate R_s , to develop the following empirical relationship between K_{RS} and the difference between air temperatures using the average monthly data of 65 weather stations.

$$K_{RS} = 0.00185 * (T_{max} - T_{min})^2 - 0.0433 * (T_{max} - T_{min}) + 0.4023 \quad [3.4]$$

Where T_{max} is maximum temperature and T_{min} is minimum temperature in degrees celsius.

3.1.2.5 Annandale

Annandale et al., (2002) introduced a correction factor for K_{RS} in Equation 3.1 to account for the effects of reduced atmospheric thickness on R_s as:

$$K'_{RS} = (1 + 2.7 * 10^{-5}Z)K_{RS} \quad [3.5]$$

Where K'_{RS} , is the adjusted coefficient, and K_{RS} is the empirical coefficient as suggested by Hargreaves and Samani, (1982) and Z is the elevation (m).

3.1.2.6 Bristow and Campbell (B-C)

Bristow and Campbell (1984) developed a relationship between daily atmospheric transmissivity and the difference between the daily maximum air temperature and average minimum temperature for the current and following day, using only 1 yr of data to estimate solar radiation as follows:

$$R_S = T_t * R_a \quad [3.6a]$$

Where R_S is the solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), T_t is the daily total atmospheric transmittance, which is calculated by:

$$T_t = A[1 - \exp(-B\Delta T^C)] \quad [3.6b]$$

where A , B , and C are empirical coefficients. A is the potential total transmittance on a clear and cloud-free day ($A = 0.70$); B is a function of the mean monthly $\overline{\Delta T}$, and ΔT is the daily range of air temperature, $B = 0.036 * \exp(-0.154\overline{\Delta T})$, and the value for C is 2.4.

3.1.2.7 Mahmood and Hubbard (M-H)

Mahmood and Hubbard, (2002) adapted the model of Cengiz et al., (1981) which predicted daily R_S as a function of the day of year, daily maximum and minimum air temperatures, and minimum relative humidity. Mohammed and Hubbard, (2002) assumed transmissivity as a function of the day of the year (DOY), and correlated daily surface incoming solar irradiation to the daily range of temperature and extraterrestrial irradiation temperature by the following equations:

$$R_S = 0.182(T_{\max} - T_{\min})^{0.69} ICSKY^{0.91} \quad [3.7a]$$

$$ICSKY = I_s T \quad [3.7b]$$

$$I_s = 0.04188 \left(A + B \sin \left[(DOY + 10.5) * \frac{2\pi}{365} - \frac{\pi}{2} \right] \right) \quad [3.7c]$$

$$T = 0.8 + 0.12 \left(\frac{|182-DOY|}{183} \right)^{1.5} \quad [3.7d]$$

where R_s is the estimated solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), $ICSKY$ is the corrected daily clear sky solar radiation, which is a function of latitude and day of the year, T is the transmissivity coefficient, T_{max} is the maximum temperature, T_{min} is the minimum temperature, I_s is the clear-day solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), DOY is the day of the year, A and B are constants which are estimated as follows (Cengiz et al., 1981):

$$A = \left\{ \sin \phi (46.355LD - 574.3885) + 816.41 \cos \phi \sin \left(LD \frac{\pi}{24} \right) \right\} (0.29 \cos \phi + 0.52) \quad [3.7e]$$

$$B = \left\{ \sin \phi (574.3885 - 1.509LD) - 26.59 \cos \phi \sin \left(LD \frac{\pi}{24} \right) \right\} (0.29 \cos \phi + 0.52) \quad [3.7f]$$

where ϕ is the latitude and LD is the longest DOY (h) estimated by

$$LD = 0.267 \sin^{-1} \left[0.5 + \left(\frac{0.007895}{\cos \phi} \right) + (0.2168875 \tan \phi) \right]^{0.5} \quad [3.7g]$$

3.1.3 Sunshine based models

3.1.3.1 Angstrom-Prescott (A-P)

The A-P model was first proposed by Ångström in 1924 and further modified by Prescott in 1940. The A-P formula was developed based on the linear relationship between monthly mean daily R_s and sunshine hours as follows:

$$R_s = \left(0.25 + 0.50 \frac{n}{N} \right) R_a \quad [3.8]$$

where R_s and R_a are respectively actual and extra-terrestrial solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$), n and N are respectively the actual and potential sunshine hours (h), and $a(=0.25)$ and $b(=0.50)$ are the empirical A-P coefficients.

3.1.3.2 Calibrated A-P (A-P calib)

Several studies have suggested that solar radiation estimation models should have site specific empirical coefficients. The Angstrom-Prescott coefficients were calibrated for the eight stations under study to test the suitability of the FAO recommended coefficients ($a=0.25$, $b=0.50$).

3.2 Materials and methods

3.2.1 Weather data

Daily weather data for Ottawa, Montreal, Beaverlodge, Winnipeg, Summerland, Swift Current, Toronto and Elora were obtained from Environment Canada (Table 3.1). The locations were selected to represent diverse ranges in climate (from semi arid to humid), latitudes and elevations, and are typical agricultural regions in Canada. Most importantly the selected locations had solar radiation data. The data collected were the maximum and minimum temperatures, sunshine, solar radiation, and wind speed. The minimum number of R_s data analysed was for seven years (Montreal), years with more than 10% missing data during the growing season (May to October) were excluded (Table 3.1). The models described above were used to estimate daily R_s and the values obtained were compared to the corresponding measured values obtained from Environment Canada.

Table 3.1: Locations, R_s data availability and years of R_s data used.

Stations*	Province	Latitude (N)	Latitude (W)	Elevation (m)	No of R_s data (years)	Most recent years ^y	Years of data used
Ottawa	Ontario	45.38	75.72	79.2	18	2002	11
Montreal	Quebec	45.47	73.75	35.97	11	1998	7
Beaverlodge	Alberta	55.20	119.40	744.9	33	2004	16
Winnipeg	Manitoba	49.92	97.23	238.7	30	2000	23
Summerland	British Columbia	49.57	119.65	454.2	34	2006	20
Swift Current	Saskatchewan	50.27	107.73	825.0	29	2000	20
Toronto	Ontario	43.67	79.40	112.5	31	2001	30
Elora	Ontario	43.65	80.42	376.4	33	2003	12

* The stations have both R_s and sunshine data, ^y The most recent years for solar radiation data only

3.2.2 Estimation of reference evapotranspiration (ET_o)

Reference evapotranspiration was estimated with the FAO-56 Penman-Monteith equation (Allen et al., 1998) (Eq. 3.9) using measured and estimated solar radiation from the nine models above. The FAO-56 Penman-Monteith (FAO-56 PM hereafter) equation is considered as a standard because it has been tested worldwide.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [3.9]$$

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

3.2.3 Model performance

The performance of the models was evaluated by comparing the calculated daily R_s with the measured daily R_s data and also the ET_o calculated with these R_s values. The accuracy of the estimated values was tested using the Mean Bias Error (MBE; Tadros, 2000; Togrul et al., 2000; Sabziparvar et al., 2007) (Eq. 3.10), Root Mean Square Error (RMSE) (Eq. 3.11), and Model Efficiency (ME; Nash and Sutcliffe 1970) (Eq. 3.12). The RMSE provides a comparison of the actual deviation between the predicted and observed values and a lower value reflect a better model performance. The MBE reveals whether a given model has a tendency to over or under predict, with MBE values closest to zero being desirable. The disadvantage associated with MBE is that errors of different signs will cancel each other and also a few values in the sum can produce a significant increase in the parameter. Therefore, ME was used to provide additional information. ME denotes the average distance between the observed and estimated values relative to the average distance between the observed and mean observed values. Values of ME

ranged from $-\infty$ to 1. A negative value indicates that the observed mean is a better predictor than the model, when the residual variance (described by the numerator in equation 3.12), is larger than the data variance (described by the denominator in equation 3.12), whereas a positive value signifies that the model is a better predictor of the observations than is the observed mean (Woli and Paz, 2011). ME of 0 indicates that the model predictions are as accurate as the mean of the observed data, ME value closer to 1 indicates better performance, and an ME of 1 corresponds to a perfect match of the modeled values to the observed data.

These error analysis parameters are as defined below:

$$MBE = \frac{\sum_{i=1}^N (x_{o,i} - x_{p,i})}{N} \quad [3.10]$$

$$RMSE = \left(\frac{\sum_{i=1}^N (x_{o,i} - x_{p,i})^2}{N} \right)^{0.5} \quad [3.11]$$

$$ME = 1 - \left[\sum_{i=1}^N (x_{o,i} - x_{p,i})^2 / \sum_{i=1}^N (x_{o,i} - \bar{x}_o)^2 \right] \quad [3.12]$$

Where MBE is the mean bias error, RMSE is the root mean square error, ME is the model efficiency, $x_{o,i}$ is the measured solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), $x_{p,i}$ is the estimated solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), $\bar{x}_o$ is the average of the observed solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), and N is the number of observations.

3.3 Results and discussion

3.3.1 Comparison of solar radiation model performances

The plot of measured versus predicted R_s is presented in Figure 3.1, while the linear regression for deriving A-P coefficients for the eight stations is shown in Figure 3.2. The values plotted were average daily values for the years under consideration. The variability explained R^2 was between 0.63-0.89. The calibrated A-P coefficients obtained were $a=0.21$ to 0.34 and $b=0.36$ to

0.61 (Table 3.2). The regression coefficients a and b showed large variations on a station-to-station basis similar to Boisvert et al., (1990). The constant K_{RS} (0.16 for inland and 0.19 for coastal) coefficients proposed by Hargreaves and Samani (H-S) worked well for all the locations except four locations where K_{RS} of 0.15 performed better. The locations are: Montreal ($K_{RS}=0.16$, $RMSE=1.14 \text{ MJ m}^{-2} \text{ d}^{-1}$; $K_{RS}=0.15$, $RMSE=1.01 \text{ MJ m}^{-2} \text{ d}^{-1}$), Beaverlodge ($K_{RS}=0.16$, $RMSE=1.19 \text{ MJ m}^{-2} \text{ d}^{-1}$; $K_{RS}=0.15$, $RMSE=0.24 \text{ MJ m}^{-2} \text{ d}^{-1}$), Elora ($K_{RS}=0.16$, $RMSE=1.44 \text{ MJ m}^{-2} \text{ d}^{-1}$; $K_{RS}=0.15$, $RMSE=0.73 \text{ MJ m}^{-2} \text{ d}^{-1}$) and Winnipeg ($K_{RS}=0.16$, $RMSE=1.07 \text{ MJ m}^{-2} \text{ d}^{-1}$; $K_{RS}=0.15$, $RMSE=0.55 \text{ MJ m}^{-2} \text{ d}^{-1}$).

Using a single K_{RS} value for a station is unrealistic because the climate variables such as humidity that affect the K_{RS} value are both spatially and temporally variable (Samani et al., 2011). Furthermore, the implicit assumption that the difference in maximum and minimum temperature is directly related to the fraction of extraterrestrial radiation received at the ground level could lead to error under some conditions (Samani et al., 2011). Factors other than solar radiation, such as cloudiness and humidity, can influence the difference in maximum and minimum temperature in a given location. These factors include latitude, elevation, topography, storm pattern, aerosol, water vapor, advection, and proximity to a large body of water (Samani et al., 2011).

The H-S model was more accurate than A-P methods in Elora, Swift Current and Winnipeg. Based on RMSE, MBE and ME, H-S was more consistent in accuracy for the eight stations with RMSE of 0.86 to $1.44 \text{ MJ m}^{-2} \text{ d}^{-1}$ followed by A-P calibrated, and A-P recommended with RMSE 0.13 to $2.12 \text{ MJ m}^{-2} \text{ d}^{-1}$ and 0.55 to $1.56 \text{ MJ m}^{-2} \text{ d}^{-1}$ respectively (Table 3.3 and 3.4). The RMSE of the other methods ranged between 1.11 to $7.34 \text{ MJ m}^{-2} \text{ d}^{-1}$. The deviations between measured and estimated R_s values using B-C and M-H models are very large compared to the others, while estimates using the S-C model were significantly different from measured R_s . Clearly, the S-C method did not work for any of the stations contrary to the conclusion by Allen (1997) that the self-calibration (S-C) procedure was more accurate than with the fixed Hargreaves and Samani constant and Allen 1995 model. The procedure by Allen (1997) has a limitation in that it does allow only for a single spatial calibration of K_{RS} and does not take into account the temporal variability of K_{RS} (Samani et al., 2011).

The percentage difference between the FAO-A-P and A-P calibrated models is low. It ranged between -0.47 to 6.97%. Based on the low difference between FAO A-P and A-P calibrated, it is not very necessary to recalibrate A-P in most of the study locations. Similar studies conducted in China by Liu et al., 2009 resulted in relatively significant mean percentage error. They found that the direct use of the FAO recommended coefficients significantly affected the estimation of ET_0 at most sites, which differed from -3% to 15% at daily scale and from -4% to 16% at monthly scale from the locally calibrated ones. S-C model had the highest RMSE (ranging from 6.39 to 7.34 MJ m⁻² d⁻¹) followed by M-H (RMSE ranging from 2.29 to 5.40 MJ m⁻² d⁻¹), B-C (RMSE ranging from 1.65 to 3.64 MJ m⁻² d⁻¹) and Allen (1995) model (RMSE ranging from 0.92 to 2.74 MJ m⁻² d⁻¹). M-H and S-C models had the worst performances in the study locations. M-H models generally overestimated R_s lower values of 5 to 7 MJ m⁻² d⁻¹, and underestimated higher values of 20 MJ m⁻² d⁻¹ (Mahmood and Hubbard, 2002). These biases are potentially associated with local-scale advection, frontal movement, and the regression method (Goodin et al., 1999).

The Samani equation was the best performed temperature based equation in Ottawa and Summerland. The H-S, Samani and Annandale model are relatively more accurate than the other temperature-based models (Table 3.3), despite the simplicity of these models and relative ease of deriving the coefficient compared to the other models. The Allen (1995) model performed the next best except for Winnipeg where the M-H model performed slightly better. B-C model overestimated the measured R_s in all the locations contrary to the findings by Chen et al., (2004), while the M-H model underestimated the measured R_s also in all the locations.

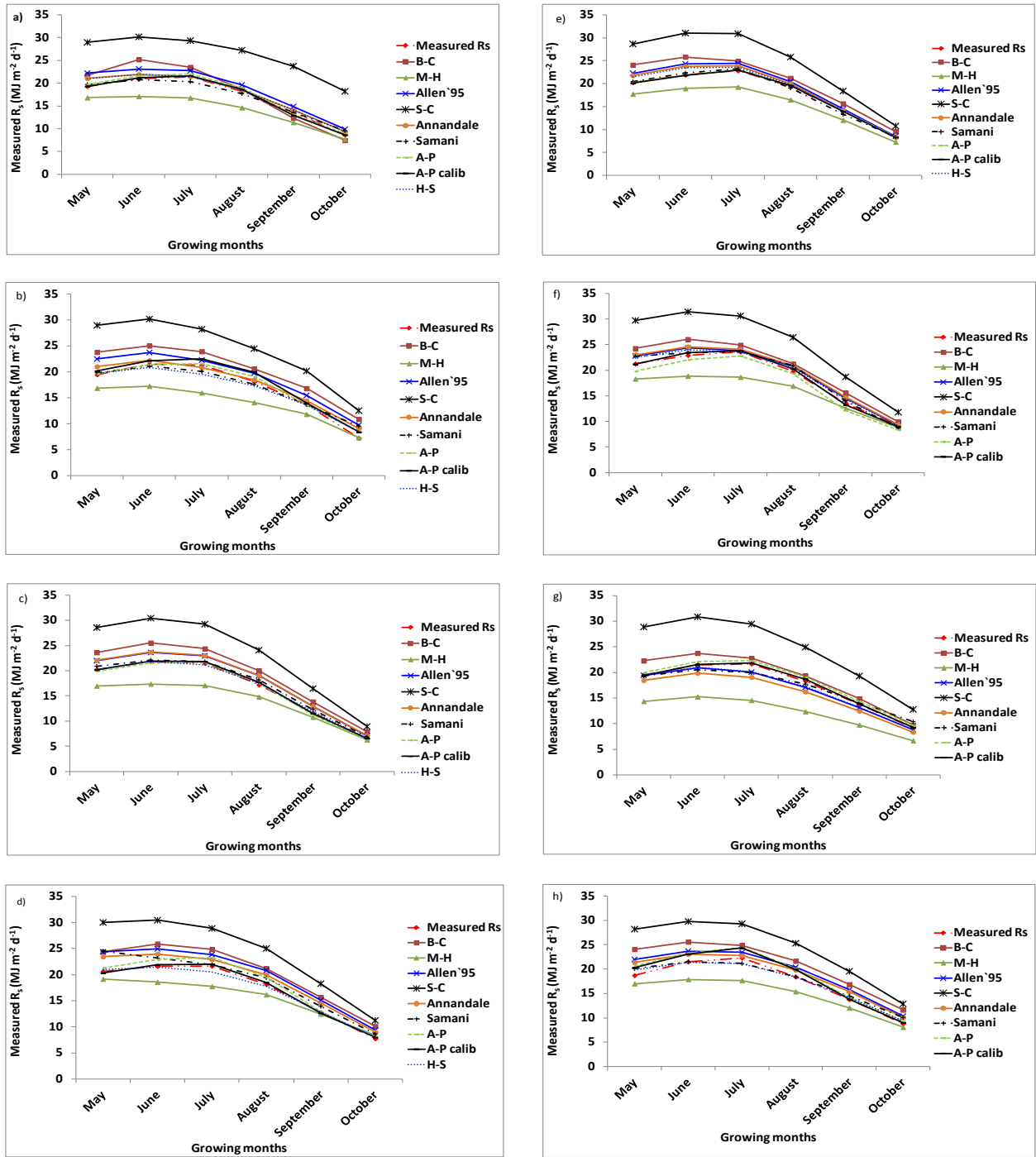
3.3.2 Comparison of reference evapotranspiration (ET_0) calculated using R_s estimates

The ET_0 s computed with FAO-56 PM using the different R_s estimates are presented in Table 3.5. It is observed that the ET_0 estimates varied from one location to another, even for stations within the same province, for example Ottawa, Toronto and Elora. There was no significant difference in the ET_0 s computed using R_s estimates generated by A-P, A-P calib, H-S, and Samani, even though studies by Almorox (2008) and Liu (2009) suggested that calibrating A-P locally will improve ET_0 estimation. The magnitude of RMSE was lower for ET_0 than that observed for R_s estimates. This was probably a result of more input variables involved in the ET_0 equation, but

the trend was the same. The R_s estimates of the S-C model gave the largest RMSE and over-predicted ET_o . The M-H model under-estimated ET_o s in all the stations by an average of 9.9%, while the B-C model over-estimated by an average of 5%. The R_s estimates generated by the Annandale model consistently resulted in over-estimation of ET_o s for all locations except Toronto, where there was under-estimation with a mean difference of 1.7%. The A-P calib, FAO A-P, H-S and Samani methods resulted in less than 1% over-estimation of ET_o . They outperformed other models; hence the suitability of these methods is validated for the locations under study.

3.4 Conclusions

The suitability of nine models to estimate R_s and their effect on the ET_o computed with FAO-56 PM was evaluated using data from eight weather stations in Canada. The A-P calib model performed well for estimation of R_s for all stations except for Montreal, Elora and Beaverlodge. The Samani model gave a better estimate than the H-S model for Ottawa and Summerland while the H-S performed better than the Samani model in Beaverlodge, Winnipeg, Swift Current, Elora and Toronto using the Hargreaves constant (K_{RS}) stated in table 3.2. Overall, the R_s estimated compared with R_s measured was not significantly different except for the Mahmood and Hubbard (M-H), the Bristow and Campbell (B-C), and the Self calibrating (S-C) models. These three models had the worst performance for all the stations. In the absence of solar radiation and sunshine data in Canada, the Samani and H-S models are recommended for estimation of R_s . When using the H-S model, a K_{RS} value of 0.15 is suggested as appropriate for Montreal, Beaverlodge, Elora and Winnipeg, 0.17 for Toronto, and 0.16 for the other three locations. The effect of R_s estimation was highly reduced in calculated ET_o using FAO-56 PM equation. From this assessment reliable R_s inputs will ensure more accurate computation of reference evapotranspiration and crop water requirements. The coefficients obtained in this study (especially Hargreaves and Samani constants) will provide baseline for R_s assessment in similar humid continental (warm and semi arid) climate.



B-C - Bristow and Campbell, M-H - Mahmood and Hubbard, S-C - Self-calibrating, A-P - FAO-56 Angstrom Prescott coefficients, A-P calib - Calibrated A-P coefficients, H-S - Hargreaves and Samani.

Figure 3.1: Measured R_s and estimated R_s for (a) Ottawa, (b) Montreal, (c) Beaverlodge, (d) Winnipeg, (e) Summerland, (f) Swift Current, (g) Toronto and (h) Elora.

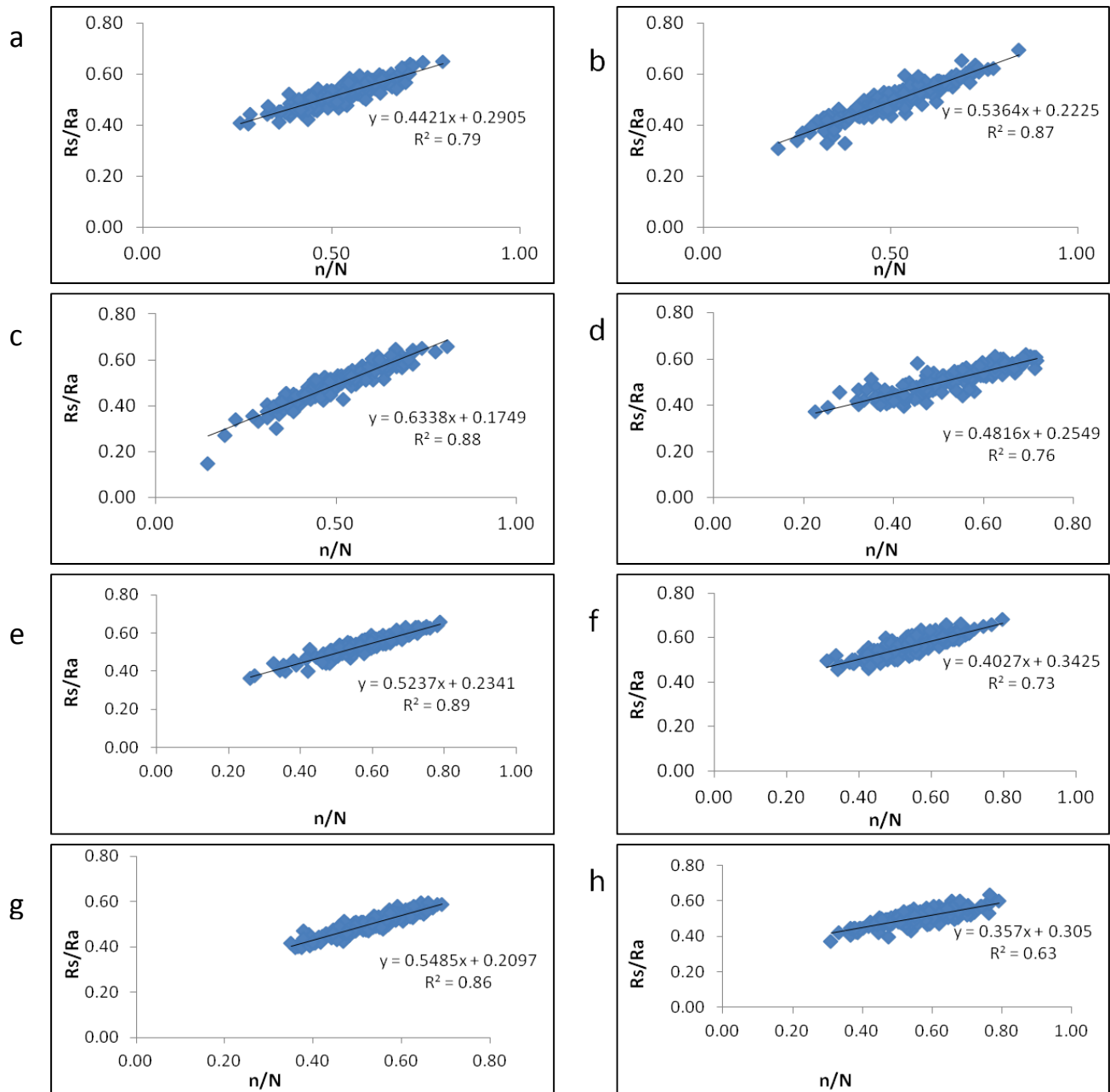


Figure 3.2: Relationship between ratio of measured solar radiation to extraterrestrial radiation (R_s/R_a) and ratio of sunshine duration to maximum daylength (n/N) for (a) Beaverlodge, (b) Elora, (c) Montreal, (d) Ottawa, (e) Summerland, (f) Swift Current, (g) Toronto and (h) Winnipeg.

Table3.2: K_{RS} values and calibrated A-P coefficientsal basis.

Stations	K_{RS}	K_{RS}	Angstrom-Prescott coefficients	
	(H-S)	(S-C)	a	b
Ottawa	0.16	0.22	0.25	0.48
Montreal	0.15	0.22	0.20	0.61
Beaverlodge	0.15	0.21	0.29	0.44
Winnipeg	0.15	0.21	0.31	0.36
Summerland	0.16	0.21	0.23	0.52
Swift Current	0.16	0.21	0.34	0.40
Toronto	0.17	0.25	0.21	0.55
Elora	0.15	0.21	0.22	0.54

K_{RS} (H-S)-Hargreaves and Samani constant, K_{RS} (S-C)-self calibrating constant adjusted to match
Rso envelopes

Table 3.3: Comparison of measured and estimated R_s based on performance evaluation criteria.

Location	Statistical parameters (MJ m ⁻² d ⁻¹)	R_s estimation methods								
		Calibrated	A-P	Samani	H-S	Annandale	Allen 95	B-C	M-H	S-C
Ottawa	RMSE	0.35	0.55	0.64	0.86	0.89	1.81	2.28	3.21	9.26
	MBE	-0.01	0.35	-0.09	0.68	0.72	1.70	1.11	-2.97	9.24
	ME	0.99	0.99	0.98	0.96	0.96	0.84	0.75	0.50	-3.19
Montreal	RMSE	2.12	1.09	0.64	1.14	1.11	1.13	3.33	3.51	7.34
	MBE	2.01	0.97	0.39	-0.29	0.78	0.10	3.27	-3.01	7.19
	ME	0.95	0.98	0.95	0.96	0.95	0.82	0.56	0.52	-1.12
Beaverlodge	RMSE	0.26	0.29	0.58	0.24	1.56	1.50	2.81	3.08	6.81
	MBE	0.11	-0.12	0.51	0.03	1.49	1.43	2.71	-2.61	6.45
	ME	0.99	0.99	0.98	0.99	0.92	0.93	0.75	0.70	-0.46
Winnipeg	RMSE	0.27	1.05	1.88	0.55	1.95	2.74	3.30	2.29	7.16
	MBE	0.12	0.88	1.49	-0.16	1.86	2.64	3.24	-1.69	6.88
	ME	0.99	0.96	0.87	0.99	0.86	0.72	0.59	0.81	-0.91
Summerland	RMSE	0.13	0.14	0.43	0.90	1.11	1.51	2.65	2.62	6.89
	MBE	0.01	0.08	0.02	0.67	0.89	1.31	2.44	-2.49	6.48
	ME	0.99	0.99	0.99	0.97	0.95	0.91	0.73	0.74	-0.82
Swift Current	RMSE	0.34	1.06	0.82	0.81	1.20	1.02	2.13	3.15	6.71
	MBE	0.12	-0.99	0.50	0.64	1.07	0.87	1.94	-2.71	6.39
	ME	0.99	0.96	0.98	0.98	0.95	0.96	0.84	0.64	-0.62
Toronto	RMSE	0.19	0.58	1.01	0.83	1.70	0.92	1.65	5.41	7.33
	MBE	0.12	0.57	-0.33	-0.65	-1.59	-0.76	1.46	-5.18	7.03
	ME	0.99	0.98	0.95	0.97	0.86	0.96	0.87	-0.44	-1.65
Elora	RMSE	1.38	1.56	0.94	0.73	1.62	2.12	3.64	2.90	7.12
	MBE	1.16	1.39	0.36	0.13	1.49	2.01	3.51	-2.58	6.90
	ME	0.91	0.89	0.96	0.98	0.88	0.80	0.39	0.61	-1.32

A-P- Angstrom-Prescott, H-S- Hargreaves and Samani, B-C-Bristow and Campbell, M-H-Mahmood and Hubbard, S-C- Self calibrating method of Allen, 1997.

Table 3.4: Ranking of different R_s models and locations based on root mean square error (RMSE).

Locations	R_s models								
	A-P calib	A-P	Samani	H-S	Annandale	Allen`95	B-C	M-H	S-C
Ottawa	1	2	3	4	5	6	7	8	9
Montreal	3	1	5	2	4	6	7	8	9
Beaverlodge	2	3	4	1	6	5	7	8	9
Winnipeg	1	3	4	2	5	6	8	7	9
Summerland	1	2	3	4	5	6	7	8	9
Swift Current	1	5	3	2	6	4	7	8	9
Toronto	1	2	5	3	7	4	6	8	9
Elora	3	4	2	1	5	6	8	7	9

H-S - Hargreaves and Samani, S-C - Self-calibrating, B-C - Bristow and Campbell, M-H - Mahmood and Hubbard, A-P - FAO-56 Angstrom Prescott coefficients, A-P calib - Calibrated A-P coefficients.

Table 3.5: Comparison of reference evapotranspiration (ET_o) calculated using R_S estimates

R_S estimation methods										
Location	Statistical parameters (mm d ⁻¹)	Calibrated A-P	A-P	Samani	H-S	Annandale	Allen 95	B-C	M-H	S-C
Ottawa	RMSE	0.03	0.06	0.06	0.08	0.08	0.18	0.36	0.37	0.78
	MBE	0.003	0.04	-0.03	0.06	0.06	0.16	0.16	-0.33	0.65
Montreal	RMSE	0.07	0.03	0.19	0.07	0.13	0.10	0.31	0.41	0.65
	MBE	0.02	0.01	-0.07	0.02	0.11	-0.06	0.21	-0.37	0.53
Beaverlodge	RMSE	0.02	0.02	0.04	0.02	0.13	0.12	0.27	0.28	0.59
	MBE	0.01	0.002	0.04	0.002	0.11	0.11	0.16	-0.26	0.45
Winnipeg	RMSE	0.02	0.10	0.14	0.05	0.15	0.22	0.24	0.63	0.31
	MBE	0.01	0.08	0.10	0.03	0.14	0.20	-0.20	0.50	0.21
Summerland	RMSE	0.01	0.01	0.04	0.10	0.12	0.16	0.33	0.30	0.76
	MBE	0.001	0.01	0.01	0.07	0.09	0.13	0.20	-0.28	0.61
Swift Current	RMSE	0.03	0.07	0.06	0.06	0.09	0.08	0.20	0.30	0.55
	MBE	0.01	-0.06	0.05	0.05	0.08	0.06	0.10	-0.27	0.44
Toronto	RMSE	0.02	0.06	0.11	0.10	0.19	0.11	0.24	0.59	0.79
	MBE	0.01	0.06	-0.06	-0.07	-0.16	-0.08	0.12	-0.55	0.67
Elora	RMSE	0.14	0.16	0.08	0.07	0.14	0.19	0.43	0.33	0.71
	MBE	0.12	0.14	0.01	-0.002	0.12	0.17	0.37	-0.28	0.60

A-P- Angstrom-Prescott, H-S- Hargreaves and Samani, B-C-Bristow and Campbell, M-H-Mahmood and Hubbard, S-C- Self calibrating method of Allen, 1997.

Connecting text to Chapter 4

Information from chapter 3 is valuable for the development of agricultural water demand model in chapter 8. In order to optimize water use in bell pepper production, information about the appropriate irrigation water applications, agronomic and physiological response to mild and severe water stress is required. In this chapter the response of greenhouse grown bell pepper to variable irrigation was determined. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis. This chapter has been accepted for publication in the March 2014 issue of Canadian Journal of Plant Science as an original research manuscript, Manuscript ID: CJPS2013-048.R3.

Chapter 4 Response of greenhouse grown bell pepper (*Capsicum annuum* L.) to variable irrigation

Olanike Aladenola and Chandra Madramootoo

Abstract

In order to optimize water use in bell pepper production information about the appropriate irrigation water applications and agronomic and physiological response to mild and severe water stress is necessary. Different water applications on yield, quality and water stress threshold of greenhouse grown bell pepper (*Capsicum annuum* L.) cultivar Red Knight were tested in 2011 and 2012 on the Macdonald Campus of McGill University, Ste Anne De Bellevue, QC. Canada. The study was carried out on a soil substrate in the greenhouse. Irrigation was scheduled with four treatments namely 120% (T_1), 100% (T_2), 80% (T_3), and 40% (T_4) of pan evaporation in a completely randomized design (CRD). Highest marketable yield, water use efficiency and irrigation water use efficiency was obtained with T_1 in both years. T_1 received 20% more water than T_2 to produce 23% more marketable yield than T_2 . Fruit total soluble solids content was highest in T_4 , and least in T_1 . The mean crop water stress index (CWSI) of the irrigation treatments ranged between 0.08 and 1.18. Leaf stomatal conductance of bell pepper was 75 to 80% lower in T_4 than in T_1 . Regressions obtained between stomatal conductance and CWSI resulted in a polynomial curve with coefficient of determination of 0.88 and 0.97 in 2011 and 2012 respectively. The results from this study indicated that the yield derived justifies the use of extra quantity of water. Information from this study will help water regulators to make appropriate decisions about water to be allocated for greenhouse production of bell pepper.

Keywords: *Capsicum annuum* L., crop response, evapotranspiration, stomatal conductance, water use efficiency.

4.1 Introduction

One of the threats facing vegetable producers in Canada is irrigation restrictions from water regulators (Agriculture and Agri-Food Canada, 2010). The major vegetables grown in Canada include tomato, bell pepper, cucumber and sweet corn. Bell pepper (*Capsicum annuum* L) is a major greenhouse and field vegetable grown for the fresh and processing markets, accounting for 37% of the Canadian greenhouse vegetable exports (Statistics Canada, 2011).

High value vegetables grown in Canada require irrigation to meet evapotranspiration demands (Bernier et al., 2010). Bell pepper plant is highly sensitive to water stress (Ferrara et al., 2011; Yildirim et al., 2012). Water stress has been shown to adversely affect physiological and nutritional development, and fruit yield of bell pepper (Kirmak et al., 2003). Pepper performs well with adequate supplies of water during its growth cycle (Gonzalez-Dugo et al., 2007; Zotarelli et al., 2011). The management of irrigation for bell pepper plants differ in terms of pepper varieties, length of growing cycle, soil type environment, climatic region, irrigation type and irrigation scheduling (Dalla Costa and Gianquinto 2002; Ezzo et al., 2010; Sezen et al., 2006). To achieve optimal bell pepper production and best irrigation regime, there is a need for a comprehensive assessment of the yield, water use efficiency and physiological response of the plant to a particular soil type, production system and irrigation regime. Based on the need to optimise greenhouse production of bell pepper, which is necessary for winter production in Canada, the effect of water application on bell pepper, cultivar Red Knight, grown on loamy sand in the greenhouse was evaluated. Though most modern commercial greenhouses use hydroponic medium, greenhouse experiments using soil medium are found in past studies (Orgaz et al., 2005; Senyigit et al., 2011). Some greenhouse growers continue to use soil, for example, Almeria in Spain with 10,000 hectare dedicated to greenhouse production (Sanchez et al., 2000). Soil was used in this study so that the findings can be used as baselines for greenhouse production where soil medium is used.

Irrigation scheduling based on pan evaporation has been used extensively for tomato (Imtiyaz et al., 2000; Sezen et al., 2010), cucumber (Yuan et al., 2006; Wang et al., 2009) and bell pepper (Sezen et al., 2006). Based on the findings from these results, the irrigation regime for achieving higher yields and improving crop quality were recommended. Irrigation scheduling can be

improved by monitoring crop canopy temperatures using an infrared thermometer (Jones, 2004). Use of an infrared thermometer increased in popularity when Idso et al., (1981) observed a linear relationship between canopy temperatures measured using infrared thermometer and air temperature and vapour pressure deficit, and used this to develop an empirical method of quantifying crop water stress. The empirical crop water stress index (*CWSI*) uses two baselines. The lower baseline represents canopy temperature (T_c) - air temperature (T_a) of a well watered crop transpiring at maximum potential rate and the upper baselines represents ($T_c - T_a$) of a non transpiring crop [Eq. 4.1].

$$CWSI = \frac{[(T_c - T_a) - (T_{nws} - T_a)]}{[(T_{dry} - T_a) - (T_{nws} - T_a)]} \quad [4.1]$$

where: T_c : canopy temperature ($^{\circ}\text{C}$), T_a : air temperature ($^{\circ}\text{C}$), T_{nws} : non-water stressed canopy temperature ($^{\circ}\text{C}$), and T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$).

Crop water stress index (*CWSI*) is based on the principle that transpiration cools the leaf surface and as water becomes limiting, stomatal conductance and transpiration decrease and leaf temperature increases. *CWSI* has been widely used as a tool to indicate plant water status and scheduling irrigation in many crops (Cremona et al., 2004; Erdem et al., 2010; Yildirim, 2012). However, *CWSI* has to be determined for particular crops and in a specific climate, in order to be an effective tool for scheduling irrigation and yield prediction. Crop response to water stress differs depending on local environmental conditions (Orta et al., 2003). *CWSI* determined often serve as a reference value for use by irrigators and it might be necessary that a range of *CWSI* should be provided for field use depending on temporal and spatial variation in climate. However, year to year variability that might affect *CWSI* and its correct application in the greenhouse is minimised. There is very little published information available for the *CWSI* of greenhouse grown bell pepper with respect to optimal crop water requirements, stomatal conductance, water use efficiency (*WUE*), and the effect of water deficit on crop growth and production (Ferrera et al., 2011). The aim of the study is to determine the yield and physiological response of greenhouse grown bell pepper to different water applications. Therefore, the objectives of this research were to: (1) determine yield, water use and corresponding stress index

values of greenhouse grown bell pepper using 120% (T_1), 100% (T_2), 80% (T_3), and 40% (T_4) of pan evaporation (E_{pan}) (2) determine the relationship between stomatal conductance and stress index values of bell pepper.

4.2 Materials and methods

4.2.1 Experimental design and irrigation treatments

This study was carried out in 2011 and 2012 on the Macdonald Campus of McGill University, Ste Anne De Bellevue, Qc. Canada. The study area was between latitude 45.43° and longitude 73.93° W with an elevation 36 m. Bell pepper (cultivar Red Knight) seedlings were transplanted on 18 February and 17 March in 2011 and 2012, respectively, into 19-litre pots. The soil was loamy sand with sand, silt and clay content of 77, 19 and 5% respectively, field capacity of 19% and wilting point of 7% by volume. The experiment was arranged in a completely randomised design (CRD) with four replicates. Plants were hand watered at a three day interval at treatment levels of 120% (T_1), 100% (T_2), 80% (T_3) and 40% (T_4) of pan evaporation and fertilized weekly with 20-20-20 NPK water soluble fertilizer. The fertilizer was changed to calcium nitrate after first fruits were about 165 and 130 mm in longitudinal and transverse circumference respectively. Irrigation was uniformly applied to all treatments at the beginning of transplanting until 24 March and 21 April (36 Days After Transplanting in 2011 and 2012 respectively), based on 100% replacement of evapotranspiration losses for plants to be well established; thereafter variable irrigation was manually applied once every three days until harvest.

4.2.2 Measurements

Air temperature, relative humidity and vapour pressure deficit were measured using a Campbell scientific psychrometer (Campbell Scientific, Logan, Utah) installed about one meter above the crop canopy and evaporation in the greenhouse during the growing season was determined using a Class A evaporation pan (121 cm in diameter and 25.5 cm in depth) was located in the greenhouse. Irrigation was initiated based on the cumulative pan evaporation measured during the irrigation interval. Irrigation water applied was calculated as:

$$IR = A * E_{pan} * K_p * K_c \quad [4.2]$$

where: IR: Irrigation water (L), A: Area of pot (m²), E_{pan}: amount of cumulative evaporation (mm), K_p: Pan coefficient, and K_c: Crop coefficient.

The pan and crop coefficient used in this study were taken from Allen et al., (1998) and Orgaz et al., (2005) and are given in Table 4.1.

Table 4.1: Growth stages and crop coefficients (K_c).

Crop growth stage	K _c values
Initial	0.2
Development (flowering)	0.7
Mid season (fruiting)	1.3
Late season (senescence)	0.9

4.2.2.1 Stomatal conductance

Stomatal conductance was measured during the growing period using a Li-6400 Portable Photosynthesis System (LICOR Ltd, USA). Licor is a device that uses infrared gas analysis to quantify CO₂ uptake and H₂O output of leaf tissues. A healthy, full sunlit leaf was selected from each pot and stomatal conductance was measured on the leaf using the LI-6400.

4.2.2.2 Canopy temperature

Leaf temperatures were obtained with infrared thermometry set at emissivity of 0.95 (Evet et al., 2000) (Fluke 572 model, Fluke Corporation, Everett, WA, USA). The instrument was held about 1.5 m above ground level and directed at the leaf of the bell pepper plant with a laser point of the instrument set at an angle about 30° below the horizontal (Nielsen and Anderson, 1989; Orta et al., 2002). Six infrared thermometer measurements were carried out when the plant canopy covered about 80% of the pot area from 14 April to 16 May in 2011 and 4 May to 5 June in 2012. Temperature of the non-stressed plants 120% E_{pan} (T₁) (lower baseline) and fully stressed 40% E_{pan} (T₄) (upper baseline) were determined from canopy and ambient air temperature data, four (north, south, east and west) viewing directions were considered and average temperature

values obtained. Measurement time was between 11:30 am-2:00 pm to assure that measurements were taken at maximum solar intensity because the sun was directed on all the plants during these hours. Mean values of the crop canopy temperature were used for calculating *CWSI* using Eq. 4.1 (Idso et al., 1981).

4.2.2.3 Fruit yield and quality

Total soluble solids content (°Brix) were estimated by measuring the refractive index with a portable refractometer model RHB-32 (Palette 100 PR-100, AT AGO-Spectrum Technologies, Plainfield, IL) that had been standardized with distilled water. Fruits and number of leaves were weighed (g), and fruit diameter (FD), fruit length (FL), and stem diameter were measured by caliper rule in cm and the average of measured values was computed. Plant height was measured with a graduated rule. Marketable peppers were classified as peppers fresh, without blemish and rot.

4.2.2.4 Water use efficiency and irrigation water use efficiency.

Water use efficiency (*WUE*) was calculated as the ratio between total yield harvested (kg plant^{-1}) and crop evapotranspiration (ET_c , m^3) and also from the ratio between marketable yield (kg plant^{-1}) and crop evapotranspiration (ET_c). Irrigation water use efficiency (*IWUE*) was calculated as the ratio between total yield (also marketable yield) harvested (kg plant^{-1}) and total volume of water applied (m^3).

4.2.2.5 Statistical analysis

Statistical analysis were carried out on crop yield, *WUE*, *IWUE* using PROC/GLM (General Linear Model) procedure of SAS institute (version 9.3 SAS Institute Inc). Analysis of variance (ANOVA) was conducted and significance of differences among treatments was separated using the Least Significant Difference (LSD) at 5% probability level. In addition, there was a regression analysis between the crop yield and water applied.

4.3 Results

4.3.1 Greenhouse and crop evapotranspiration and applied irrigation water

Mean temperature, humidity and vapour pressure deficit in the greenhouse ranged from 20.4 to 27°C, 59 to 81% and 4.6 to 14.8 kPa, respectively, in 2011 and from 23.0 to 32.4°C, 54.1 to 98.9% and 2.0 to 12.9 kPa in 2012, respectively. The E_{pan} was approximately 295 mm in 2011 and approximately 246 mm in 2012. A total of 10.3 and 9.5 mm of water was applied to each pot prior to variable irrigation in 2011 and 2012, respectively. During the growing season, total water applied for the different growth stages for all treatments ranged from 40 to 99 mm in 2011 and 31 to 102 mm in 2012 (Table 4.2). Total water used by the crop for each irrigation treatment ranged from 34 to 84 mm in 2011 and 30 to 81 mm in 2012 for the entire growing season.

Table 4.2: Equivalent depth of water applied (mm) per growth stage for the different irrigation treatment for 2011 and 2012.

Year	2011					2012			
Growth stages ^z	Irrigation Treatments (% of E _{pan})								
	Days	120%	100%	80%	40%	120%	100%	80%	40%
Initial	20	11.9	11.3	10.7	9.4	8.7	8.3	7.9	6.9
Development	30	24	20	16	8	20.6	17.1	13.7	7.2
Mid season	30	34.9	29.1	23.2	11.6	36.6	30.4	24.1	11.6
Late season	25	13.5	11.6	9.7	5.9	15.5	12.4	9.9	4.9
Total	105	84.2	71.9	59.6	34.9	81.4	68.2	55.6	30.6

^zDevelopment-flowering, Mid season-fruiting, Late season-senescence, E_{pan} -Pan evaporation

4.3.2 Fruit yield and quality

Maximum and minimum total and marketable yields and average weight per fruit were obtained respectively from treatments 1 (T_1 , 120% E_{pan}) and 4 (T_4 , 40% E_{pan}) in 2011 and 2012 (Table 4.3). The relations between bell pepper yield (total and marketable) and total water applied as derived through regression analysis was $T_1 > T_2 > T_3 > T_4$ (Figure 4.1). Marketable yield in T_1 was 23% higher than T_2 while total yield in T_1 was 4% higher than T_2 . T_1 had significantly higher total and marketable yield than the other treatments in 2011 while in 2012, total and marketable

yields from T_1 and T_2 were not significant from each other but both were significantly higher than T_4 (Table 4.4). The plant height decreased with decreasing water applied for the two seasons, the heights were 52.3 and 55 cm, 51.7 and 51.3 cm, 45.3 and 41 cm, and 35.3 and 34.5 cm for T_1 , T_2 , T_3 and T_4 for 2011 and 2012 respectively.

Table 4.3: Effect of irrigation treatment on total and marketable fruit yield, average weight of fruit, irrigation water use efficiency (*IWUE*) and water use efficiency (*WUE*).

Year	Treatments	Total yield ^y (kg plant ⁻¹)	Marketable yield (kg plant ⁻¹)	Average weight per fruit (g)	Average fruit diameter (mm)	<i>IWUE</i> (kg m ⁻³)	<i>IWUE</i> (kg m ⁻³)
2011	Trt 1	0.63 ^a	0.59 ^a	58 ^a	51.9	31.6 ^a	5.5 ^a
	Trt 2	0.60 ^a	0.49 ^a	52 ^a	50.1	29.3 ^a	4.8 ^a
	Trt 3	0.32 ^b	0.19 ^b	35 ^{ab}	47.6	7.3 ^b	1.8 ^b
	Trt 4	0.12 ^c	0.02 ^c	16 ^c	35.4	2.9 ^b	0.3 ^b
2012	Trt 1	0.56 ^a	0.53 ^a	60 ^a	52.8	28.2 ^a	3.8 ^a
	Trt 2	0.50 ^a	0.40 ^a	57 ^a	50.1	25.1 ^a	3.4 ^a
	Trt 3	0.32 ^{ab}	0.17 ^b	39 ^{ab}	48.0	13.1 ^b	1.5 ^b
	Trt 4	0.06 ^c	0.02 ^c	21 ^c	36.2	3.3 ^c	0.2 ^c

^yMeans followed by the same letter within the column are not significantly different at $p < 0.05$. Reported values are average of three replicates.

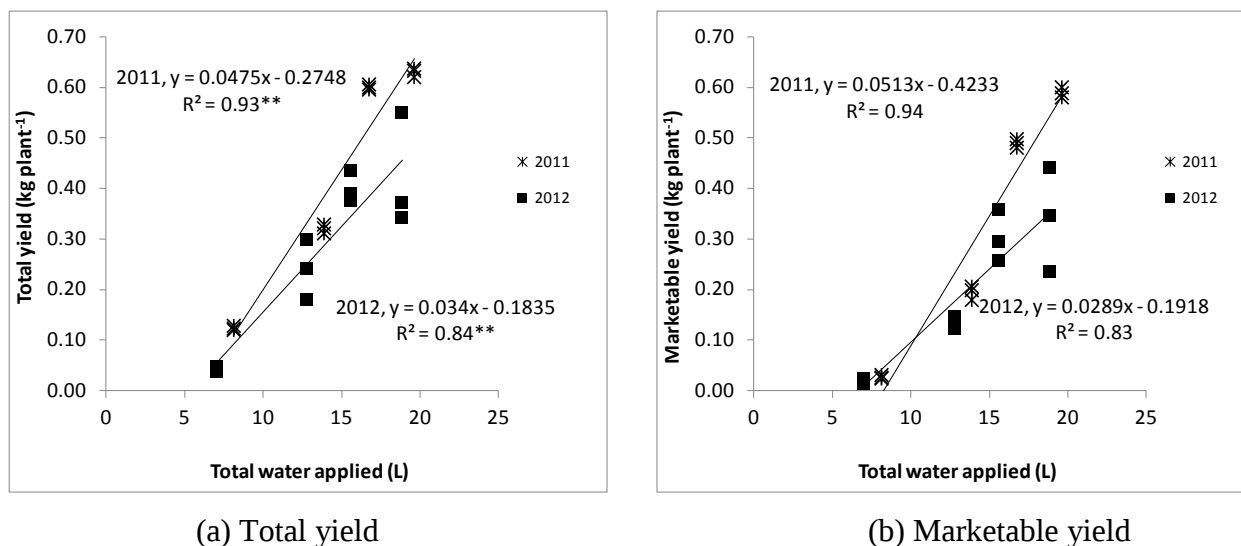


Figure 4.1: Yields of bell pepper versus total water applied in 2011 and 2012.

Table 4.4: Statistical analysis of fruit yield (total and marketable) and irrigation water use efficiency (*IWUE*) showing the paired comparison of treatments means.

	Total yield		Marketable yield		<i>IWUE</i>	
	2011	2012	2011	2012	2011	2012
Treatment	p value ^y					
1 vs 2	0.82ns	0.74ns	0.13ns	0.47ns	0.74ns	0.81ns
1 vs 3	0.0098*	0.06ns	0.0001*	0.04*	0.0002*	0.042*
1 vs 4	0.0003*	0.02*	0.0001*	0.02*	<0.0001*	0.04*
2 vs 3	0.0152*	0.34ns	0.0004*	0.03*	0.0004*	0.29*
2 vs 4	0.0004*	0.03*	0.0001*	0.04*	<0.0001*	0.07*
3 vs 4	0.073ns	0.18ns	0.04*	0.04*	0.03*	0.04*

^yns-not significant, *- significant at $p < 0.05$

The fruit total soluble solids content in relation to water applied are shown in Figure 4.2. Fruit total soluble solids for plants produced with T_1 were on average 7.8%, 5.1% and 25.1% relatively lower to plants produced with T_2 , T_3 and T_4 .

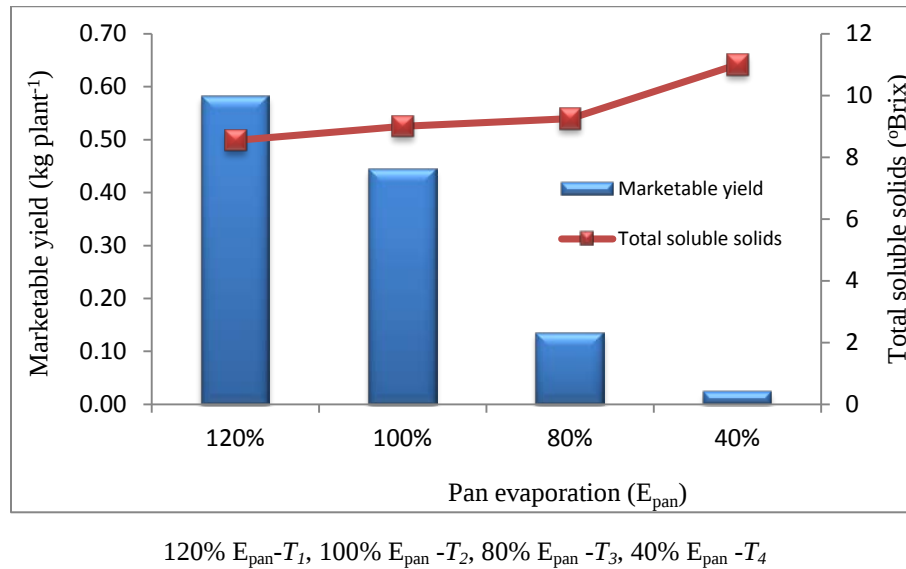


Figure 4.2: Fruit total soluble solids content ($^{\circ}Brix$) in relation to marketable fruit yield and irrigation levels (Average of 2011 and 2012).

4.3.3 Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Water use efficiency (WUE) and irrigation water use efficiency ($IWUE$) values are shown also in (Table 3). Highest water use efficiency (WUE) and irrigation water use efficiency ($IWUE$) values were obtained with T_1 , while the lowest WUE and $IWUE$ values were obtained from the treatment with 40% E_{pan} , (T_4). WUE followed the same trend as fruit marketable yield. $IWUE$ and WUE in T_1 was not different from that of T_2 but significantly lower $IWUE$ and WUE were observed for T_3 and T_4 for the two years under study (Table 4.4).

4.3.4 CWSI and stomatal conductance

Mean $CWSI$ values of 0.08 (T_1), 0.31 (T_2), 0.65 (T_3) and 1.0 (T_4) were determined in 2011 and mean $CWSI$ values of 0.1 (T_1), 0.30 (T_2), 0.86 (T_3) and 1.18 (T_4) were obtained in 2012. The curve of $CWSI$ against yield (marketable and total) is presented in (Figures. 4.3 a& b). Polynomial relationships exist between $CWSI$ and yield, indicating a decrease

in yield as crop water stress increases. The increase in *CWSI* from 0.31 to 0.65 in 2011 and 0.3 to 0.86 in 2012 led to difference in bell pepper yield between treatments T_2 and T_3 (Table 4.4). The relationship between stomatal conductance and *CWSI* is shown in Figure 4.4. The polynomial relationship was used because it minimises the deviation between stomatal conductance and *CWSI*. The coefficient of determination (R^2) for the *CWSI* and stomatal conductance was 0.88 and 0.97 in 2011 and 2012, respectively. *CWSI* increase with increasing water stress while stomatal conductance decrease with increasing water stress. T_1 had the lowest *CWSI* and highest stomatal conductance while T_4 had the highest *CWSI* and lowest stomatal conductance. This shows an inverse relationship between *CWSI* and stomatal conductance.

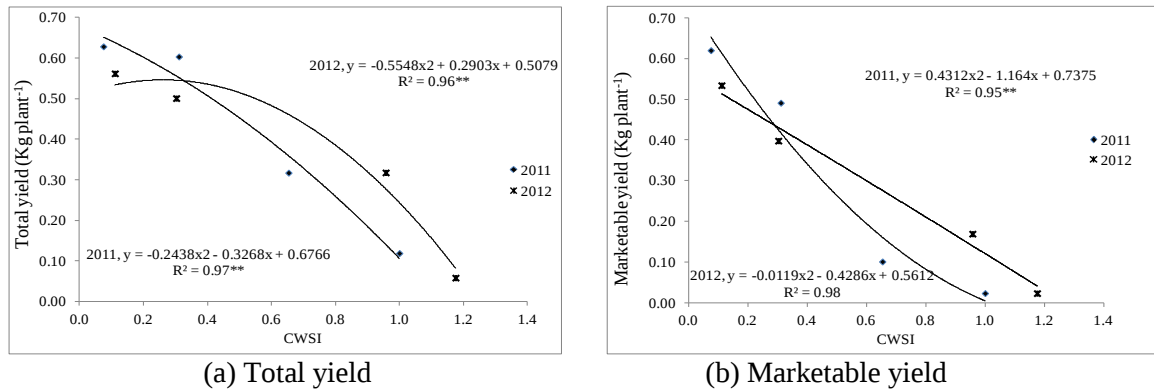


Figure 4.3: Yields against *CWSI*

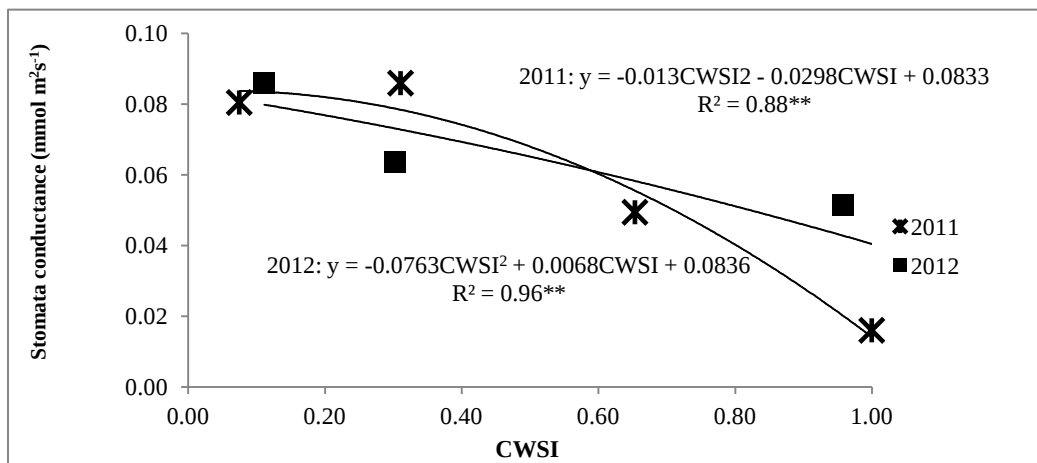


Figure 4.4: Stomatal conductance against *CWSI*

4.4 Discussion

Overall, yields in 2011 were higher than in 2012 because of higher temperature in the greenhouse which led to early maturity. Higher temperature has been documented to inhibit fruit set and size of bell pepper (Erickson and Markhart, 2001; Saha et al., 2010). The rise in temperature was due to a defect misting system in 2012, which made the greenhouse to be warmer. The growing season in 2011 was 128 days until harvest, compared to 103 days in 2012. Total fruit yield was highly influenced by the volume of irrigation water applied resulting in a linear relationship (Figure 1a); this indicates that more water applied based on pan evaporation resulted in more yield. This linear relationship is similar to finding on green bean and sweet corn, (Sezen et al., 2008; Oktem, 2008) and bell pepper (Dorji et al., 2005). The range of irrigation treatments used for this study provided a clearer option for evaluating the interaction between applied water and plant responses as compared to irrigation schedule (deficit irrigation, partial rootzone drying and commercial irrigation) by Dorji et al., 2005. Highest yield obtained in T_1 (120% E_{pan}) water application is an indication that T_2 (100% E_{pan}) is not the same as 100% actual crop evapotranspiration (ET_c) and the treatment at 100% E_{pan} (T_2) might be undergoing mild stress, similar finding were reported by Dalla Costa and Gianquinto (2002). The most water stressed treatment (T_4) had the highest fruit total soluble solids, the bigger the fruit (which was as a result of the water applied), the lower the fruit total soluble solids content. WUE and $IWUE$ values increased with the increasing irrigation water based on E_{pan} , this is in conformity with other studies (Babik and Elkner, 2002; Gutezeit, 2004).

Increasing $CWSI$ with decreasing water application was observed similar to studies determining $CWSI$ of broccoli (Erdem et al., 2010) and water melon (Orta et al., 2003). The relationship obtained between yield and $CWSI$ may be used to predict yield potential of bell pepper. $CWSI$ value of 1.18 obtained for T_4 exceeded the range of 0 to 1.0 commonly reported in the literature. These results confirmed the study by Yuan et al., (2004) that the values of the $CWSI$ based on empirical baselines would slightly exceed the range. The reason for the exceedance might be attributed to low vapour pressure deficit (VPD) in the study area which ranged between 11 to 15 kPa, whereas the locations

where *CWSI* of 0 to 1.0 were reported had VPD ranging from 20 to 40 kPa (Idso 1982; Alderfasi and Nielsen, 2001). The high correlation (polynomial) between *CWSI* and stomatal conductance is similar to studies for other crops (Leinonen et al., 2006; Zia et al., 2009).

An average *CWSI* value of 0.09 before irrigation will produce the maximum yield and a *CWSI* limit of about 0.3 to 0.65 prior to irrigation will prevent significant yield loss. The *CWSI* and stomatal conductance adequately reflected the variability in water status at different irrigation levels. This gives a better understanding of the sensitivity of bell pepper to water stress. The strong correlation between *CWSI* and stomatal conductance is an indication of their potential suitability for timing irrigation.

4.5 Conclusions

Highest marketable bell pepper yields can be achieved in the greenhouse (using soil medium) with a 120% of pan evaporation (E_{pan}) and irrigation timing determined by a *CWSI* value of 0.09. Highest fruit total soluble solids were produced by plant irrigated with 40% pan evaporation (T_4). Increasing the amount of water applied from 100% E_{pan} to 120% E_{pan} increased the marketable yield of bell pepper by 23%. The equation from the correlation between yield and *CWSI* can be used for total yield prediction. The correlation between *CWSI* and stomatal conductance is an indication of their potential suitability for timing irrigation. The equation determined can thus be integrated into an agricultural water demand model. It could be used as an adjunct to soil moisture sensors and/or evapotranspiration methods for irrigation scheduling, to improve the efficiency of irrigation water use and lead to water savings in greenhouse production systems. The study provided information on irrigation application required for producing high fruit yields and high fruit total soluble solids and *CWSI* threshold required for timing irrigation.

Connecting text to Chapter 5

The successful use of plant water status indicators (*CWSI* and stomatal conductance) for timing irrigation requires that their threshold should be established because of the effect of variation due to soil type, climate, cultivar. In this chapter the *CWSI* of bell pepper grown on two soil types in the greenhouse was established. In addition, the interaction between water stress, *CWSI*, stomatal conductance and yield was assessed. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis.

Chapter 5 Effects of irrigation levels and soils on yield and physiological response of bell pepper (*Capsicum annum. L*)

Olanike Aladenola and Chandra Madramootoo

Abstract

Greenhouse experiments were conducted over two years to determine crop water stress index (CWSI) and investigate stomatal response of bell pepper grown on clay and on loamy sand soil, and also to evaluate the effect of irrigation levels, soil types and their interactions on yield, irrigation water use efficiency (IWUE) and water use efficiency (WUE) of bell pepper. Four irrigation levels - 120% (T_{120}), 100% (T_{100}), 80% (T_{80}) and 40% (T_{40}) of crop water use (CWU) were applied on the soils using a 3-day irrigation interval. The experiment was laid out in a 4x2 factorial design and three replications for each treatment. The results showed that for all irrigation treatments, plants grown on clay soil had higher stomatal conductance and CWSI. Bell pepper performed best at T_{120} with a corresponding CWSI of 0.18 to 0.20 on clay, and a CWSI of 0.09 to 0.11 on loamy sand. The yield obtained with T_{120} on loamy sand was significantly higher than yields obtained by T_{120} for clay soil in one season. Averaged over the two seasons, bell pepper grown on loamy sand soil and at T_{120} produced the maximum marketable yield ($0.44 \text{ kg plant}^{-1}$), IWUE (23.6 kg m^{-3}) and WUE (4.8 kg m^{-3}) compared to clay soil where the marketable yield, IWUE and WUE were $0.36 \text{ kg plant}^{-1}$, 19.6 kg m^{-3} and 4.0 kg m^{-3} respectively. Marketable bell pepper yield on loamy sand is higher by an average of 24.4 and 32.3% respectively in 2012 and 2012/13 when compared to clay soil. The interaction effects of the irrigation levels and soil type on yield, WUE and IWUE of bell pepper were not significant ($p < 0.05$) in both years. The correlation between CWSI, water applied, yield and stomatal conductance was highly significant.

Keywords: Crop water stress index, irrigation scheduling, soil types, stomatal conductance.

5.1 Introduction

The choice of irrigation scheduling method depends to a large degree on the objectives of the irrigator and on the available irrigation system (Jones, 2004). One of the main decisions an irrigator makes during crop production is the timing of irrigations. This decision is critical for the sustainable production of vegetables such as bell peppers which are sensitive to water stress (Sezen et al., 2006; Zotarelli et al., 2011). It is important to understand the response of specific crops to water stress for the purpose of irrigation scheduling because the stomata of cultivars of the same species may show contrasting response to water stress. This understanding is essential because the physiological responses of plants to water stress varies with species, soil type, nutrients, and climate (Akıncı and Lösel., 2012; Orta et al., 2003).

Bell pepper's response under different irrigation water levels and different soil type were determined to provide baseline information that can be used for scheduling irrigation on the field and greenhouses where soil medium is used, although it is expected that variations may arise under field conditions. This study is necessary because studies on yield response of bell pepper to irrigation treatments (Sezen et al., 2006), crop water stress index relationship to yield and water applied are based on result from one soil type (Erdem et al., 2010). This relationship may or may not be appropriate if applied to different soil types.

There are many studies involving evaluation of yield and water use of greenhouse grown bell pepper (Candido et al., 2009; Ferrara et al., 2011; Aladenola and Madramootoo, 2014) and field grown bell pepper (Sezen et al., 2006). However, to our knowledge there is not much work on *CWSI* baselines (Aladenola and Madramootoo, 2014) and stomatal response of bell pepper to irrigation strategies under greenhouse or field conditions (Yao et al., 2001; Agele et al., 2006). Aladenola and Madramootoo, (2014) determined the fruit yield, water use and *CWSI* of greenhouse grown bell pepper to variable irrigation under loamy sand, however, a further assessment of its yield, *CWSI* and stomatal response under different soil types and irrigation levels is necessary because plant water use is generally influenced both by its hydraulic conductance (Agele et al., 2006) and the

texture of soil on which it is grown (Zeng et al., 2013). Further understanding of the influence of different soil texture on *CWSI* is required for its adoption as a tool for making more effective irrigation decision. This study is different from other studies because it investigated the interaction of irrigation levels and different soils on yield, water use and physiological parameters of bell pepper.

The use of any plant-based indicator for irrigation scheduling requires the definition of reference or threshold values, beyond which irrigation is necessary, (Fereres and Goldhamer, 2003). Plant-based sensors for irrigation typically measure plant responses that are related to moisture uptake (sap flow), transpiration (e.g. canopy temperature/reflectance) or growth rate (White and Raine, 2008). Variations in these measurements indicate crop stress which can be used to infer when to apply irrigation (White and Raine, 2008). Plant stress indices have been related to soil water availability (Jackson et al., 1981; Thompson et al., 2007) and yield (Ajayi and Olufayo, 2004). The crop water stress index (*CWSI*) is often used to quantify water stress in crops based on canopy surface temperature (Gardner et al., 1992; Yuan et al., 2004).

CWSI is a measure of the relative transpiration rate occurring from a plant at the time of measurement. The calculation of the *CWSI* is based on plant canopy temperature (T_c), air temperature (T_a) and atmospheric vapour pressure deficit (*VPD*) which is the difference in pressure due to the amount of water in the atmosphere (calculated as saturation vapour pressure - actual vapour pressure of the air). The calculation of *CWSI* based on the Idso et al., (1981) definition relies on two baselines: the non-water-stressed baseline (lower baseline) corresponding to the temperature of a well watered crop, and the fully stressed baseline (upper baseline) representing the temperature of a non-transpiring crop (stomata fully closed) (Idso et al., 1981; Yuan et al., 2004).

The application of the *CWSI* in irrigation scheduling has been evaluated for different crops including vegetables (Cremona et al., 2004; Erdem et al., 2010). Erdem et al. (2006) observed that trends in potato *CWSI* values were consistent with the soil water contents induced by deficit irrigation. He concluded that different non water-stressed baselines should be used for potato under different irrigation application times. Erdem et

al. (2010) highlighted that *CWSI* values were useful for evaluating crop water stress in broccoli, and could be useful for timing irrigation and predicting yield. They stated that an average *CWSI* of about 0.51 before irrigation will produce the maximum yield and further confirmed that *CWSI* has good relations with some growth parameters for developing the crop growth model. *CWSI* values are also affected not only by $T_c - T_a$, depending on the transpiration of crop but also by the VPD of the air (Candogan et al., 2013).

Stomatal conductance (the speed or rate at which water vapour exits through the stomata of a leaf) regulates many plant processes (carbon dioxide assimilation, respiration, transpiration) and like *CWSI*, may be used to determine bell pepper water use, water status and response to growth environment. Plant stress response monitored through the stomatal conductance can be used to regulate sugar content in the bell pepper fruit. Stomatal conductance is directly related to stomata opening and plant water status. Stomatal conductance of plants experiencing water stress can be correlated with changes in soil water in some plants especially in isohydric crops such as *Capsicum annum L.* (cultivar Vau Maor) (Yao et al., 2001) but not in others. Isohydric characteristics are exhibited when plants have tight and continuous control of leaf water potential by root-to-shoot signalling of hydraulic and chemical interactions thus managing water loss through stomata particularly during initial onset of water stress (Limpus, 2009). Jones (2008) stated that measurements of stomatal conductance are sensitive to declining soil water and thus water stress. The size of the stomata aperture is also sensitive to other environmental factors (radiation, air temperature, wind) and leaf size (Jones et al., 2009; Scherrer et al., 2011).

The critical threshold value (beyond which there will be yield loss or reduction) of *CWSI* and stomatal conductance should be determined for a particular crop in different climates and soils before it can be used effectively for yield prediction and irrigation scheduling. Such a study will contribute to a greater understanding of the interactions between *CWSI*, water applied, yield and stomatal conductance and would be beneficial for scheduling irrigation. The objectives of this study were to (1) determine the *CWSI* and stomatal conductance value at which maximum yield and water use efficiency are produced and

the point at which irrigation water must be applied to avoid significant reductions in yield; (2) determine the effect of soil types and irrigation treatment interactions on yield, water use efficiency (*WUE*), irrigation water use efficiency (*IWUE*) and (3) evaluate the relationships between *CWSI*, water applied, yield, and stomatal conductance.

5. 2 Materials and methods

The greenhouse experiments were conducted from March to June 2012 and October 2012 to January 2013 on the Macdonald Campus of McGill University located at Ste. Anne-de-Bellevue, QC (45.43°N, 73.93°W and elevation 39 m). The Red Knight cultivar of bell pepper (*Capsicum annum* L.), was used in this study. Bell pepper plants were transplanted five weeks after seeding into 24 pots (19-L each and one plant per pot). The pots were placed on 330 × 150 × 150 mm brick and then randomly positioned in the greenhouse (Fig. 1). Three taps were fixed to each of the pots so that excess water can drain out. The pots were saturated and allowed to drain out for 24 hours so that the soil water content can be at field capacity before crops were transplanted. The experimental design included four treatments: 120% (T_{120}), 100% (T_{100}), 80% (T_{80}) and 40% (T_{40}) replenishment of crop water use, with two types of soil (loamy sand and Montmorillonite clay soil). The pots were weighed (with a weighing balance) every other day, and the four irrigation treatments were maintained by adding the required amount of water to overcome the loss through evaporation and transpiration. Irrigation water was manually applied. The treatments were taken as the fractions of the water necessary to always maintain the weight of the 100% treatment (T_{100}), T_{120} was applied by adding 20% more to T_{100} while T_{80} and T_{40} treatments were applied by subtracting 20% and 60% respectively from T_{100} water application. There were few times that there was a drain in the T_{120} water application, the water was applied back into the pot after 30 minutes.

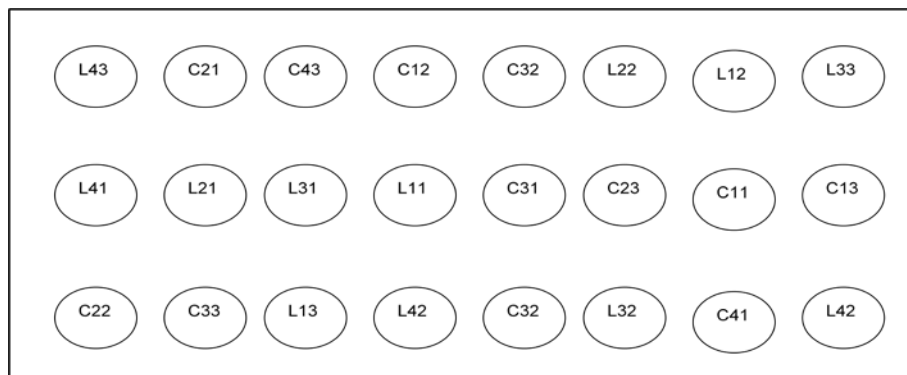
The two soil types are representative of the available soil in Macdonald horticultural farm and also the typical textural content of the soils will allow a more objective comparative analysis of their productivity and plant water uptake. The soil properties are presented in Table 5.1. The available water holding capacity (AWHC) is unusually low for clay soil (typical values for clay are 15 to 20%, Keller and Bliesner, 1990). However, the AWHC

was similar to that published for the Oxisol soil (Coto clay) in northwest Puerto Rico (AWHC 9%) (Harmsen et al., 2003; Soil Conservation Service, 1967).

The experiments have a factorial design with four levels (treatments) and two factors (soil types) replicated three times each (Figure 5.1). Plants were fertilized weekly with 2 g of 20-20-20 NPK water soluble fertilizer per litre of water. The fertilizer was changed to calcium nitrate according to the guidelines provided by Le ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) after the longitudinal and transverse circumferences of the first fruits were about 165 and 130 mm, respectively. For 20 days after transplant, all plants received 100% replenishment of crop water use to ensure their survival. Thereafter, the four irrigation treatments were implemented.

Table 5.1: Physical properties of the soil

Properties	Soil types	
	Loamy sand	Clay
Sand (%)	77	29
Silt (%)	19	5
Clay (%)	5	65
Organic matter (%)	3	5
Field capacity (% by volume)	19	45
Wilting point (% by volume)	7	34
Bulk density (g cm ⁻³)	1.4	1.3



C-clay, L-loamy sand soil, numbers represent treatments and replicates e.g L43 means treatment 4 (T_{40}) in loamy sand soil and the third replicate.

Figure 5.1: Experimental layout

5.2.1 Measurements

The air temperature, relative humidity, and vapour pressure deficit were obtained using temperature and relative humidity sensors (enclosed in a multi-plate radiation shield, model 41003, Young company, Michigan, USA) installed about one meter above the crop canopy. The sensors were connected to a CR23X data logger (Campbell scientific Inc., Logah, Utah). The data was scanned every 5 minutes and recorded every 15 minutes, hourly and daily. The data was retrieved from the CR23X using a computer and Campbell Scientific Inc. loggerNet software.

5.2.1.1 Stomatal conductance and plant morphological parameters

The stomatal conductance was measured during the growing period using a LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA). Three fully expanded sunlit leaves from the top of the plant were selected for weekly measurements; these leaves were marked for subsequent measurements. On the last harvest date, all plants were sampled for growth analyses. Total number of leaves was counted and weighed (g), fruit diameters (FD), stem diameter were measured by caliper rule and plant height was measured with a graduated rule.

5.2.1.2 Leaf temperature

Measurements of leaf temperature were made with a Fluke infrared thermometer (Model 572) (Evett et al., 2000), set at an emissivity setting of 0.98. The viewing angle of the thermometer was 30° and its spectral response range was 8 to 14 µm. The instrument was adequately temperature compensated for changes in temperature drift using a blackbody reference. The instrument was held about 1.5 m above ground level and directed at the leaf of the crop with the help of the laser point of the instrument, at an angle about 30° below the horizontal (Nielsen and Anderson, 1989; Orta et al., 2002). The measurement time was between 11:30 am and 2:00 pm (Daylight Saving Time in 2012 and Standard Time in 2012/2013) because it is expected that during these hours, the sun will be directed on all the plants and the solar elevation angle is stable thereby reducing the changes in incoming solar radiation that are likely to occur. Leaf temperature readings were taken on 10 clear cloudless days. Out of these 10 days, four days had somewhat

significant cloud cover for approximately 5 to 15 minutes and the data were discarded due to variability in the readings, as a result of the cloud passage. The six remaining canopy temperatures were measured on: April 17, 27, May 9, 18 and 30 in 2012 and on, November 11, 25, and 30, December 8, 12 and 22 for the 2012/2013 growing period. The first temperature measurements of each growing season, April 17, 2012 and November 11, 2012, were taken when the plants covered about 80% of the pot area. On each date, four temperature readings with the infrared thermometer facing north, south, east and west directions were taken on each pot.

5.2.1.3 Crop water stress index (CWSI)

The mean values of the crop foliage temperature over all sampling dates and directions were used for calculating the crop water stress index (CWSI) from Eq. (5.1) (Idso et al., 1981).

$$CWSI = \frac{[(T_c - T_a) - (T_{nws} - T_a)]}{[(T_{dry} - T_a) - (T_{nws} - T_a)]} \quad [5.1]$$

Where: T_c : canopy temperature ($^{\circ}\text{C}$), T_a : air temperature ($^{\circ}\text{C}$), T_{nws} : non water-stressed canopy temperature ($^{\circ}\text{C}$), and T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$).

Treatments T_{120} for each soil type were used in order to determine non water-stressed baseline, while the treatment T_{40} was used for determination of a fully stressed baseline. T_{120} and T_{40} were used for establishing the bsaelines because these treatments received more and less water respectively. *CWSI* values that are close to “0” indicate well-watered, non water-stressed plants, while fully water-stressed plants would have *CWSI* values closer to a value of “1”, indicating that the crop canopy temperature was approaching that expected for a non-transpiring, highly water-stressed plant canopy (Idso, 1982).

5.2.1.4 Water use efficiency and irrigation water use efficiency

Water use efficiency (*WUE*) was calculated as the ratio of total marketable harvested yield (kg plant^{-1}) to total seasonal crop water use (m^3). Irrigation water use efficiency

(*IWUE*) was calculated as the ratio of total marketable harvested yield (kg plant^{-1}) to total seasonal volume of water applied (m^3).

5.2.1.5 Fruit quality

Total soluble solids ($^{\circ}$ Brix) were estimated by measuring the refractive index with a portable refractometer model RHB-32 (Palette 100 PR-100, AT AGO-Spectrum Technologies, Plainfield, IL) that had been standardized with distilled water. Fruit firmness was measured using a portable penetrometer model FT-327 (Facchini, Alfonsine, Italy).

5.2.1.6 Statistical analysis

The crop yield, water use efficiency (*WUE*), irrigation water use efficiency (*IWUE*) and amounts of water applied for each treatment and soil type were statistically analysed using PROC MIXED in SAS. Analysis of variance (ANOVA) was conducted and differences among the treatments were separated by least significant means, adjusted using the Bonferroni method at $p=0.05$ probability level. The Bonferroni correction was used to reduce the chances of obtaining false-positive results.

5.3 Results and Discussion

5.3.1 Greenhouse climatic conditions and crop evapotranspiration (ET_c)

There was a variation in the crop water use with respect to irrigation treatments in each growing season. The crop evapotranspiration was 296 and 322 (T_{120}), 247 and 269 (T_{100}), 198 and 215 (T_{80}) and 99 and 107 (T_{40}) in mm for 2012 and 2012/2013, respectively. Total crop evapotranspiration was lower in 2012 season despite the warmer temperature because the growing season in 2012 was 103 days compared to 128 days in 2012/2013. Extended growing days in 2012/13 season accounted for the increase in crop evapotranspiration. High temperature may reduce fruit set indirectly by increasing vapor pressure deficits (VPDs), which can result in water deficits, if the VPD creates a water deficit within the plant, stomata will close and leaf water potential will decrease resulting in decreased photosynthesis (Erickson and Markhart, 2001). Increased VPD results in increased evaporation and transpiration from leaf surfaces (Erickson and Markhart,

2001). The vapour pressure deficit (*VPD*) ranged from 1.24 to 3.24 kPa in 2012 as compared to 0.90 to 2.59 kPa in 2013. The changes in the misting condition in the greenhouse affected the environment's temperature, vapour pressure and humidity. The greenhouse conditions in 2012 were slightly warmer (average temperature of 22.3°C) than 2013 (average temperature of 20°C). Stomata conductance decreases as *VPD* increases (in 2012 growing season) because of an increase in transpiration that lowers the leaf water potential (Matzner and Comstock, 2001).

5.3.2 Effects of irrigation levels (water applied)

There were significant differences among treatments (irrigation levels) in relation to fruit yields, *IWUE*, and *WUE* (Table 5.2). Both total and marketable yields were highest at the highest water application (T_{120}) (Figure 5.2). Only the result of the marketable yield is presented because marketable fruit production was more sensitive to water stress, followed by total fruit production. In 2012, marketable yields obtained for T_{80} and T_{40} were significantly lower than T_{120} on both soil types while the yield from T_{120} (that received the highest water) was not significantly different from T_{100} ($p=0.07$ to 1.00). In 2012/13 season, marketable yields from T_{120} and T_{100} ($p=0.08$), and T_{100} and T_{80} ($p=0.07$) were not significantly different on loamy sand, whereas marketable yields from clay soil were significantly different for the different irrigation water applied with the exception of T_{100} and T_{80} ($p=0.89$). The marketable fresh fruit productions for T_{120} relative to T_{100} , averaged over the two seasons were higher by 17% in loamy sand and by 23% in clay soils. This result is similar to that of Dalla Costa and Gianquinto (2002) which showed that irrigating above 100% ET_c could lead to higher yield. Reductions in marketable fruit production in T_{80} relative to T_{120} treatment, were very high (Table 5.2). T_{80} had high proportion of unmarketable fruits due to small fruit size, shrinkages and blemish. This result is similar to findings for pepper crop grown in the greenhouse (Chartzoulakis and Drosos, 1997; Fernandez et al., 2005). It was observed that there were not much difference in the morphological parameters of T_{80} and T_{100} (Table 5.3).

Figure 5.3 presented the rate of plant water uptake in the two soils, it was observed that rate of water uptake was generally higher in loamy sand throughout the growing period.

The impact of water stress on yield is more pronounced in clay soil, this is due to the fact that the particles of clay soil are tightly packed and it becomes more difficult for the roots of the plant to extract water (Figure 5.3). Soil and plant hydraulic characteristics optimize water uptake (Agele et al., 2006; Zeng et al., 2013) and it has been shown that well watered bell pepper had greater water uptake rate and remarkably higher within plant (hydraulic) and stomatal conductance (Agele et al., 2006). Bell pepper plant requires adequate supply of water throughout its growing period (Sezen et al., 2006, Ferrera et al., 2011). Overall, yields in 2012 were slightly lower than in 2012/13 because of a defection in the greenhouse misting system in 2012, which made it warmer and led to early maturity. The growing season in 2012 was 103 days until harvest, compared to 128 days in 2012/13.

In 2012, the differences in mean *IWUE* and *WUE* between T_{100} and T_{120} were 5.6% and 5.1% in loamy sand, and 4.9% and 5.7% in clay soil, while in 2012/13, the mean *IWUE* and *WUE* increased at T_{120} relative to T_{100} by 7 to 9% and 12 to 15% in loamy sand and clay soil, respectively. Mean *IWUE* and *WUE* were highest for T_{120} in both years.

The total soluble solids of fruits grown in clay and loamy sand soil followed a similar trend. The fruits total soluble solids ($^{\circ}$ Brix content) were higher for T_{40} relative to the other treatments although the differences were not significant. The high fruit total soluble solids of T_{40} is consistent with findings by Sezen et al., (2006). It was observed in this study that total soluble solids content decreased with increasing water applied. Increasing water application probably led to more water being absorbed by the plant roots and hence diluting the sugar content. There was no particular trend in the firmness for all the treatments except in T_{40} where the firmness was significantly lower relative to other treatments in both soil types (Figure 5.4).

Table 5.2: Effect of irrigation levels, soil types and their interaction on marketable yield, *IWUE* and *WUE* in 2012 and 2012/13 seasons.^y

		Year 2012			Year 2012/2013		
Treatments	Soil type	Marketable yield (kg plant ⁻¹)	IWUE (kg m ⁻³)	WUE (kg m ⁻³)	Marketable yield (kg plant ⁻¹)	IWUE (kg m ⁻³)	WUE (kg m ⁻³)
120 % CWU	Clay	0.34 ^a	17.0 ^a	3.7 ^a	0.42 ^a	22.2 ^{ab}	4.4 ^a
	Loamy sand	0.33 ^a	19.0 ^a	3.8 ^a	0.55 ^a	29.1 ^{bc}	5.7 ^b
100 % CWU	Clay	0.25 ^a	15.8 ^a	3.4 ^a	0.28 ^{ab}	17.4 ^a	2.9 ^c
	Loamy sand	0.30 ^a	18.1 ^a	2.8 ^a	0.43 ^a	26.6 ^b	4.3 ^{ab}
80 % CWU	Clay	0.16 ^a	12.4 ^{ac}	1.5 ^a	0.20 ^b	14.9 ^a	2.1 ^c
	Loamy sand	0.13 ^a	10.2 ^c	1.8 ^{ab}	0.31 ^b	22.8 ^{ab}	3.1 ^c
40 % CWU	Clay	0.01 ^b	1.4 ^d	0.1 ^c	0.02 ^c	2.1 ^d	0.2 ^d
	Loamy sand	0.02 ^b	2.9 ^d	0.2 ^c	0.03 ^c	3.3 ^{ed}	0.3 ^d
Treatments	120 % CWU	0.34 ^a	17.6 ^a	3.8 ^a	0.47 ^a	25.7 ^a	5.0 ^a
	100 % CWU	0.28 ^a	17.4 ^a	3.1 ^a	0.36 ^b	22.0 ^a	3.7 ^b
	80 % CWU	0.15 ^b	11.3 ^a	1.6 ^b	0.25 ^c	18.8 ^{ab}	2.6 ^c
	40 % CWU	0.02 ^c	2.1 ^b	0.2 ^c	0.02 ^d	2.7 ^c	0.2 ^d
Soil type	Clay	0.19 ^a	11.7 ^a	2.1 ^a	0.22 ^a	14.2 ^a	2.4 ^a
	Loamy sand	0.20 ^b	12.6 ^b	2.2 ^b	0.33 ^b	20.4 ^b	3.4 ^b
Significant levels	Treatment	***	***	***	***	***	***
	Soil type	NS	NS	NS	***	***	***
	Treatment*Soil type	NS	NS	NS	NS	NS	NS

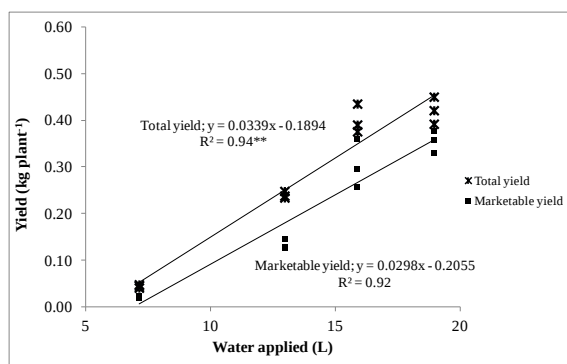
NS- non significant, *- significant at 5%, ** -significant at 1%, ***- significant at < 0.1%. ^yMeans separation within columns by least significant difference at the 5% level. Each value represents the average of three replications. Means not followed by the same letter differ significantly.

Table 5.3: Effect of water treatments and soil type on stem diameter, number of leaves, weight of leaves and plant height in 2012 and 2012/13 seasons.^y

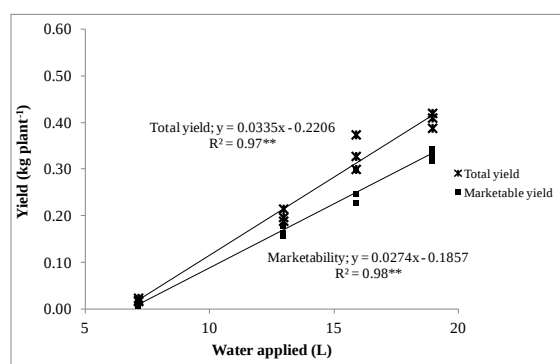
Treatments	Soil type	Year 2012				Year 2012/2013			
		Stem diameter (mm)	Number of leaves	weight of leaves (g)	height (cm)	Stem diameter (mm)	No of leaves	weight of leaves (g)	height (cm)
120 % CWU	Clay	8.1 ^a	50 ^c	39.9 ^a	44.0 ^a	8.6 ^a	50 ^c	39.4 ^a	44.0 ^a
	Loamy sand	11.5 ^b	71 ^d	82.5 ^b	63.0 ^b	11.9 ^b	73 ^d	86.6 ^c	63.5 ^b
100 % CWU	Clay	7.9 ^a	41 ^a	37.1 ^a	41.0 ^a	8.1 ^a	36 ^a	41.1 ^a	44.0 ^a
	Loamy sand	11.0 ^b	61 ^b	53.9 ^a	51.7 ^{ab}	10.8 ^b	61 ^b	60.0 ^b	52.0 ^{ab}
80 % CWU	Clay	7.7 ^a	40 ^a	34.3 ^a	36.3 ^a	8.1 ^a	34 ^a	32.6 ^a	34.0 ^a
	Loamy sand	10.6 ^{bd}	53 ^{bc}	44.2 ^a	45.3 ^a	11.3 ^{bd}	54 ^{bc}	55.3 ^b	45.0 ^a
40 % CWU	Clay	5.6 ^c	23 ^e	13.3 ^c	26.3 ^c	6.0 ^c	22 ^e	15.7 ^c	27.0 ^c
	Loamy sand	7.4 ^a	29 ^e	19.9 ^d	35.3 ^{ad}	8.9 ^a	28 ^e	29.8 ^a	37 ^{ad}
Treatments	120 % CWU	9.8 ^a	61 ^a	61.2 ^a	53.5 ^a	10.3 ^a	61 ^a	63.0 ^a	53.8 ^a
	100 % CWU	9.4 ^a	51 ^b	45.5 ^b	46.3 ^a	9.5 ^a	48 ^b	50.5 ^b	48.0 ^a
	80 % CWU	9.2 ^a	46 ^b	39.3 ^c	40.8 ^{ac}	9.7 ^a	44 ^b	43.9 ^b	39.5 ^{ac}
	40 % CWU	7.0 ^b	26 ^c	16.6 ^d	30.8 ^b	7.5 ^b	25 ^c	22.7 ^d	32.0 ^b
Soil type	Clay	7.3 ^a	39 ^a	31.1 ^a	36.9 ^a	7.7 ^a	36 ^a	32.2 ^a	37.3 ^a
	Loamy sand	10.4 ^a	53 ^{bc}	50.1 ^b	48.8 ^b	10.7 ^a	54 ^{bc}	57.9 ^b	49.4 ^b
Significant levels	Treatment	***	***	***	***	***	***	***	***
	Soil type	***	***	***	***	***	***	***	***
	Treatment*Soil type	NS	NS	***	NS	NS	NS	***	NS

NS= non significant, *= significant at 5%, ** = significant at 1%, ***= significant at < 0.1%. ^yMeans separation within columns by least significant difference at the 5% level.

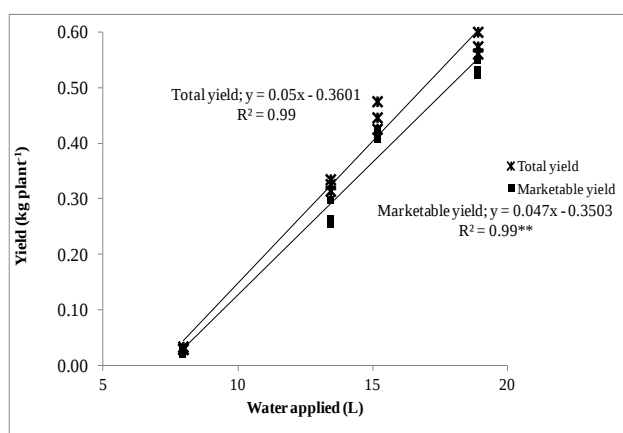
Each value represents the average of three replications. Means not followed by the same letter differ significantly.



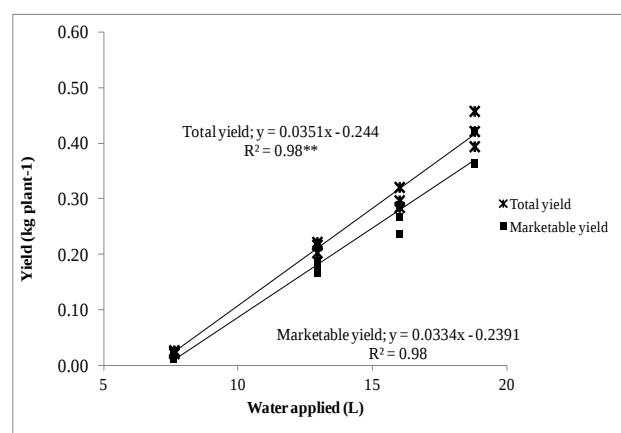
(a) Loamy sand



(b) Clay



(c) Loamy sand



(d) Clay

Figure 5.2: Relationship between yields (total and marketable) and water applied for (a) loamy sand, (b) clay in 2012, (c) loamy sand and (d) clay in 2012/13 seasons.

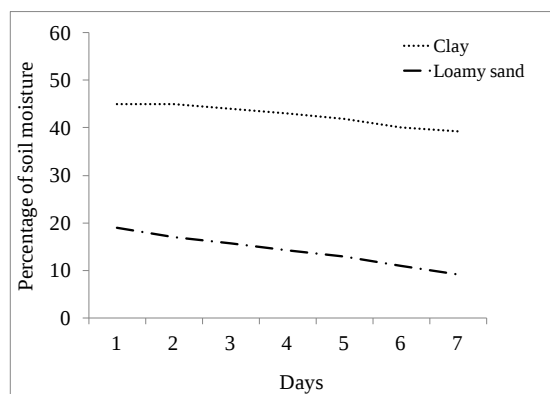
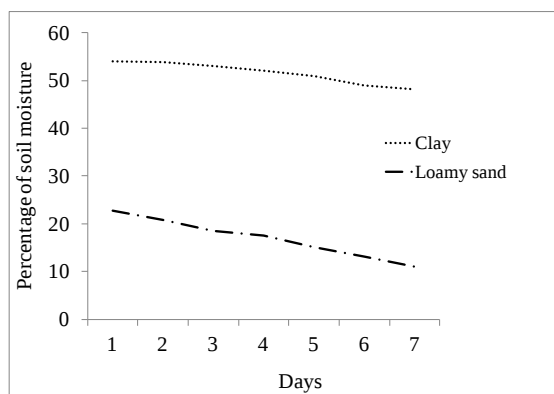


Figure 5.3: Rate of plant water uptake at selected (50-57) days after transplanting (DAT) from clay and loamy sand soil for (a) T_{120} , (b) T_{100}

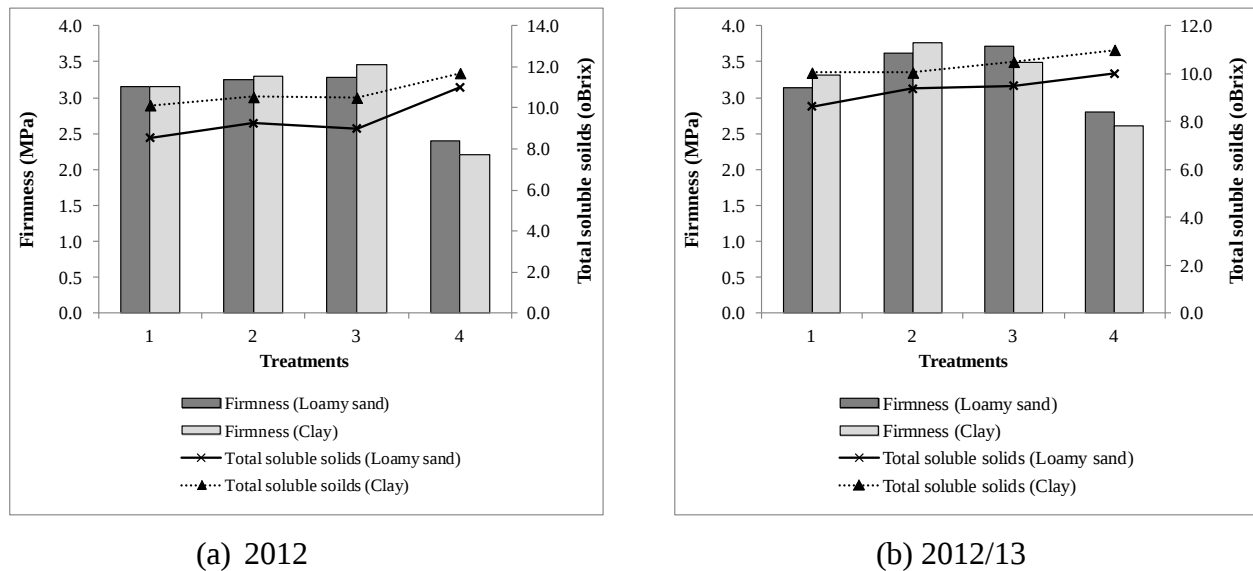


Figure 5.4: Firmness and total soluble solids content in relation to treatments

5.3.3 Effect of soil types

The effect of clay and loamy sand soil types on yields, *IWUE*, and *WUE* is presented in (Table 5.2). Marketable yields, *IWUE* and *WUE* obtained for loamy sand were not significantly higher than clay soil except for T_{40} in 2012. However in 2013, the effect of soil types on yields, *WUE* and *IWUE* are significant for all the treatments with $p < 0.0001$ except T_{40} . Marketable yields from T_{100} and T_{80} were not significantly different within soil types but across soil types (for instance, there was a significance difference when yield from T_{100} loamy sand was compared to yield from T_{80} in clay soil). Plants grown in loamy sand soil and irrigated with T_{120} had the highest values for most of the characteristics being measured for both years.

The yields from loamy sand were generally higher than yields obtained with clay soil; this was contrary to the study by Ezzo et al., (2010) that reported under field conditions, significantly superior vegetative growth traits and yields in sweet pepper grown in clay soil as compared to those grown in sandy soil. The difference in yield might be due to the fact that the loamy sand used had less sand, more clay and higher field capacity. The use of loamy sand soil increased marketable bell pepper yield by about 40% in 2012 and

approximately 36% in 2012/13, when compared to clay soil. Analysis of data with respect to the soil textures showed that yields were significantly different due to irrigation treatments except for T_{80} and T_{40} . Fruit firmness for the two soils was not different. The fruits total soluble solids of plants grown in clay soil were not significantly superior to those grown in loamy sand soil (Figure 5.4). This is because plants grown on loamy sand can extract water easily and at a faster rate thereby diluting the sugar content of the crops. It is easier to extract water from the loamy sand than clay soil because of its lower soil water tension. For water to move from the soil, to roots, to stems, to leaves, to air the water potential must always be decreasing.

5.3.4 Effects of interactions between irrigation levels and soil types

There were no significant interactions between irrigation treatments and soil types at $p < 0.05$ level for marketable yield, irrigation water use efficiency (*IWUE*) ($p = 0.09-0.68$) and water use efficiency (*WUE*) ($p = 0.05-0.72$) for both seasons (Table 5.2). Only irrigation treatment effects were significant on marketable yield, *IWUE* and *WUE* in 2012, while significant effects of irrigation treatments and soil types were observed for marketable yield, *IWUE* and *WUE* in 2013 (Table 5.2). This variation was due to the defect in the mist system in 2012. The lowest yield, *IWUE* and *WUE* were obtained from bell peppers grown on clay soil and irrigated at 40% *CWU* (T_{40}) while the highest yield, *IWUE* and *WUE* were obtained for bell peppers grown on loamy sand soil that received the highest amount of water (T_{120}). This result showed a positive relationship between water applied and soil types. The effect of water treatments on marketable yield was significant ($F_{3,16} = 129.52$, $p < 0.0001$), as well as the effect of soil type on marketable yield ($F_{1,16} = 32.47$, $p < 0.0001$) such that the plants that received the highest amount of water on loamy sand produced the highest yield. T_{120} and T_{100} irrigation treatments produced numerically greater yields on loamy sand compared with clay soil in 2012 but in 2013 produced significantly greater yields on loamy sand compared with clay soil.

5.3.5 Effect of irrigation treatments and soil types on morphological parameters

The data obtained in this study clearly suggests that irrigation treatments and soil types have a significant effect ($p < 0.001$) on plant height, stem diameter, weight of leaves and total number of leaves for both years (Table 5.3). There was an observed increase in the morphological parameters under all treatments in accordance to the water applied for both soil types. This was in agreement with Luvaha et al., (2008). Morphological parameters of plants grown on clay soil are generally lower than that on loamy sand soil. Plants grown on clay soil exhibited a 23 to 85% and 15 to 68% decrease in plant height, stem diameter, leaf number, weight of leaves and total number of leaves in 2012 and 2012/13 respectively. The magnitude of the reduction in plant height, stem diameter, weight of leaves, and leaf number between loamy sand and clay soil was greater in T_{40} than all the other treatments. The higher increase in plant length in loamy sand could be due to less root damage which could have occurred as a result of the cracking and swelling attribute of clay soil. The effect of the different irrigation treatments on weight of the leaves also revealed that there was a significant interaction effect between the irrigation treatments and the type of soil in all the parameters measured with the exception of the weight of leaves in 2013. Bell pepper grown on loamy sand responded better to irrigation treatments compared to those grown on clay soil.

5.3.6 Crop water stress index (CWSI) thresholds and stomatal conductance

Canopy temperatures differed among soil types, dates of sampling and between directions of measurement. The difference in canopy temperature of bell pepper plants across the soil types was because of the differences in the rate of water intake from the soils. Water extraction was easier and faster from loamy sand than clay. The average temperature of all leaves increased consistently with time, plant maturation, and decrease in available water for transpiration. Similarly, stomatal conductance values obtained varied by irrigation levels, soil types and year (Table 5.4).

Table 5.4: Variation in *CWSI*, stomatal conductance, *IWUE* and *WUE* for 2012 and 2012/2013 seasons.

Year	Treatment (% CWU*)	Loamy sand				Clay			
		<i>CWSI</i>	Stomatal conductance (mol m ⁻² s ⁻¹)	<i>IWUE</i> (kg m ⁻³)	<i>WUE</i> (kg m ⁻³)	<i>CWSI</i>	Stomatal conductance (mol m ⁻² s ⁻¹)	<i>IWUE</i> (kg m ⁻³)	<i>WUE</i> (kg m ⁻³)
2012	120	0.11	0.12	18.1	3.8	0.18	0.14	17.0	3.7
	100	0.28	0.10	19.1	3.4	0.32	0.11	15.8	2.8
	80	0.64	0.08	10.2	1.5	0.67	0.08	12.4	1.8
	40	1.18	0.06	2.9	0.2	1.29	0.07	1.4	0.1
2012/13	120	0.09	0.17	29.1	5.7	0.20	0.19	22.2	4.3
	100	0.35	0.13	26.6	4.4	0.40	0.15	17.4	2.9
	80	0.57	0.11	22.7	3.1	0.62	0.15	14.9	2.1
	40	0.98	0.09	3.3	0.3	1.05	0.12	2.1	0.2

*CWU-crop water use

The parameters that define the lower and upper limits of the *CWSI* based on the theory proposed by Idso et al., (1981) are presented in Figure 5.5. The equations that define the lower *CWSI* baseline obtained in this study were:

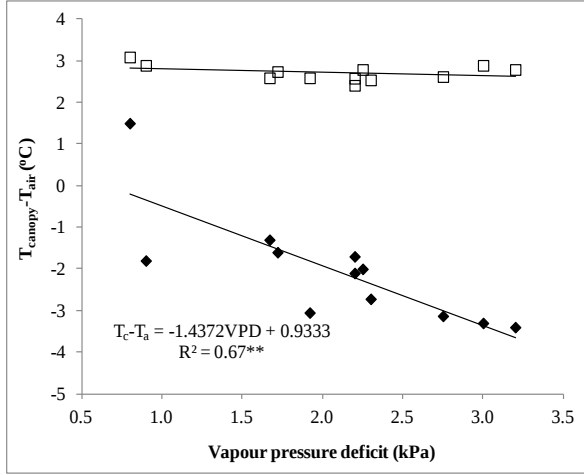
$$T_c - T_a = 0.9333 - 1.4372VPD, (R^2=0.67) \text{ for loamy sand,} \quad (\text{Eq. 5.2a})$$

$$T_c - T_a = 0.999 - 1.2249VPD (R^2=0.69) \text{ for clay soil in 2012.} \quad (\text{Eq. 5.2b})$$

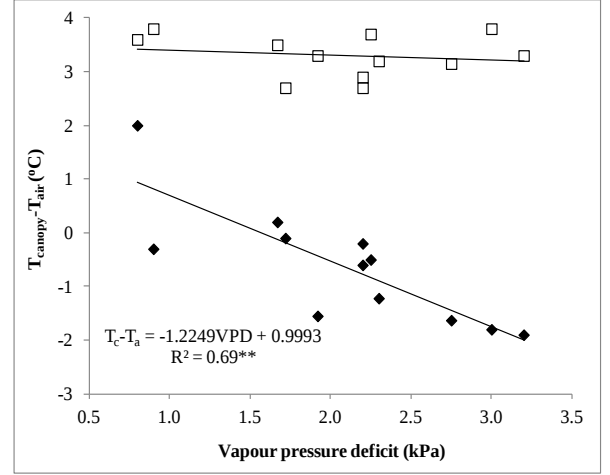
Whereas in 2012/13, the equations were

$$T_c - T_a = 0.9039 - 1.0131VPD, (R^2=0.73) \text{ for loamy sand,} \quad (\text{Eq. 5.3a})$$

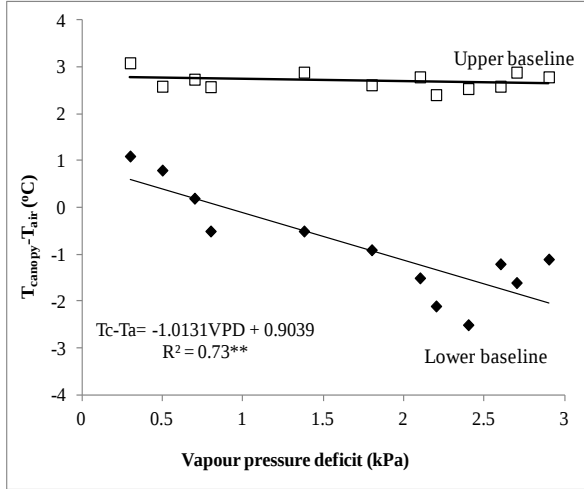
$$T_c - T_a = 0.9663 - 1.0498VPD (R^2=0.75) \text{ for clay soil.} \quad (\text{Eq. 5.3b})$$



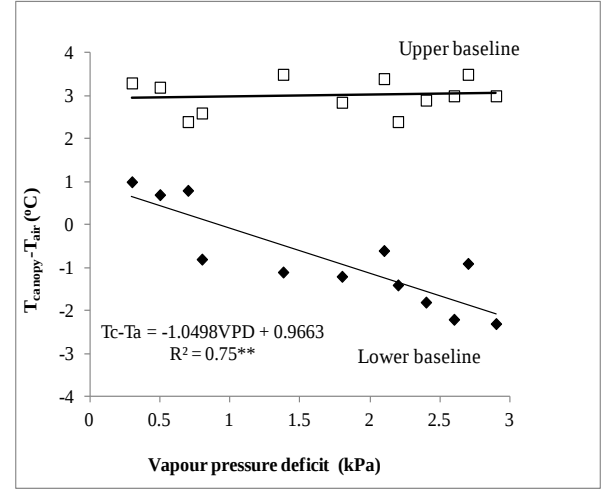
(a) Loamy sand (2012)



(b) Clay (2012)



(c) Loamy sand (2012/13)



(d) Clay (2012/13)

Figure 5.5: Canopy-air temperature difference ($T_c - T_a$) and vapour pressure deficit of non-water stressed (lower baseline) and fully stressed (upper baseline) for 2012 and 2012/13 seasons.

The defect of the misting system in the greenhouse in 2012 which made it warmer (and led to early maturity, 103 days until harvest in 2012, compared to 128 days in 2012/13) might have played a major role in the slight variation in the baseline equations obtained for 2012 and 2012/13 seasons. Irmak et al., (2000) reported $T_c - T_a = 1.39 - 0.86VPD$ as lower limit for corn, López-López et al., (2011) found the relation $T_c - T_a = 1.21 - 1.31VPD$ for Mexican tomatoes, while Nielsen, (1990) obtained $T_c - T_a = 2.51 - 2.02VPD$ for corn. It can be

observed from these results that all relations are different, which is in agreement with the results obtained by Bucks et al., (1985), who reported that the intercept and slope values vary depending on the climate, type of soil, type of crop being cultivated and even the cultivar.

The *CWSI*/stomatal conductance threshold at which highest yield and water use efficiency occurred is shown in Table 5.4. The *CWSI* of T_{120} for clay and loamy sand were 0.18 to 0.20 and 0.09 to 0.11 respectively. The corresponding stomatal conductance was 0.14 to 0.19 for clay and 0.12 to 0.17 for loamy sand. Clay soil had higher stomatal conductance and *CWSI* values than for loamy sand. Average maximum *CWSI* thresholds of 0.3 and 0.4 for loamy sand and clay soil respectively can be used to schedule irrigation, beyond which the plants will suffer stress. The critical *CWSI* values reported for other crops are 0.33 for corn under Texas conditions (Yazar et al., 1999), 0.22 for corn under Mediterranean conditions (Irmak et al., 2000), 0.2 for corn grown on Rago silt loam soil in Colorado (Nielsen, 1990) and 0.22 and 0.26 in 1999 and 2000, respectively for watermelon (Orta et al., 2003) while Anconelli et al. (1994) observed 0.1 to 0.35 for processing tomato and concluded that tomato grown on sandy loamy soil in Bologna (Italy) can withstand *CWSI* of 0.35 with no yield reduction. Critical threshold are points below which irrigation must be applied to prevent yield loss. The *CWSI* and yield has high correlation (Figure 5.6). As irrigation water decreased, *CWSI* increases and yield decreases. The rate of decrease in yield is not proportional with the rate at which *CWSI* increases. The correlation between *CWSI* and yield resulted in an R^2 of 0.99. This is an indication that bell pepper is highly sensitive to water stress and that *CWSI* can potentially be employed to predict yield. High correlations between *CWSI* and yield were also reported for other crops (Candogan et al., 2013).

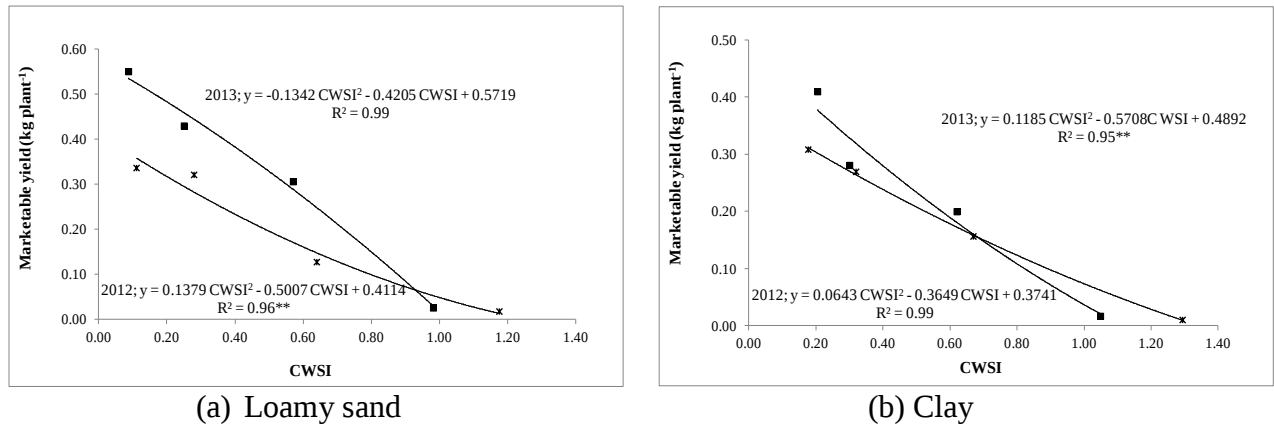


Figure 5.6: Marketable yield against crop water index (CWSI)

5.3.7 Crop water stress index and stomatal conductance in relation to water applied

The relationship water applied and CWSI or stomatal conductance is presented in Figures 5.7 and 5.8. A correlation coefficient (R^2) of 0.96 to 0.99 was obtained for the relationships for CWSI and stomatal conductance with water applied. Variation in the curves was due to differences in year and soil types. CWSI increased as the amount of water applied decreased, and the stomatal conductance of the crop decreased with a decrease in water applied. This trend was similar for the two soils. The stomatal response to varying water application confirms that bell pepper cultivar Red Knight is isohydric. A past study also reported that *Capsicum annum L* (cultivar Vau Maor) is isohydric (Yao et al., 2001). This result showed that CWSI and stomatal conductance are good indicators of the variability in the water status of bell peppers.

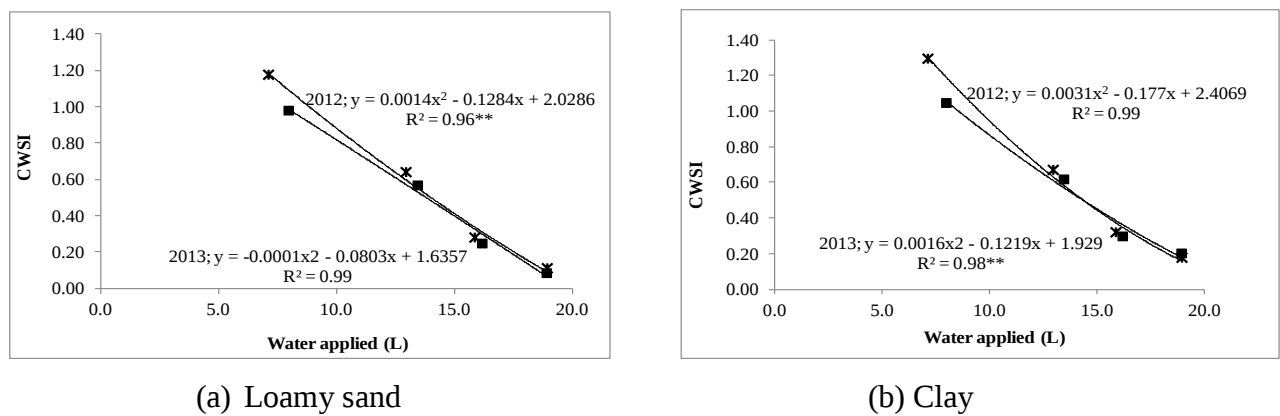
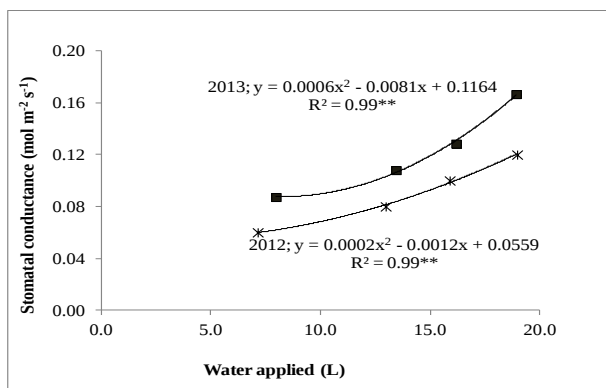
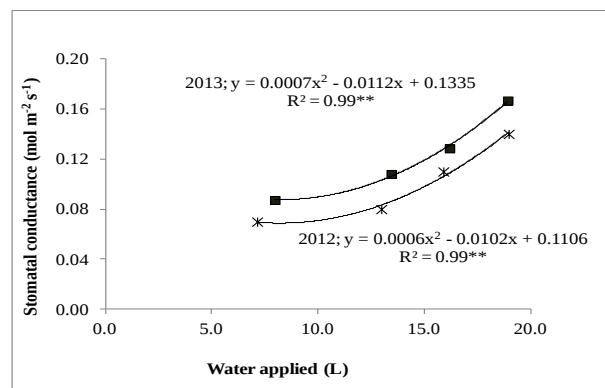


Figure 5.7: Mean Crop water stress index against average water applied



(a) Loamy sand

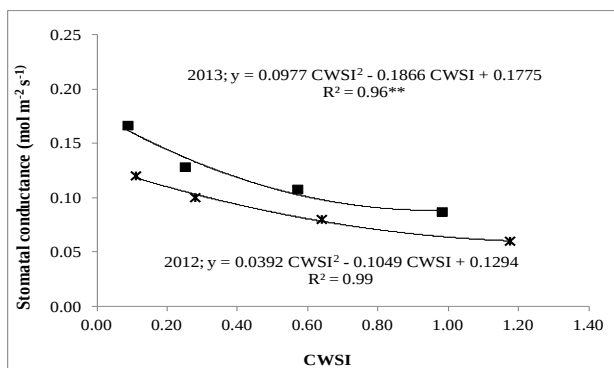


(b) Clay

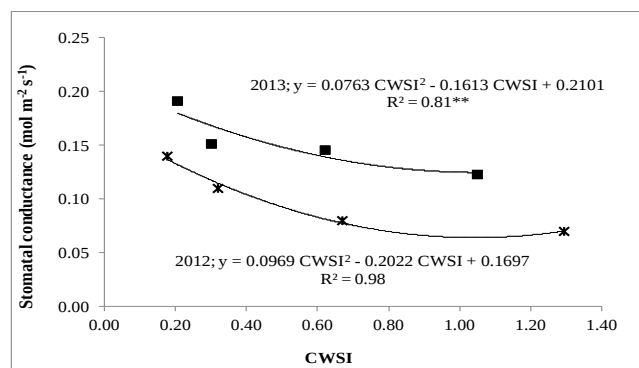
Figure 5.8: Stomatal conductance against water applied

5.3.8 Relationship between stomatal conductance and crop water stress index

The relationship between stomatal conductance and *CWSI* is presented in Figure 5.9. The yearly variation in the relationship is higher compared to variation due to soil type. The trend is similar for the two soils and for both years. The coefficient of determination R^2 ranged between 0.83 and 0.99. The *CWSI* has been correlated with stomatal conductance (Zia et. al., 2011, Leinonen, et. al., 2006). The bell pepper stomatal conductance decreased with increasing water stress (Table 5.4). It has been observed that plants under soil water deficit often decrease stomatal conductance, thereby reducing transpiration, increasing leaf temperature and the crop water stress index (Ballester et al., 2013). The stomata response of bell pepper cultivar Red Knight to varying water application confirmed it as an isohydric plant.



(a) Loamy sand



(b) Clay

Figure 5.9: Stomatal conductance against crop water stress index

5.4 Conclusions

The crop water stress index and stomatal conductance response thresholds of bell pepper were determined in the greenhouse under different irrigation levels and soil types. Agronomic optimum bell pepper yield can be achieved when the plants are grown in loamy sand and irrigated at 120% replenishment of crop water use (T_{120}). Highest yield and water use efficiency were obtained with *CWSI* of 0.18 to 0.20 under clay soil, and 0.09 to 0.11 under loamy sand. The maximum *CWSI* values (beyond which there will be yield reduction) for clay were 0.47 to 0.50 and 0.30 to 0.45 for loamy sand. These values could serve as reference baselines for bell pepper under similar conditions for these two soils. The correlation between *CWSI*, water applied, yield and stomatal conductance was highly significant and the equations derived were different for the soil types. The potential of the *CWSI* for yield prediction and irrigation scheduling was validated with the correlation. The results demonstrated that it is necessary to emphasize the soil type used for determining *CWSI* reference values for each crop. This result was obtained under greenhouse conditions; further studies under field conditions should be conducted to determine the effect of soil type on *CWSI*. Furthermore, this study revealed that water deficit and soil types significantly affected the growth and morphological characteristics.

Connecting text to Chapter 6

The integrated use of soil moisture sensing and plant water status indicators for scheduling irrigation requires that the level at which water should be applied to plants to avoid water stress and yield loss (threshold) should be established. In this chapter available soil water content threshold (AWC_t) and crop water stress index ($CWSI$) were determined for field grown bell pepper. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis. The results of this study are presented in the manuscript that follows.

Chapter 6 Determination of available soil water content thresholds and crop water stress index (CWSI) for bell peppers (*Capsicum annuum* L.)

Olanike Aladenola and Chandra Madramootoo

Abstract

A two year field study was conducted in 2011 and 2012 to evaluate the effect of four irrigation levels on fruit quality and yield, water use efficiency, crop water stress index (CWSI), stomatal conductance on bell peppers grown on a clay soil in southern Quebec, Canada. In addition to the four irrigation treatments, the performance of the bell pepper yield under no irrigation (T_5) was evaluated. Available soil water content (AWC_t) threshold of 85% (T_1) received the highest amount of water and gave the highest yields; while, irrigation when the soil available water reached 75% (T_2) and 50% (T_3) received less water than 85%, and resulted in better irrigation water use efficiency for both years. Increasing the amount of applied water resulted in a decrease in the total soluble solids. The CWSI ranged between 0.1 to 0.6 in 2011 for T_1 to T_4 and 0.08 to 1.0 in 2012 for T_1 to T_5 . An irrigation strategy using 50-75% of AWC_t and a CWSI of 0.3-0.4 for bell pepper production in southern Quebec's clay soil and summer weather conditions will assist irrigators to improve water use efficiency.

Keywords: Available water threshold (AWC_t), crop water stress index (CWSI), irrigation management, yield.

6.1 Introduction

Vegetable production in Canada includes approximately 108,320 ha in the field as well as another 1255 ha of greenhouse cultivation (Statistics Canada, 2011). Of this, bell peppers (*Capsicum annuum* L.) comprise 2356 ha. These vegetables require irrigation to meet their evapotranspirative demands (Bernier et al., 2010). High value, field grown vegetables are produced during the warm summers in the southern regions of Ontario, Quebec and British Columbia, Canada. Bell peppers, a major greenhouse and field vegetable, are grown for the fresh and processing markets in Canada; they are highly sensitive to water stress. Bell peppers require adequate applications of water throughout their growth stages and particularly, during flowering and fruit setting. For the duration of the growing season, appropriate irrigation scheduling is required due to variations in the amount and distribution of rainfall.

In this study, the level at which bell peppers grown on clay soil would be irrigated to prevent water stress and yield loss (available soil water content threshold) was determined. A range of available soil water content threshold (AWC_t) values (25-70%) was provided by several authors, in order to obtain maximum growth, yield, and water use efficiency (WUE) (Allen et al., 1998; Coolong et al., 2011). AWC_t values require site specific calibration and there is uncertainty in using fixed values for irrigation scheduling (Girona et al., 2002). To the best of our knowledge, no study has been conducted to determine the appropriate AWC threshold and crop water stress index for scheduling field grown drip irrigated bell pepper in southern Quebec clay soils.

Irrigation scheduling is based on the calculation of crop water requirements (Allen et al., 1998; Walter et al., 2001) or by monitoring the soil water status (Dane and Topp, 2002) and plant water status (Jones, 2004a; Cifre et al., 2005). The use of soil water sensors for irrigation management requires that soil water be maintained within the upper and lower limits (Campbell and Campbell, 1982). For optimal irrigation scheduling using soil moisture sensors, accurate threshold values for individual crops and soil types is required (Thompson et al., 2007). Research has shown that soil moisture sensor-based irrigation of vegetable crops has good potential to reduce the amount of irrigation water applied in tomatoes (Zotarelli et al.,

2009) and green bell peppers (Dukes et al., 2003). Soil water sensors measure either soil matric potential (SMP) or volumetric soil water content (SWC).

Plant water status provides information that can be used to prevent a crop water deficit through irrigation (Köksal, 2008). Soil moisture conditions can be maintained and physiological stress avoided by identifying threshold values of soil moisture for irrigation management, either as SMP or AWC, using plant water status (Thompson et al, 2007). Yazar et al., (1999) suggested that irrigation scheduling based upon crop water stress should be more advantageous, since it responds to the combined soil and aerial environment. The crop water stress index (*CWSI*) is based on the principle that transpiration cools the leaf surface and as water becomes limited, stomatal conductance and transpiration decrease and leaf temperature increases. Idso et al., (1981a) observed a linear relationship between canopy temperatures measured using an infrared thermometer and air temperature and vapour pressure deficit, and this was used to develop an empirical method of quantifying crop water stress. *CWSI* has to be determined for particular crops and in a specific climate in order to be an effective tool for scheduling irrigation and yield prediction. Crop response to water stress differs depending on the local environmental conditions (Orta et al., 2003). The application of the *CWSI* in irrigation scheduling has been evaluated for different crops including vegetables (Erdem et al., 2010; Köksal 2008; Erdem et al., 2006). Studies on the *CWSI* of bell pepper are limited to the best of our knowledge. Therefore, the objectives of this study were to (1) assess the yield, quality and water use efficiency of field grown bell peppers under different available soil water content thresholds (AWC_t) and (2) quantify the water stress index of bell peppers under the available soil water content (AWC_t) thresholds.

6.2 Materials and methods

6.2.1 Study area

These experiments were conducted from June to October 2011 and 2012 at the McGill University Macdonald campus horticultural research farm located in Ste Anne De Bellevue, QC, Canada, (45.43°N, 73.93°W and elevation 36 m). The study area is a humid region having the climate variables for the 2011 and 2012 growing seasons as well as the long-term averages summarized in table 6.1. The soil of the field site is classified as Montmorillonite

clay soil (United State Department of Agriculture soil classification system) with a clay, silt and sand content of 65, 5 and 20 %, respectively and a field capacity of between 39-45 % by volume. Field capacity was measured in situ at 10, 20 and 30 cm soil depths after 48 hr of thorough wetting and covering the soil surface with plastic and planks. The permanent wilting point was estimated in the laboratory to be 27-33%, using the pressure plate apparatus.

Table 6.1: Average weather conditions during the 2011 and 2012 growing seasons and long-term (1971-2000) average values from environment Canada.

Years	Growing months	T _{max} (°C)	T _{min} (°C)	T _{average} (°C)	Average RH (%)	Average u ₂ (m/s)	P _{Total} (mm)
2011	June	24.3	14.1	19.2	74.8	2.6	52.8
	July	28.5	16.7	22.6	67.5	2.5	35.6
	August	26.5	15.7	21.1	66.2	2.1	138.3
	September	22.6	11.2	16.9	75.4	2.0	80.2
	October	13.7	5.3	9.5	77	1.9	74.9
2012	June	24.6	14.2	19.4	67	2.2	54.8
	July	27.8	15.7	21.7	64.3	1.9	85.5
	August	26.6	16.1	21.3	70.7	2.1	49.2
	September	21.3	9.5	15.4	72.3	2.1	95.6
	October	14.6	6.2	10.4	76.1	2.4	74.6
Average (1971- 2000)	June	23.4	12.9	18.1	51.8	2.5	88.6
	July	26.2	15.7	21	52.4	2.2	93.6
	August	24.8	14.7	19.8	53.5	2.1	104.2
	September	19.5	9.7	14.6	53.0	2.3	96.0
	October	12.4	3.8	8.1	55.7	2.6	77.2

T_{max}-maximum temperature, T_{min}-minimum temperature, RH-relative humidity, u₂-wind speed, P_{Total}-total precipitation.

6.2.2 Experimental design

The experimental site was divided into four blocks; each block was divided into four plots in 2011 and five plots in 2012, one for each treatment, for a total of sixteen and twenty plots in 2011 and 2012, respectively. Each plot consisted of 4 m long rows in 2011 and 3.5 m long rows in 2012 (Figure 6.1). The experiment was laid in a randomised complete block experimental design (RCBD) with four replicates consisting of four irrigation treatments (T_1 to T_4) in 2011 and five irrigation treatments (T_1 to T_5) in 2012 based on the available soil water

content (Table 6.2). The treatments were selected based on inconsistent available soil water content threshold recommended in similar studies. The plots were covered with plastic with two rows of bell pepper plants per bed. Five weeks old seedlings of bell peppers (cultivar Red Knight) were transplanted on the 9th and 11th of June in 2011 and 2012, respectively. The transplanted bell pepper plants were grown 30 cm apart between the rows and spaced 30 cm within the rows yielding 30 000 plants ha⁻¹. At sowing, 1.04 kg of the starter feed 10-52-10 fertilizer to 520 litres of water was applied to all of the plots; this was followed by 4 kg ha⁻¹ of NPK 20-20-20 after 3 weeks and 6 kg ha⁻¹ of calcium nitrate (injected through drip irrigation system) when the first fruits were about 165 and 130 mm in longitudinal and transverse circumference, respectively. This was done in accordance with the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) bell pepper growing guidelines. At the beginning of the planting seasons, all plots received the same depth of water from winter snowmelt and spring rainfall, bringing the soil water content almost to field capacity for all treatments and providing adequate and uniform soil moisture for planting. After the seedlings were transplanted, the same irrigation water was applied to bring the soil moisture up to field capacity through a drip irrigation method for one hour daily for three weeks until the crops were established; thereafter, the different irrigation levels were initiated.

Table 6.2: Experimental design and irrigation treatments

Year	Experimental design	Irrigation type	Treatments (% AWC)				
			1	2	3	4	5
2011	RCBD	Drip	85	75	50	25	
2012	RCBD	Drip	85	75	50	25	No irrigation

AWC-available soil water content, RCBD-randomized complete block design. Treatments 1, 2, 3, and 4 means when 15, 25, 50 and 75% of the available soil water is depleted. The treatments are hereafter referred to respectively as T_1 , T_2 , T_3 , T_4 and T_5 (no irrigation).

The irrigation system was a drip irrigation system consisting of laterals $\Phi 16$ mm in diameter. In 2011, each plot had 4 m of drip tape with 16 drippers each delivering 0.869 L hr⁻¹ and spaced every 30 cm while in 2012, there were 12 drippers per drip tape per plot. In both years, one lateral was placed in the middle of the plant row (Figure 6.1). Soil moisture sensors were

installed in the central area of each plot, 10 cm away from the drippers to monitor soil water status at depths of 0-30 cm during the growing season. This was done because it is expected that the majority of the roots of the plants are concentrated at a depth of 30 cm. A time domain reflectometer (TDR) (CS625 Campbell Scientific Inc., Logan, UT) was used in 2011 and was changed to an Irrigation and Drainage Research Group soil moisture sensor (IDRG-SMS-T2) in 2012 due to malfunctioning during calibration prior to the commencement of the experiment. Calibration curves for the sensor was developed for the study area over the rooting depth of the crop (0 to 30 cm) against measured volumetric data at the beginning of the experiments. From the calibration curves for the sensor, the upper and lower volumetric water content and sensor threshold values (beyond which irrigation is necessary to avoid beyond which irrigation water need to be applied) were determined. For all treatments the upper threshold value was field capacity (FC). The soil moisture sensors from all plots were connected to a CR23X data logger (Campbell scientific Inc., Logah, Utah). The data was scanned every 5 minutes and recorded every 15 minutes, hourly and daily. The data was retrieved from the CR23X using a computer and Campbell Scientific Inc. loggerNet. When soil moisture content for each plot depleted to its predetermined moisture treatment level (available soil water content, Table 6.2), irrigation was initiated and irrigation was ended when the FC moisture content was reached. The irrigation scheduling process for each plot was done throughout the growing season. All plots were fertigated simultaneously for the same duration during the experiments.

Five plants were randomly selected from each plot for data collection on growth and yield characteristics during the growth of the plants and the harvesting of the crop. These were stem diameter (mm), number of leaves per plant, fruit length (cm), fruit breadth (cm), number of fruits per plant, individual fruit weight (g), yield per plant (g) and yield per plot (kg).

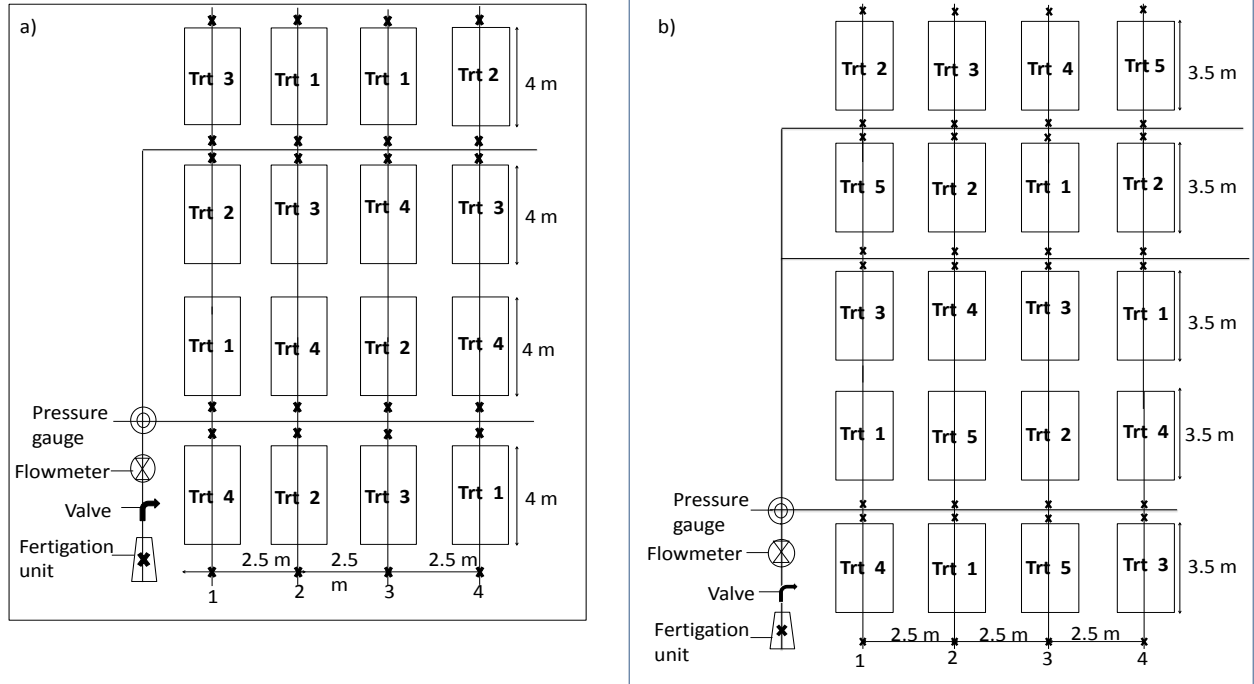


Figure 6.1: Experimental design and irrigation layouts for (a) 2011 and (b) 2012.

6.2.3 Measurements

6.2.3.1 Water volume

A Kent C700 flowmeter with 0.001 m^3 per rev pulse output (AMCO Water Metering Systems Inc., Ocala, FL, USA) was installed to continuously measure water flow into the plots at a pressure of 10 psi.

6.2.3.1 Crop water stress index (CWSI)

Canopy temperature measurements were initiated when the plants covered about 80% of the soil using a fluke infrared thermometer (Model 572) (Evelt et al., 2000), set at an emissivity of 0.95. The instrument was held about 1.5 m above ground level and directed at the bell pepper plants canopy with the help of the laser point of the instrument at an angle of about 30° below the horizontal. The temperatures of the non-stressed plants (lower baseline, T_1) and fully stressed (upper baseline, T_4 in 2011 and T_5 (no irrigation) in 2012) were determined from the canopy and ambient air temperature data. Four (north, south, east and west) viewing directions were considered and the average temperature values taken. The measurement time was between 11:30 am and 2:00 pm because it is expected that during these hours, the sun will be

directed on all of the plants. The mean values of the crop canopy temperature were used for calculating the crop water stress index (CWSI) using Eq. 6.1. (Idso et al., 1981).

$$CWSI = \frac{[(T_c - T_a) - (T_{nws} - T_a)]}{[(T_{dry} - T_a) - (T_{nws} - T_a)]} \quad [6.1]$$

Where: T_c : canopy temperature ($^{\circ}\text{C}$), T_a : air temperature ($^{\circ}\text{C}$), T_{nws} : non-water stressed canopy temperature ($^{\circ}\text{C}$), and T_{dry} : water-stressed canopy temperature ($^{\circ}\text{C}$).

6.2.3.2 Fruit harvest and quality

Bell pepper fruits were hand-harvested eight times in 2011 and six times in 2012 due to early frost. The first fruit yield was harvested after 81 days of transplanting in 2011. The second, third, fourth, fifth, sixth, seventh and eight fruit yields were collected after 8, 11, 16, 25, 32, 41 and 51 days from the first harvest, respectively. While in 2012, the first fruit yield was harvested 77 days after transplanting and the second, third, fourth and fifth fruit yields were collected after 7, 15, 24, 36 and 45 from the first harvest. Marketable fruits were classified based on firmness, tight skin and without blemish or rot. In both years, three fruits from each replication of each treatment were selected during each of the harvest periods for total soluble solids (TSS) ($^{\circ}\text{Brix}$) determination using a portable refractometer, model RHB-32 (Palette 100 PR-100, AT AGO-Spectrum Technologies, Plainfield, IL) that had been standardized with distilled water. Fruit firmness was measured using a portable penetrometer model FT-327 (Facchini, Alfonsine, Italy). Average values for these measurements were taken.

6.2.3.3 Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

WUE and IWUE in all the treatments were calculated using Eqs. 6.2 and 6.3.

$$WUE = \frac{Y}{ET} \quad [6.2]$$

$$IWUE = \frac{Y_i - Y_{ni}}{I} \quad [6.3]$$

Where, WUE is the water use efficiency (kg mm^{-1}), Y_i is the marketable yield (kg ha^{-1}), ET is the crop evapotranspiration (mm), $IWUE$ is the irrigation water use efficiency (kg m^{-3}), Y_{ni} is the yield obtained from the non-irrigation treatment (kg ha^{-1}) and I is the irrigation water (m^3).

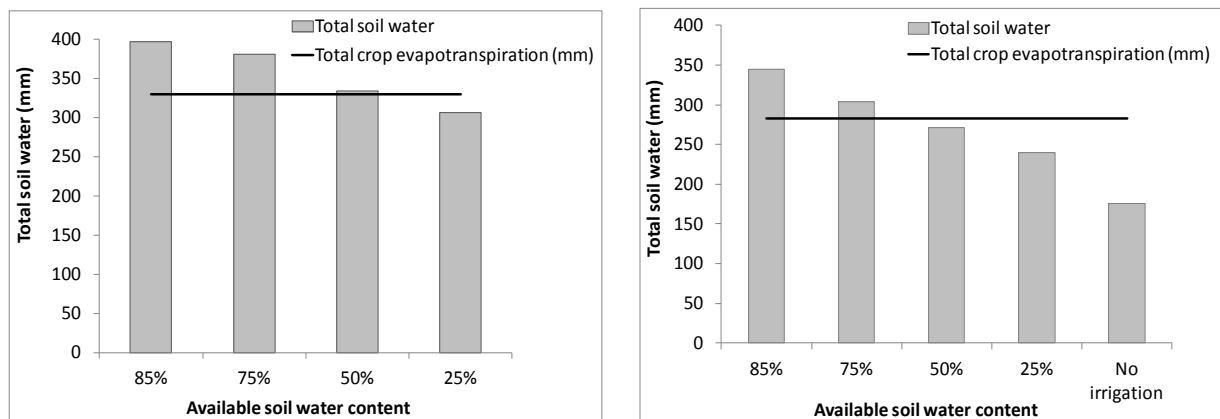
6.2.3 Statistical analysis

Yield data (kg ha^{-1}), *WUE* and *IWUE* were analyzed using PROC GLM in SAS v.9.3 (SAS Institute, Inc., Cary, NC). Treatment means were compared using the least significant difference (LSD) test. Differences were considered to be significant at $p < 0.05$ or $p < 0.01$ level. Statistical results were analyzed for individual seasons.

6.3 Results and discussion

6.3.1 Climatic conditions and total soil water

Treatments had different soil water (rainfall and irrigation water applied) according to the growth stages during the two seasons. The total soil water (all growth stages) for each treatment was compared with the crop water requirement estimated using climatic data of the study area (Figure 6.2). There was a 14 to 40% increase in the total soil water in 2011 compared to 2012; this might be due to variation in the rainfall for the month of August. Rainfall in August 2011 was 138 mm, 64% above that of August 2012 (49.2 mm) and 25% above average normal (104.2 mm). The long-term average growing season rainfall was 457 mm, while the seasonal total rainfall in 2011 and 2012, respectively, were 382 mm (17% below normal) and 360 mm (21% below normal), but rainfall was more uniformly distributed in 2012 than in 2011 and also for the long term (1971-2000) (Table 6.1). The variability was necessary to test how rainfall affects bell pepper response to different irrigation treatments.



*Total soil moisture=available soil water + effective precipitation + irrigation water applied.

Figure 6.2: Total soil moisture* and total crop water requirement at the end of the seasons (a) 2011 and (b) 2012.

6.3.2 Fruit yield and irrigation water application

Total and marketable fruits yields for all treatments were greater in 2012 than in 2011. Maximum total and marketable yields were obtained from T_1 (85% AWC_t) in both years and the minimum from T_4 in 2011 and T_5 (No irrigation) in 2012. T_1 , T_2 , T_3 , and T_4 produced a marketable yield of 21.4, 18.7, 21.3 and 18.5 Mg ha⁻¹ against applied water depth of 241, 228, 174 and 163 mm in 2011, while in 2012, T_1 , T_2 , T_3 , T_4 and T_5 produced 20.9, 18.2, 20.4 and 17.2 and 12.5 Mg ha⁻¹ against 222, 190, 148, 121 and 52 mm depth of water applied, respectively (Figure 6.3). The results indicated that while yield was maximized in T_1 , the slightly lower yields in the T_2 , T_3 and T_4 were similar to T_1 with approximately 28 to 47% less water used to achieve those yields. Similar results obtained by Demirtaş and Ayas (2009) showed that pepper plants which received the highest amount of water at 100% evaporation from a Class A pan produced maximum yield. Fruit yields obtained were highest in T_1 , followed by T_3 in both years though T_1 produced 0.5 to 2.4% fruit yield more than T_3 in both years. In comparison to T_1 , less water (28 to 47%) was used by T_3 . Over the two year study, the two treatments (T_1 and T_3) were consistent even though the two growing seasons were quite different in terms of rainfall. T_5 (no irrigation) produced 42, 31, 41 and 33% less marketable yield than T_1 , T_2 , T_3 and T_4 , respectively. Similar findings by Ngouajio et al., (2008) showed that a lack of irrigation reduced total marketable yield when compared with irrigated treatments.

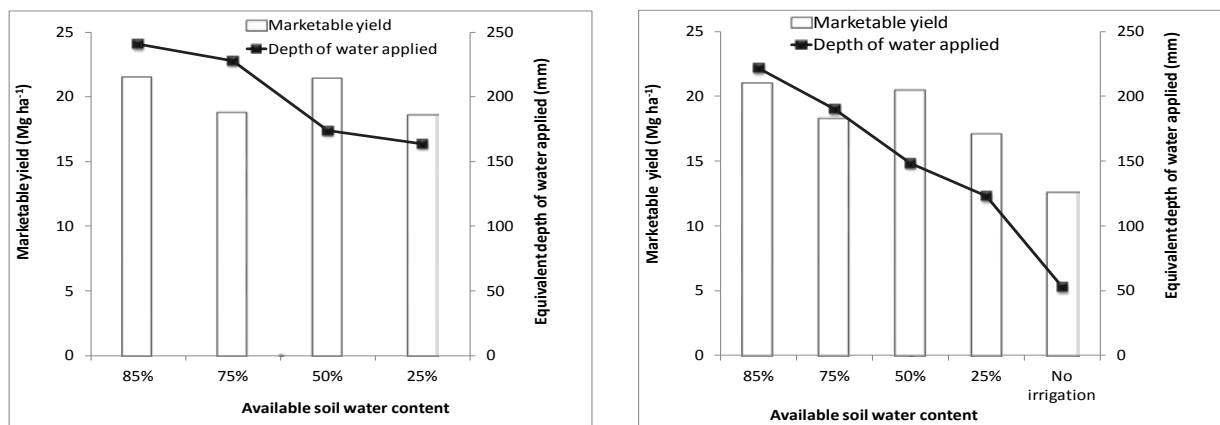


Figure 6.3: Mean marketable yield response to depth of water applied (a) 2011 (b) 2012.

Table 6.3 shows the significant difference in yield between the different irrigation levels. Marketable yields from the different irrigation treatments were not significant in 2011. In 2012, marketable yields from T_5 (no irrigation treatment) had a statistically significant lower value ($P < 0.05$) than T_1 , T_2 , T_3 and T_4 . The trend in marketable yield could be as a result of rainfall distribution because interval and rate at which irrigation was applied is greatly influenced by rainfall.

Table 6.3: Statistical analysis of marketable yield as influenced by irrigation levels

Treatments ^y	Marketable yields (Mg ha ⁻¹)		Equivalent depth of water(mm)	
	2011	2012	2011	2012
1	21.4 ^a	20.9 ^a	240.9 ^a	221.5 ^a
2	18.7 ^a	18.2 ^a	227.7 ^a	190.2 ^a
3	21.3 ^a	20.4 ^a	173.9 ^a	148.2 ^b
4	18.5 ^a	*17.2 ^a	*163.4 ^a	*121.1 ^b
5		12.5 ^b		52.5 ^c

^yWithholding irrigation until the available soil water content reached 85%, (T_1), 75% (T_2), 50% (T_3), 25% (T_4), and no irrigation (T_5). Means followed by the same letter are not significant ($p < 0.05$), * = significant at $p < 0.01$.

6.3.3 Effect of irrigation levels on plants morphological parameters

Average fruit weight increased with more frequent irrigation water applications. The effect of treatment was found to be significant on individual fruit weight at the 1% probability level except for T_5 which was significantly lower than the other treatments at the 5% probability level (Table 6.4). It was also found that T_1 produced the plants with the highest number of fruits per plant followed by T_3 as compared to other treatments; T_4 and T_5 were found to produce a number of fruits significantly lower than other treatments at the 5% probability level. T_1 produced the thickest stem diameter (13.46 mm in 2011 and 14.78 mm in 2012) and the thinnest plants stem diameter (10.5 and 8.1 mm in 2011 and 2012) were obtained from T_4 and T_5 , respectively. Maximum average numbers of leaves (148 in 2011 and 142 in 2012) per

plant were recorded from plants that received the highest amount of water (T_1). The lowest average yields per plant were recorded from T_4 and T_5 , which were statistically different from other treatments.

Table 6.4: The effect of irrigation levels on morphological parameters of bell pepper

Year	Treatments	^y Individual fruit weight (kg)	Number of fruits /plant	Average yield/plant (kg)	Stem diameter (mm)	Average number of leaves/plant
2011	1	0.199 ^a	6.1 ^a	1.208 ^a	13.5 ^a	148 ^a
	2	0.182 ^a	5.4 ^b	0.977 ^b	13.1 ^a	138 ^a
	3	0.196 ^a	5.9 ^a	1.162 ^a	12.7 ^b	100 ^b
	4	0.156 ^b	*4.6 ^c	0.720 ^c	10.5 ^c	*68 ^c
2012	1	0.185 ^a	6.0 ^a	1.105 ^a	14.8 ^a	142 ^a
	2	0.167 ^b	5.5 ^b	0.911 ^b	14.3 ^a	108 ^b
	3	0.184 ^a	5.7 ^a	1.044 ^a	13.8 ^a	104 ^b
	4	0.170 ^b	*4.5 ^c	0.765 ^c	10.4 ^b	*72 ^c
	5	*0.92 ^c	*3.8 ^d	0.352 ^d	*6.1 ^d	*56 ^d

^yMeans followed by the same letter are not significant ($p < 0.01$), * = Significant at 0.05 level of probability

6.3.4 Fruit quality

Fruit total soluble solids ranged from 5.7 to 6.0 and 5.8 to 6.1 °Brix respectively in 2011 and 2012. The highest fruit total soluble solids (6.0 °Brix) was obtained in T_4 in 2011, T_2 (6.1 °Brix) and T_5 (6.1 °Brix) in 2012. Firmness ranged from 3.5 to 3.8 in 2011 and 3.2 to 4.1 in 2012, the highest values were in T_3 in both years (Figure 6.4). It was observed in this result that the total soluble solids content decreased in plants with the highest water application. Similar increases in the total soluble solids content with increase in water stress have been reported in tomato fruits (Colla et al., 1999; Hanson and May, 2003). Increasing the amount of water applied probably led to more water being absorbed by the plant roots and hence, diluted the sugar content. There was no significant difference in the fruit total soluble solids and firmness values among treatments at a significance level of 0.05%.

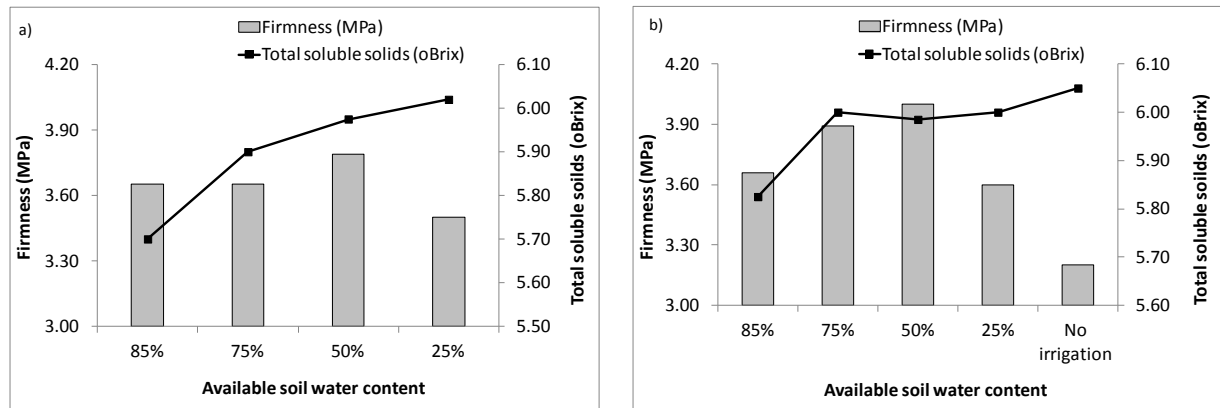


Figure 6.4: Firmness and total soluble solids content in relation to treatments (a) 2011 (b) 2012.

6.3.5 Water Use Efficiency (WUE) and Irrigation Water Use Efficiency (IWUE)

WUE and *IWUE* values were different depending on the treatment and the year (Table 6.5). The *WUE* was between 6.3 to 4.7 kg m⁻³ in 2011 and 6.4 to 2.8 kg m⁻³ in 2012 while *IWUE* varied from 24.6 to 14.8 kg m⁻³ in 2011 and 36.8 to 17.1 kg m⁻³ in 2012. The greatest amount of irrigation water was applied to *T*₁ in both years at 241 and 222 mm in 2011 and 2012, respectively; *IWUE* values were lowest in *T*₂ in 2011 and *T*₁ in 2012 while *T*₃ had the highest *IWUE* in both years. *T*₁ had the highest *WUE* in both years while the lowest *WUE* values were obtained from *T*₄ and *T*₅ in 2011 and 2012, respectively. The findings from Table 6.5 were in agreement with Howell (2001) that reported higher *IWUE* with less irrigation, implying full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both the stored soil water and the growing season rainfall. The highest irrigation volume does not necessarily result in higher yields and the highest *IWUE* because excessive soil moisture could reduce plant yield (Sezen et al., 2006). The highest irrigation water use efficiency was obtained in *T*₃ in both years. The *IWUE* was significantly different from *T*₁ but similar to *T*₂ and *T*₄ (Table 6.5). *T*₃ was able to use the irrigation water applied better than *T*₁ and *T*₂ probably because much of the water was for consumptive use in order to meet its evapotranspirative needs (Figure 6.2), not much water was lost through evaporation. Excessive soil moisture such as in *T*₁ and *T*₂ (Figure 6.2) has been shown to slow down crop

growth and reduce crop yield (Sezen et al., 2011). The excessive soil moisture was as a result of rainfall which cannot be controlled on the field.

Table 6.5: Effect of irrigation levels on water use efficiency and irrigation water use efficiency

AWC (%) *	IWUE (kg m ⁻³)		WUE (kg m ⁻³)	
Treatments	2011	2012	2011	2012
85	16.1 ^a	17.1 ^a	6.3 ^a	6.4 ^a
75	14.8 ^a	18.3 ^b	5.5 ^a	5.5 ^a
50	24.6 ^b	32.1 ^b	6.2 ^a	6.4 ^a
25	16.1 ^a	28.9 ^b	4.7 ^a	5.6 ^a
No irrigation				2.8 ^b

*AWC-available soil water content, Means followed by the same letter within column are not significant (p<0.05)

6.3.6 Available soil water content thresholds

In terms of fruit yield, fruit quality, the irrigation water use efficiency T_3 harvest was consistent for both years. Based on the overall performance of T_3 (AWC_t of 50%), it is the optimum strategy for scheduling irrigation in bell peppers under the site and weather conditions. This result is similar to the recommended FAO AWC threshold value (50-70%) for bell peppers; Hedge (1987) recommended 40-60% AWC under sandy clay loam soil. Dalla-Costa et al. (2002) reported that the critical available soil water content threshold for bell peppers is 60-65% on a loamy soil. Thompson et al., (2007) reported AWC threshold values of 70-81% which corresponded to a depletion factor of 19-30% of AWC for bell peppers grown on a sandy loam soil under Spain's greenhouse conditions. The AWC threshold obtained from this study and the various thresholds obtained in past studies highlighted the importance of the need to determine this value under different soil types and different evaporative conditions for its effective use in irrigation scheduling.

6.3.7 Relation of CWSI, irrigation levels and yield

The calculated CWSI values were compared for each treatment and related to marketable yields for both seasons. T_4 and T_5 had the maximum water deficits in 2011 and 2012,

respectively and were used to determine the fully stressed baseline. On the other hand, T_1 , suggesting that the irrigation water applied was adequate to meet the full crop water requirements, was used to determine non-water stressed baseline. This was true in this case simply because water was applied when only 15% of the AWC was depleted. Figure 6.5 shows the variation in *CWSI* according to the growing days. The *CWSI* values ranged from 0.05 to maximum values of 0.15 in T_1 , from 0.16 to 0.23 in T_2 , from 0.20 to 0.40 in T_3 , and from 0.50 to 0.74 in T_4 , respectively in 2011, while in 2012, *CWSI* values ranged from 0.07 to maximum values of 0.15 in T_1 , from 0.19 to 0.31 in T_2 , from 0.32 to 0.43 in T_3 , from 0.46 to 0.75 in T_4 , and from 0.90 to 1.13 in T_5 , respectively. On average, for each of the treatments, the seasonal mean *CWSI* values for T_1 , T_2 , T_3 , and T_4 were 0.10, 0.22, 0.34 and 0.61, respectively in 2011. In 2012, the mean *CWSI* values for T_1 , T_2 , T_3 , T_4 and T_5 were 0.08, 0.26, 0.45, 0.63 and 1.01, respectively (Figure 6.6). As reported in other studies (Erdem et al., 2006) the seasonal mean *CWSI* values increased with a decrease in irrigation water. As *CWSI* values increase, a decrease in yield was observed (Figure 6.7). The results of this study indicate that initiating irrigation on clay soil when the *CWSI* value is between 0.3 and 0.4 will lead to an average 50% savings in water. On the other hand, permitting the seasonal mean *CWSI* values to exceed 0.65 values would result in decreased bell pepper yields. The relationship between marketable yield, and linear correlation between mean *CWSI* values and irrigation water applied can be used for yield prediction. This is similar to other *CWSI* studies (Irmak et al., 2000; Erdem et al., 2006).

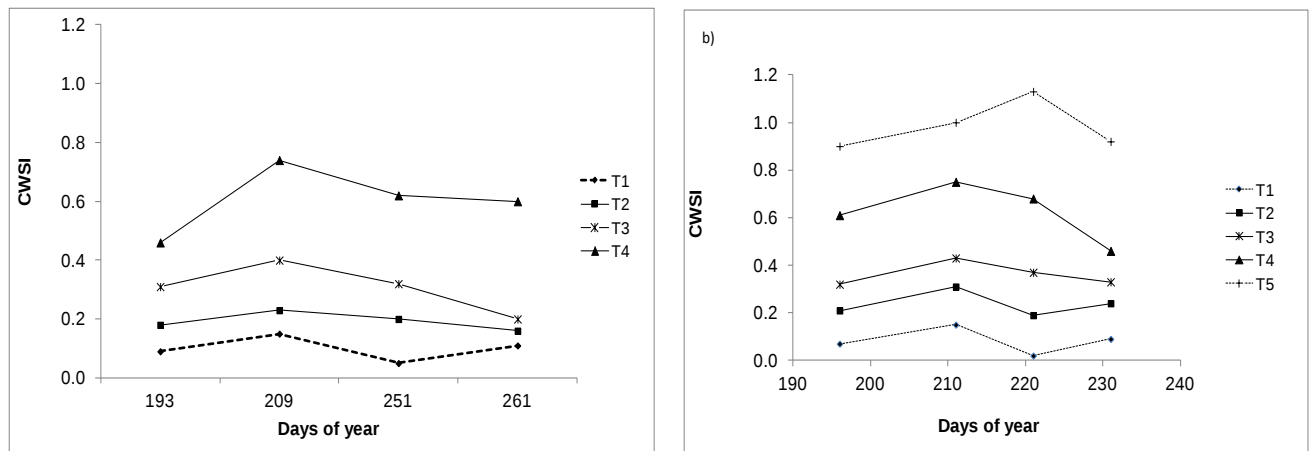
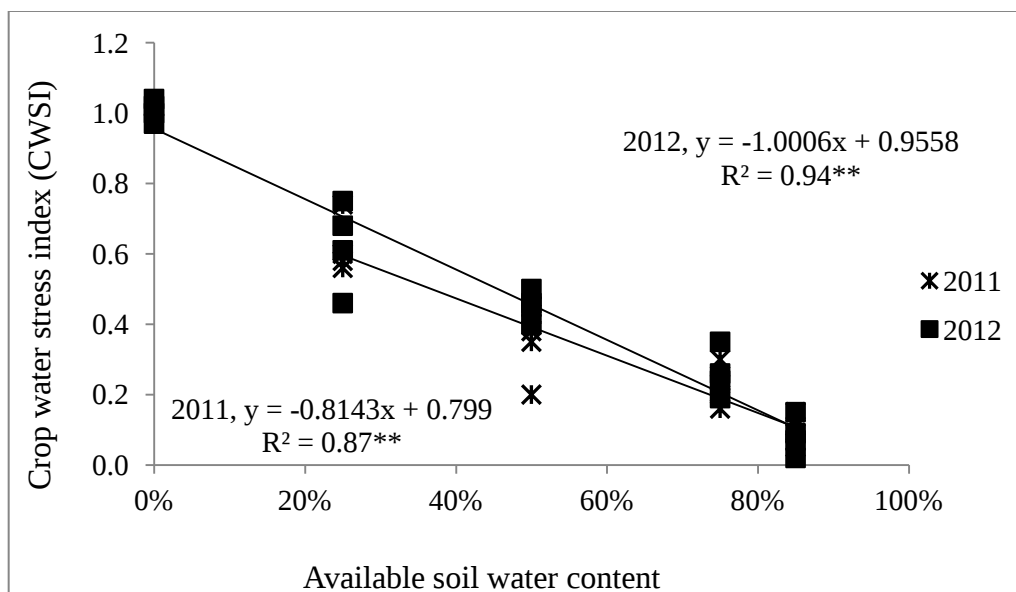


Figure 6.5: Variation in *CWSI* for the growing seasons (a) 2011 (b) 2012



0% available soil water content = No irrigation

Figure 6.6: Mean CWSI relative to irrigation treatments

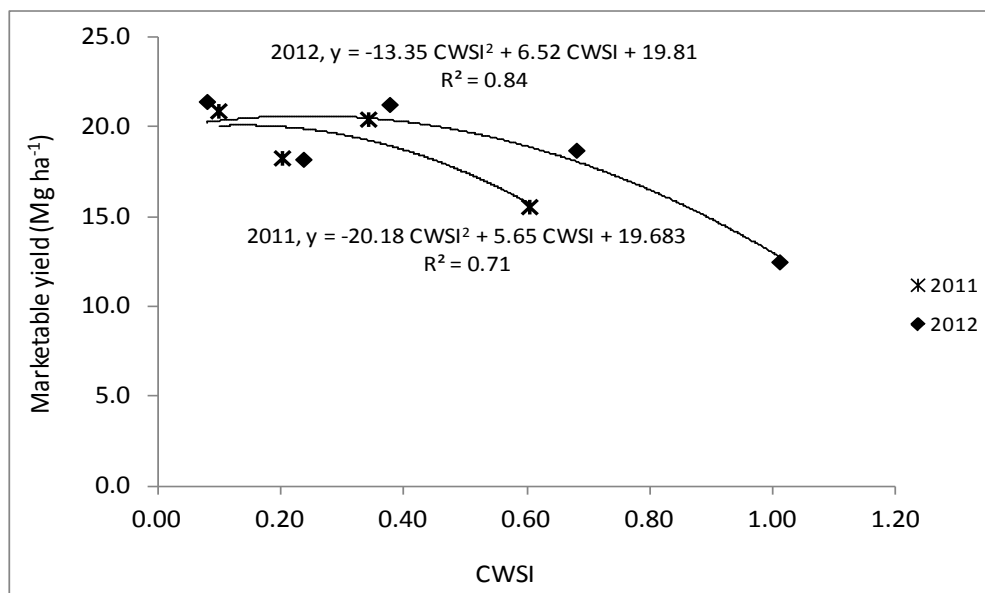


Figure 6.7: Mean CWSI in relation to mean marketable yield

6.4 Conclusions

The highest marketable yield was obtained in T_1 (85% AWC_t) with an average of 21.4 Mg ha⁻¹ for 2011 and an average of 20.9 Mg ha⁻¹ for 2012. The agronomic optimum marketable yields (21.3 and 20.4 Mg ha⁻¹ in 2011 and 2012) were achieved in bell peppers irrigated when 50% (T_3) of the available soil water content (AWC) had been depleted. The optimum marketable yields did not differ significantly ($P < 0.05$) from the maximum yield obtained from T_1 that was irrigated when 15% of the AWC was depleted and received the highest amount of water. Results from this study indicated that initiating irrigation on clay soil at a threshold of 50% AWC when the $CWSI$ value is at 0.3-0.4 is appropriate for bell pepper production. This resulted in higher and more consistent yields, better quality fruit and average 50% savings in water. On the other hand, permitting the seasonal mean $CWSI$ values to exceed 0.65 values would result in decreased bell pepper yields.

Connecting text to Chapter 7

This chapter is a continuation of chapter 6. In this chapter, the effects of elevated CO_2 on bell pepper evapotranspiration were evaluated. This study is important for simulating the future irrigation demands of bell pepper. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis. The results of this study are presented in the manuscript that follows.

Chapter 7 Effects of elevated CO_2 on bell pepper (*Capsicum annuum* L.) evapotranspiration

Olanike Aladenola and Chandra Madramootoo

Abstract

In 2012, effects of elevated CO_2 and water stress on the stomatal conductance, canopy resistance and water requirements of field grown bell pepper in southern Quebec, Canada were investigated for three CO_2 levels- ambient CO_2 (~400 ppm), elevated CO_2 predicted for 2050 (550 ppm) and elevated CO_2 predicted for 2100 (750 ppm). A decrease in stomata conductance with increasing CO_2 was observed. The stomata conductance measured was used to calculate surface resistance. which was used to recalibrate The FAO-56 PM equation for estimating reference evapotranspiration was recalibrated with The result showed a decrease of 6-42% in bell pepper water requirement under elevated CO_2 of 550 ppm and 28-58% for elevated CO_2 of 750 ppm. The difference between evapotranspiration computed using fixed and varied surface resistance for ~400 ppm CO_2 levels was 4.6-52.5% for July and August. The relations between surface and aerodynamic resistance increased under water stress and elevated CO_2 .

Keywords Canopy resistance, elevated CO_2 , Penman Monteith equation, reference evapotranspiration

7.1 Introduction

Increased atmosphere carbon dioxide (CO_2) contributes to global warming and thus affects climatic variables and evapotranspiration (ET) (Goyal, 2004, IPCC, 2007, Lovelli et al., 2010). An increase in CO_2 can lead to reduced evapotranspiration rates due to the stomata closure which cause increases in canopy resistance (Long et al., 2004). The 'bulk' surface resistance (r_s) describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. It is one of the inputs in the Penman Monteith equation for estimating evapotranspiration. In the FAO-56 PM equation, a recommended value of 70 s m^{-1} is provided for the r_s of a well watered crops (Allen et al., 1998). The term is affected by environmental variables, plant characteristics e.g leaf area index, height, growth stage and soil factors (such as available soil water content and salinity). The combination of the effects of these factors in r_s directly affects crop water use (Kamer et al., 2004). Allen et al., (1998) stated that where the vegetation does not completely cover the soil, the resistance factor should include the effects of the evaporation from the soil surface, and if the crop is not transpiring at a potential rate, the resistance will be influenced by the water status of the vegetation. The bulk surface resistance is calculated as:

$$r_s = \frac{r_1}{LAI_{active}} \quad [7.1]$$

Where, r_s : (bulk) surface resistance (s m^{-1}), r_1 : bulk stomatal resistance of the well-illuminated leaf (s m^{-1})(calculated as a reciprocal of stomatal conductance), LAI_{active} : (sunlit) leaf area index ($\text{m}^2 \text{ (leaf area)} \text{ m}^{-2} \text{ (soil surface)}$), calculated as:

$$LAI_{active} = 24 h \quad [7.2]$$

Where h : hour, the bulk stomatal resistance, r_1 , is the average resistance of an individual leaf. This resistance (r_1) is crop specific and differs among crop varieties and crop management. The stomatal resistance, r_1 , is influenced by climate and by water availability. However, influences vary from one crop to another and different varieties can be affected differently. The resistance increases when the crop is water stressed and soil water availability limits crop evapotranspiration.

Using the assumption of a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m ($z_m = z_h = 2$ m) in FAO-56 Penman Monteith equation in eq. 2.13, , the aerodynamic resistance r_a for the grass reference surface became;

$$r_a = \frac{208}{u_2} \quad [7.3]$$

r_a : is aerodynamic resistance which is the transfer of heat and water vapour from the evaporating surface to the air above the canopy (Allen et al., 1998), u_2 : wind speed (ms^{-1}). Allen et al. (1998) stated that where the vegetation does not completely cover the soil, the resistance factor should indeed include the effects of the evaporation from the soil surface, and if the crop is not transpiring at a potential rate, the resistance depends also on the water status of the vegetation. Investigation of the response of canopy resistance to varying soil water availability could help to determine its potential use for scheduling irrigation. To the best of our knowledge, studies investigating the canopy response to soil water availability under elevated CO_2 are limited; Lovelli et al., (2010) used the Penman–Monteith equation to simulate the future changes of reference evapotranspiration (ET_o) by the recalibration of the canopy resistance parameter. Currently study on canopy response of bell pepper to available soil water under elevated CO_2 is not available. The objective of this study was to evaluate the effects of elevated CO_2 on bell pepper evapotranspiration.

7.2 Materials and methods

7.2.1 Study area

This experiment was conducted from June to October 2012 at the McGill University Macdonald campus horticultural research farm located in Ste Anne De Bellevue, QC, Canada, (45.43°N , 73.93°W and elevation 36 m). The study area is a humid region having the climate variables for 2012 growing season as well as the long-term averages (1971-2000) summarized in Table 7.1. The soil of the field site is classified as clay soil with a clay, silt and sand content of 65, 5 and 20%, respectively and a field capacity of between 39-45 % by volume. Field capacity was measured in situ at 10, 20 and 30 cm soil depths after 48 hr of thorough wetting and covering the soil surface with plastic and planks. The permanent wilting point was estimated in the laboratory to be 27-33%, using the pressure plate apparatus.

Table 7.1: Average weather conditions during 2012 growing seasons and long-term (1971-2000) average values from environment Canada.

Years	Growing months	T _{max} (°C)	T _{min} (°C)	T _{average} (°C)	Average RH (%)	Average u ₂ (m/s)	P _{Total} (mm)
2012	June	24.6	14.2	19.4	67	2.2	54.8
	July	27.8	15.7	21.7	64.3	1.9	85.5
	August	26.6	16.1	21.3	70.7	2.1	49.2
	September	21.3	9.5	15.4	72.3	2.1	95.6
	October	14.6	6.2	10.4	76.1	2.4	74.6
Average (1971-2000)	June	23.4	12.9	18.1	51.8	2.5	88.6
	July	26.2	15.7	21	52.4	2.2	93.6
	August	24.8	14.7	19.8	53.5	2.1	104.2
	September	19.5	9.7	14.6	53.0	2.3	96.0
	October	12.4	3.8	8.1	55.7	2.6	77.2

T_{max}-maximum temperature, T_{min}-minimum temperature, RH-relative humidity, u₂-wind speed, P_{Total}-total precipitation.

7.2.2 Experimental design

The experimental site was divided into four blocks; each block was divided into five plots (one for each treatment) for a total of twenty plots. Each plot consisted of 3.5 m long rows (Figure 7.1). The experiment was laid in a completely randomised experimental design with four replicates consisting of four irrigation treatments (T_1 to T_4) in 2011 and five irrigation treatments (T_1 to T_5) in 2012 based on the available soil water content (Table 7.2). The plots were covered with plastic with two rows of bell pepper plants per bed. Five weeks old seedlings of bell peppers (cultivar Red Knight) were transplanted on 11th of June. The transplanted bell pepper plants were grown 30 cm apart between the rows and spaced 30 cm within the rows yielding 30 000 plants ha⁻¹. At sowing, 1.04 kg of the starter feed 10-52-10 fertilizer to 520 litres of water was applied to all of the plots; this was followed by 4 kg ha⁻¹ of NPK 20-20-20 after 3 weeks and 6 kg ha⁻¹ of calcium nitrate (injected through drip irrigation system) when the first fruits were about 165 and 130 mm in longitudinal and transverse

circumference, respectively. This was done in accordance with the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec bell pepper growing guidelines. At the beginning of the planting seasons, all plots received the same depth of water from winter snowmelt and spring rainfall, bringing the soil water content almost to field capacity for all treatments and providing adequate and uniform soil moisture for planting. After the seedlings were transplanted, the same irrigation water was applied to bring the soil moisture up to field capacity through a drip irrigation method for one hour daily for three weeks until the crops were established; thereafter, the irrigation water treatments were initiated.

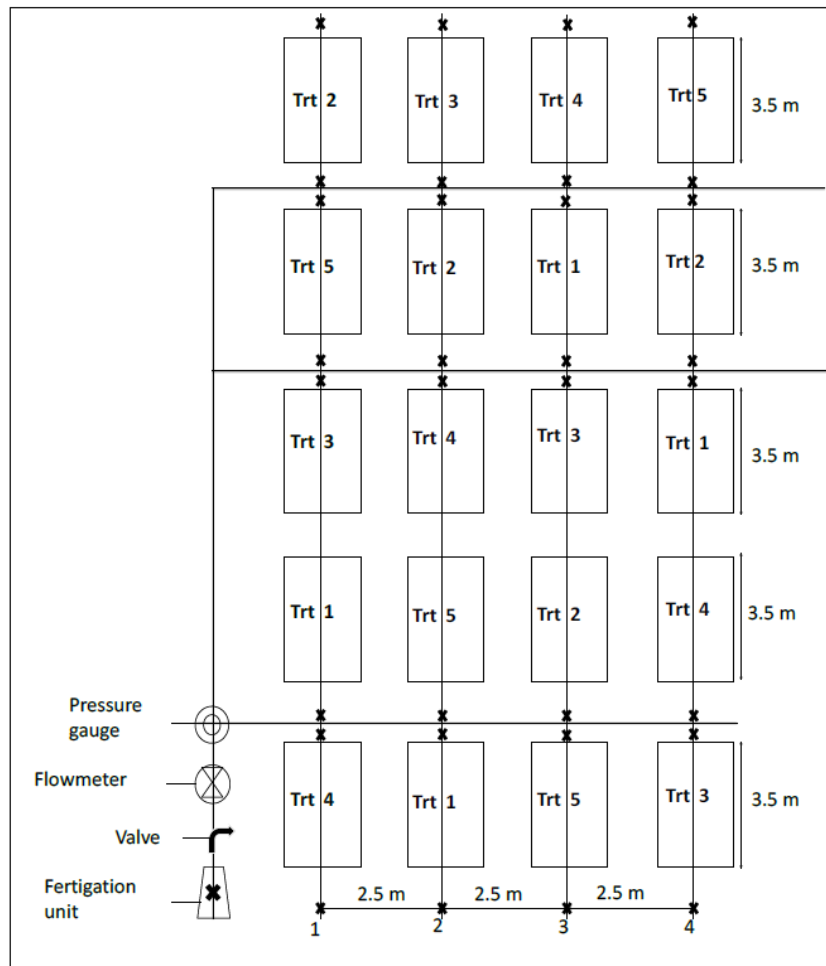


Figure 7.1: Experimental design and irrigation layouts

Table 7.2: Experimental design and irrigation treatments

Year	Experimental design	Irrigation type	Treatments (% AWC)				
			1	2	3	4	5
2012	RCBD	Drip	85	75	50	25	No irrigation

AWC-available soil water content, RCBD-randomized complete block design. Treatments 1, 2, 3, and 4 means when 15, 25, 50 and 75% of the available soil water is depleted. The treatments are hereafter referred to respectively as T_1 , T_2 , T_3 , T_4 and T_5 (no irrigation).

The irrigation system was a drip irrigation system consisting of laterals $\Phi 16$ mm in diameter. Each plot had one lateral placed in the middle of the plant row with 12 drippers spaced every 30 cm, each delivering 0.869 L hr^{-1} of water (Figure 7.1). Irrigation and Drainage Research Group (IDRG-SMS-T2) soil moisture sensors were installed in the central area of each plot, 10 cm away from the drippers to monitor soil water status at depths of 0-30 cm during the growing season. This was done because it is expected that the majority of the roots of the plants are concentrated at a depth of 30 cm. These sensors were calibrated using field and laboratory measurements at the beginning of the experiments.

7.3 Measurements

7.3.1 Stomatal conductance

The stomatal conductance was measured during the growing period using a LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA) equipped with a broadleaf chamber (6.0 cm^2). Three fully expanded sunlit leaves from the top of five randomly selected plants per plot were selected for the measurements; these leaves were marked for subsequent measurements. All measurements were taken at a reference CO_2 concentration similar to ambient ($400 \mu\text{mol mol}^{-1}$) and representing current situation, the CO_2 concentration was then increased to 550 and 750 ppm based on climate change predictions of 2050 and 2100 respectively. For the elevated CO_2 conditions, neither the plants nor the growing environment were injected with CO_2 , the simulations were done by changing the CO_2 concentration levels in the LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA).

7.4 Results and Discussion

7.4.1 Effect of elevated CO_2 on stomatal conductance and canopy resistance

The effect of elevated CO_2 on stomatal conductance of bell pepper is presented in Figure 7.2. Stomatal conductance of bell pepper reduced under elevated CO_2 . Bell pepper with no irrigation and the treatment with the least water application had the least stomatal conductance irrespective of the CO_2 concentration. It has been well established that reductions in soil water availability increase levels of increased hydraulic and/or chemical signals associated with decreasing stomatal conductance (Dodd, 2005; Schachtman and Goodger, 2008). The stomatal conductance values ranged between 24-46% for (400-550 ppm) and 68-70% for (400-750 ppm) across irrigated (T_1 - T_4) and no irrigation (T_5) treatments. Decrease in stomatal conductance resulted in canopy resistance increase. The resistance increases when the crop is water stressed (Table 7.3). The relationship between canopy resistance and soil water availability is similar to (Kamer et al., 2004).

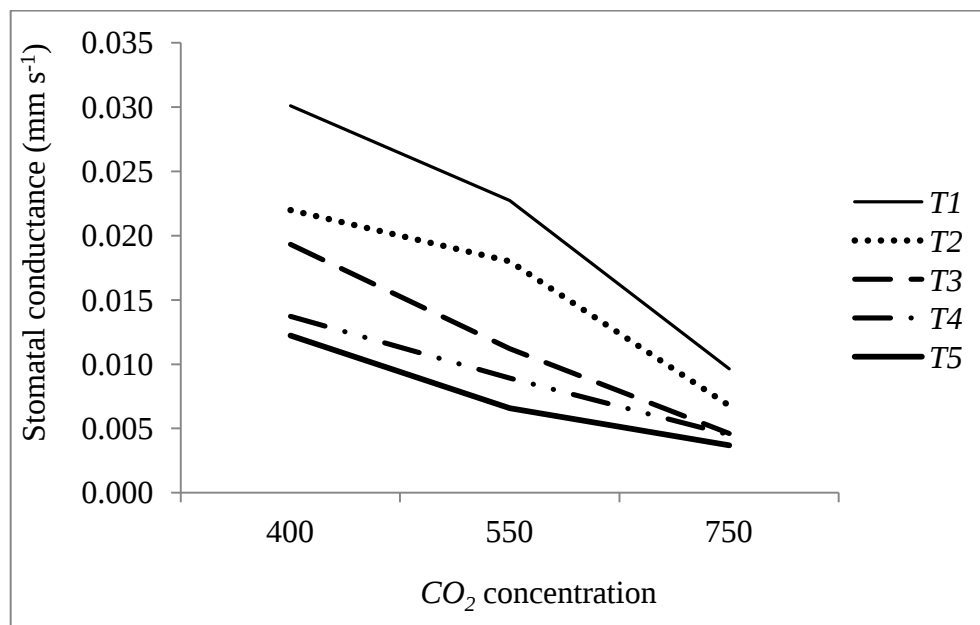


Figure 7.2: Stomatal conductance at different CO_2 concentrations

Table 7.3: Effects of irrigation treatments and elevated CO_2 on surface resistance (r_s)

Treatments	CO_2		
	400	550	750
	r_s		
1	33.5 ^a	44.3 ^a	104.4 ^a
2	51.0 ^a	50.2 ^a	162.6 ^a
3	56.9 ^a	98.2 ^b	238.9 ^b
4	76.9 ^b	118.5 ^c	234.0 ^b
5	88.2 ^b	163.8 ^d	291.4 ^b

7.4.2 Effect of fixed and variable canopy resistance on evapotranspiration

The effects of irrigation treatments and different CO_2 concentration on ratio of surface to aerodynamics resistance factors are presented in Table 7.4. Bell pepper evapotranspiration estimated with varied and fixed ratio of surface to aerodynamic resistance factors (r_s/r_a) differ for the peak months of July and August by 4.6-52.5% (Figure 7.3). ET_c decreased by 6-42% under elevated CO_2 of 550 ppm and 28-58% for CO_2 of 750 ppm. In addition to changing CO_2 level, it is important to note that temperature, precipitation trend and distribution, crop coefficients, change in plants growing duration will affect future crop evapotranspiration.

Table 7.4: Effects of irrigation treatments and different CO_2 concentration on ratio of surface to aerodynamics resistance factors

Treatments	^y CO_2		
	400	550	750
	r_s/r_a		
1	0.30 ^a	0.40 ^a	0.95 ^a
2	0.46 ^a	0.46 ^a	1.48 ^a
3	0.52 ^a	0.89 ^b	2.17 ^b
4	0.70 ^b	1.08 ^b	2.13 ^b
5	0.80 ^b	1.49 ^c	2.65 ^c

^yMeans followed by the same letter with the column are not significantly different at $p < 0.05$

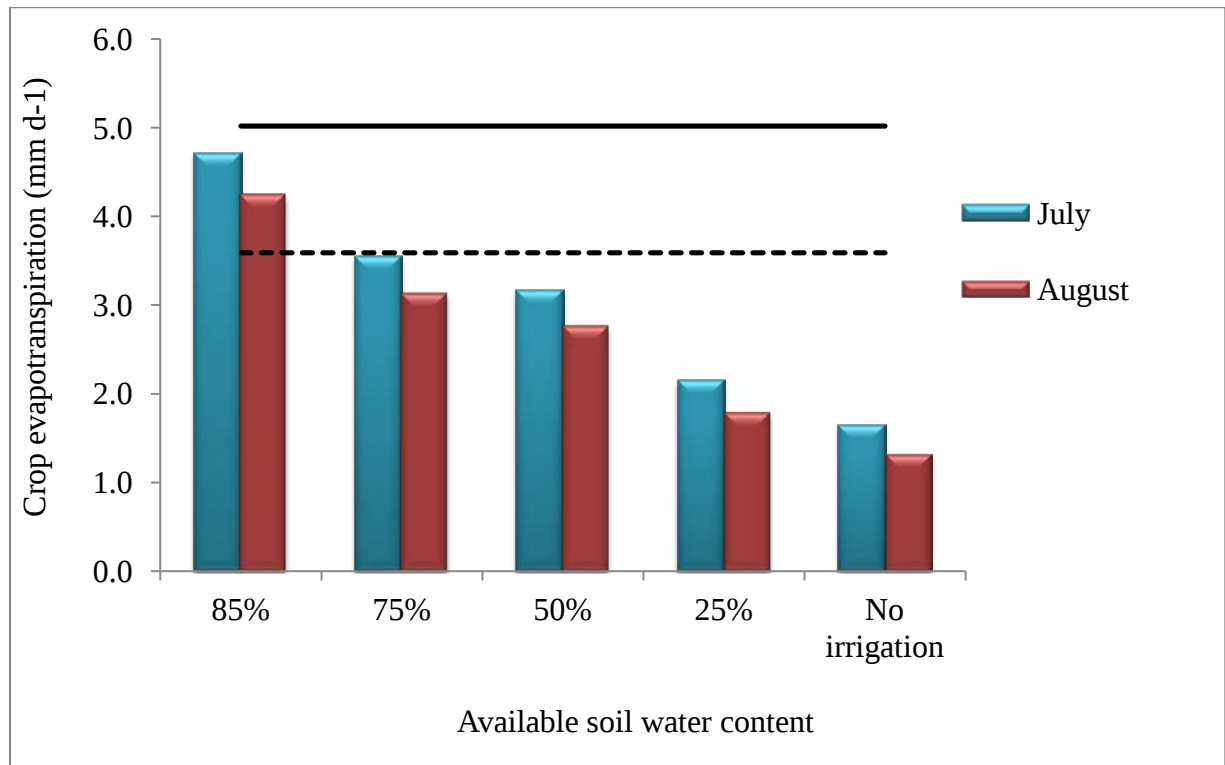


Figure 7.3: Crop evapotranspiration (ET_c) based on fixed and variable surface resistance (r_s)

7.5 Conclusions

The effects of CO_2 on stomatal conductance, canopy resistance and bell pepper evapotranspiration under different irrigation levels were evaluated. Stomatal conductance of bell pepper reduced under both water stress and simulated elevated CO_2 . Crop evapotranspiration decreased by 6-42% under elevated CO_2 of 550 ppm and 28-58% for CO_2 of 750 ppm. The use of variable surface resistance for crop evapotranspiration modelling was practicable for site-specific irrigation scheduling and future simulations of crop evapotranspiration.

Connecting text to Chapter 8

The main goal of this research is using accurate methods for estimating irrigation water demand and irrigation scheduling processes which incorporate plant-water status indicators. The information from Chapters 3, 6 and 7 were processed to develop an integrated water demand management model which provided estimation methods for improving the accuracy of reference evapotranspiration, crop water requirements and irrigation requirements. The model provided irrigation management protocol for managing field production of bell pepper. The manuscript is co-authored by my supervisor, Prof C.A Madramootoo. All literature cited in this chapter is listed in the reference at the end of this thesis. The results of this study are presented in the manuscript that follows while a detailed description of the model is presented in the appendix.

Chapter 8 Field and modelling assessment of irrigation water requirements for bell peppers (*Capsicum annum. L*) in Southern Quebec, Canada

Olanike Aladenola and Chandra Madramootoo

Abstract

Irrigation water use in many parts of Canada is not well documented because of inadequate reporting and a wide variability associated with climate, soils, crops, and at times, agronomic practices. To help water managers and decision-makers better understand irrigation water use in Eastern Canada, an integrated agricultural water demand model (IAWDM) was developed using a graphical user interface (GUI) in Matlab. IAWDM is a crop-water-demand model that uses daily soil water balance to estimate the water needs of a crop on a given day based on climate, soil, and plant properties. Output from IAWDM was compared with the CROPWAT model and metered irrigation water-use data for bell peppers (*Capsicum annum. L*) grown at the McGill University research station. IAWDM predictions of water use deviated from field data by 7 to 28% while CROPWAT deviated by 7 to 42% based on four irrigation levels of 85%, 75%, 50% and 25% available soil water content. Recalibration of the PM equation with aerodynamic constants (ratio of surface/aerodynamic resistance factors (r_s/r_a)) reduced the percentage deviation of predicted IWR (for bell peppers grown at 25% available soil water content) from 28% to 8%. Future IWR was also estimated using generated climate change data for 2040 to 2069. It was observed in this study that IWR of bell peppers will increase by 19 to 27% in the future. This assessment does not consider the effect of CO_2 . Analysis of the sensitivity of irrigation requirements indicated that temperature, reference evapotranspiration (ET_o) and crop coefficients were the most sensitive, followed by solar radiation and precipitation.

Keywords Climate change, crop water modelling, evapotranspiration, irrigation requirements

8.1 Introduction

Increasing competition for water resources makes it essential that the agricultural demands for irrigation are effectively managed. In Canada, the use of water resources for irrigated agriculture must be optimized where there are concerns about water use efficiency and vulnerability of water availability to climate change. Climate change has already resulted in an increase in mean temperature in Canada and is likely to affect local precipitation patterns (Zhang et al., 2011). The result of potential climate change on agriculture depends on the region (IPCC 2007), crops (Long et al., 2004), the significance of extreme events (Sivakumar et al., 2005), and changes in temperature (Battisti and Naylor, 2009), atmospheric CO_2 concentration (Tubiello and Fisher, 2006) and precipitation (Reilly et al., 2003).

Penman– Monteith model is widely-accepted to be most accurate for simulating *ET* (Allen et al., 1998; Rana and Katerji, 2000). However , the model is highly sensitive to the variation in underlying surface resistance (Rana and Katerji, 1998). Many empirical models have been developed to estimate canopy resistance (Jarvis, 1976; Katerji and Perrier, 1983) for many agricultural crops (Katerji and Rana, 2006; Rana et al., 2011; Whitley et al., 2009, Li et al., 2013). Allen et al. (1998) stated that where the vegetation does not completely cover the soil, the resistance factor should indeed include the effects of the evaporation from the soil surface, and if the crop is not transpiring at a potential rate, the resistance depends also on the water status of the vegetation. Investigation of the response of canopy resistance to varying soil water availability could help to determine its potential use for scheduling irrigation. Description of the resistance factors is presented in Figure 8.1.

An understanding of the weather, and soil-water plant relationships is required to design management tools that maximize crop yield, improve water use efficiency and ensure that agrochemical do not degrade available water. Information obtained from irrigation management studies provides data inputs for computer based irrigation management models. While there are some irrigation water demand models, there is need to adapt these models to specific environments or to new problems (Van Ittersum et al., 2003). It is important to note that the availability of data often determines the model that is chosen. Similar models for the same region might produce consistent estimates; however, each region requires its own model that must be updated regularly.

The models that have been used extensively for estimating irrigation requirements at the field and plot scale are empirical one dimensional bucket models based on budgeting techniques (Bastiaansen et al., 2007). Currently, these models include CROPWAT (Clarke et al., 1998), and the upgraded version (CROPWAT 8.0) which has new features. In the US, many models have been developed in different states based on data availability and the specific needs of the location. Various states have developed one-dimensional volume balance irrigation scheduling programs (Sammis et al., 2012). Some of the recent models are used jointly in Michigan and Kansas (Michigan State University, 2010; KS-State, 2010). Arkansas, Mississippi, Louisiana, Tennessee, and Missouri also developed a regional water balance computer program appropriate for use in those states (University of Arkansas, 2010). Other models that are widely used are the ISAREG (Teixeira and Pereira, 1992), WaterGAP (Döll et al., 1999; Alcamo et al., 2000), Decision support system for Agrotechnology Transfer (DSSAT) model (IBSNAT, 1993) and the Water Simulation model (WaSim) (Hess et al., 2000). The WaterGAP model has been used to quantify globally the impact of climate change on annual and seasonal irrigation water demand. In Canada, the two main irrigation water demand models are the Alberta Irrigation Management Model (AIMM) (Tollefson et al., 2002) and the Okanagan Irrigation Water Demand Model (AWDM) developed to provide current and future agriculture water demands for the Okanagan basin (Van de Gulik et al., 2010). The models are often more accurate at the local or regional scale, provided they have been extensively calibrated and validated. The difference between the models is often the result of the equations used to calculate the reference evapotranspiration (ET_o), the crop coefficient (K_c), rooting depth and effective precipitation (Smith et al., 2012). In this study, a decision support model (integrated agricultural water demand model, IAWDM) was developed.

To date, studies on the effects of weather data, ET_o , crop coefficient, canopy resistance and equations used to calculate inputs on irrigation models are limited. For example, Porter et al., (2012) determined the relative effects of measurement errors in climate data input parameters on the accuracy of calculated ET_o using the ASCE-EWRI standardized ET_o equation. Studies indicating the sensitivity of calculated evapotranspiration (ET) to weather data are Irmak et al., (2006) (Nebraska, USA), Bakhtiari and Liaghat, (2011) for Iran, Gong et al., (2006) for China, Ambas and Baltas, (2011) for Greece, Estevez et al., (2009) and Moratíel et al., (2010)

for Spain. The results of all of these studies indicated that the level of variation in sensitivity of ET_o to climatic inputs is dependent on time and location. Knowledge about the interaction of the variables with irrigation requirements will help modellers and irrigators to understand the effects of variations in data inputs on irrigation water modelling accuracy.

The objectives of this study were to (1) estimate current and future irrigation water requirements of field grown bell peppers in southern Quebec (2) Develop an integrated agricultural water demand model and evaluate its performance, and (3) assess the sensitivity of irrigation water requirements to changes in solar radiation (R_s), temperature, crop coefficient (K_c), effective precipitation and evapotranspiration (ET).

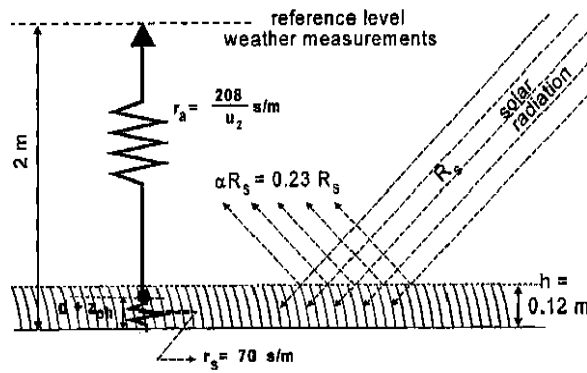


Figure 8.1: Characteristics of hypothetical reference crop

Source: Allen et al., (1998)

8.2 Material and methods

8.2.1 Field study

Study area

The experiment was conducted from June to October 2012 at the horticultural research station of McGill University, Macdonald campus located in Ste Anne De Bellevue, QC, Canada (45.43°N , 73.93°W and elevation 36 m). The study area has a humid, moderate temperate climate. The frost-free days in the study region restrict the growing period from the end of May to the beginning of October. The average climate for the 30 year period from

1971-2000 showed an average total rainfall of 270 mm for the months of June, July and August with a mean daily *ET* of 4.5 mm. The soil at the field site is classified as clay soil with a clay, silt and sand content of 65, 5 and 20 %, respectively with a field capacity of between 39-45 % by volume. Table 8.1 shows the average weather conditions for 2011 and 2012.

Table 8.1: Average weather conditions during the 2012 growing season and the long-term (1971-2000) average values from environment Canada

Years	Growing months	T _{max} (°C)	T _{min} (°C)	T _{average} (°C)	Average RH (%)	Average u ₂ (m/s)	P _{Total} (mm)
2012	June	24.6	14.2	19.4	67	2.2	54.8
	July	27.8	15.7	21.7	64.3	1.9	85.5
	August	26.6	16.1	21.3	70.7	2.1	49.2
	September	21.3	9.5	15.4	72.3	2.1	95.6
	October	14.6	6.2	10.4	76.1	2.4	74.6
Long term average (1971-2000)	June	23.4	12.9	18.1	51.8	2.5	88.6
	July	26.2	15.7	21	52.4	2.2	93.6
	August	24.8	14.7	19.8	53.5	2.1	104.2
	September	19.5	9.7	14.6	53	2.3	96.0
	October	12.4	3.8	8.1	55.7	2.6	77.2

T_{max}-maximum temperature, T_{min}-minimum temperature, RH-relative humidity, u₂-wind speed, P_{Total}-total precipitation.

Experimental design

The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replications. Blocks were separated by a 1.5 m wide strip with each block consisting of five plots (3.5 m X 1 m each), separated by 1 m space and raised by 10 cm and covered with plastic to reduce evaporation and weed growth. Five week old bell pepper seedlings were transplanted in twin rows on June 11, 2012. Five treatments were randomly assigned to the five plots within each block. The treatments were defined as: 85, 75, 50, 25% of available water content threshold (AWC_t) and no irrigation (hereafter referred to as T_1 , T_2 , T_3 , T_4 and T_5 , respectively). Bell pepper (*Capsicum annuum* L.) was chosen as the test crop because of its high market value and high susceptibility to water stress. Beds were 2.5 m apart (centre to

centre) and plants were 0.30 m apart between and within rows yielding 30,000 plants per hectare.

At sowing, 1.04 kg of the starter fertilizer 10-52-10 were added to 520 litres of water was applied to all of the plots; this was followed by 4 kg ha⁻¹ of NPK 20-20-20 after 3 weeks and 6 kg ha⁻¹ of calcium nitrate (injected through the drip irrigation system) when the first fruits were about 165 and 130 mm in longitudinal and transverse circumference, respectively. This was done in accordance with the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec bell pepper growing guidelines. After the seedlings were transplanted, irrigation water was applied up to field capacity through a drip irrigation method for one hour daily for three weeks until the crops were established for all the plots; thereafter, the treatments were initiated.

One drip tape was placed in the middle of the plant row before covering the plots with plastic. The drip tape consisted of laterals Φ 16 mm in diameter. Each plot had 3.5 m of drip tape with 12 drippers each delivering 0.869 L hr⁻¹ and emitters spaced every 30 cm per. Irrigation and Drainage Research Group soil moisture sensors (IDRG-SMS-T2) were installed in the central area of each plot, 10 cm away from the drippers to monitor soil water status at a depth of 0-30 cm during the growing season. This was done because it is expected that the majority of the roots of the plants are concentrated at a depth of 30 cm. These sensors were calibrated using field and laboratory measurements of gravimetric soil sampling at the beginning of the experiments.

Measurements

A Kent C700 flowmeter with 0.001 m³ per rev pulse output (AMCO Water Metering Systems Inc., Ocala, FL, USA) was installed to continuously measure water flow into the plots at a pressure of 10 psi. The stomatal conductance was measured during the growing period using a LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA). Three fully expanded sunlit leaves from the top of the plant were selected for the measurements; these leaves were marked for subsequent measurements. The effective rainfall is the rainfall above 5 mm that infiltrates into the soil (Nyvall & Tam, 2005). It is assumed that any rainfall less than

5 mm will be intercepted by vegetation and quickly evaporate and the available soil water is assumed to be at field capacity as a result of wet conditions at the time of planting.

$$P_e = (R - 5) * 0.75 \quad [8.1]$$

Where P_e : effective rainfall/precipitation (mm) and R : rainfall (mm).

Future irrigation water requirements (IWR)

Future irrigation water requirements (*IWR*) were estimated using the projected 2040-2069 climate change from a prior statistically downscaled Agriculture and Agri-Food Canada-General Circulation Model (AAFC-GCM) for minimum and maximum temperatures, solar radiation and precipitation. This model was used because it simulated the baseline period (1961-1990) closer to measured historical data than other models (Hadley climate model (HADCM3) and Canadian regional climate model (CRCM v4.2)) that were tested in this study. AAFC-GCM is driven by coupled global climate models (CGCM3) which considers the future scenario based on the special report on emission scenarios (SRES) A1, A1B and A2 for 2040-2100 in Canada.

8.2.2 Irrigation water simulation

Cropwat model

The *CROPWAT* 8.0 for Windows is a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. All calculation procedures used in *CROPWAT* 8.0 are based on the two *FAO* publications of the Irrigation and Drainage series, namely, No. 56 "Crop Evapotranspiration - Guidelines for computing crop water requirements" and No. 33 titled "Yield response to water. Water balance models including *CROPWAT* require accurate estimation of effective precipitation and reference evapotranspiration for quantification of crop water requirement and irrigation water demand. There are several methods for estimating effective precipitation and reference evapotranspiration. Four effective precipitation incorporated to *CROPWAT* are Fixed percentage, Dependable rain, Empirical formula, USDA Soil Conservation Service. It was assumed in *CROPWAT* that rainfall values below 100 mm/month will have an efficiency of

approximately 80%. FAO-56 Penman-Monteith equation is the default reference evapotranspiration method. Detailed information about the model is available on FAO Cropwat 8.0 website.

Integrated agricultural water demand model (IAWDM)

IAWDM computes reference evapotranspiration (ET_o) in order to estimate crop water demand, using four different equations, namely, FAO-56 Penman-monteith, Hargreaves, Turc and ASCE, two radiation (R_s) estimation methods, Hargreaves and Angstrom-Prescott ($A-P$) and two effective rainfall methods - 80% of total precipitation (Smith, 1992) and Nyvall and Tam (2005) method (Eq. 2.38). The model also determines irrigation demand using a combination of climate data, soil moisture measurements and plant water status. R_s coefficients, using Hargreaves K_{RS} and $A-P$ "a" and "b" coefficients have been calibrated for eight locations in six provinces across Canada. IAWDM was tested for bell peppers (cultivar Red Knight) in Ste Anne de Bellevue (southern Quebec) using the crop factors determined for this location. A detailed description of the model is in the appendix.

8.3 Recalibration of the PM equation with aerodynamic constants (ratio of surface/aerodynamic resistance factors (r_s/r_a))

The stomatal conductance was measured during the growing period using a LI-6400 Portable Photosynthesis System (LI-COR Inc., Nebraska, USA). Three fully expanded sunlit leaves from the top of five randomly selected plants per plot were selected for the measurements; these leaves were marked for subsequent measurements. The measurements of stomata conductance was used to calculate stomata resistance (r_1). Aerodynamic resistance (r_a) (the transfer of heat and water vapour from the evaporating surface to the air above the canopy) was calculated using Eq. 8.2.

$$r_a = \frac{\ln \frac{z_m - d}{z_{om}} \ln \frac{z_h - d}{z_{oh}}}{k^2 u_z} \quad [8.2]$$

Where, r_a : aerodynamic resistance ($s\ m^{-1}$), z_m : height of wind measurements (m), z_h : height of humidity measurements (m), d : zero plane displacement height (m), z_{om} : roughness length

governing momentum transfer (m), z_{oh} : roughness length governing transfer of heat and vapour (m), k : von Karman's constant, 0.41 (-), u_z : wind speed at height z (ms^{-1}).

The zero plane displacement height d and the roughness length governing momentum transfer, z_{om} can be estimated from the crop height h for a wide range of crops using:

$$d = \frac{2}{3} h \quad [8.3]$$

$$z_{om} = 0.123h \quad [8.4]$$

The roughness length governing transfer of heat and vapour, z_{oh} can be approximated by:

$$z_{oh} = 0.1z_{om} \quad [8.5]$$

The 'bulk' surface resistance (r_s) (the resistance of vapour flow through the transpiring crop and evaporating soil surface) was calculated as:

$$r_s = r_1 / LAI_{active} \quad [8.6]$$

Where, r_s : (bulk) surface resistance (s m^{-1}), r_1 : is bulk stomatal resistance of a well-illuminated leaf (s m^{-1}) which is the reciprocal of stomata conductance, LAI_{active} : active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)].

8.4 Sensitivity analysis

Impact of changes in solar radiation (R_s), temperature (T), crop coefficient (k_c) and reference Evapotranspiration (ET_o) on irrigation water requirement (IWR) were evaluated. Sensitivity analyses was conducted by increasing each of the variables one at a time by 20% while keeping other parameters constant and the sensitivity coefficients were derived by dividing the amount of increase or decrease in IWR by the increase or decrease in the inputs (equation 3) (Smajstrla et al., 1987; Irmak et al., 2006). Monthly and yearly average sensitivity coefficients were obtained by averaging the daily values. Daily sensitivity coefficients and the slope of the linear regression line between the increase and decrease in IWR with respect to the increase and decrease in these variables was used to quantify the effect of each variable on ET_o . Positive/negative sensitivity coefficient of a variable indicates that IWR will increase/decrease

as the variable increases and the larger the sensitivity coefficient, the larger the effect that a given variable has on *IWR*.

$$C_s = \frac{CH_{ET_o}}{CH_{CV}} \quad [8.2]$$

where C_s : sensitivity coefficient, CH_{ET_o} : change in ET_o with respect to change in input variable and CH_V : change (increase or decrease) in input variable.

8.5 Results and discussions

8.5.1 Measurement and of irrigation water requirements

Irrigation water requirements (*IWR*) of bell peppers measured with a soil moisture sensor, estimated with integrated agricultural water demand (*IAWDM*) and *CROPWAT* models are presented in Figure 8.6. The irrigation water requirements for peppers based on T_1 (85), T_2 (75), T_3 (50) and (T_4) 25% AWC_t were 222, 190, 148 and 121 mm, respectively. The percent deviation between the *IWR* estimated by the *IAWDM* model and the field measured was 7 to 28%. The differences in *IAWDM* and the field *IWR* may be due to uncertainty in the estimated or determined local factors such as soil water holding capacity, rooting depth and reference evapotranspiration (ET_o), and interval between rainfall events which affects actual *ET* (Hess et al., 2010).

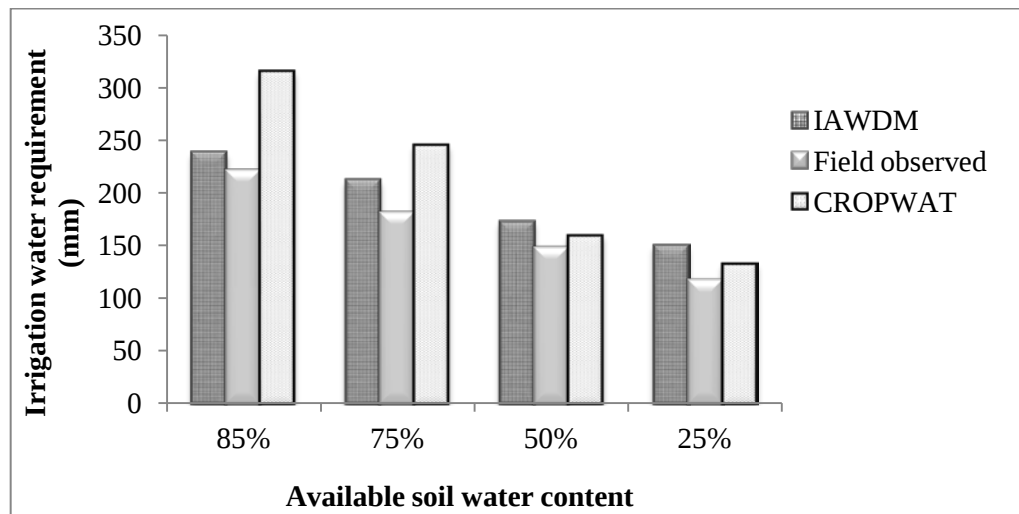


Figure 8.2: Field and model estimation of present irrigation water requirement

8.5.2 Effect of recalibrating aerodynamic constant (r_s/r_a) in FAO-56 Penman Monteith equation

The large percentage deviation between irrigation water requirements (IWR) outputs from IAWDM and field measurements for T_4 may also be due to its surface resistance (r_s)/aerodynamic resistance (r_a) ratio which varies greatly from the Food and Agriculture (FAO) recommended value for well watered plants as stated in Allen et al., (1998). This is because the soil moisture for T_4 actual evapotranspiration is far below what is required for maximum evapotranspiration. IAWDM estimated ET_o and IWR with a fixed aerodynamics constant (r_s/r_a) 0.34 from Allen et al., (1998.) The ratio of r_s computed from field measured stomatal conductance to r_a ranged from 0.3 (T_1) to 0.8 (T_4) while the recommended value for well watered plants was 0.34 (Allen et al., 1998). Difference between the crop canopy and aerodynamic resistance relative to the reference crop are accounted for within K_c . Factors affecting K_c include crop type, stage of growth, soil moisture, health of plants and cultural practices such as mulching. K_c for the same crop may vary from place to place based on factors such as climate and soil evaporation (Allen et al., 1998; Kang et al., 2003).

Theoretical recalibration of the PM equation with the r_s/r_a ratio reduced the percentage deviation of IWR from 28% to 8% in T_4 . However, the recalibration of r_s/r_a did not improve the IWR computed for other irrigation treatment levels.

8.5.3 Comparison of field measured and CROPWAT simulated data

The percentage deviation between the irrigation water requirements estimated using CROPWAT model and the field measured IWR was 7 to 42%. IAWDM estimates were in closer agreement with field measurements than CROPWAT at T_1 and T_2 irrigation levels while CROPWAT was in closer agreement with field measurements at T_3 and T_4 . IAWDM performance was better than CROPWAT based on the range of percentage deviation from the field measurement; this confirms that models developed with local data may outperform other models. The differences in IAWDM and CROPWAT outputs might be due to the method used to estimate effective precipitation. IAWDM used the Nyvall and Tam, (2005) method (which assumed that only rainfall in excess of 5 mm will infiltrate and become useful to plants, further multiplied by 0.75 to account for runoff and deep percolation) and CROPWAT used 80% of total precipitation.

In addition, *IAWDM* considers daily variations in climatic data for predicting the soil moisture depletions whereas *CROPWAT* uses average monthly *ET* value which may result in under or over-prediction of irrigation depth if there is a large variation in daily climatic conditions. Furthermore, *IAWDM* is capable of selecting *ET_o* estimation method based on climatic data availability (Penman Monteith Temperature method). *CROPWAT* model calculated *ET_o* using FAO-56 PM equation and Angstrom coefficient to estimate solar radiation from the monthly average of historical sunshine hours whereas *IAWDM* calculated daily *ET_o* using the Penman-Monteith-Temperature (*PMT*) method. In the *PMT* method, daily solar radiation was estimated with the Hargreaves equation and the *ET* was estimated with the FAO-56 PM equation. Accurate daily estimate of solar radiation by the Hargreaves equation has been reported (Hargreaves and Allen, 2003). The *PMT* method has been evaluated by Raziei and Pereira, (2013) and Todorovic et al., (2013) and others; they found that the method gave reasonable results when compared with observed *R_s* data.

8.5.4 Future changes in irrigation water requirements

Tables 8.2 and 8.3 show the baseline (1961-1990) and projected (2040-2069) mean temperature and solar radiation, respectively. The variation in the predicted irrigation water requirements for the three scenarios (A1, A1B and A2) ranged from 39 to 67% (Figure 8.7). Future IWR for bell peppers is expected to increase by 19 to 27%.

Table 8.2: Baseline and projected mean temperature

Growing months	Baseline ^y meanT	Projections 2040-2069		% change from baseline	
		CGCM3 A1B	CGCM3 B1	CGCM3 A1B	CGCM3 B1
May	12.9	16.1	16.0	25.4	24.0
June	18.0	20.8	20.5	15.6	14.0
July	20.7	23.8	23.3	14.8	12.5
August	19.2	22.6	21.9	17.4	13.9
September	14.5	17.6	16.8	21.6	15.9
October	8.3	10.9	10.5	30.9	26.1
		Average		20.9	17.7

^yBaseline=1961-1990, mean T=mean temperature, CGCM=coupled global climate models

Table 8.3: Baseline and projected solar radiation

Growing months	Baseline ^y	Projections 2040-2069			
		% change from baseline			
		CGCM3			
	R_s	A1B	CGCM3 B1	CGCM3 A1B	CGCM3 B1
May	20.3	19.3	19.7	-5.1	-3.1
June	22.1	22.6	22.5	2.2	1.8
July	21.9	23.3	22.8	6.4	3.9
August	18.4	19.0	19.1	3.6	4.1
September	14.0	14.9	14.2	6.3	1.4
October	9.2	9.6	9.2	4.4	0.1
		Average		3.0	1.4

^yBaseline=1961-1990, CGCM = coupled global climate models

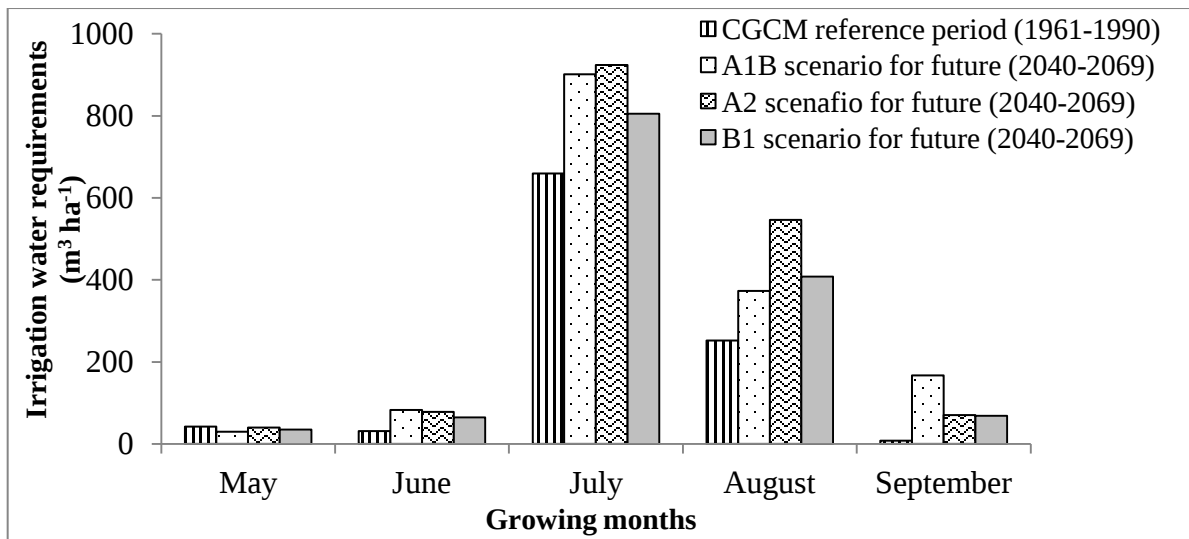
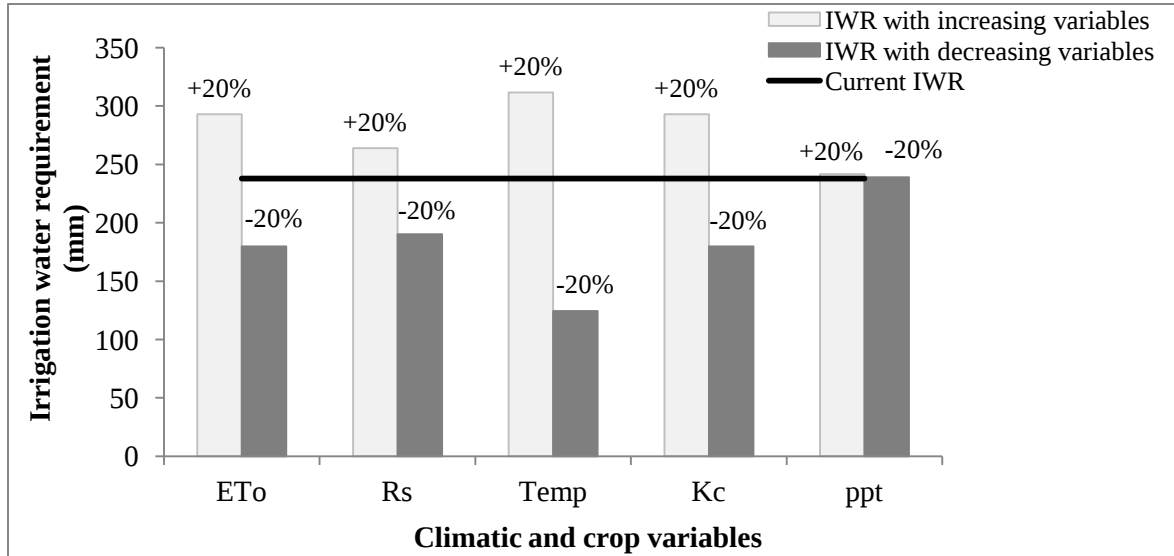


Figure 8.3: Future irrigation water requirements of bell pepper

8.5.5 Sensitivity of irrigation water requirements to climatic inputs

The sensitivity of irrigation water requirements to evapotranspiration (ET_o), solar radiation (R_s), temperature, crop coefficient (K_c) and precipitation is shown in Figure 8.8. A 20% increase in all of these variables resulted in 13 to 45% deviation in IWR. The highest deviation is caused by temperature, while ET_o and K_c had the same effect on IWR, followed by R_s and

precipitation. A 20% decrease in the variables caused 0.4 to 48% deviation in IWR; the highest change in IWR was caused by temperature and the lowest deviation by precipitation. Temperature and precipitation data are widely available in weather stations but R_s , K_c and ET_o are not often available, therefore have to be estimated.



ET_o -reference evapotranspiration, R_s -solar radiation, Temp-temperature, K_c -crop coefficient, ppt-precipitation

Figure 8.4: Irrigation water requirements with increasing and decreasing variables

8.6 Conclusions

Current and future irrigation water requirements for bell peppers were determined using soil water moisture sensors and an integrated agricultural water demand (IAWDM) model. IWR outputs from IAWDM were compared with CROPWAT. The percentage deviation between the measured IWR and IAWDM was 7 to 28%. The developed model output was in closer agreement with the measured IWR than CROPWAT. The sensitivity of the model to key inputs showed that IWR is most and least sensitive to temperature and precipitation, respectively. The IWR for bell peppers is expected to increase by 19 to 27% in the future. More accurate crop coefficient, solar radiation data and the use of variable aerodynamic constant for modelling Penman Monteith calculated evapotranspiration for plants under limiting water condition will help to improve the accuracy of irrigation water requirements.

Chapter 9 General summary and conclusions

9.1 Summary

Optimizing limited water resources is the challenge currently facing irrigated agriculture. To ensure that adequate water is available for crops on the farm, methods of allocating water and estimating crop water requirements must be accurate. The allocated water must be judiciously used and the process of applying water to the crops must be based on crop water needs. Irrigation decisions should achieve optimal crop production (high yield, good quality and high water use efficiency). This task requires a decision support system for more effective irrigation water allocation, application and optimisation. The system will be highly beneficial for the production of high value horticultural crops in Canada. In this context, this study provided a decision tool to assist irrigators and water managers in determining the reference evapotranspiration (ET_o) (using locally calibrated coefficients for solar radiation (R_s) estimation), crop water requirements, irrigation water requirements and irrigation scheduling for more effective water allocation and application. The integrated agricultural water demand model (IAWDM) presented in this study, unlike most existing models, uses plant water status monitoring as an adjunct to climatic parameters and soil moisture measurements for irrigation scheduling. The irrigation water requirements determined with this model were validated with two years of field studies in southern Quebec using bell peppers as a test crop. The future irrigation water requirements for bell peppers were also determined using climate change scenarios *A1*, *A2* and *A1B*. Overall, the present study comprised an evaluation of estimation methods for improving R_s and ET_o , field and greenhouse studies for crop production optimisation and the development of a computer model for managing irrigation.

This study evaluated the accuracy of nine currently used solar radiation (R_s) estimation models and their effects on reference evapotranspiration (ET_o) using the FAO-56 Penman-Monteith equation and data from eight meteorological stations from six Canadian provinces for the purpose of improving the accuracy of estimated crop water demand and irrigation requirements. Field studies were carried out to determine the effect of an available water content threshold (AWC_t) of 85% (T_1), 75% (T_2), 50% (T_3), 25% (T_4) and no irrigation (T_5) on fruit yield and quality, water use efficiency and irrigation water use efficiency. Thresholds for

the crop water stress index (*CWSI*) were also assessed for field grown bell peppers under clay soil in southern Quebec, Canada. In addition, greenhouse experiments were conducted over two years to investigate stomatal response and the crop water stress index (*CWSI*) for bell peppers grown on clay and on loamy sand soil. Furthermore, the effects of irrigation levels, soil types and their interactions on yield, irrigation water use efficiency (*IWUE*) and water use efficiency (*WUE*) of bell peppers were evaluated.

Finally, a decision support model to assist water managers and irrigators make irrigation water allocation and scheduling decisions was developed using a graphical user interface (GUI) in Matlab. The main attribute of the developed model (IAWDM) is that it calculates ET_o with locally calibrated R_s coefficients. Furthermore, the irrigation schedule component is based on either, the water balance approach, or the soil moisture sensor reading, or a combination of both. *CWSI* was determined from the plant water status monitoring. Data from the bell pepper field studies was utilized to calibrate and verify the model.

9.2 Conclusions

Objective 1 Evaluate the suitability of solar radiation estimation methods and their effect on reference evapotranspiration (ET_o) estimation in Canada

The suitability of nine models to estimate R_s and their effect on the ET_o computed with FAO-56 PM was evaluated using data from eight weather stations in Canada. Most accurate R_s estimates (based on *RMSE*) were obtained when A-P coefficients were calibrated in Ottawa (Ontario), Summerland (British Columbia), Winnipeg (Manitoba), Swift Current (Saskatchewan) and Toronto (Ontario). R_s estimated were not significantly different from measured R_s , therefore, it might not be necessary to calibrated A-P coefficients in these locations. K_{RS} coefficient of 0.15 gave R_s estimates that were more accurate than the A-P methods in Beaverlodge (Alberta) and Elora (Ontario) study sites. Mahmood and Hubbard (M-H), Bristow and Campbell (B-C), and Self calibrating (S-C) models performed poorly for all stations. In the absence of sunshine data, Hargreaves and Samani (*H-S*) should be used for R_s estimates in Montreal, Beaverlodge, Winnipeg and Swift Current, while the Samani model is recommended for Ottawa and Summerland.

Objective 2 Investigate the effect of irrigation levels and soil types on yield, water use efficiency of greenhouse bell pepper and determine the crop water stress index (CWSI) baselines

The highest marketable yields were achieved in the greenhouse with peppers grown in loamy sand and irrigated at 120% replenishment of crop evapotranspiration (T_{120}). The highest yield and water use efficiency were obtained with a CWSI of 0.18 to 0.20 for a clay soil, and 0.09 to 0.11 for a loamy sand. The CWSI limits beyond which there might be a crop yield loss for clay were 0.47 to 0.50 and 0.30 to 0.48 for loamy sand. These values serve as reference baselines for bell peppers under similar conditions as the two soils in this study. The correlations between CWSI, water applied, yield and stomatal conductance were highly significant (0.88-0.98) and the correlation equations derived were different for the various soil types. The results also demonstrated the necessity for emphasizing soil type in determining CWSI reference values for each crop.

Objective 3 Determine an optimum irrigation schedule and CWSI baselines for timing irrigation in the field

The highest marketable yield for field grown peppers was obtained at the available water content threshold (AWC_t) of 85% (T_1) with averages of 20.9 Mg ha⁻¹ and 21.5 Mg ha⁻¹ for 2011 and 2012, respectively. The optimum marketable yields (21.3 and 20.4 Mg ha⁻¹ in 2011 and 2012, respectively) were achieved for irrigated bell peppers at T_3 (50% AWC_t), when 50% of available soil water content (AWC) has been depleted. The optimum marketable yields were not significantly ($P < 0.05$) different from the maximum yield obtained from T_1 (irrigated when 15% of the AWC was depleted and received the highest amount of water). This revealed that frequent irrigation at a threshold of 85% AWC_t (T_1) and 75% AWC_t (T_2) did not improve the yield. CWSI values obtained (0.30-0.40 were determined for T_3 as compared to 0.1 to 0.2 obtained for T_1) showed that initiating irrigation on clay soil when the CWSI value is at 0.3 to 0.4 lead to an average of 50% savings in water. On the other hand, permitting the seasonal mean CWSI values to exceed 0.65 values would result in decreased yields. Also, the highest water use efficiency and firmness obtained from T_3 (50% AWC_t) indicated that T_3 would be the most profitable for a grower to achieve higher economic returns.

Objective 4 Evaluate the effect of fixed and varied surface resistance and elevated CO_2 , on bell pepper water requirements

Crop evapotranspiration (ET_c) decreased from 6 to 42% at an elevated CO_2 of 550 ppm, and from 28 to 58% for a CO_2 of 750 ppm. The ratios of surface to aerodynamic resistance factors (r_s/r_a) derived from stomatal conductance of peppers grown with 85 (T_1), 75 (T_2), 50 (T_3), 25% (T_4) available soil water content (AWC) and no irrigation (T_5) were (0.30, 0.46, 0.52, 0.70 and 0.80). It was observed that the fixed FAO-56 Penman Monteith r_s/r_a factor (0.34) could simulate irrigation requirements when water was not limiting in the bell pepper plant, as is the case for 85, 75, 50% AWC. Whereas, at 25% AWC, the percent deviation from field measured irrigation requirement was reduced from 28 to 8%, when a variable ratio (r_s/r_a) of 0.7 was used.

Objective 5 Development of an integrated climatic/crop physiological based irrigation management model for water allocation

An integrated agriocultural water demand model (IAWDM) was developed to estimate irrigation water requirement (IWR). The IAWDM uses locally calibrated reference evapotranspiration equations, and plant physiological parameters which is a better and more direct method for irrigation scheduling. The model's focus is on Eastern Canada, but it may also be used for other locations where input data are available. The percent deviation between the measured IWR and IAWDM was 7 to 28%. IAWDM performance was 7-42% better than CROPWAT, indicating that the model is reasonably accurate in predicting the amount of water required to meet crop needs. A sensitivity analysis of IWR showed that temperature and precipitation is most and least sensitive, respectively. Future irrigation water requirements (2041-2070) of bell peppers were estimated using climate change scenarios obtained from a General Circulation Model (GCM) statistically downscaled using the weather generator approach of Agriculture and Agri-Food Canada (AAFC-GCM), Canadian Regional Climate Change Model (CRCM v 4.2) and Hadley Model (HADCM3) generated by the Ouranos Climate Change Simulation Team. The IPCC SRES A2, A1B and B2 scenarios were considered. Temperature, rainfall and R_s data generated from these models were input into the IAWDM, to quantify the effects of climate variability on bell pepper plant water use and

irrigation water requirements. Outputs from the AAFC-GCM, CRCM and Hadley Models as well as the IPCC SRES A2, A1B and B2 were compared to assess variability in the future climate predictions. Future IWR of bell peppers is expected to increase by 19 to 27%. The variation in the predicted irrigation water requirements for the three scenarios ranged from 39 to 67 % while the AAFC-GCM was found to outperform the other models.

9.3 Contributions to knowledge

This research contributed the following to scientific knowledge:

1. Coefficients for solar radiation (R_s) empirical methods and their effect on ET_o estimation

Hargreaves and Samani (H-S) method is the best alternative method for estimating solar radiation (R_s) in Canada when observed R_s and sunshine data are lacking. A determined $H-S$ coefficient (k_{RS}) coefficient of 0.15 (outside the range proposed by Hargreaves and Samani, (1985) gave R_s estimates that were more accurate than the A-P methods at Beaverlodge (Alberta) and Elora (Ontario) study sites.

2. Optimum irrigation schedule and crop water stress index (CWSI) thresholds for producing peppers in the greenhouse

Water application at 120% crop evapotranspiration produced the highest marketable yield and irrigation water use efficiency. $CWSI$ of bell pepper on loamy sand and clay soil were determined.

3. Available soil water content threshold (AWC_t) and crop water stress index (CWSI) baselines for irrigation timing in the field

The study identified the optimal irrigation strategy for producing field grown bell pepper on clay soil in southern Quebec. Irrigating at 50% of AWC_t resulted in the highest irrigation water use efficiency. The $CWSI$ baselines were also established.

4. Varied ratio of surface to aerodynamic resistance (r_s/r_a) and impact of change in CO_2 on irrigation water requirements.

Varied aerodynamic constant (r_s/r_a) increased the accuracy of the irrigation water requirements for bell pepper under water limiting conditions by 20%. Bell pepper's evapotranspiration will decrease by 6 to 42% under elevated CO_2 of 550 ppm and at 750 ppm, will decrease by 28 to 58% based on water applications ranging from 85% of available soil water content to no irrigation.

5. Integrated climatic/plant physiological based irrigation management model for water allocation/application

The IAWD model developed under this research simulated irrigation water requirements more accurately than the widely used CROPWAT model. The use of weather data, soil moisture sensor data, and crop water stress index allows more precise timing of irrigation. The model provided a comprehensive irrigation management protocol for the production of bell peppers in southern Quebec and other regions. The model has a wider application and transferability than other models developed for a specific region in Canada.

9.4 Recommendations for future research

1. Spatial interpolation of solar radiation and mapping of ET_o for accurate estimation of crop water requirements

Global solar radiation (R_s) is one of the most important parameters affecting the accuracy of evapotranspiration estimation. R_s data is not available in many parts of Canada. Empirically estimated R_s data, or data from neighbouring stations, are often used. But, R_s vary in space and time, causing variability in ET , crop water and irrigation requirements. The accuracy of using empirically estimated R_s or data from neighbouring stations has to be evaluated considering that R_s might be influenced by distance and topography. Considering the extensive vegetable irrigation activities in Ontario, British Columbia and Quebec, accurate quantification of ET is necessary for proper design of irrigation systems. Thus, ET_o mapping in these major vegetable regions will provide a database for water users and managers, decision makers, and

policymakers to better allocate water resources and develop water resources management strategies for enhancing vegetable crop water productivity.

2. Irrigation scheduling using the crop water stress index (CWSI)

It has been established that as water becomes limited, the canopy temperature of crops relative to air temperature will increase due to the lack of water for transpiration. Studies should be conducted using the canopy-air temperature difference ($T_c - T_a$) method in conjunction with the use of soil moisture sensors, or the water balance method, for irrigation scheduling of bell peppers.

3. Determination of CWSI for major vegetables produced on predominant soils in Canada

The critical threshold value of *CWSI* should be determined for a particular crop in different climates and soils before it can be used effectively for yield prediction and irrigation scheduling. There is a need to validate the *CWSI* baselines determined for bell peppers grown on different types of soil under field conditions. Developing empirical and theoretical *CWSI* baselines for bell peppers and comparing the consistency of the *CWSI* values predicted by the empirical and theoretical approaches, as well as their relation to soil water and climatic variables, will help to determine the variation and the level of confidence in these methods.

4. Improvement to the IAWDM Model

There is no universally applicable irrigation demand model, because each model is developed based on the availability of data in the location where it is developed. Irrigation decisions are better made at the local level with site specific needs. Further research is needed for parameter estimation for major crops and predominant soils and model calibration and verification in combination with field tests in other agricultural zones. Model improvements can focus on interlinking plant measurement and soil moisture measurements, and receiving water stress alerts on the go. The model can be further improved by incorporating parameters such as crop varieties and detailed cropping patterns and thus, increasing its reliability to predict yield. There is a need to also expand the model to estimate irrigation water required for more than one crop.

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Appendix

Development of an integrated agricultural water demand model (IAWDM)

Summary

An irrigation scheduling model consisting of a database management system, model base and graphical user interface (GUI) was developed for performing irrigation scheduling. The GUI is an approach with pop-up windows, pull-down menus and button controls. The model is a crop-water-demand model that uses a daily soil water balance, soil moisture measurements to estimate the water needs of a crop on a given day based on climate, soil, and plant properties. The model also uses a plant-water status; crop water stress index (*CWSI*) to determine when to irrigate. *CWSI* has not been given much attention because of its inability to function as a stand-alone tool for scheduling irrigation. However the use of *CWSI* as an adjunct to other irrigation scheduling methods is beneficial for effective irrigation management. The model was developed using bell pepper as a test crop. The model takes into account the rainfall, irrigation infiltration and plant water uptake processes. The model should be applicable to other crops, soils and climate conditions as long as specific and local data are provided.

1.0 Introduction

In agricultural water management, significant improvements can be achieved through irrigation scheduling (George et al., 2000). Irrigation scheduling deals with two questions, when and how much to irrigate a crop. Quantitative irrigation scheduling methods are based on three approaches, namely, crop monitoring, soil monitoring and water balance technique. Soil water balance based irrigation scheduling models use soil water budgeting over the root zone. A number of computerized simulation models, (Smith, 1991; George et al., 2000) for crop water requirements have been developed using this approach. However there is no universal agriculture or irrigation water demand model. Furthermore none of the available models included the use of plant water status monitoring i.e crop water stress index (*CWSI*) in the irrigation scheduling process.

CWSI is a plant water status indicator that has been tested in a number of crops. However, climate, soil and crop cultivar could influence *CWSI*. *CWSI* and soil water sensors have

thresholds for scheduling. This threshold has to be established for crops before it can be included into an integrated irrigation management model. Thus, the use of *CWSI* as an adjunct to other irrigation scheduling methods has the potential for improving irrigation water management.

Reference evapotranspiration (ET_o) requires maximum and minimum temperatures, rainfall, solar radiation or number of sunshine hours, relative humidity and wind speed. The main feature of this component is that it calculates ET_o with locally calibrated R_s coefficients. The irrigation schedule component of the model is based on the water balance method and soil water measurements and/or plant water status monitoring. This User's Guide provides directions on the calculations that are made by this model and explains how to select the information that populates the entry boxes. The integrated agricultural water demand model (IAWDM) model was developed in Matlab, version 2013a using a Graphical User Interface (GUI). The model was designed to be user friendly and run in MS Windows. The flowchart of the model is presented in (Figure 1), and Figure 2 presents the front page of the model. IAWDM allows the user to enter either measured ET_o values or to input the climatic data stated in the flowchart (Figure 1); then, the model calculates ET_o in order to estimate crop water demand, using four different equations, namely, FAO-56 Penman-monteith, Hargreaves, Turc and ASCE, two radiation (R_s) estimation methods, Hargreaves and Angstrom-Prescott (*A-P*) and two effective rainfall methods - 80% of total precipitation (Smith, 1992) and Nyvall and Tam (2005) method. The model also determines irrigation demand using a combination of climate data, soil moisture measurements and plant water status. R_s coefficients, using Hargreaves K_{RS} and *A-P* "a" and "b" coefficients have been calibrated for eight locations in six provinces across Canada and these were incorporated into the model. However, users can enter their *A-P* and Hargreaves coefficients or use the FAO recommended values.

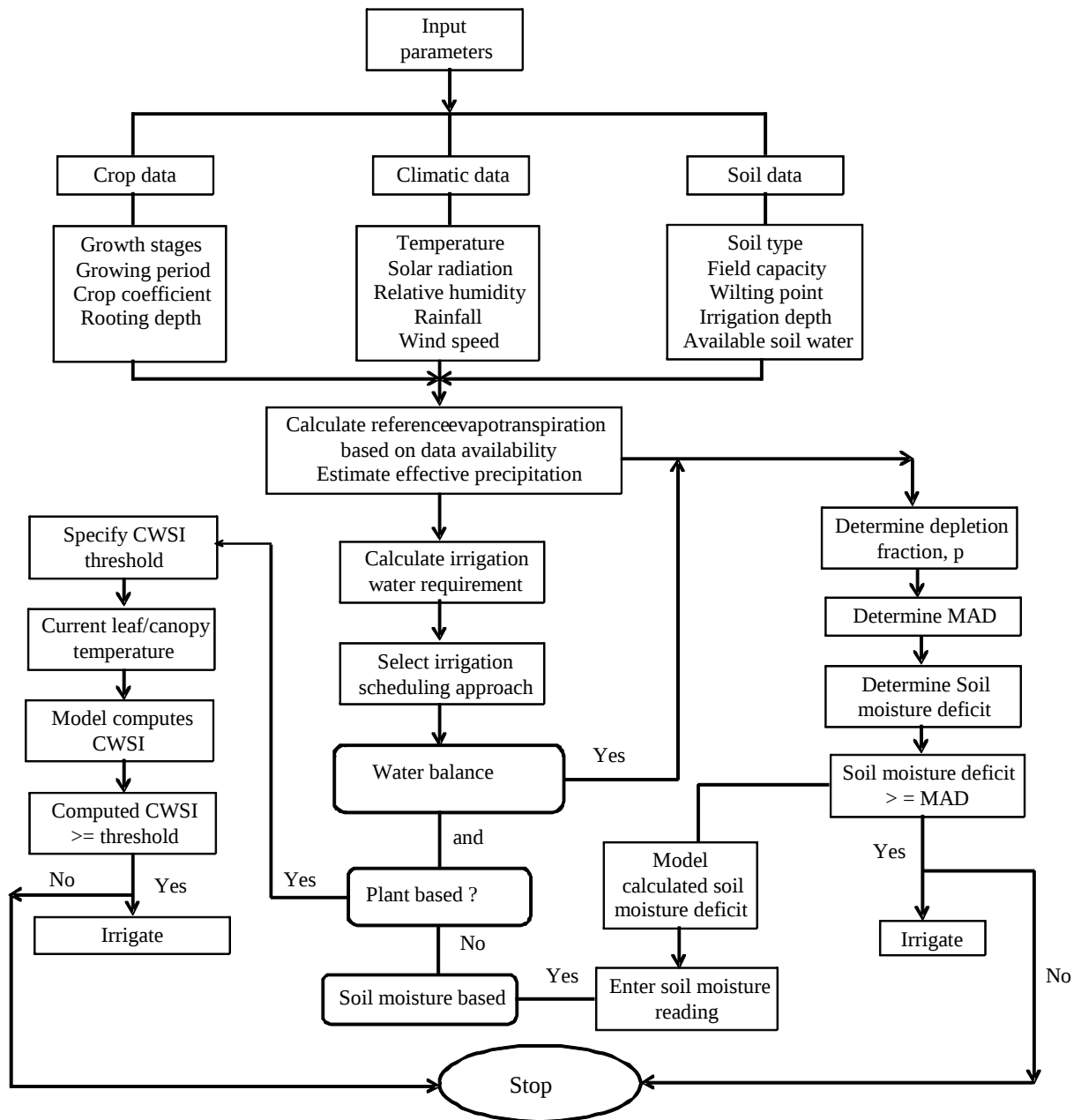


Figure 1: Model flowchart

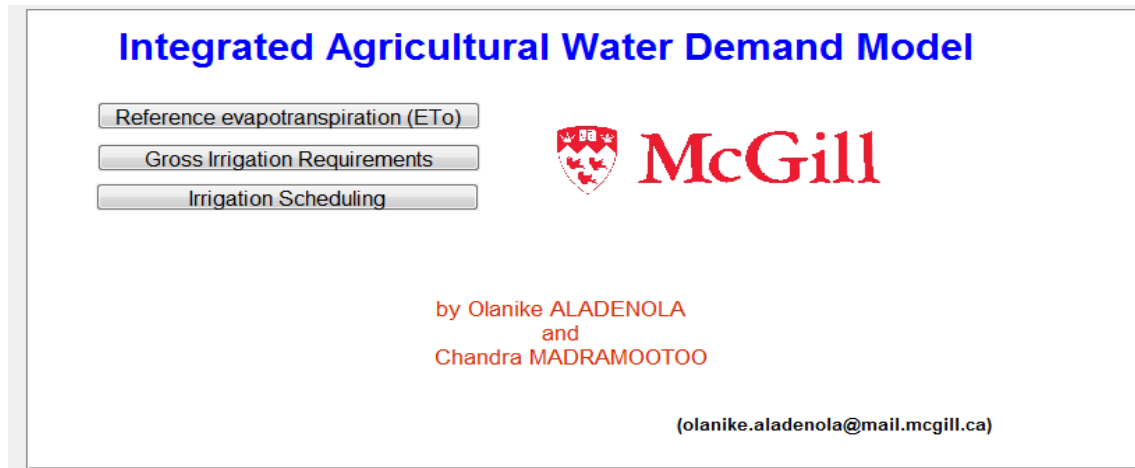


Figure 2: Model front page

2.0 Model calculations

Three sections of the model must be completed to develop a schedule. These are: ET_o , crop water demand and irrigation scheduling. The sequence of calculations is as follows :

Reference evapotranspiration (ET_o)

The model is designed to first calculate ET_o using a combination or any of FAO-56 Penman Monteith, Turc, Hargreaves and American society of civil engineers (ASCE) equations (Eqs. 1 to 4). ET_o can be calculated on a monthly or daily basis (Figure 3). Six locations with their climatic parameters, namely, the monthly and daily average of 30 years, from 1971-2000 obtained from environment Canada, have been built into the model but the user can specify a different location. The user can select any, or all, of the four ET_o equations, but only one of the R_s methods (Hargreaves or Angstrom-Prescott method (A-P)) can be used at a time. The A-P coefficients have been locally calibrated for the six stations in this study but the default is the FAO recommended values of $a=0.25$, $b=0.50$ and $K_{RS}=0.16$. The user may choose to use the default A-P and Hargreaves coefficients or enter locally calibrated values. There is also an option to calculate ET_o should there be an increase in CO_2 concentration as a result of climate change. The effect of elevated CO_2 was quantified and was used to determine stomata resistance (r_s) for the computation of ET_o using FAO-56 PM or ASCE methods. The import button imports climatic data from the excel sheet in the ET_o folder; however, the user will have to copy and paste his own data into the excel sheet. ET_o values are shown in the tables

and graphs on the interface. In addition, the calculated ET_o will be exported to the output sheet in the ET_o folder.

(a) FAO-56 PM method

The Penman Monteith equation was modified by FAO and hereafter referred to as the FAO-56 Penman Monteith (FAO-56 PM) equation. This method uses the concept of a reference surface/combination approach to calculate ET_o (Eq. 1). ET_o is determined for a hypothetical reference crop which closely resembles an actively growing grass surface of uniform height with adequate water and completely shading the ground. The surface has an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen et al., 1998; Droogers and Allen 2002).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} u_2\right)} \quad [1]$$

Where, ET_o : reference evapotranspiration (mm d^{-1}), R_n : net radiation at the crop surface ($\text{MJ m}^{-2} \text{ d}^{-1}$), G : soil heat flux density (taken as zero for daily calculations) ($\text{MJ m}^{-2} \text{ d}^{-1}$), T : mean daily air temperature at 2m height ($^{\circ}\text{C}$), u_2 : wind speed at 2 m height (m s^{-1}), r_s , r_a : (bulk) surface and aerodynamic resistances (s m^{-1}), e_s : saturation vapour pressure (kPa), e_a : actual vapour pressure (kPa), $e_s - e_a$: saturation vapour deficit (kPa), Δ : slope vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ : psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

(b) ASCE (tall reference) method (ASCE Penman Monteith equations)

This method was developed by defining ET_o as the rate of ET from a uniform surface of dense, actively growing vegetation that is not short of water and represents an expanse of at least 100 m (ASCE 2005). This equation is physically based and provides a consistent and standardized definition of reference evapotranspiration for a tall reference surface.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{1600}{T + 273}\right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.38u_2)} \quad [2]$$

Where the parameters are as defined in FAO-56 equation (Eq. 1).

(c) Hargreaves and Samani equation

A major limitation to the use of *FAO 56* and *ASCE PM* equations is the requirement for detailed climatic data, some of which are estimated from other measured climatic parameters which might be of questionable quality. Hargreaves and Samani (1985) developed a model which used only the commonly measured temperature data. This model was adopted by *FAO* based on previous studies that assessed the performance of *ET* temperature methods (Jensen et al., 1990). The result of the assessment showed that ET_o can be estimated using the empirical Hargreaves–Samani (*H-S*) equation in areas where R_s or sunshine hours is not available (Allen et al., 1998, Hargreaves and Allen 2003).

$$ET_o = 0.408 * 0.0135R_s(T_{mean} + 17.8) \quad [3]$$

Where, T_{mean} : mean temperature calculated as $(T_{min} + T_{max})/2$, T_{min} : minimum temperature, T_{max} : maximum temperature, Coefficient 0.408 converts from $\text{MJ m}^{-2} \text{ day}^{-1}$ to mm day^{-1} , K_{RS} : empirical coefficient.

(d) Turc method

The Turc model (1961) was developed in the Netherlands and has been used to some extent in the United States (e.g., Amatya et al., 1995; Irmak et al., 2003b). This equation was chosen because it has been found to compare well with *FAO-56* in humid areas, although it does not consider the effect of wind speed (Irmak et al., 2003b; Nandagiri and Kovoov, 2006).. Turc's equation was defined for use by Allen (2003) as:

$$ET_o = a_T 0.0133 \left(\frac{T_{mean}}{T_{mean} + 15} \right) 23.886R_s \quad [4a]$$

Where, ET_o : reference crop evapotranspiration (mm d^{-1}), T_{mean} : mean air temperature ($^{\circ}\text{C}$), R_s : solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$).

The coefficient a_T is a humidity-based value. If the mean daily relative humidity (RH_{mean}) is greater than or equal to 50%, then $a_T = 1.0$. If the RH_{mean} is less than 50%, then a_T has the value:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \quad [4b]$$

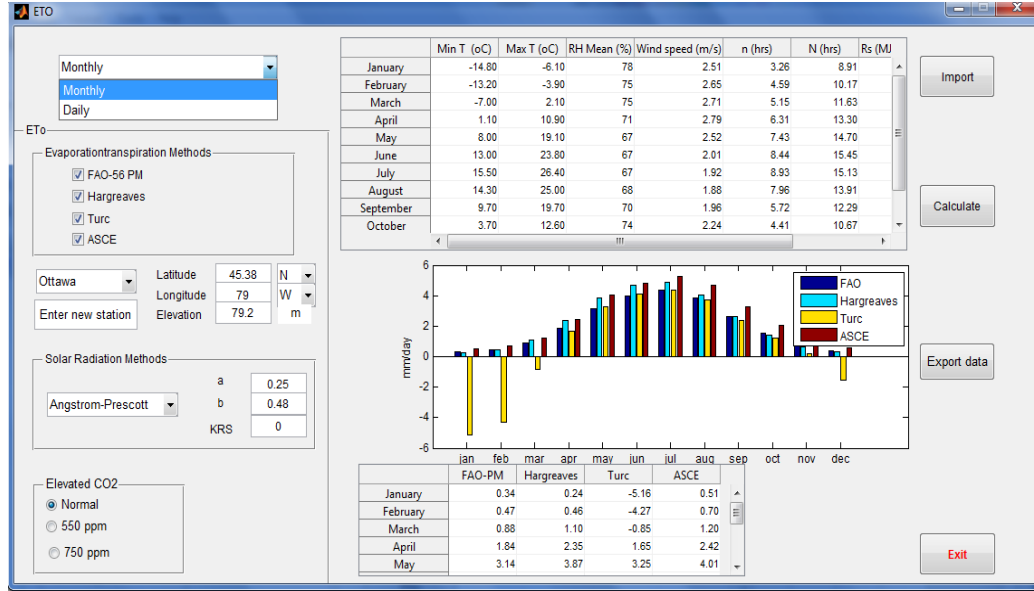


Figure 3: ET_o interface

2.1 Crop water demand

The crop water demand is computed from the reference evapotranspiration (ET_o, mm d⁻¹) and the crop coefficients (K_c). IAWDM calculates the ET_o while the user has to enter the K_c based on the location and type of crop.

$$ET_c = K_c \times ET_o \quad [5]$$

Crop coefficient (K_c)

The concept of K_c was introduced by Jensen (1968) and further developed by other researchers (Doorenbos and Pruitt, 1977; Burman et al., 1980a, 1980b; Allen et al., 1998). K_c represents an integration of the effects of three primary characteristics that distinguish the crop from the reference crop. These characteristics are: crop height (affecting roughness and aerodynamic resistance); crop- soil surface resistance (affected by leaf area, the fraction of ground covered

by vegetation, leaf age and condition, the degree of stomatal control, and soil surface wetness); and albedo (reflectance) of the crop-soil surface, affected by the fraction of ground covered by vegetation and by the soil surface wetness (Allen et al., 1998).

Gross irrigation water requirements

When the model is run, crop evapotranspiration (ET_c) and rainfall are used in every in-season, time-step; these values are then used to calculate the crop water requirement that is not satisfied by natural rainfall and to calculate the trigger date for the start of irrigation. This model calculates crop water requirements by calendar year (Jan – Dec). The user will click the `load` button to import the precipitation and ET_o (previously calculated or entered) in the model's database. The user has to select one of the two effective rainfall methods in the model. (Eqs. 6 and 7).

Effective precipitation methods

Percentage method

A simplified daily or monthly method for determining effective precipitation is to multiply the rainfall (precipitation) by a user-specified percentage. Smith (1992) assumed that rainfall values below 100 mm/month will have an efficiency of approximately 80%.

Nyvall and Tam

Effective rainfall as used in this study 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 (Nyvall and Tam, 2005). It is suggested the remaining precipitation ($R - 5$) should be multiplied by a factor of 0.75 to account for runoff and deep percolation losses.

$$P_e = (R - 5) * 0.75 \quad [7]$$

Where, P_e : effective rainfall (mm), R : rainfall (mm).

The rooting depth, crop coefficient and duration per growing stages have to be specified by the user and the model will estimate the depth of water to be applied daily (based on the

irrigation practice adopted), daily crop water demand and gross irrigation requirements per month (Figure 4).

Gross_Irrigation_Water_Requirements

Precipitation

	Jan	Feb	Mar	Apr	May	June	July	Aug	S
Precipitation (mm)	64.19	54.64	64.94	67.75	81.02	91.21	88.92	87.57	
ETo (mm/d)	0.34	0.47	0.88	1.84	3.14	3.95	4.36	3.84	
Effective Rainfall (mm)	44.39	37.23	44.95	47.06	57.02	64.66	62.94	61.93	

Field Conditions

Soil Type: Clay

SWC (Field Capacity) mm: 0.47

SWC (Wiltting Point) (mm): 0.36

Total available water (mm): 0.11

p-threshold: 0.5

Irrigation Efficiency: 0.75

Area/plot (sq. m): 4

Length (m): 2.5

Width (m): 1

No of plots: 1

Crop type: Bell pepper

Crop Conditions

	Rooting Depth (m)	Length of Growth Phase	Kc
Initial	0.1	20	0.5
Development	0.2	30	0.78
Middle	0.3	35	1.03
End	0.5	30	0.88

Irrigation requirements

	Decade	ETo (mm/decade)	ETc (mm/decade)	IWR (mm/decade)
June	1	0	0	0
	2	39.6	19.8	0.5
	3	41.5	20.7	0
July	1	43.6	34.0	21
	2	43.9	34.3	15
	3	43.2	33.7	15

Total IWR (m3/season): 1.5

Buttons: Exit, Clear, Calculate

Figure 4: Crop water demand and gross irrigation water requirements interface

2.2 Irrigation scheduling

The model compute the net crop irrigation requirements, generate an irrigation scheduling using user selected irrigation thresholds, including the frequency of irrigation water application. This model has three irrigation scheduling approaches: water balance, soil moisture monitoring and plant water status monitoring. The water balance approach is the default and can be used either independently, or in conjunction with, soil moisture or plant based approaches (Figure 5).

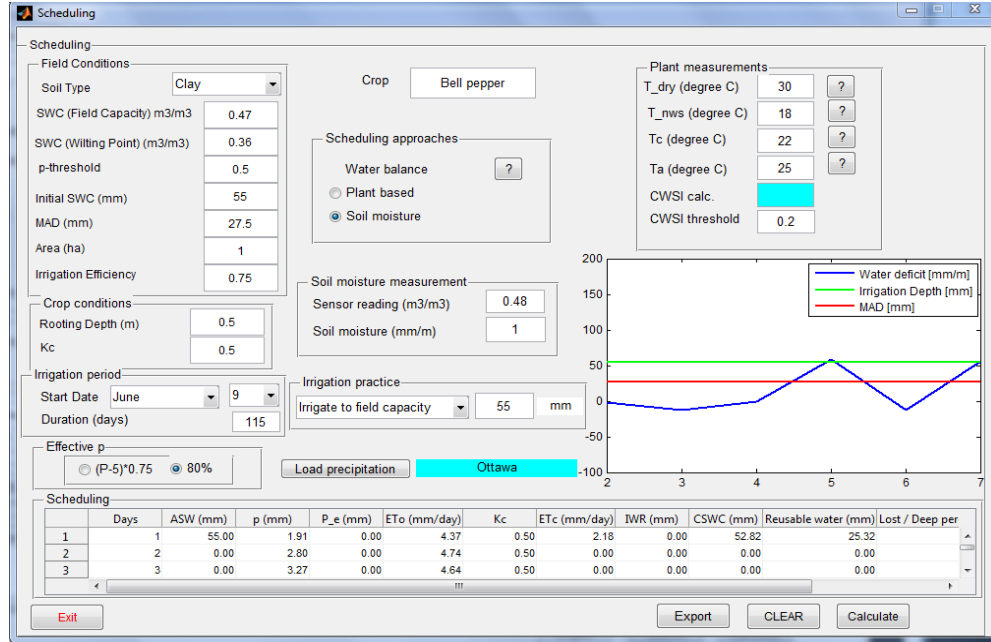


Figure 5: Irrigation scheduling interface

Water balance approach

Input data include precipitation, reference evapotranspiration, total and readily available soil water, soil water content at planting, potential groundwater contribution, crop coefficients and soil water depletion, crop growth stages and root depths. The model performs the water balance computation for a single layered soil according to the methodology in two ways: the field's soil water depletion status is estimated for each day using the data the user enters for each day; otherwise, the "load" button will import the precipitation data and ET_o (that would have been computed previously using this model) from the database. The first precipitation and ET_o data in the database have to be the data for the first day of the growing season. For instance, if the growing season starts on May 14, the user will enter the ET_o and precipitation data or compute ET_o data from May 14. Water balance provides the current soil water status (CWSI), reusable water and days until the next irrigation (Figure 5). By clicking on the "clear" button, all previously computed values on the interface will be deleted.

Current soil water status (CWSI) is calculated as:

$$\theta_i = \theta_{i-1} + \frac{p_{e,i} - RO_i + I_{rr} - (ET_o * k_c) - DP}{1000 Z_{r,i}} \quad [8]$$

where θ_i and θ_{i-1} are soil water content in the root zone ($\text{m}^3 \text{ m}^{-3}$), in the current (i) day and previous (i-1) day, $P_{e,i}$ is the effective precipitation (mm), RO_i is the runoff (mm), I_{ir} is the net irrigation depth (mm) that infiltrates the soil, ET_{oi} is the reference evapotranspiration (mm), K_c is the crop coefficient, $Z_{r,i}$ is the rooting depth (m) in day i and DP_i represents deep percolation (mm). This model assumes that any water input in excess of field capacity will runoff.

The irrigation threshold to avoid water stress will be specified by the user, irrigation thresholds according to the soil water depletion fraction for no stress (management allowable depletion, $MAD = \text{fraction of total available water, } p$). The default for irrigation depth in this model (IAWDM) is the field capacity, but the user can specify or fixed the depth. The corresponding irrigation depth is calculated as:

$$I_{ni} = 1000 Z_{r,i} (\theta_{FC} - \theta_{PWP}) \quad [9]$$

Where θ_{FC} and θ_{PWP} are soil water content at field capacity and wilting point ($\text{m}^3 \text{ m}^{-3}$) respectively

Net irrigation water requirement is calculated as:

$$IWR = ET_c - P_e - RO - \Delta S \quad [9]$$

where ET_c is crop water demand (mm, calculated as $ET_o \times K_c$), P_e is the effective precipitation (mm), ΔS is the cumulative variation of the soil water storage, and RO is the runoff. The gross irrigation water requirement is computed as:

$$GIWR = \frac{IWR}{I_{eff}} \quad [10]$$

Where I_{eff} is the irrigation efficiency, specified by the use depending on the irrigation system.

Irrigation is scheduled when the user defined management allowable depletion (MAD) is attained.

Soil moisture monitoring

The irrigator will enter the soil moisture reading on a daily basis and the percentage of soil moisture available will be determined by the model. This will enable the irrigator to know the quantity of water to be applied to bring soil moisture to field capacity, or to a fixed depth, depending on the choice of irrigation practice. The model contains graphing routines that will visually show the estimated percentage of soil moisture on a daily basis. The soil water deficit of the root zone is calculated as:

$$SWD = (\theta_{FC} - \theta) * Z_r * 1000 \quad [11]$$

Where SWD : soil water deficit of root zone (mm), θ_{FC} : volume of water at field capacity ($m^3 m^{-3}$), θ : current soil water content reading ($m^3 m^{-3}$), Z_r : rooting depth, m.

Plant water status monitoring

Crop water stress index ($CWSI$) indicates when it is time to irrigate. It is computed based on ambient temperature and leaf or canopy temperature of the crop (Eq. 12, Figure 6); the user enters this data daily. The default $CWSI$ value is 0.2-0.4 for bell peppers. When the $CWSI$ value on a given day is between 0.2 and 0.4 (this value can be changed depending on the crop type and cultivar), the grower should irrigate with an amount of water that is appropriate given the crop water demand (ET_c) calculated by the grower on the basis of daily water balance measurements. Knowing the ET_c is essential for determining the amount of water to be applied at the next irrigation and will help the irrigator to avoid problems associated with under- and over-irrigation. Clicking the “?” beside the temperature values shows the user what the acronyms represent.

$$CWSI = \frac{[(T_c - T_a) - (T_{nws} - T_a)]}{[(T_{dry} - T_a) - (T_{nws} - T_a)]} \quad [12a]$$

Where T_c : canopy temperature ($^{\circ}C$), T_a : air temperature ($^{\circ}C$), T_{nws} : non-water stressed canopy temperature ($^{\circ}C$), T_{dry} : water-stressed canopy temperature ($^{\circ}C$).

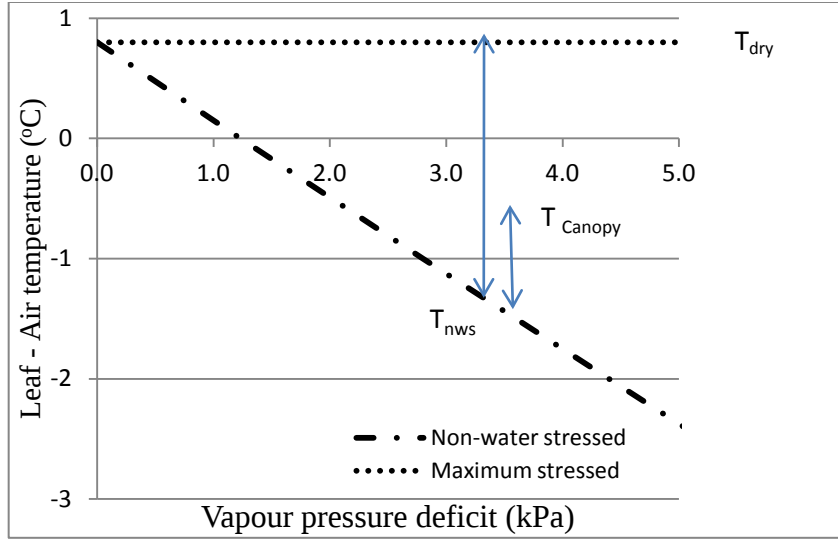


Figure 6: Leaf-Air temperature vs vapour pressure deficit

$$T_{nws} = Intercept + Slope(VPD) \quad [12b]$$

$$T_{dry} = Intercept + Slope(VP_{sat}(T_a) - VP_{sat}(T_a + Intercept)) \quad [12c]$$

Where VPD: vapour pressure deficit (kPa), $VP_{sat}(T_a)$: saturation vapour pressure at air temperature (kPa), T_{nws} : non-water stressed canopy temperature ($^{\circ}C$), T_{dry} : water-stressed canopy temperature ($^{\circ}C$).

3.0 Results

The results obtained are as follows:

Reference evapotranspiration - Reference evapotranspiration calculated using FAO-56 Penman-Monteith, ASCE Penman-Monteith, Hargreaves and Turc equations in tabular and graphical forms.

Irrigation volumes - Irrigation depths (mm); cumulated depths per week and month; and total irrigation depths (mm); total runoff (mm) and irrigation scheduling frequency using water balance, soil moisture and plant water status monitoring. The model also allows that the soil water balance results may be exported as an excel file. To export the results the user should select the button ``export.