Best Management Practices of A Solar Powered Mini-Pivot for Irrigation of High Value Crops

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ABSTRACT

During the 2005 growing season two irrigation management practices were developed for cabbage production utilizing a Greenfield solar powered miniature pivot, located at the Canada-Saskatchewan Irrigation Diversification Centre (CSIDC) near Outlook, Saskatchewan. Solar and battery power was used to operate the drive and control system of the miniature centre pivot located on CSIDC's pressurized pipeline. The management practices included a low-flow, 94 litres per minute (lpm) schedule with irrigation events occurring in the evening and night periods, and a high-flow, 370 lpm schedule with irrigation events occurring during the daytime hours. In each management practice, the soil moisture content was maintained above 65% of field capacity to optimize yield and head development (Waterer 2005).

Over the 2006 growing season, testing was conducted to evaluate the performance of each management practice. Performance was based upon application uniformity, water use efficiency and energy use efficiency. In addition to performance evaluation, tests were conducted to determine operational characteristics of this relatively new irrigation system to identify potential use in agricultural production.

The uniformity coefficient of the high-flow management practice was greater than that of the low-flow management practice. This was a result of nozzle selection and layout of each application system, as determined by the manufacturer.

Water use efficiency increased significantly when converting from a high-flow operating system to the low-flow system. This increase in water use efficiency was a result of reduced water loss, in the high flow system, through evaporation and potential run-off due to decreased application rates and environmental factors between watering

times. Water loss through this manner is not beneficial to plant growth and results in elevated operating costs with little to no improvement in yield.

Energy use efficiency, due to differences in water use efficiency and friction loss in the piping system, also increased upon switching from a high-flow system to the low-flow system. In general, converting this type of system from a high-flow management practice to a low-flow management practice will help conserve water and energy resulting in savings in operating and capital costs.

Testing to determine the operating characteristics of the power system was completed during the 2006 growing season. It was concluded that these systems have potential use in operating small-scale pivot and pumping systems on high-value crops.

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NOMENCLATURE

AAFC = Agriculture and Agri-Food Canada

AC = Alternating Current

ASAE = American Society of Agricultural Engineers

BMP = Best Management Practice,

C = Hazen-Williams coefficient of friction,

C_p = Crop production,

CSIDC = Canada-Saskatchewan Irrigation Diversification Centre,

CU_H = Heermann and Hein coefficient of uniformity,

D =deep percolation

DC = Direct Current,

DM = dry matter harvested,

e_s = saturation vapor pressure of the air,

e_o = actual vapor pressure of the air,

E = evaporation loss expressed as the percentage of the total volume discharged by sprinklers,

E_{160Wp} = daily energy produced by a 160 W_p PV cell

$E_{irrcycle}$ = energy required by the total system, per irrigation cycle

E_{I+C} = energy requirements of the pivot and control systems

E_{pv} = PV cell energy requirements to supply irrigation system demand

E_{pump} = Energy requirements of a pump

ET = Evapotranspiration

ET_o = Evapotranspiration of a grass reference crop

F = Flux across lower boundary layer

F.C. = Field Capacity

F_{ag} = Agriculture water use efficiency

g = Acceleration due to gravity

GPM = US Gallons per Minute

h = pumping head

h_A = energy added to fluid by pump or total head on pump

H_f = Hazen Williams Coefficient of Friction

HI = harvest index,

i = number assigned to identify a particular collector beginning with $i = 1$ for the collector located nearest the pivot point and ending with $i = n$ for the most remote collector from the pivot point.

I = Total seasonal irrigation

I.D. = Inside Diameter

LPM = Litres per Minute

M_s = mass of solids within the soil sample

M_w = mass of water within the soil

n = number of collectors used in the data analysis

P = Total seasonal precipitation

P_A = power added to fluid

P_{pv} = PV cell power production

P_{rated} = PV cell peak-watt rating

P_s = sprinkler operating pressure

PFRA = Prairie Farm Rehabilitation Administration

PV = Photovoltaic

Q = volumetric flow rate of fluid

R_{on} = Run-on

R_{off} = Run-off

s_i = the distance of the ith collector from the pivot point

SAF = Saskatchewan Agriculture and Food

SW = soil water depletion

T = transpiration,

$t_{irrcycle}$ = duration of an irrigation cycle

T_a = air temperature

u = wind velocity at 2 m above the ground

U = Volume of water applied or consumed

V = Total volume pumped

V_i = volume of water collected in the *i*th collector

$\overline{V}_p$ = the weighted average of the volume of water collected

W = weight flow rate of fluid

W_p = Watt-peak

WC = water content of yield

ΔS = Change in soil water storage

ρ = fluid density

θ_m = gravimetric soil moisture content

θ_v = volumetric soil moisture content

ρ_w = density of water

ρ_b = bulk density

1.0 INTRODUCTION

Irrigation can be defined as the replacement or supplementation of precipitation with water from another source in an attempt to meet crop water requirements. In Saskatchewan irrigation began in the late 1890's and has grown to 81 000 hectares (200 000 acres) with sprinkler irrigation systems, most notably pivot irrigation, making up 53% of the total irrigated acres in Saskatchewan in 2004 (Madramootoo 2006).

Pivot irrigation systems take water from a source (e.g. ground water, canal, river or lake), with the use of a pump or gravity, and applies the required water at a desired rate to the crop canopy and soil.

Currently, single- and three-phase power lines are the primary power source for pivot irrigation systems and the producer is limited to irrigate where these power lines exist or are in close proximity due to the high cost of line construction. Where these sources do not exist, a combustion generator is a common alternative. These generating systems can be time consuming, high maintenance and rely on a steady fuel supply. As the price of petroleum continues to increase, the operating cost of combustion systems increases. In Saskatchewan, average retail price of regular unleaded gasoline escalated 76% from 78 cents per litre in 2002 to 137 cents per litre in 2008 (Statistics Canada, 2008).

To cope with the increasing price of fuel and issues associated with isolated operating systems, new stand alone power systems are being investigated and introduced into the market. Solar power is one of the more attractive alternative power sources available due to the continuous supply of 'free' energy, low maintenance and high life expectancy.

Solar panels, also known as photovoltaic (PV) cells, are used to generate electricity by absorbing solar energy to create an available DC power source. PV cell efficiency and construction costs are limiting factors in the success of the sun as a power source. If the price of non-renewable fuels continues to increase, the economics behind solar power will become more appealing to the general public. Carlson (1989) determined that at a selling price of about 3 USD per peak watt (W_p), PV cells start to become cost effective with diesel motors in remote applications such as irrigation and village power.

Solar panel efficiency and production volumes are continually increasing, which results in a decrease in the price of these systems. The Canadian Solar Industries Association (2005) presented data showing that the price of solar cells is dropping by an average of 3% per year and is the only energy source that has seen its price drop consistently over the last 20 years; the average price of solar cells peaked at 48 US$ per peak watt (Wp) in 1975 and dropped to a price of 3 US$ per Wp in 2002. Carlson (1989) determined that for solar panels to compete in the market with diesel generators for use in irrigation and power generation in isolated villages this value of 3 US$ per Wp had to be reached by the manufacturer. New technology continues to increase production volumes and performance efficiency; NanoSolar®, a solar panel manufacturer in the United States predicts panel prices to drop to 1 US$ per Wp within the next few years due to advancements in manufacturing technology (www.nanosolar.com, 2007).

The Lindsay Manufacturing Company introduced a miniature irrigation pivot system in 2003 that utilized solar panels to power the system in the field. The introduction of solar panels in irrigation has created an alternate choice for producers to the combustion generator.

With solar cell irrigation systems becoming commercially available to producers, understanding their capabilities and identifying the beneficial management practices (BMPs) becomes important. This project will look at developing a BMP package for the first solar miniature pivot of its kind in Canada located at the Canada-Saskatchewan Irrigation Diversification Centre (CSIDC) in Outlook Saskatchewan. The BMP will address two key aspects associated with irrigation systems: 1) maximizing water use efficiency and, more importantly with a system where the available energy is limited, 2) maximize energy use efficiency. This project will also investigate the capacity of the solar-powered irrigation system and identify the potential for vegetable production under this type of system in the prairie environment.

2.0 OBJECTIVES

The principle objective of this thesis is to develop BMP package for a solar-powered miniature pivot irrigation system for use on high value crops. The high value crop used for this study was cabbage. The specific objectives of this study are:

1) To investigate the water use efficiency of cabbage grown under a two tower solar-powered mini-pivot using two different controlled management practices; a low-flow, 94 litres per minute (lpm) schedule with irrigation events occurring in the evening and night periods, and the high-flow, 370 lpm schedule with irrigation events occurring during the daytime hours, currently utilized at the Canada Saskatchewan Irrigation Diversification Centre.

2) Identify the energy use efficiency of cabbage grown under a two tower solar-powered mini-pivot using the two defined controlled management practices.

3) Investigate the capacity of the solar power system and subsequent power demand of the irrigation system to determine the potential of a completely solar-powered irrigation system, involving both a pivot and pumping system.

3.0 LITERATURE REVIEW

3.1 Irrigation in Canada

Irrigation in Canada has been practiced in some form since this country was settled over a hundred years ago. Since that time, irrigation has evolved from border dyke and flood application to electronically controlled centre-pivot irrigation systems.

There is currently over one million hectares of irrigated land in Canada, with approximately 95 % of this land located in the western provinces (Madramootoo 2006). Alberta currently is the most intensive irrigator in Canada with 728,450 hectares of land under some form of irrigation (Madramootoo 2006). Irrigation in Saskatchewan however, is considerably less, with 80,939 hectares of land irrigated in 2004. There is considerable potential for development in Saskatchewan to propose irrigated hectares of 404,694 (Table 3.1) (Madramootoo 2006).

A major obstacle to irrigation in Saskatchewan is the lack of infrastructure to supply water and power to operate mechanical move irrigation systems. Electrical deficiencies, most notably 3-phase power supply lines, we one of the most common obstacles to irrigation development. Producers who wish to irrigate off-grid are forced to rely on expensive and labour intensive combustion generators

Table 3.1: Potential for irrigation in Canada, 2004 (Madramootoo 2006)

Province	2004 Provincial Government Estimates (ha)	Potential Irrigated Area (ha)	Potential Irrigated Area as % of Actual
British Columbia	121,408	182,113	150
Alberta	728,450	1,011,736	139
Saskatchewan	80,939	404,694	500
Manitoba	30,352	60,704	200
Ontario	60,704	202,347	333
Quebec	25,000	35,000	140
New Brunswick	500	575	115
Nova Scotia	3,642	7,285	200
P.E.I	2,023	4,047	200
Newfoundland	45	136	300
Canada	1,053,065	1,908,637	181

3.2 Centre-pivot irrigation systems

The centre-pivot, as it is known today, has evolved from the original ‘self-propelled sprinkling irrigation apparatus’ invented in 1948 and later patented in 1952 by Frank Zybach, a dry-land farmer from eastern Colorado, USA (Casteel 2004). The irrigation system was accepted due to its high degree of automation requiring less labour than traditional ‘hand’-move irrigation systems and its ability to irrigate variable terrain not suitable for flood irrigation (Casteel 2004). The rights to Zybach’s patent were purchased by the Valmont Irrigation Company, which began marketing the apparatus under its Valley Irrigation division. Following Valmont’s lead, the centre-pivot irrigation industry expanded in the 1960’s and transformed over the next 50 years with company’s including Reinke Manufacturing Co., T-L Irrigation Co. and Lindsay Manufacturing Co. in addition to the Valmont Irrigation Co. as the main players.

The original irrigation systems were driven with water pistons or water wheels that transferred the high-pressure water supply into mechanical power to drive the irrigation system through the field. This water drive system evolved to alternating current (AC) electric or hydraulic drive systems in the 1960's and 1970's to reduce energy requirements and operating costs (Casteel 2004). Recently, certain pivot electrical systems have been designed to utilize a direct current (DC) source to make use of advancements in wind and solar energy generating systems.

Solar technology has existed for decades but, until recently, had never been implemented as a centre-pivot power supply. According to J. Parker, Accounts Manager Lindsay Manufacturing Co. (personal communication, October 5, 2005), in 2003 the Lindsay Manufacturing Co. introduced a solar panel power option for their Greenfield miniature centre-pivot irrigation system. They became one of the first centre-pivot irrigation producers in Canada to market a solar system packaged with its pivot irrigation system.

The Greenfield miniature pivot system was put into production in 2000 to irrigate small-scale fields or in turf production where system weight is a concern. In 2003 the Greenfield system could be purchased with a solar array power alternative. Due to the high-capital cost of these systems sales were slow, but are now steadily increasing with increasing oil price and the cost of solar cells decreasing. With the increase in oil prices continuing to steadily grow in the future, alternative power systems such as solar panels will continue to replace traditional combustion generators in areas of electrical grid isolation.

3.3 Solar pivot irrigation studies

Studies involving solar powered centre-pivot irrigation methodology have been limited in Canada. Although research is readily available on solar panels and centre-pivot irrigation technology separately, studies involving the combination of these two systems in Canada has not been conducted.

3.3.1 National Water Quality and Availability Management (NAWQAM)

The National Water Quality and Availability Management (NAWQAM) Project was a co-operative project between the Government of Canada through the Canadian International Development Agency (CIDA) and the Government of Egypt through the Ministry of Water Resources and Irrigation (MWRI). The goal of the project was to develop an effective coordinated national system for sustainable water resources management in Egypt (Nassar et al. 2006).

One of the tasks of the NAWQAM project was to purchase and test a solar powered centre-pivot irrigation system, similar to the one located at CSIDC. The objective was to evaluate the performance of a miniature irrigation system in the Egyptian environment utilizing solar energy. The project was designed to address energy supply concerns in remote regions of Egypt whose industry is completely reliant on irrigation (Nassar et al. 2006).

It was determined that using a mini-pivot irrigation system powered by solar energy resulted in a high water distribution and water use efficiency and improved the soil properties compared to traditional irrigation methods (Nassar et al. 2006). Nassar et al. (2006) also concluded that solar radiation is efficient and sufficient not only for operating the system during daylight hours but also overnight, using batteries, when no solar radiation exists. This study strongly recommended that solar energy be used in the Toshka region of Egypt for use in irrigation (Nassor et al. 2006).

3.4 Water use efficiency

The term water use efficiency (WUE) is a general term in agriculture that has various definitions depending on the scope of water uses and losses investigated. D. Hillel (1997) of the Food and Agricultural Organization of the United Nations defined water use efficiency as the ratio of total crop production, in the form of total dry matter or marketable produce, to the total volume of water applied or consumed.

Input water-use efficiency further expands on the idea of water use efficiency and focuses on the total water inputs for a system and considers losses through run-off, deep-percolation, conveyance and application (Sinclair et al. 1984). From this definition it was determined that if crop yield was plotted against the total water input, the slope of the resulting function would be equal to the input water use-efficiency.

The most cited goal of irrigation best management practices is to increase the water use efficiency during crop production; Sinclair et al. (1984) suggested 5 options for improving water use efficiency in crop production.

i) Biochemical alterations of a plant to improve photosynthetic efficiency, which allows a plant to increase yield production with the same inputs of nutrients, water and sunlight;

ii) by developing crops with high stomata sensitivity would prevent high transpiration rates during periods of elevated temperature. This would increase WUE but requires the growing season of the crop to be extended to compensate for periods of lost CO_2 assimilation;

iii) improving the harvest index of a plant through breeding and genetics to increase the amount of fruit or harvestable matter with respect to the total biomass of the plant; this would increase the amount of water directly utilized for fruit production thus increasing WUE;

iv) WUE is directly improved when the difference between the saturation vapor pressure and the actual vapor pressure of the environment is minimized; this condition reduces the amount of water evaporated to the atmosphere. Altering the growing conditions by growing crops in humid areas or developing crops in which maximum growth is achieved during cooler periods of the year would promote this type of environment;

v) beneficial management practices which minimize surface runoff, soil evaporation, and deep percolation will increase the amount of water transpired through the plant, utilized for yield production, therefore increasing WUE.

In a more recent study by Wallace and Batchelor (1997), the concept of WUE was further defined to include all the agronomic and mechanical mechanisms that they identified as having an effect on water use efficiency in irrigated crop production. From their definition the following equation was produced to represent water use efficiency:

$$WUE = \frac{(HI \times DM)}{\left(T(1-WC)\left[1+\frac{E}{P+I+SW-D-R_{off}-E}\right]\right)} \qquad (3.1)$$

where:

HI = harvest index (ratio dry yield per unit dry matter),

DM = dry matter harvested ($g\ m^{-2}$),

T = transpiration (mm),

WC	=	water content of yield (ratio),
E	=	soil water evaporation (mm),
P	=	precipitation (mm),
SW	=	soil water depletion (mm),
D	=	deep percolation (mm),
R_{off}	=	surface runoff (mm),
I	=	irrigation (mm)

Wallace and Batchelor (1997) also suggested methods to increase the WUE of a farming and/or irrigation system;

i) Increasing the harvest index (*HI*) through crop breeding or management,

ii) Reducing the transpiration ratio (*T/DM)* by improved species selection or crop breeding,

iii) Maximizing the dry matter (*DM*) yield through enhanced fertility, disease and pest control and optimum planting,

iv) Increasing the transpiration (*T*) component relative to other water balance components by:

- reducing soil water evaporation by increasing residue,
- reducing deep percolation below the root zone by avoiding overfilling root zone,
- reducing surface runoff by avoiding soil compaction, utilize sprinklers with lower application intensity,

The last method of increasing WUE, suggested by Wallace and Batchelor (1997), is significantly affected by the design and management of the irrigation system itself and should be the focus when developing a best management practice or designing an irrigation system.

Technological advances in irrigation design continue to increase the application efficiency of centre-pivot systems, although inefficient management of the same irrigation system can cause reduction in WUE. Keller (1965) found that systems with ‘poor’ application efficiency under proper management overall performed more efficiently than systems with ‘better’ application efficiency that were poorly managed.

Scheduling irrigation using the water balance method (i.e. no ‘excess’ water is applied to the field), has the potential to save irrigators between 15 % and 35 % in their annual water delivery requirements (Stagman and Ness 1974; Heerman 1975). As a result it can be stated that even if a system has 100% application efficiency, if irrigation is not scheduled properly, between 15% and 35% of this water could be lost and not benefit plant growth. This is why BMP’s, in irrigation, are as important, if not more, then the irrigation system design itself.

3.5 Best management practices

Irrigation Best Management Practices (BMP’s) include irrigation scheduling, equipment modification, land leveling, tail water recovery, proper tillage and residue management (Waskom 1994, Colorado U.S.). BMP’s involving the use of irrigation water can aid in increasing efficiency, uniformity and reduce water resource contamination (Waskom 1994), resulting in increased WUE and, in turn, promote an increase in energy use efficiency.

How efficiently irrigation systems use water and energy is determined primarily by the type of system and the way it is operated, maintained and managed (Evans et al. 1996). Water losses can occur through drainage/flux out of the root zone, evaporation and runoff. Each loss can be controlled by applying a different management practice. The BMP cited to be the most beneficial in irrigation management is that of irrigation scheduling, which is used to prevent the over-application of water while maximizing net return (Waskom 1994). Irrigation scheduling tracks water removal and inputs in an attempt to maintain soil moisture within desired levels. Desired soil moisture varies depending on the irrigated crop. Cabbage for example, which is the focus crop in this study, Saskatchewan Agriculture and Food recommends a soil moisture content maintained between 65% field capacity and field capacity (Waterer 2005). Sanders (1997) suggested a soil moisture content to be maintained above 60% of available moisture. Soil moisture recommendations very with soil type and location, but for this study the Saskatchewan Agriculture and Food recommendation will be followed.

Water loss through surface runoff during irrigation application can occur when the sprinkler package is incorrectly matched with the infiltration rate of the soil. A study conducted by Kay and Abo Ghobar (1990), demonstrated that as application rate and duration increase, the volume of run-off water also increases (Figure 3.1). To minimize the amount of run-off from the field, an irrigation system should be designed to reduce the application rate by increasing the wetted diameter of the sprinkler or reducing the flow through each sprinkler. This allows a larger portion of water to infiltrate into the root zone compared to the amount of lost through run-off.

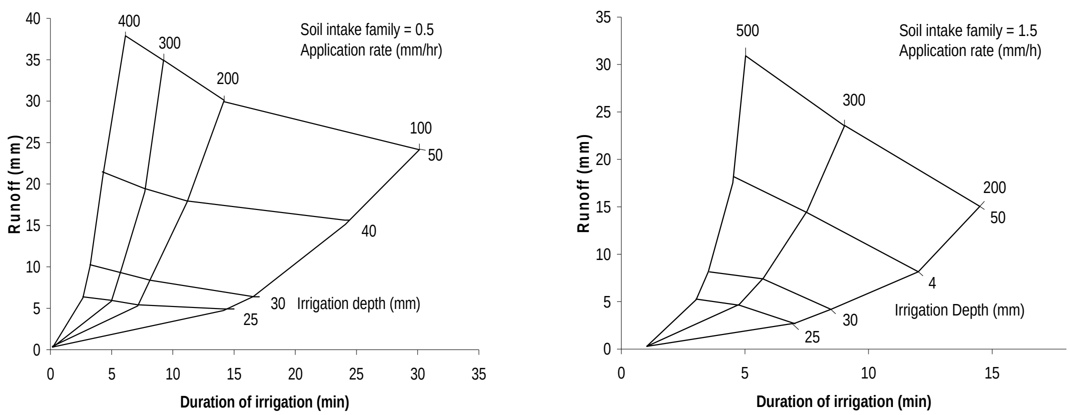

Figure 3.1: Potential for irrigation water run-off related to application rate, application duration and soil intake family (adapted from Kay and Abo Ghobar 1990).

The most cited meteorological variables affecting water loss due to wind drift and evaporation are wind speed, air pressure, temperature, relative humidity and vapour pressure (Playán et al. 2005, Zaragoza, Spain). It has been proposed that there is an exponential relationship between evaporation losses and these stated environmental factors (Yazar 1984), illustrated by the following equation:

$$E = 0.003\exp(0.20u)(e_s - e_o)^{0.59} T_a^{0.23} P_s^{0.76} \quad (3.2)$$

where:

E = evaporation loss expressed as the percentage of the total volume discharged by sprinklers,

u = wind velocity at 2 m above the ground (m s^{-1}),

e_s = saturation vapor pressure of the air (mbar),

e_o = actual vapor pressure of the air (mbar),

T_a = air temperature (degrees C),

P_s = sprinkler operating pressure (kPa).

It was concluded from this relationship that by minimizing environmental factors such as wind speed, vapor pressure deficit, operating pressure and air temperature that evaporation from sprinkler irrigation can be reduced (Yazar 1984). The potential wind drift and evaporative losses have been reported as modest (5 – 10%) up to 30% depending on these environmental conditions (Playán et al. 2005). Since, these factors are out of the irrigators' control, with the exception of sprinkler operating pressure, the alternative is to irrigate when these factors promote reduced evaporation rates such as during cool calm days or during nighttime hours.

Night sprinkler irrigation has long been practiced by farmers world wide, since the environmental factors inducing wind drift and evaporation loss are reduced during night time (Playán et al. 2005). A study by Koumanov et al (1997) (Davis, California U.S.) investigated the application efficiency of micro-sprinkler irrigation of almond trees; the objective of the study was to quantify the components of the water balance to investigate irrigation efficiency. Study results showed that the majority of water loss due to evaporation occurred immediately following irrigation application. The study concluded that significant water savings could be achieved if the irrigation system is operated during the evening and night time hours; when air temperature and wind speed are minimal and humidity is relatively high (Koumanov et al. 1997). Other studies suggest that when switching from day to night time operation, wind drift and evaporation losses are reduced up to 50% (Playán et al. 2005). A decrease in wind speed results in increased irrigation uniformity, which is commonly observed during night time (Dechmi et al. 2004). Environmental factors may not always be ideal during evening and night hours but they tend to be more favorable to reduce evaporation than daytime irrigation.

Sprinkler height also plays a significant role in the evaporative losses related to atmospheric exposure and wind-drift effects. Sprinkler heights greater than 1.8 m significantly increase spray losses due to wind drift and evaporation (King and Kincaid 1997, Idaho, U.S.). Spray losses averaged 3 and 5 percent for sprinkler heights of 0.9 m and 1.8 m respectively and increased to 10 percent for sprinklers (spray and impacts) mounted on the top of the centre pivot at a height of 3.6 m (King and Kincaid 1997).

From all the cited studies, the developed BMP to be study in this project will i) have operating hours during evening and night; ii) require the system to be equipped with a low pressure sprinkler system (such as drop hose nozzles) and; iii) reduce the travel distance between the nozzle and crop canopy with the aid of drop nozzles and most importantly; iv) schedule irrigation applications on the basis of maintaining the soil moisture content between 65% of field capacity and field capacity.

3.6 Energy use efficiency

Utilizing a solar power system requires the user to be conscious of the total energy requirements of the operating system. With constraints on total energy production and storage associated with these systems, energy use efficiency has greater significance with management practice selection.

Energy use efficiency can be quantified by calculating the total energy (pump and pivot) consumed during water delivery for each kilogram of crop produced (Lyle et al. 1983). Lyle et al. (1983) compared the water and energy use efficiencies between centre pivot irrigation systems equipped with impact (high-pressure) and drop (low-pressure) sprinkler nozzles. At the conclusion of the two year study it was determined that the water use efficiency of a system had a direct effect on the energy use efficiency

(EUE) of the same system under comparable environmental conditions. Table 3.2 shows that as WUE increases, the amount of energy required to produce a kilogram of crop decreases resulting in greater energy conservation.

Table 3.2: Water and energy use efficiencies of LEPA[1] and impact sprinkler application system for soy bean production (Adapted from Lyle et al. 1983)

	Water Use Efficiency (kg/ha-cm)		Energy Use Efficiency (kwh/kg)	
	LEPA	Impact	LEPA	Impact
1980	46.3	40.2	0.729	1.106
1981[2]	129.7	101.9	0.259	0.364

[1]LEPA – Low-energy precision application (general term including drop nozzle application systems)
[2]1981 had significant periods of rainfall in the later stages of crop growth that affected efficiency values

In irrigation, the greatest requirement of energy is to pump water and therefore energy-saving practices in irrigation are related to the efficiency at which water is pumped, distributed, and used by the crop (Gilley 1983). The most basic method to reduce the amount of energy required is to reduce the quantity of water pumped, through improvements in irrigation efficiency or reduction in net irrigation (Gilley 1983).

In irrigation, pumping energy is required to pump a volume of water at the required pump head. By increasing the WUE of the system the volume of water pumped is reduced, but by reducing the pumping head will also reduce the total pump energy requirements. This concept and increasing energy costs have lead to the development of low-energy drop nozzles. Another benefit in decreasing the operating pressure of the irrigation system, referring back to equation 3.2, results in a larger water droplet diameter resulting in a decrease in wind drift and evaporative loss (Playán et al. 2005).

A study by Gilley and Supalla (1981) identified the specific practices for reducing energy used in centre-pivot irrigation as: 1) improving the overall irrigation efficiency of the system, 2) reduce the pumping volume delivered through improved water management and irrigation scheduling, 3) implementation of reduced-pressure systems and, 4) improved pumping system performance.

Evans et al 1996 summarized the idea of improving energy use efficiency in irrigation stating, 'Energy is consumed for every gallon of water pumped. For a given system, an increase in water use results in a proportional increase in energy consumption. Any water not actually used by the crop reduces water-use efficiency and consequently the energy use efficiency'.

3.7 Crop water requirements for cabbage

Cabbage is a high valued vegetable crop that requires irrigation for sustainable production. This project focused on cabbage production due to the high water demand of the crop which would allow for increased irrigation events.

The government of Saskatchewan through Saskatchewan Agriculture and Food (Waterer 2005) concluded that due to the large leaf area, cabbage requires at least 25 mm of water per week to sustain growth. To ensure good yield and head quality, the soil must be kept between 60 and 70 percent of field capacity (Waterer 2005). This recommendation was incorporated into the irrigation management practices used for this study.

Cabbage crop water requirements, as with most vegetable and fruit crops, will vary depending on environmental conditions and stage of crop growth. In irrigation management, crop water requirements can be predicted utilizing the regional ET and a crop use coefficient, which is dependent on crop type and growth stage. ET is the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration (Allen et al. 1998). For the Canadian prairies, more specifically Saskatchewan, Maulé et al. (2006) presented an average observed ET value for the summer months of 1999, 2003 and 2004 of 4 mm/day, with peak seasonal ET values ranging between values of 6 mm/day and 8 mm/day for the same observation periods.

Since crop water use is related to the regional ET, a crop coefficient can be utilized to determine the water consumed by a specific crop during each observed stage of growth (Allen et al. 1998). The expected ET for cabbage can be calculated by multiplying an observed reference ET by the crop use coefficient depending on the specific stage of growth. The reference ET is commonly represented by a grass reference crop and denoted by ET_o, other references commonly utilized are associated with alfalfa, pan evaporators or atmometers (BCMAFF 2001).

4.0 Methods and Materials

4.1 Introduction

The solar centre pivot irrigation system tested was located at CSIDC in Outlook Saskatchewan, approximately 75 kilometers south of Saskatoon, Saskatchewan. CSIDC is a federal / provincial / industry centre dedicated to sustainable irrigated production. The Centre currently utilizes a high-flow, 370 lpm, application nozzle system operating during the daytime hours as a result of labour restrictions. The high-flow application system was supplied by the manufacturer at the request of the Centre, this study will look at changing the application nozzle system and management practices to promote water and energy conservation.

4.2 Irrigation System

The irrigation system is a Greenfield two-towered miniature pivot equipped with a low energy drop hose sprinkler package (Figure 4.1), and is powered by a 160 W_p (Watt-peak) solar array and battery backup system. Water is supplied through a pressurized line inter-connecting this irrigation system, along with other systems at the centre, to a pump station located three kilometers off site on an irrigation district canal. The presence of the pressurized pipeline means no solar power was utilized in the pumping system, solar and battery power was only utilized by the miniature pivots drive and control systems.

Figure 4.1: Greenfield two-tower miniature centre-pivot located at CSIDC, Outlook, SK

The Greenfield mini-pivot has a total system length of 67 meters, with the first tower measuring 34 meters and the second tower 33 meters. The system is composed of 97 mm I.D. galvanized span pipes with the required trussing and tower structures. The pivot is driven around a fixed pivot point, located in the centre of the field, by two 93 watt electric motor and gearbox drive systems, one located on each tower (Figure 4.2).

Figure 4.2: Electric motor and gearbox drive system for a Greenfield miniature centre-pivot

4.2.1 Sprinkler Package

The sprinkler package installed on this system included drop hose mounted Nelson Irrigation D3000 spray nozzles equipped with 70 kPa pressure regulators (Figure 4.3). As two proposed application rates were to be tested, an interchangeable nozzle system was employed, that allowed nozzles to be manually changed depending on application requirements. The nozzle layout for both the high flow rate and low flow rate application systems were designed and supplied by the manufacturer.

Figure 4.3: Nelson D3000 spray nozzle with 70 kPa regulator and interchangeable nozzle attachment

Each spray nozzle was located approximately 1 meter above the soil surface with 1.5 meter spacing between adjacent nozzles. The nozzle spacing is determined by the outlet spacing in the pivot span pipes; different manufacturers may have different specifications.

4.2.2 Power System

The power system makes this particular irrigation system unique from the common centre-pivot irrigation systems located in the region. The system utilizes a 160 W_p solar array to power the electrical motors located on each tower of the mini-pivot. Since the system is fed by an underground pressurized line, power produced by the solar panels is not required to operate the pumping system. The pumping system utilizes the 3-phase power grid to operate a four pump system located off site.

The solar array consists of four 40 W_p solar cells connected in series, which gives the array its 160 W_p production capacity (Figure 4.4). A solar array consists of photovoltaic (PV) cells that absorb solar energy, in the form of photons, to create an electrical DC power source. In general, PV cells consist of two semiconductors, a positively charged ‘p’-type and a negatively charged ‘n’-type, layered creating a ‘p/n’ junction at their contact surface. Since these two semiconductors are in close contact and are of opposite charge they develop an electric field at this contact surface. When photons, from sunlight, absorb onto the ‘n’-type layer and energize the electrons within the layer, these electrons ‘jump’ towards the surface of the ‘p’-type layer where they are collected by a metallic grid and flow into the electrical circuit. The electrons complete work within the electrical circuit before returning to balance the electron deficit of the ‘p’-type layer (New Zealand Photovoltaic Association 2003).

Figure 4.4: 160 watt-peak solar array located at CSIDC, Outlook SK

With solar power systems, a battery back-up is incorporated to account for periods where solar radiation is absent, minimized or additional power is required to meet system demands. The battery backup incorporated into the system consists of eight, six volt Surrette deep cycle batteries connected in series giving a 48 volt total potential difference with a 460 Amp-hour capacity (Figure 4.5). These batteries are contained beneath ground level; this aids in cooling batteries during charging and prevents damage during cold temperature exposure.

Figure 4.5: 48 Volt 460 amp-hour Surrette deep-cycle battery bank

The system located at CSIDC utilizes a lead-acid battery storage system, common with the solar based systems. Lead-acid batteries consist of plates constructed from lead, referred to as the electrode, with a diluted sulphuric acid electrolyte added to convert electrical energy into a chemical potential energy during charging and subsequently converting chemical potential energy into electrical energy during discharge. Storage capacity of battery systems are described in terms of amp-hours; a battery rating of 20 amp-hours can sufficiently provide 20 amps of current, at the rated voltage, for approximately 1 hour or alternatively can provide 1 amp of current for 20 hours.

Lead-acid battery charging requires three stages to insure that overheating and damage does not occur. The first stage consists of charging the battery at a constant current to approximately 70% of total charge capacity. Stage 2, referred to as the topping charge, consists of charging at a constant voltage with a variable current. This stage limits current to reduce high temperatures within the battery resulting in longer cooling times causing sulfation. Sulfation can limit a batteries ability to reach full charge capacity. The final stage is the float charge, this compensates for the batteries tendency to self-discharge over time.

The full charge efficiency of lead-acid batteries is commonly represented by a value of 85 % as presented by Stevens and Corey (1996), with efficiency values of close to 100 % during first stage of charging and drastically drops when charging at levels above 80 % state of charge (second stage charging) where efficiency is reduced to 50 to 60%. This indicates that during full charge, if a photovoltaic system outputs 100 Amp-hrs at a rated voltage, the total converted battery storage will equal approximately 85 Amp-hrs. The primary loss in efficiency is due to dissipation of energy in the form of heat; batteries tend to heat up the faster they are charged and the closer they become to full state of charge.

The electrical system, which includes the batteries, solar array and pivot are all connected in parallel with each other utilizing a DC regulator located inside the irrigation system control panel (Figure 4.6). The current regulator is the key component that allows a solar powered system to function properly. The current regulator acts as a switching mechanism to allow the required current levels to be supplied to the batteries and/or pivot system depending on the power demand of the pivot and instantaneous solar output. When the pivot is in motion, current is diverted from the solar panels and the batteries to satisfy the electrical motor power demands; when the pivot is stationary or powered down, the regulator diverts current at the required rate to the batteries for charging.

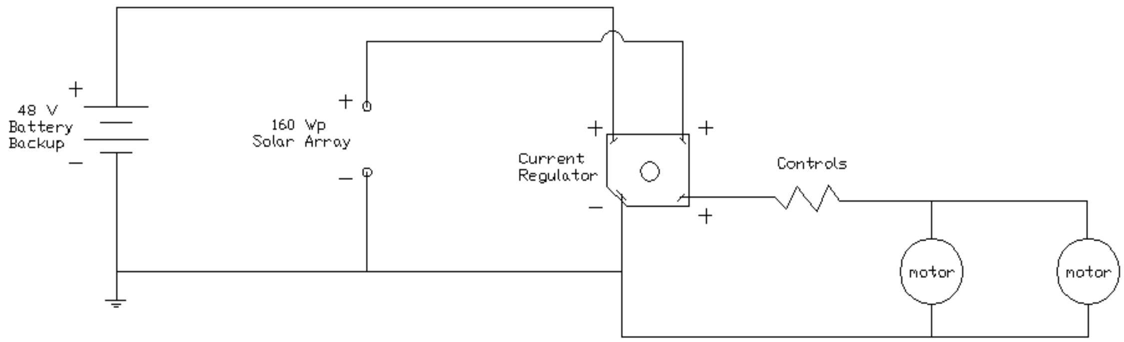

Figure 4.6: Wiring diagram of electrical system components of Greenfield miniature solar powered pivot.

4.3 Field Layout

The field located on site at CSIDC consists of 1.5 total irrigated hectares (3.6 acres), initially divided in two sections; a vegetable test section and durum wheat fill section (Figure 4.7). This division was required to follow crop rotation practices. The vegetable test field consisted of cabbage, cauliflower, brussel sprouts, broccoli and celery with the majority of the area being planted to cabbage to obtain an adequate sample volume to meet project objectives.

Cabbage was initially seeded on May 5, 2006 and grown in the on-site greenhouse to insure proper crop formation and later transplanted to the test plot on May 25, 2006. Cabbages were planted with an in-row spacing of 0.45 m (1.5 feet and a row spacing of 0.75 m (2.5 feet), with each plant having an approximate area of 0.35 m^2.

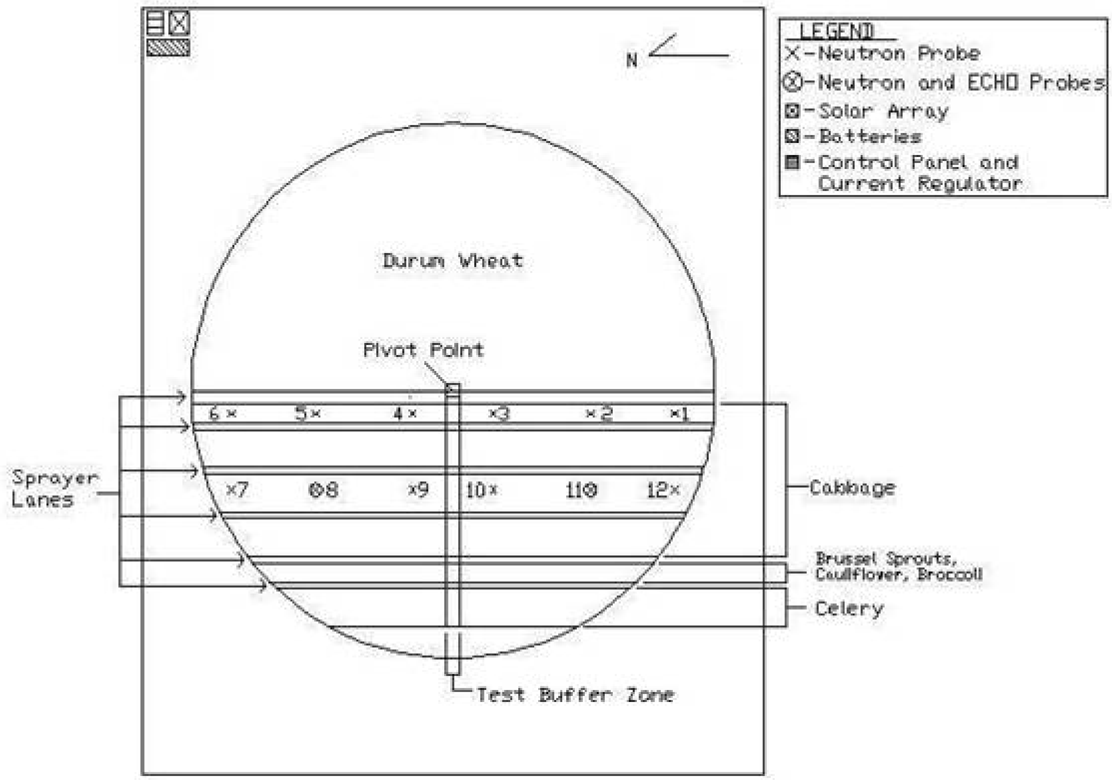

Figure 4.7: Field layout and sampling plan for the summer of 2006, CSIDC, Outlook, SK.

The vegetable test field was further subdivided into two similar fields to accommodate the testing of the high-flow and low-flow management practices. The north half of the vegetable test field was subjected to the high-flow (370 lpm) management practice with the south half subjected to the low-flow (94 lpm) management practice. A buffer zone between each field was incorporated into the layout; this allowed for system re-nozzling between applications preventing over watering and plant damage from increased foot traffic.

Twelve sampling sites were chosen within the cabbage planting area, six samples located in each management test section, spaced evenly to obtain a sufficient generalization of the field and application patterns, shown in Figure 4.7. Soil moisture content measurements were taken at each site using both gravimetric (soil depth 0 – 150 mm) and neutron probe (soil depth 150 – 600 mm) sampling techniques. At the conclusion of the growing season, yield samples were taken at each sampling site so a relationship between water use and yield production could be established with confidence.

4.4 Field Tests

Field testing was done to determine the water and energy use efficiency of a solar powered mini-pivot utilizing high-flow and low-flow management practices for the summer of 2006. Testing also allowed for calculations to determine the characteristics and capacity of the system so that recommendations for potential use could be made.

4.4.1 Uniformity coefficient

The uniformity coefficient of both management practices was determined as per ASAE S436.1 DEC01 with modifications proposed by Stonehouse et al. (1996) for low clearance drop hoses.

The centre pivot coefficient of uniformity can be calculated using the modified formula of Heermann and Hein (1968), given by

$$CU_H = 100\left[1 - \frac{\sum_{i=1}^{n} S_i \, | V_i - \overline{V}_p \, |}{\sum_{i=1}^{n} V_i S_i}\right] \qquad (4.1)$$

where:

CU_H = the Heermann and Hein uniformity coefficient,

n = the number of collectors used in the data analysis,

i = number assigned to identify a particular collector beginning with $i = 1$ for the collector located nearest the pivot point and ending with $i = n$ for the most remote collector from the pivot point.

V_i = is the volume of water collected in the ith collector,

S_i = is the distance of the ith collector from the pivot point,

$\overline{V_p}$ = is the weighted average of the volume of water caught.

where $\overline{V_p}$ is computed as:

$$\overline{V}_p = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i=1}^{n} S_i} \qquad (4.2)$$

The Heermann and Hein uniformity coefficient for centre pivot irrigation systems quantify the application uniformity of an irrigation systems sprinkler package. A sprinkler package with a uniformity coefficient of 100 % represents ideal application patterns; a system with a value below 100 % has a reduced uniform application pattern.

Two rows of catch cans were placed under the mini-pivot in a radial pattern from the pivot point out towards the end tower (Figure 4.8 and 4.9). The opening of each catch can was placed 160 mm above the ground surface with the distance between adjacent catch cans measuring 1.36 meters. Placement of the first catch can differed between the first and second row, with distances from pivot point measuring 3.85 m and 3.90 m respectively, this was done to obtain a generalization of the uniformity patterns along the entire system.

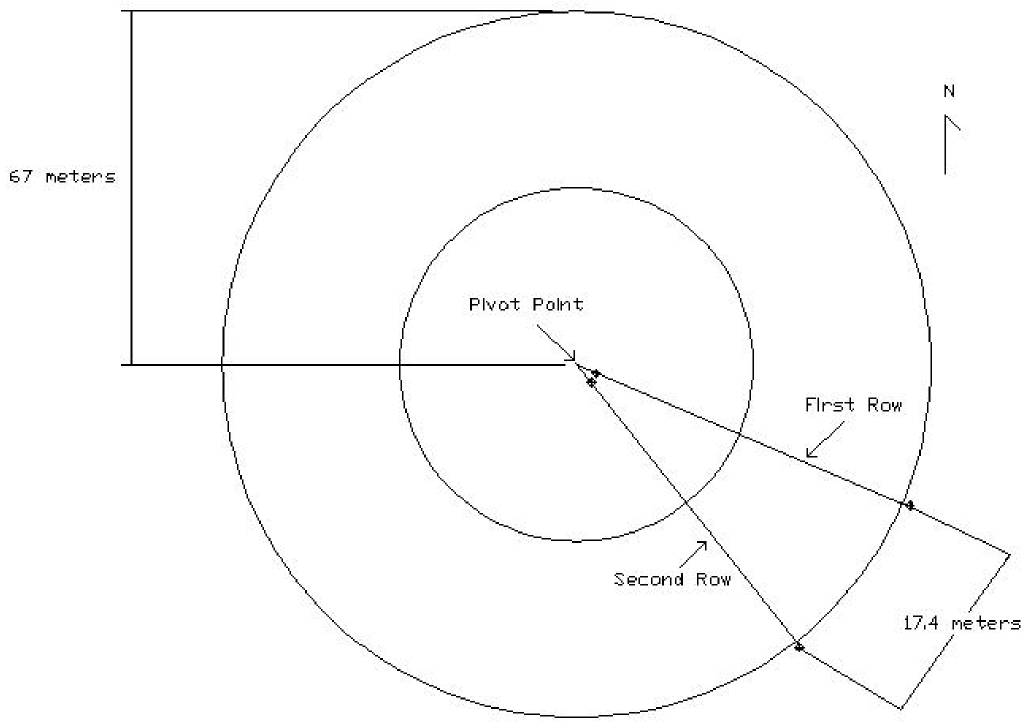

Figure 4.8: Catch can placement for uniformity coefficient testing under a two tower Greenfield miniature centre-pivot

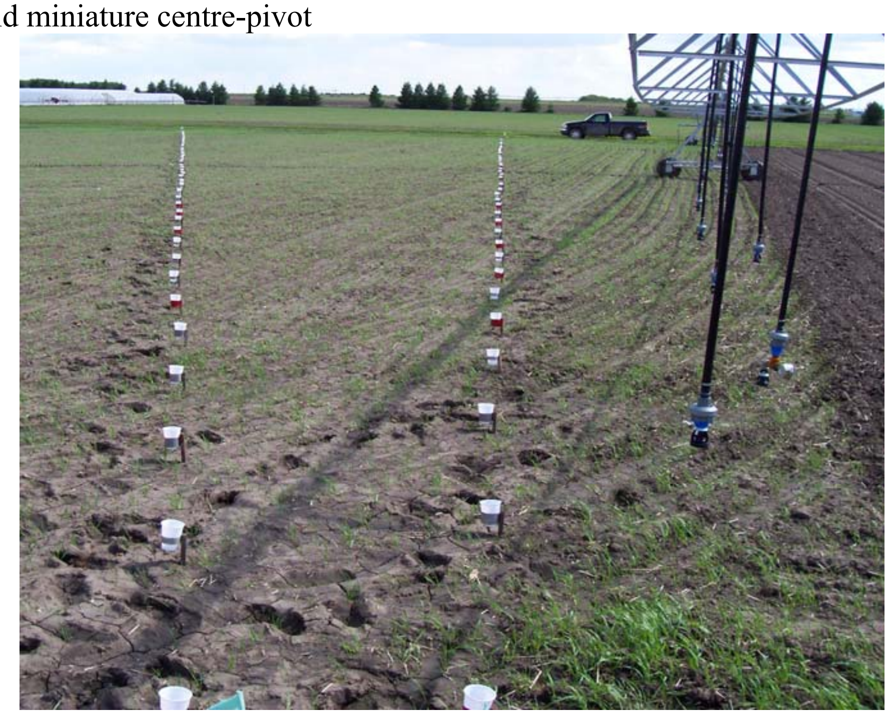

Figure 4.9: Radial placement of catch cans for uniformity coefficient testing under a two tower Greenfield miniature centre-pivot

Initial setup of the irrigation system's sprinkler package had the location of the sprinklers at 0.5 meters (1.5 feet) above the soil surface, the sprinkler levels were raised to 1 meter (3 feet) after poor application patterns were observed. Because the system was altered, a total of four tests were conducted, one for each of the two application rates and sprinkler height combinations. These additional tests were required to identify if sprinkler height modifications had an effect on the uniformity coefficient.

To compare the uniformity values between the high-flow and low-flow application rates, the end tower speed was altered such that each system would apply approximately the same depth of water with each test. The system speed for the low flow application setup was 30% of maximum system velocity. To achieve approximately the same application depth for the high-flow test the controller was increased to 100% of maximum system velocity.

Irrigation systems operate on a 60 second timer that controls the amount of time the end tower operates. Since motors on irrigation systems operate at a constant rate, 0.91 m min^{-1} end tower velocity, the watering duration is determined by the amount of time the end tower is in motion. A timer setting of 60% would result in the end tower being in motion for 36 seconds and stationary for 24 seconds. Varying the percent timer will vary the amount of time the system is in motion and directly affect the application time and resulting application depth.

The uniformity tests were conducted for both the high-flow and low-flow management practices at sprinkler heights of 0.5 m and 1.0 m, as per ASAE S436.1 DEC 01 with modifications proposed by Stonehouse et al. (1996). This resulted in a total of four controlled tests, one for each combination of application rate, by appropriately varying the systems nozzle sizing, and nozzle height.

Fig. 4.10 to 4.13 inclusive depicts the water distribution along the pivot lateral, for each of the four tests conducted. The project test zone is noted on each graph, this zone represents the area within which cabbage was sampled for water use and energy use efficiency calculations.

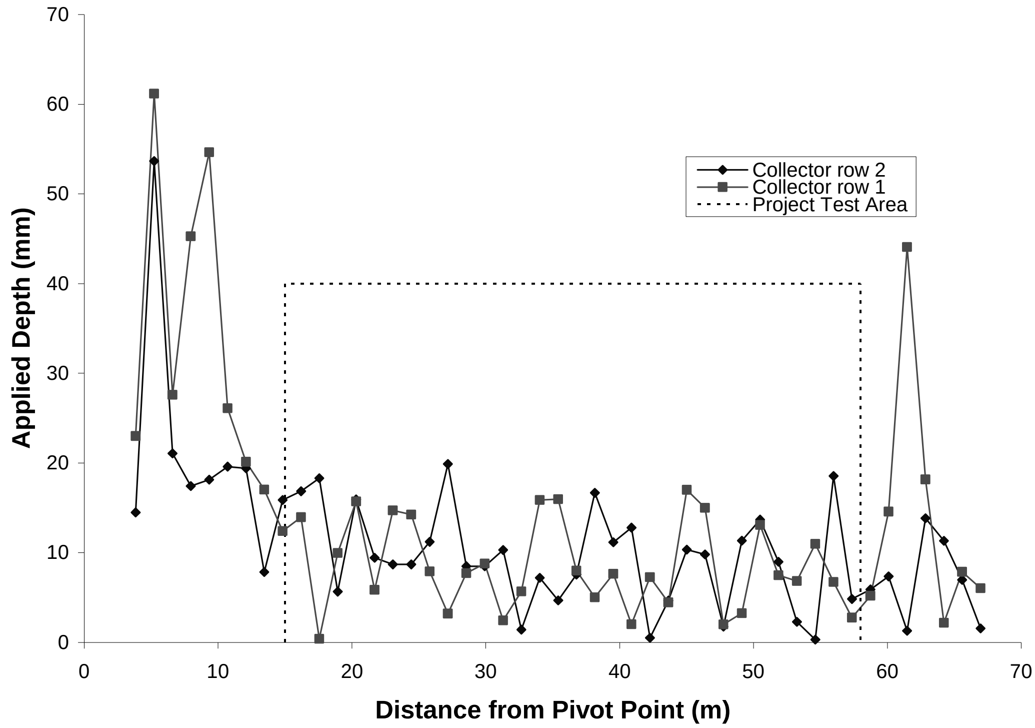

Figure 4.10: Water distribution along lateral section Greenfield miniature centre pivot, 94 lpm system flow rate and 0.5 m nozzle height, CSIDC May 18 2006

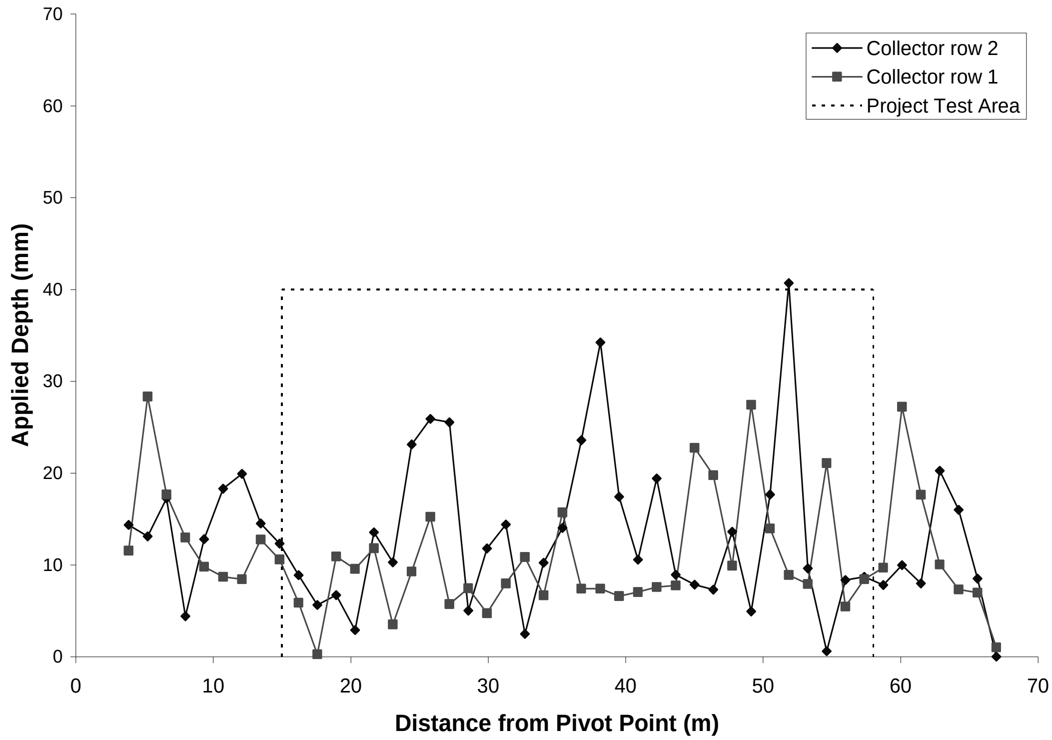

Figure 4.11: Water distribution along lateral section Greenfield miniature centre pivot, 370 lpm system flow rate and 0.5 m nozzle height, CSIDC May 18 2006

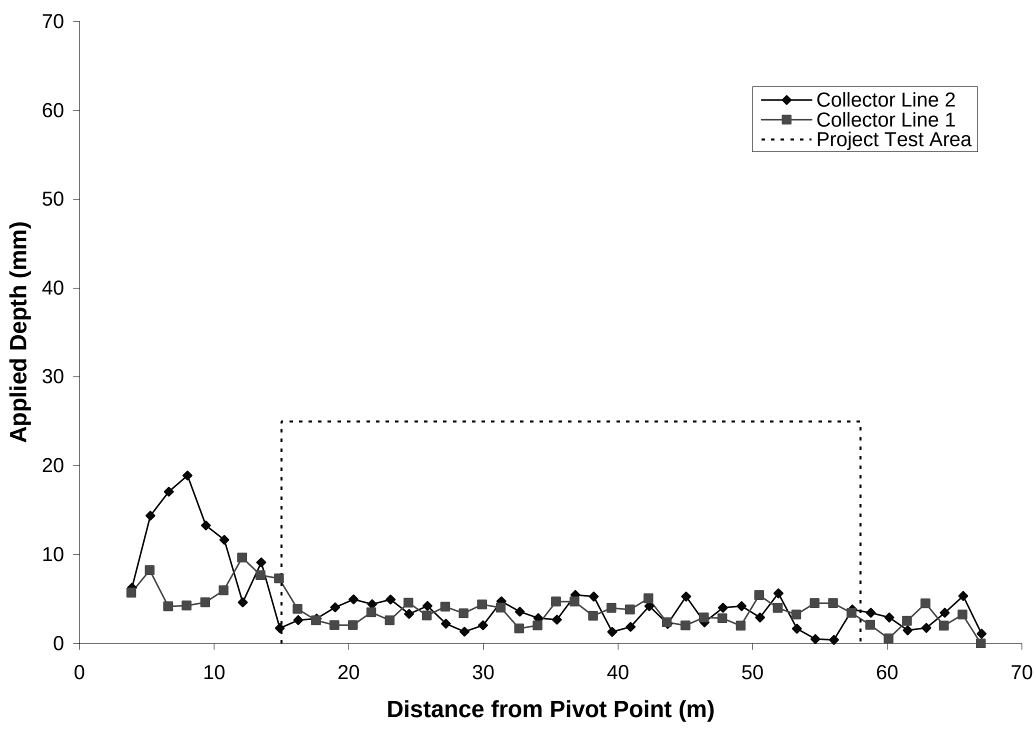

Figure 4.12: Water distribution along lateral section Greenfield miniature centre pivot, 94 lpm system flow rate and 1 m nozzle height, CSIDC June 1 2006

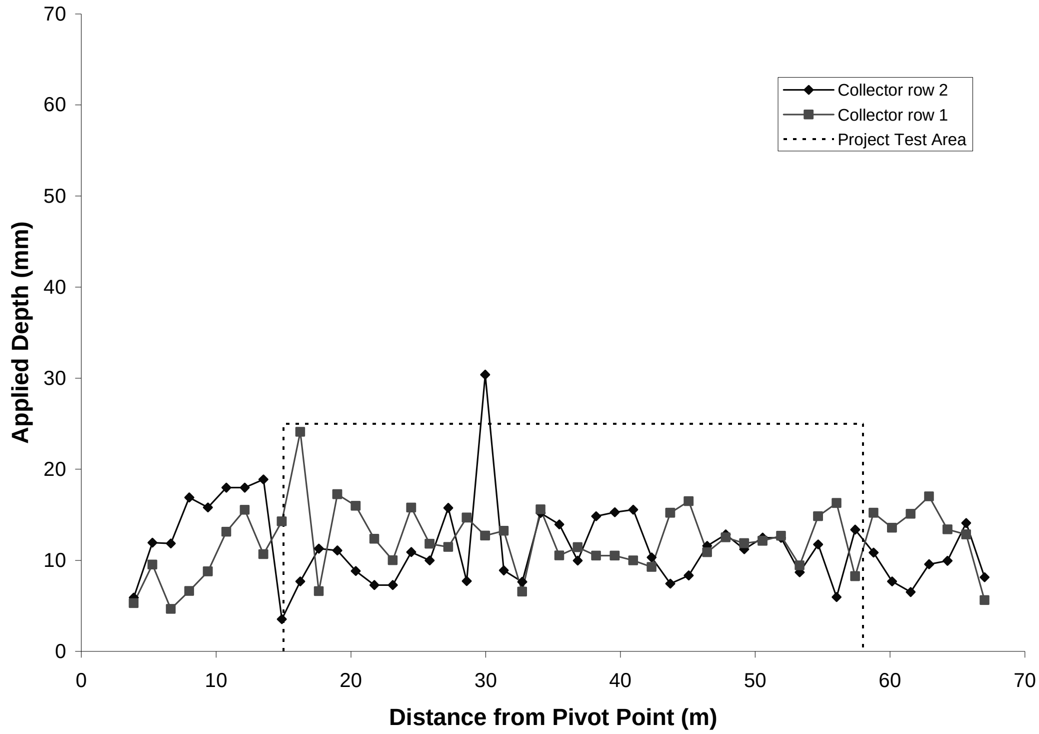

Figure 4.13: Water distribution along lateral section Greenfield miniature centre pivot, 370 lpm system flow rate and 1 m nozzle height, CSIDC June 1 2006.

Differences in uniformity occurred between each flow rate tested as well as the nominal height of the spray nozzle above the soil surface. From the test results, it can be concluded that there is an increase in uniformity converting from a low-flow rate application system to a high-flow rate application system. It should also be noted that uniformity can be increased by raising the spray nozzle height from 0.5 m to 1 m above the soil surface. Coefficient of uniformity differences between the 94 lpm and 370 lpm at 1 m nozzle height test is not readily apparent in Figure 4.12 and Figure 4.13, but the difference is numerically shown in Table 4.1. Because of the relatively small application depths observed along the lateral during the testing of the 94 lpm at 1 m nozzle height, the increase application depth near the pivot point had a significant affect on the coefficient of uniformity then similar variations observed during testing of the 370 lpm at 1 m nozzle height..

The variation between collector row 1 and row 2 of the coefficient of uniformity test (Table 4.1) is due to the offset of the collectors in row 1 and row 2. This offset insures that the average coefficient of uniformity is determined for the entire length of the centre pivot lateral.

Table 4.1: Uniformity coefficients for Greenfield solar powered miniature pivot with variations in system flow rate and above ground nozzle height

Test (System Flow rate / Nozzle Height)	Uniformity Coefficient, Collector Row 1 (%)	Uniformity Coefficient, Collector Row 2 (%)	Average Coefficient of Uniformity for System (%)
94 LPM / 0.5 m	38	48	43
94 LPM / 1 m	53	64	59
370 LPM / 0.5 m	53	48	51
370 LPM / 1 m	74	80	77

The increase in uniformity, caused by increasing the flow rate of the system, ranges from approximately 8 - 18 % depending on nozzle height. This is caused by a fundamental problem with nozzle availability by the manufacturer due to an increased probability of nozzles plugging with a smaller orifice diameter. This results in larger nozzle sizes than required near the pivot point due to a lack of smaller nozzle availability for low-flow application systems. Therefore over watering is more frequent in low-flow systems then high-flow systems near the pivot point, as system flow rate is dependent on the orifice sizing along the length of the centre-pivot system. Over-watering near the pivot point causes a decrease in the coefficient of uniformity and increases the potential for washout, run-off and disease development. To correct this problem irrigators must increase the flow rate of the system or pay for filter systems to allow reductions in nozzle size; but in many cases these costs outweigh the overall benefit of increased system uniformity.

The second aspect of the sprinkler package setup studied was the fixed height of the sprinkler above the soil surface. Spray nozzles, like the ones utilized by the Greenfield mini-pivot tested, rely on sprinkler spray overlap when delivering water to the crop canopy. Nozzle location, for this reason, is important in insuring that exactly two nozzles are supplying water to every point beneath the centre pivot lateral. Because sprinkler spacing along the lateral is generally predetermined, the other method for varying a sprinklers spray radius is to change the nozzle height above the soil surface.

The initial height of each spray nozzle above the soil surface was 0.5 m; this level was selected when the irrigation system was installed. During system testing in the spring of 2006, poor spray patterns were observed (Figure 4.14). The soil was showing areas, directly below each nozzle, where soil moisture levels were below the average for the irrigated area. The primary cause for these patterns was determined to be the low sprinkler height resulting in areas where spray overlap was not occurring. To correct this problem sprinklers were raised from 0.5 m to 1 m; resulting in an increased spray radius of each nozzle causing spray overlap and an increase in application uniformity.

Figure 4.14: Application pattern of Greenfield miniature pivot with a 0.5 m above ground nozzle height

Testing of application patterns at a 1 m sprinkler height showed noticeable improvement (Figure 4.15), with a more uniform application pattern and reduced occurrence of dry spots within the field. The uniformity test data supported observations when increasing nozzle height, with an increase in the coefficient of uniformity from 43 % to 59 % at 94 lpm and 51 % to 77 % at 370 lpm. An adjustment to sprinkler height is simple and has minimal cost associated with the process and can translate into increases in application uniformity.

Figure 4.15: Application pattern of Greenfield miniature pivot with a 1 m above ground nozzle height

Further testing should be conducted to look at the effects of miniature pivot sprinkler height on application efficiency and uniformity to determine the tradeoff and understand the optimal solution depending on a producer's situation and requirements.

4.4.2 Pivot characteristics

Pivot characteristics, such as end tower speed, operating pressure and system flow rate are given by the manufacturer, but testing was done to insure that accurate values were used in calculations. Due to the lack of data logging equipment and the high power demand of the flow meter, pivot characteristics could not be continually monitored throughout the season for use in calculations. Tests were conducted several times to obtain a sufficient generalization of system flow characteristics, which were observed to be consistent, for use in calculating water and energy use efficiencies.

End tower speed is important in determining the full-circle rotation time of a centre-pivot as well as the application depth of each pass. The rated end tower velocity given by the manufacturer was 0.91 m min^{-1} (3 ft min^{-1}). Testing conducted to determine the end tower velocity of the miniature centre pivot involved staking the tower wheel track at intervals of 6 meters (20 feet) to a distance of 42 meters (140 feet). The percent timer was then set to 100 % and the time duration to reach each distance interval was measured and recorded. This process was repeated for both high-flow and low-flow application rates to determine if the increase in application rate would affect tire slippage and alter end tower velocity. It was the thought that because end tower velocity is constant, an increase in surface wetness may result in an increase in tire slippage but this was not the case. This test however was conducted on a relatively level field; slippage due to surface wetness may increase on as the incline increases. From testing, the measured velocities were close to the stated manufacturer tower velocities (Table 4.2).

Table 4.2 End tower velocity for Greenfield miniature solar pivot

System flow rate (lpm)	Trial 1 velocity (m min.$^{-1}$)	Trial 2 velocity (m min.$^{-1}$)	Average velocity (m min.$^{-1}$)
94	0.91	0.94	0.93
370	0.91	0.93	0.92

The operating pressure had to be estimated from measurements and calculations, because the system tested was supplied from a pressurized pipe line. The pressurized line supplies water to a number of systems at any given time from the pump station that has four pumps that turn on or off depending on the demand. This on/off cycle can cause fluctuations to occur in the operating pressure depending on the number of pivots operating on the line and the number of supply pumps in use. For this reason, regulators were added to each sprinkler to insure that the operational pressure and application rate were generally consistent. To estimate the operating pressure of the pivot system at the pivot point calculations were performed using the Hazen-Williams equation and pressure measurements taken from sprinklers spaced evenly along the length of the system. Gauges were positioned on six sprinklers, between the pressure regulator and the spray nozzle (Figure 4.16), at distances of 5.7 m, 18 m, 30 m, 42.3 m, 54.5 m and 66.7 m from the pivot point. Pressure measurements were taken concurrently with flow rate measurements over a 45 min. period and repeated for both the high-flow and low-flow application setups.

Figure 4.16: Pressure gauge mounted between regulator and spray nozzle of low-pressure drop hose

Several pressure parameters were desirable in identifying the characteristics of the irrigation system; average overall sprinkler operating pressure, the operating pressure of the sprinkler located furthest from the pivot point and the resulting system pressure at the pivot point calculated utilizing the Hazen-Williams equation (Table 4.3).

Table 4.3: Operating pressure characteristics for Greenfield system determined from in-field testing

Application setup	Average sprinkler pressure (kPa)	End sprinkler pressure (kPa)	Pivot point operating pressure (kPa)
94 lpm	79	84	92
370 lpm	77	81	94

The operating pressures between the low-flow and high-flow application setups on the miniature pivot were essentially equal. The similarity in operating pressure was a result of the use of pressure regulators on each sprinkler. This was required to maintain proper sprinkler operating pressure and avoid pressure fluctuations that may occur with a pressurized pipeline.

The final characteristic to determine pump power requirements is the flow rate of each application system. Flow was measured with a magnetic flow meter attached to the riser pipe located at the pivot point (Figure 4.17). The flow meter was installed and calibrated using a sonic flow-meter, by an irrigation technician with Lindsay Manufacturing. The flow meter displayed instantaneous flow rate and total flow on a digital display. Flow rate was determined by measuring the total flow for 5 minute time intervals over 45 minutes. This process was repeated for both the high-flow and low-flow application systems.

Figure 4.17 Growsmart magnetic flow meter and digital totalizer located on the pivot point riser pipe

A total of eight flow rate trials were conducted, simultaneously with pressure measurements, three trials on the high-flow system and five trials on the low-flow system. The low-flow system garnered extra trials on the basis that there was significant variation between manufacturer values and values obtained from in-field trials (Table 4.4). In-field trial values were reproduced confidently and therefore were utilized in data analysis calculations. The final values used in each calculation were 94 LPM and 370 LPM for the low and high flow rates respectively.

Table 4.4: Application system rated and measured flow rates of Greenfield two-tower miniature pivot with low-flow and high-flow nozzle setup

Application Setup	Manufacturer Rated Flow rate (lpm)	Trial 1 (lpm)	Trial 2 (lpm)	Trial 3 (lpm)	Trial 4 (lpm)	Trial 5 (lpm)	Average (lpm)
Low-flow	114	93	95	93	94	96	94
High-flow	379	374	370	366	--	--	370

Table 4.5 and 4.6 were developed from trial data and were used in determining application depths. These tables are comparable to charts available to irrigators from sprinkler and pivot manufacturers.

Table 4.5: Two-tower Greenfield centre pivot irrigation water application chart at 94 lpm system flow rate and 92 kPa operating pressure

Main Panel Timer (%)	Full Circle Time (Hrs.)	1/4 Circle Time (Hrs.)	Total Volume Pumped (Liters)	Applied Depth (Gross) mm
100	7.6	1.9	43232	**3**
90	8.5	2.1	48035	**3**
80	9.5	2.4	54039	**4**
70	10.9	2.7	61759	**4**
60	12.7	3.2	72053	**5**
50	15.3	3.8	86463	**6**
40	19.1	4.8	108079	**7**
30	25.5	6.4	144105	**10**
29	26.3	6.6	148920	**10**
20.7	36.8	9.2	208445	**14**
20	38.2	9.6	216158	**15**
16.1	47.4	11.9	268352	**18**
11.2	68.4	17.1	387032	**27**
10	76.4	19.1	432315	**30**

Table 4.6: Two-tower Greenfield centre pivot irrigation water application chart at 370 lpm system flow rate and 94 kPa operating pressure

Main Panel Timer (%)	Full Circle Time (Hours)	1/4 Circle Time (Hrs.)	Total Volume Pumped (Liters)	Applied Depth (Gross) mm
100	7.7	1.9	170826	**12**
96.5	8	2.0	176985	**12**
90	8.5	2.1	189807	**13**
80	9.6	2.4	213533	**15**
70	11	2.8	244038	**17**
60.3	12.7	3.2	283153	**19**
60	12.8	3.2	284711	**20**
53.3	14.4	3.6	320740	**22**
50	15.4	3.9	341653	**23**
48.3	15.9	4.0	353971	**24**
40	19.2	4.8	427066	**29**
34.5	22.3	5.6	495580	**34**
30	25.6	6.4	569421	**39**
20	38.4	9.6	854132	**59**
10	76.9	19.2	1708263	**117**

4.4.3 Seasonal moisture content and water use

The term water use efficiency is a general term in agriculture and may have various definitions depending on the relationship to be quantified. Daniel Hillel of the Food and Agricultural Organization of the United Nations (1997) defined water use efficiency as the ratio of total crop production, in a form of total dry matter or marketable produce, to the total volume of water applied or consumed, given by

$$F_{ag} = \frac{C_p}{U} \tag{4.3}$$

where:

F_{ag} = agricultural water use efficiency ($kg \cdot m^{-3}$),

C_p = crop production (kg),

U = volume of applied water or consumed (m^3).

Crop production is determined from the harvest of the entire field or a crop sample based on dry matter weight or marketable weight as is the case with vegetables and fruits (Hillel 1997).

Warrick (2002) discussed the common form of a water balance equation that was used for this project (Eq 4.4). To identify the total amount of water consumed for a growing season a water balance must be conducted using measurements of water inputs including rainfall, irrigation, run-on and flux into the root zone, while monitoring the change in soil water content to identify the total losses from the system including deep percolation, runoff and evapotranspiration (ET). The resulting change in soil water storage is the difference between the defined inputs and outputs, given by

$$\Delta S = P + I + F + R_{on} - R_{off} - ET \qquad (4.4)$$

where:

ΔS = change in soil water storage (mm),

P = total seasonal precipitation (mm),

I = total seasonal irrigation (mm),

F = flux across lower boundary layer (mm),

R_{on} = total seasonal run-on (mm),

R_{off} = total seasonal run-off (mm),

ET = total evapotranspiration from crop canopy and soil surface (mm).

Gravimetric soil samples were taken at each of the twelve sampling sites, illustrated in Fig. 4.7, from the top 150 mm of soil on a weekly basis. These samples were important in determining crop water use and evaporative losses as well as aiding in irrigation scheduling to maintain soil water content above the stated 65 % of field capacity. Each sample was obtained from the midpoint of the top 150 mm of soil using aluminum cylindrical cores, which have approximate dimensions of 50 mm diameter and 30 mm height. Samples weighed approximately 50 g depending on moisture content; this weight is considered an adequate size for determining soil moisture (Reynolds 1970).

Samples were place in individual plastic bags in the field and transported to the centre for weighing and drying. Drying occurred over a 24 hour period at 103 degrees Celsius with an oven located in the onsite laboratory. Measurements and sampling followed procedure presented by Reynolds (1970).

Gravimetric soil moisture content (θ_m) was further converted into volumetric soil moisture content (θ_v) as per equation 4.5 (Warrick 2002).

$$\theta_v = \frac{M_w \cdot \rho_b}{M_s \cdot \rho_w} = \frac{\theta_m \cdot \rho_b}{\rho_w} \qquad (4.5)$$

where:

θ_v = volumetric soil moisture content ($m^3 \cdot m^{-3}$)

θ_m = gravimetric soil moisture content ($g \cdot g^{-1}$)

M_w = mass of water within the soil (g)

M_s = mass of solids within the soil sample (g)

ρ_w = density of water ($g \cdot m^{-3}$) considered as 1000 $kg \cdot m^{-3}$

ρ_b = bulk density, ratio of the mass of dry soil to the bulk volume ($g \cdot m^{-3}$); determined by weighing dry sample and dividing by the total core sample volume.

The average soil moisture content of the top 150 mm of soil was assumed to be equivalent to the soil moisture calculated from each sample core; following assumptions presented by Reynolds (1970) that soil moisture variability near the soil surface is minimal and a small sample can be representative of a larger area. These values were the primary measurements utilized in irrigation scheduling and included in calculating crop water use efficiency.

Neutron probe access tubes were inserted in the test field, at each of the twelve sampling locations, using a hydraulic corer supplied by SAF on June 19, 2006. Each tube was installed vertically to a depth of 1.2 meters, this depth minimized the section of the tube located above ground that could interfere with sprayer operation and allowed measurements sufficiently below cabbage rooting depth. Tubes were manufactured from thin-walled aluminum piping measuring 50 mm in diameter to insure a tight fit between the probe and access tube to maximize probe performance.

The neutron probe used was a CPN 503 DR Hydro probe (Figure 4.18), which converts measurements from a radioactive source into volumetric soil water content. At the beginning of the season the neutron probe was standardized as recommended by the manufacturer to correct for reading drift associated with storage and radioactive decay that occurs with age.

Figure 4.18: CPN 503 DR Hydro Probe and access tube used during soil moisture content measure

Neutron probe readings were taken between 150 mm and 600 mm below the soil surface, at intervals of 150 mm, on a weekly basis for use in irrigation scheduling. At the beginning and end of the growing season the measurement range increased from 600 mm to 1200 mm below the soil surface for water balance calculations. Due to the nature of the neutron probe, moisture content measurements cannot be accurately taken within the top 150 mm of soil surface; this issue led to gravimetric analysis being included in the project setup.

Field capacity was determined by taking soil samples throughout the test area at 10 sample locations for three depths, 0 – 300 mm, 300 – 600 mm and 600 – 900 mm. These samples were then prepared at the CSIDC laboratory and analyzed using a soil potentiometer. A soil potentiometer is an instrument that can be used to determine the soil-water potential, in terms of pressure (MPa), for sample with known moisture content. The methodology for these test followed that prepared by Terry Hogg P.Ag, Agronomist, CSIDC. Using this procedure the field capacity and permanent wilting point was determined for each sample (Table 4.7). From this data, a value of 65 % of field capacity could be calculated for irrigation scheduling purposes.

Table 4.7: Field Capacity and Permanent Wilting Point for Test Field

Sample Depth (mm)	# Tests Run	Field Capacity (mm mm^{-1})	Std Dev.	Permanent Wilting Point (mm mm^{-1})	Std. Dev.	65% of Field Capacity (mm mm^{-1})
0 – 300	100	0.271	0.052	0.093	0.011	0.176
300 – 600	100	0.325	0.075	0.103	0.013	0.211
600 - 900	100	0.434	0.120	0.127	0.034	0.282

Additional soil information was available in a soils report conducted for the Centre by Stushnoff and Acton from the Saskatchewan Institute of Technology in 1978.

4.4.4 Pivot power and energy requirements

For this research project the definition of EUE will vary slightly from the definition utilized by Lyle et al.(1993); EUE in vegetable production can be defined as the ratio of total marketable weight to the total energy required by the system, in this case the irrigation system. Because the solar panels are supplying power to the drive system of the centre pivot it is important to include drive energy in addition to the pumping energy in the final calculations.

The pivot's power requirement is the rate at which energy is drawn from the electrical source to drive the system through the field around the fixed pivot point. Power draw, for an electrical system, is the product of the voltage and current draw where energy is a function of power draw over time. To determine the power and energy requirements of the miniature pivot system, voltage and current were measured and logged for the pivot, solar array and battery systems during operation.

Voltage was measured in the control panel using a voltage transducer connected across the positive and negative poles of each of the three electrical systems (Figure 4.19). Current transducers were connected on either the positive or negative lead of each system, also located in the control panel. By installing these devices within the control panel they were protected from damage associated with environmental conditions.

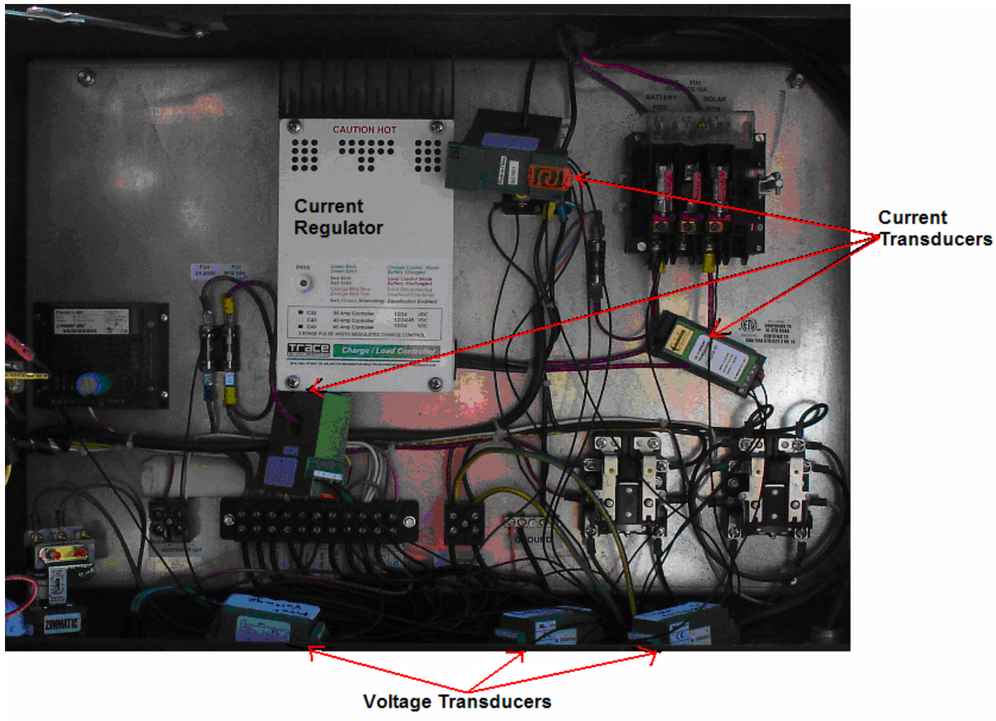

Figure 4.19: Greenfield solar powered mini-pivot control panel wiring showing current and voltage transducer placement.

Each transducer device was connected to a common Campbell Scientific 21X data logger and battery pack located in a storage bin adjacent to the control panel (Figure 4.20). This allowed system voltage and current draw to be measured, logged and time-stamped during operation for energy use calculations.

Figure 4.20: Campbell Scientific 21X data logger and battery pack located in storage bin adjacent to solar array and control panel

During regular watering and system operation, CSIDC had several incidences of pressure loss on their water lines as a result of computer errors and pipe failure. The drastic loss in pressure, on a number of occasions, caused the mini-pivot to shut down during active watering. This problem caused errors in reading and calculating the power draw and energy use of the system. As an alternative to identifying the energy use of each application, individual controlled tests were conducted on the mini-pivot for both high-flow and low-flow system nozzling. These tests were conducted over the entire range of settings, 0 – 100%, at intervals of 10% to develop a characteristic power draw curve for the system. Using these developed characteristic curves (Figure 4.21 and Figure 4.22) and determining the operation time required by each irrigation application, which is dependent on timer setting, travel distance and end tower velocity, energy requirements of both the high-flow and low-flow application set-ups could be determined for the season.

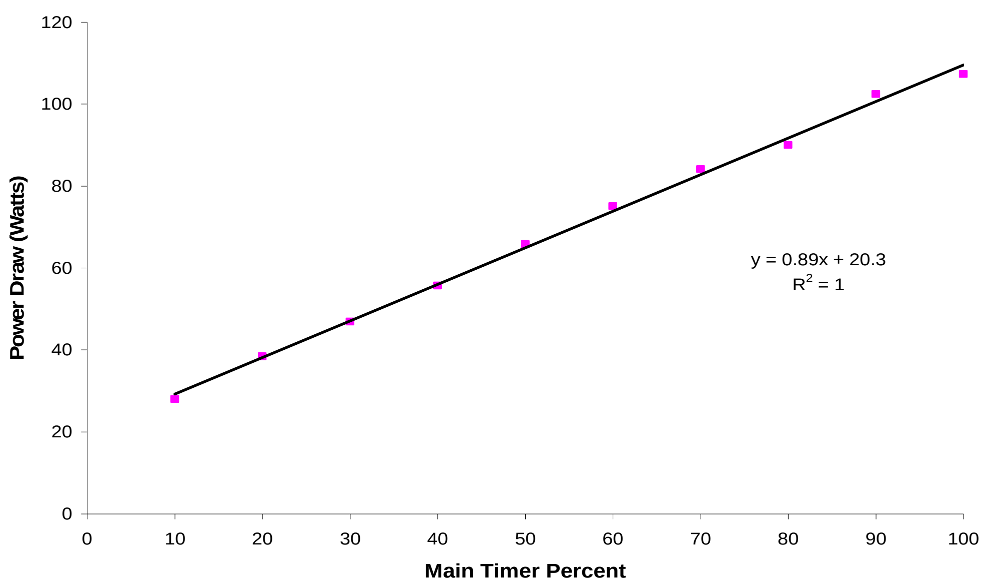

Figure 4.21: Power draw curve of two-tower Greenfield solar pivot with a 94 lpm system flow rate

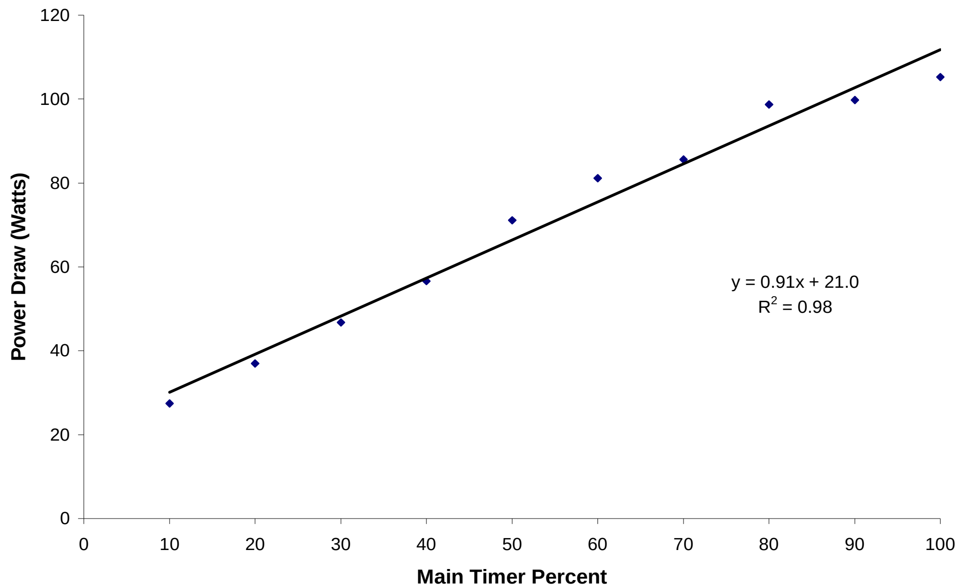

Figure 4.22: Power draw curve of two-tower Greenfield solar pivot with a 370 lpm system flow rate

The power draw, to operate the pivot drive and control system, is comparable in each application situation, suggesting that an increase in system flow rate and resulting increase. This test however was conducted on a relatively level field; power draw on an incline should be expected to increase. It should be noted, for each application practice, that there is a constant power draw of approximately 16 Watts; this draw is a result of power demand of the current regulator, indicator lights and control devices within the system that are in continuous operation.

4.4.5 Pump power and energy requirements

Pump power and energy requirements can be calculated using Bernoulli's extended equation presented by Mott (1994), knowing the flow rate, operating pressure and hours of operation of the irrigation system:

$$P_A = h_A \cdot W \qquad (4.6)$$

where:

P_A = power added to fluid (watts),

h_A = energy added to fluid by pump or total head on the pump (m),

W = weight flow rate ($N\cdot s^{-1}$).

But since, $W = \rho \cdot g \cdot Q$ equation [4.6] can be expressed,

$$P_A = h_A \cdot \rho \cdot g \cdot Q \tag{4.7}$$

ρ = density of fluid ($kg\cdot m^{-3}$),

g = acceleration due to gravity ($m\cdot s^{-2}$),

Q = volumetric flow rate of fluid ($m^3\cdot s^{-1}$).

Flow rate measurements were conducted using a Growsmart magnetic flow meter and digital readout. Pressure was measured using pressure gauges mounted between pressure regulators and spray nozzles spaced evenly along the length of the system. Utilizing the Hazen-Williams equation and the pressure measured at the end sprinkler nozzle, system pressure was calculated to a common point; this point was selected as the pivot inlet as the distance to the pump or water source will vary between all irrigation systems.

The Hazen-Williams equation [Eq. 4.8] (Pair et al. 1983) is a method of determining the friction loss in water pipes, and is the basis of many of the friction loss tables supplied by pipe manufacturers. The three primary components involved with this equation include the length and inside diameter of the pipe and the flow rate through the system. A fourth factor, the Hazen-Williams coefficient of friction, is incorporated into this equation to account for the inside surface roughness of the pipe.

$$H_f(100) = 1.22 \times 10^{12} \frac{(Q/C)^{1.852}}{D^{4.87}} \tag{4.8}$$

where:

$H_f(100)$ = friction loss (m/100m),

C = Hazen-Williams coefficient of friction,

= 150 for plastic pipe,

= 140 for galvanized pipe,

= 120 for aluminum with couplers,

= 100 for 15 year old steel.

D = inside diameter of pipe (mm),

Q = volumetric flow rate of fluid ($l \cdot s^{-1}$).

The characteristic flow rate and operating pressure of each application setup of the miniature pivot, high-flow and low-flow, determined from controlled field tests was used in the calculation of pumping requirements to resolve the problem of an absence of data loggers on measurement instruments.

4.4.6 Yield measurements

Yield sampling occurred on August 24 and 28 of 2006. Samples were taken two to three weeks prematurely due to a severe hail storm that occurred on August 23. The hail storm significantly reduced the leaf area of each cabbage and slowed biomass production. Damage to cabbage heads was observed as negligible and it was concluded that sample results would not be affected (Figure 4.23). The damage to celery and brussel sprout plants was extensive (Figure 4.24) and yield values could not be determined with confidence. This damage contributed to the decision to use cabbage head weight values as the lone data source.

Figure 4.23: Damage to cabbage crop from hail storm occurring at CSIDC on August 23, 2006

Figure 4.24: Damage to brussels sprout crop from hail storm occurring at CSIDC on August 23, 2006

Ten plant samples, consisting of ten cabbage heads due to hail shredding leaves, were harvested at each of the twelve sampling sites directly surrounding each moisture tube. Each sample was weighed in-field and recorded; weights were measured using a portable scale and storage container to insure cabbage did not contact the ground resulting in measurement errors (Figure 4.25). Cabbage head and above ground biomass was obtained, but above ground biomass values were disregarded as a result of the leaf degradation caused by the hail storm.

Figure 4.25: Portable scale and storage container for cabbage yield measurements

It was decided that the head weight value would be a more representative sample than total above ground weight in both water and energy use efficiency calculations, as head weight is the marketable weight and of value to a producer.

5.0 RESULTS AND DISCUSSION

5.1 Field Tests Results

Field tests were conducted during the 2006 growing season at CSIDC in Outlook, Saskatchewan. Field tests were also conducted during the 2005 growing season, but due to abundance of rainfall, those tests were used as a trial run to aid in project setup and were not included in the analysis of this project. Seasonal water use, energy use and yield production were measured to evaluate the production efficiency of each management practice.

5.1.1 Seasonal soil moisture content and crop water use

Seasonal soil moisture content was measured to identify the net seasonal change in soil moisture, water use of the crop under each management practice, as well as to trigger irrigation applications based upon the minimum soil moisture content of 65% of F.C. stated in the management objectives. The average moisture content of the top 150 mm, for each management practice (Figure 5.1), was the primary measurement used to trigger irrigation. This is a logical assumption that when soil moisture is adequate for crop water requirements 30%, or more, of an average plant's root water uptake comes from the top 10 % of the plant root zone (1.5 to 2 m for cabbage) if water is readily available, as modeled by Li et al. 1999.

In some incidences the water content dropped below the low level threshold. Sufficient soil moisture below 150 mm, Figure 5.2 and 5.3, insured suitable water until irrigation was able to raise the available moisture in the top 150 mm.

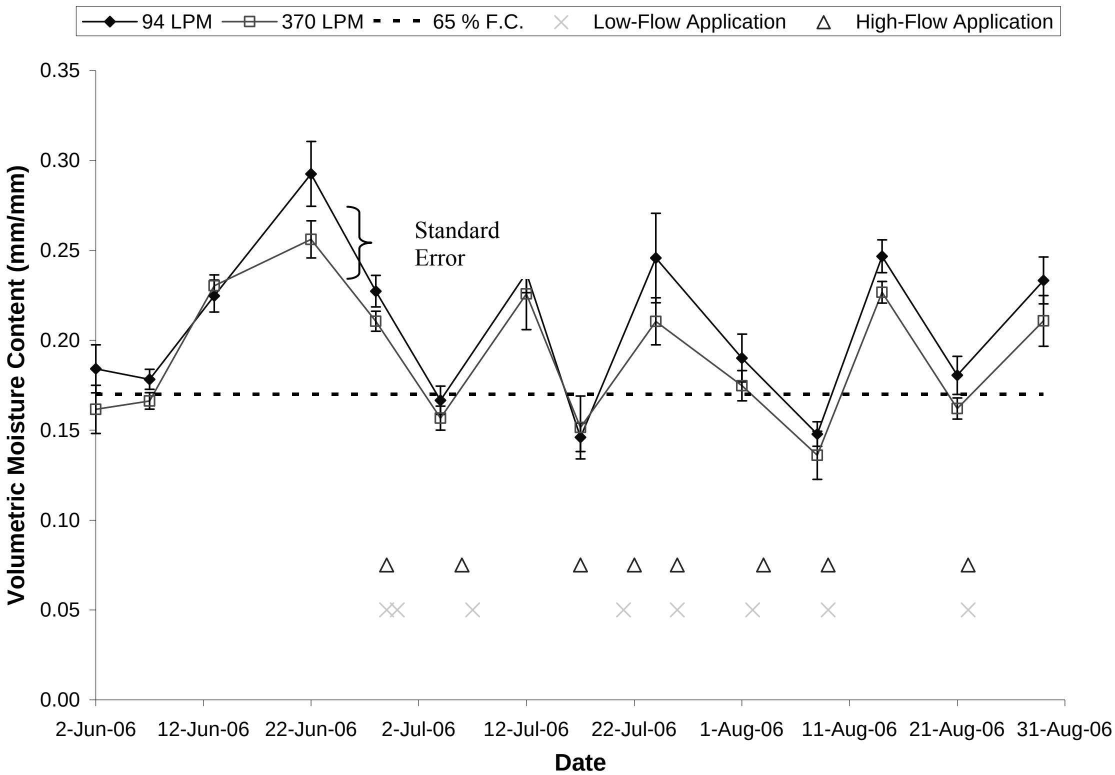

Figure 5.1: Volumetric moisture content of the top 150 mm of soil for each irrigation management practice

Water content measurements, below 150 mm, were taken using a neutron probe and access tube setup; one was located at each of the twelve sampling sites within the test field. The neutron probe was selected based upon the availability of probe and access tubes as well as being an accepted method to measure soil moisture content (Vincente et al. 2002). Neutron probe samples were taken weekly to a depth of 600 mm within the defined control zone of the project; the control zone was referenced in uniformity coefficient testing shown in Figures 4.10 to 4.13 inclusive. The sample depth was extended to 1200 mm at the beginning (June 27) and end (August 29) of the sampling period to identify possible water losses to flux across the root zone boundary layer for use in water balance calculations.

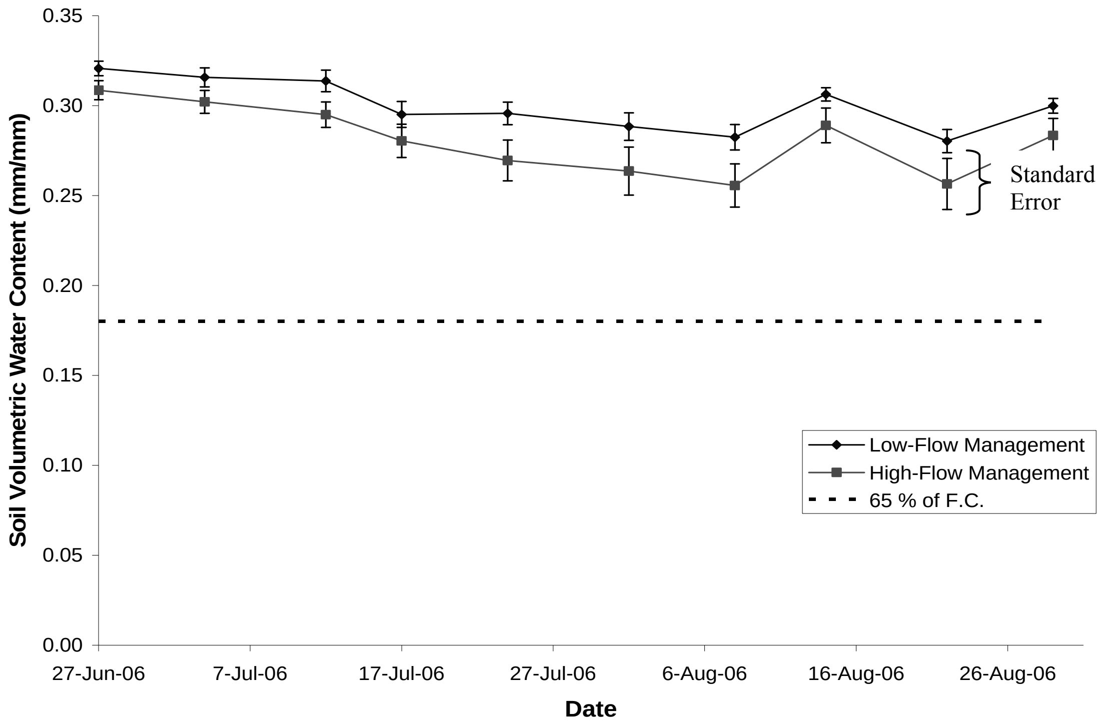

Figure 5.2: Volumetric moisture content, 150 – 300 mm soil depth, for each proposed irrigation management practice

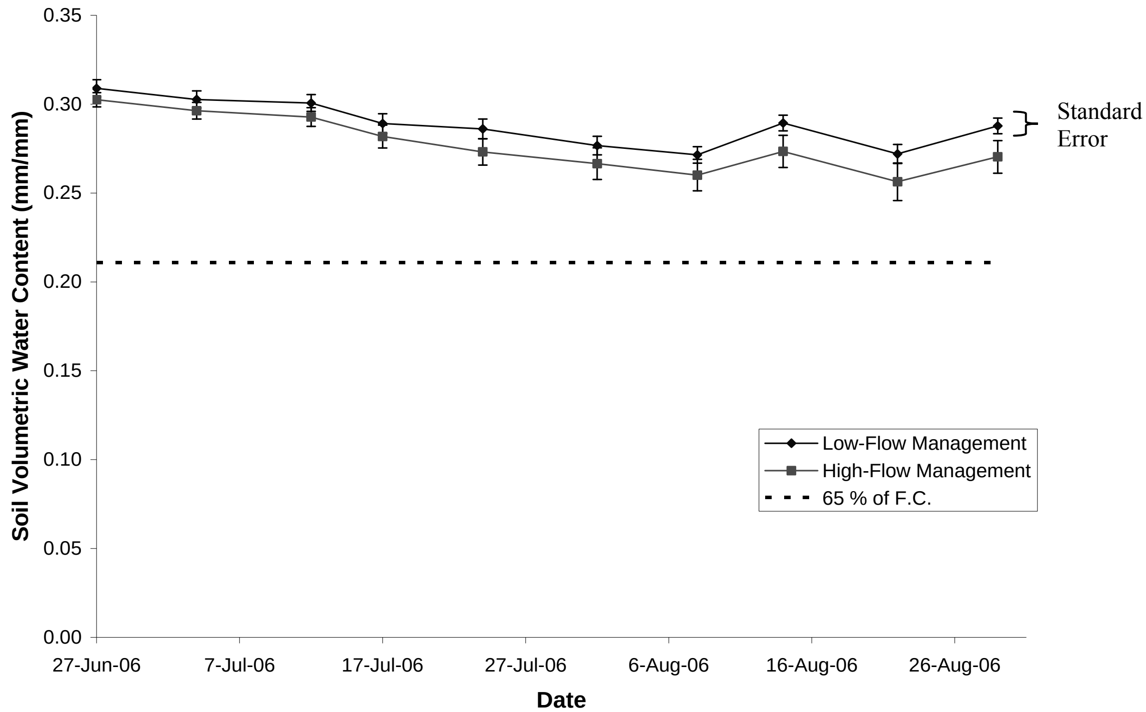

Figure 5.3: Volumetric moisture content, 300 – 600 mm soil depth, for each proposed irrigation management practice

Seasonal crop water use was required to determine the water use efficiency and evaluate the performance of each management practice. Recalling the basic water balance discussed previously [Eqn. 4.4], each component of this equation must be identified through measurements taken from the field or assumptions based upon known factors. The change in soil water storage was quantified using gravimetric and neutron probe readings at the beginning and end of the sampling season. The change in soil water storage was determined for each of the twelve sampling sites; this was completed to relate yield production to water use. An average for each management practice was later determined from these samples.

Precipitation was measured and recorded at the onsite Environment Canada meteorological station at the end of the season. The total rainfall (P) measured from the initial sampling date (June 2) to the harvest date (August 28) was 172 mm and the P parameter in the water balance for both management practices was assigned this value. The initial sampling date, June 2, was a full week after the transplanting date, May 25. This was to allow CSIDC employees to apply pesticides to the field without the neutron probe access tubes interfering with application equipment.

Irrigation data was determined using the characteristic charts developed from in-field testing (Tables 4.5 and 4.6), and recording the duration and percent timer setting of each individual irrigation event. This was done as a solution to a number of issues that came forth over the duration of the project. Issues involving the flow meter included; the lack of a logging device on the meter, technical failures with the meter, high-power demand of the meter restricting the continuous operating time and pressurized line problems that caused the system to shut down during active watering. By developing a series of controlled in-field tests and recording data manually, the above stated issues were avoided and irrigation characteristics were estimated. Using the field test data, the percent timer settings were converted into equivalent application depth for each event.

Table 5.1: Application depth and date for scheduled irrigation events

	Low-flow irrigation management (94 LPM)			**High-flow irrigation management (370 LPM)**		
Date	Timer Percent	Applied Depth (mm)	Cumulative Depth (mm)	Timer Percent	Applied Depth (mm)	Cumulative Depth (mm)
June 29, 2006	100.0	3	3	100.0	12	12
June 29, 2006	100.0	3	6	0.0	0	12
June 30, 2006	100.0	3	9	0.0	0	12
July 6, 2006	0.0	0	9	53.3	22	34
July 7, 2006	16.1	18	27	0.0	0	34
July 17, 2006	0.0	0	27	53.3	22	56
July 21, 2006	29.0	10	38	0.0	0	56
July 22, 2006	0.0	0	38	96.5	12	68
July 26, 2006	29.0	10	48	60.3	19	87
August 2, 2006	16.1	18	66	0.0	0	87
August 3, 2006	0.0	0	66	48.3	24	111
August 9, 2006	11.2	27	93	34.5	34	145
August 22, 2006	20.7	14	107	60.3	19	165
Seasonal Totals			**107**			**165**

These values correspond to the average gross application depth for the entire irrigated area. Irregularities within the field may be caused by poor system uniformity and it should be noted that application efficiency is not equal to 100 %. Any water loss due to evaporation from spray nozzles, surface ponding or runoff will be grouped into total losses.

Irrigation scheduling and application depths between each management practice were comparable during early stages of crop development. The irrigation requirements increased under high-flow management practices in the later stages of growth, from August 1 until a hail storm affected production on August 23 (Fig. 5.4). Because irrigation events were scheduled to maintain soil moisture content at 65% of field capacity (crop produced under similar growing conditions), logically there are two possible causes for differences in irrigation requirements. The first possibility is that yield production is increased under high-flow conditions resulting in increased transpiration rates and water demands. The second possibility is an increase in evaporative or runoff losses prior to infiltration resulting in reduced irrigation efficiency. Water use efficiency can be used to identify which case is most probable; this will be explained in further detail as water use efficiency values are determined.

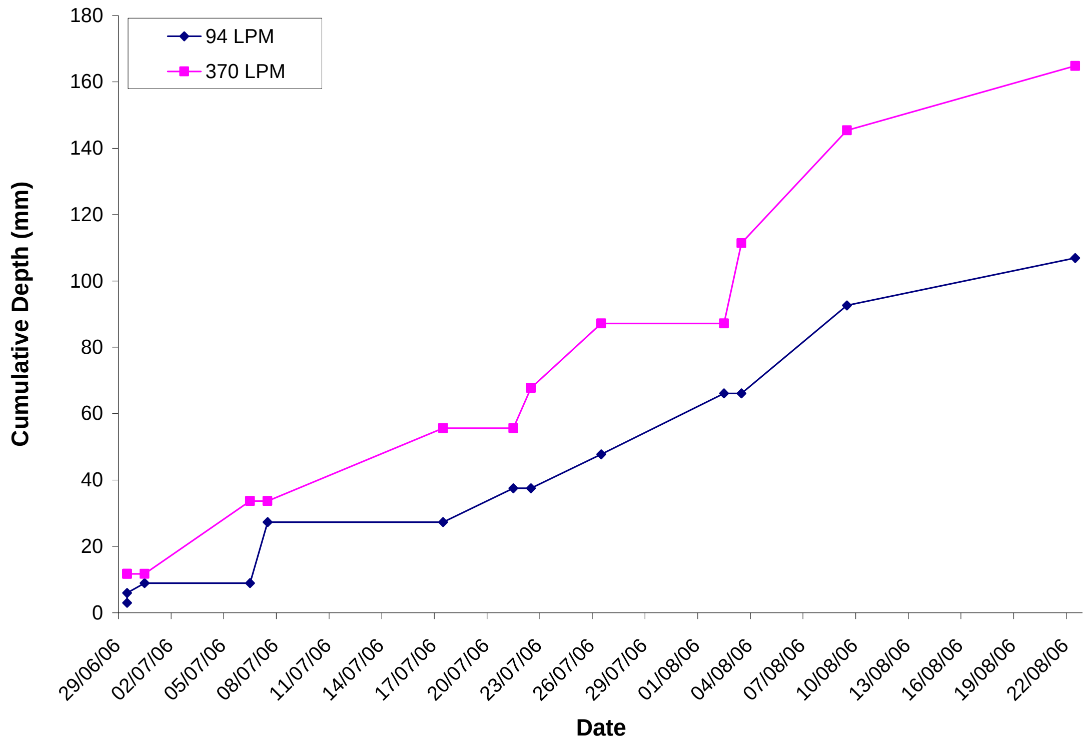

Figure 5.4: Cumulative irrigation depths for tested management practice

Movement of water across the lower boundary, set at 600 mm, was determined to be negligible over the growing season. This is confirmed by neutron probe measurements between 600 mm and 1200 mm. Over the depth of soil, the average volumetric moisture contents at the beginning of the season (June 27) was 0.326 mm/mm and 0.314 mm/mm for the low-flow and high-flow fields respectively. At the end of the season (August 29), these values had decreased to 0.311 mm/mm and 0.3 mm/mm respectively. These values translate into differences of 4.6 % and 4.5 % and were decided to be negligible for this analysis.

Run-on and run-off values were not measured directly due to lack of instrumentation. Run-off is likely to occur with increased application rates and application durations as proposed by Kay and Abo Ghobar (1990). Since these values cannot be quantified, they will be grouped into general water losses from the plant environment.

Taking into account the previously stated assumptions and values obtained from field testing, the total field evapotranspiration and losses associated with irrigation efficiency (pre-infiltration evaporation and run-off) the standard water balance [Eqn. 4.4] can be simplified,

$$\textbf{Total losses} = \textbf{Rainfall} + \textbf{Irrigation} - \Delta \textbf{S} \qquad (5.1)$$

The change in soil moisture content was calculated from field measurements taken weekly during the growing season, with seasonal change in soil moisture content being averaged from these values. Total losses from the system (field) include consumptive losses through transpiration, evaporation, runoff and efficiency losses, each of these were calculated using equation 5.1, for each of the twelve sampling sites located in the test field (Table 5.2).

Table 5.2: Seasonal (June 2 – August 29) evapotranspiration and irrigation losses from irrigation management test plots (0 – 600 mm depth)

Sample	Irrigation (mm)	Irrigation and Precipitation (mm)	ΔS (0 – 600 mm depth) (mm)	Total losses (mm)
1	107	279	-4	283
2	107	279	-1	281
3	107	279	19	261
4	165	337	-9	346
5	165	337	3	335
6	165	337	2	335
7	165	337	-25	362
8	165	337	-5	342
9	165	337	-2	339
10	107	279	-8	287
11	107	279	-5	284
12	107	279	-13	292
94 lpm	107	279	-2	282
370 lpm	165	337	-6	343

Average change in soil moisture content, the amount of rainfall and irrigation were used to calculate total evapotranspiration and efficiency losses between each management method and varied significantly, 282 mm and 343 mm for low-flow and high-flow management practices respectively. The ratio of the yield data over these values of total losses will result in WUE values for each of the sampling location within the project area.

5.1.2 Pivot power and energy requirements

Energy used by the pivot drive system for each management practice was determined from information about the average power draw of each irrigation event and integrating over the time required irrigating each management test plot (Table 5.3). Energy use had to be determined for each management practice, ¼ pivot revolution; energy demand of individual sampling sites within the field cannot be identified with confidence. Considerations must be taken into account to accommodate this issue when determining the energy use efficiency of each management practice.

Table 5.3: Seasonal energy use of Greenfield two-tower miniature centre pivot drive system under irrigation management practices

	Treatment 1 (94 LPM)				Treatment 2 (370 LPM)			
Date	Timer Percent	1/4 Circle Time (Hrs.)	Average Power Draw (Watts)	Drive Energy Requirements (kJ)	Timer Percent	1/4 Circle Time (Hrs.)	Average Power Draw (Watts)	Drive Energy Requirements (kJ)
June 29, 2006	100.0	1.9	110	749	100.0	1.9	112	764
June 29, 2006	100.0	1.9	110	749	0.0	0.0	21	0
June 30, 2006	100.0	1.9	110	749	0.0	0.0	21	0
July 6, 2006	0.0	0.0	20	0	53.3	3.6	69	899
July 7, 2006	16.1	11.9	35	1486	0.0	0.0	21	0
July 17, 2006	0.0	0.0	20	0	53.3	3.6	69	899
July 21, 2006	29.0	6.6	46	1098	0.0	0.0	21	0
July 22, 2006	0.0	0.0	20	0	96.5	2.0	109	782
July 26, 2006	29.0	6.6	46	1098	60.3	3.2	76	873
August 2, 2006	16.1	11.9	35	1486	0.0	0.0	21	0
August 3, 2006	0.0	0.0	20	0	48.3	4.0	65	933
August 9, 2006	11.2	17.1	30	1865	34.5	5.6	52	1055
August 22, 2006	20.7	9.2	39	1286	60.3	3.2	76	873
Seasonal Totals				**10567**				**7078**

The total seasonal drive energy required by each system was 10567 kJ and 7078 kJ for low-flow and high-flow management practices respectively. The ability of the high-flow system to apply water at an increased rate results in shorter operating times reducing the energy required to operate the control system, the increased observations of starting and stopping by the end tower during low-flow applications may have also accounted for the increase in seasonal energy requirements. Drive power is only one component of total system power requirements; pumping, in terms of irrigation systems, generally has a higher power demand and is required for energy use efficiency calculations.

5.1.3 Pump power and energy requirements

The power and energy required by a pump to transfer water from a source to the field is considerably larger then the energy required to power a centre pivot system. Pump power can be determined by identifying a systems flow rate and operating pressure and utilizing the extended Bernoulli's equation.

The average pivot point operating pressure, determined in section 4.4.2, for the low-flow and high-flow systems was 92 kPa and 94 kPa respectively. This is the average operating pressure at the pivot inlet and will vary depending on the water source location and corresponding elevation. It was decided to calculate pump power requirements at the pivot point, common to all pivot systems, to simplify the analysis.

The average flow rate for each application system, low-flow and high-flow, was equal to 94 lpm and 370 lpm respectively. Therefore, utilizing the extended Bernoulli equation [Eq. 4.6], the average pump power requirement is 145 Watts during low-flow and 581 Watts during high-flow applications. These values do not take into account pump efficiency; values will vary from pump to pump. Knowing the average power requirements to supply water for each irrigation event, the seasonal pump energy requirements can be determined in a similar method as the pivot drive requirements (Table 5.4).

Table 5.4: Seasonal energy use of pumping system to supply water to Greenfield two-tower miniature centre pivot under proposed irrigation management practices

	Treatment 1 (94 lpm)			Treatment 2 (370 lpm)		
Date	Timer percent	¼ Circle time (hrs.)	Pump energy requirements (kJ)	Timer percent	¼ Circle time (hrs.)	Pump energy requirements (kJ)
June 29, 2006	100.0	1.9	994	100.0	1.9	4018
June 29, 2006	100.0	1.9	994	0.0	0.0	0
June 30, 2006	100.0	1.9	994	0.0	0.0	0
July 6, 2006	0.0	0.0	0	53.3	3.6	7555
July 7, 2006	16.1	11.9	6170	0.0	0.0	0
July 17, 2006	0.0	0.0	0	53.3	3.6	7555
July 21, 2006	29.0	6.6	3426	0.0	0.0	0
July 22, 2006	0.0	0.0	0	96.5	2.0	4165
July 26, 2006	29.0	6.6	3426	60.3	3.2	6676
August 2, 2006	16.1	11.9	6170	0.0	0.0	0
August 3, 2006	0.0	0.0	0	48.3	4.0	8330
August 9, 2006	11.2	17.1	8898	34.5	5.6	11678
August 22, 2006	20.7	9.2	4795	60.3	3.2	6676
Seasonal Totals			35867			56654

Resulting seasonal pump energy requirements are 35867 kJ under a low-flow management practice and 56654 kJ for the high-flow management practice. This difference in energy requirements is a result of an increase in pumped volume as well as an increase in pressure loss when using a high flow application system. Increasing flow rate will result in an increase in energy loss, through friction, as illustrated by the Hazen-Williams equation. To maintain pressure requirements of the fluid within the system, the pressure supplied by a pump must increase accordingly. Referring back to equation 4.6, the Bernoulli's extended equation, as the pressure requirements increase the power and subsequent energy requirements will also increase.

The total system energy requirement for each management practice is equal to the summation of seasonal drive and pumping energy. The low-flow management practice had a drive energy value of 10.6 MJ and pump energy requirement of 35.9 MJ resulting in a seasonal system energy requirement of 46.5 MJ. In comparison to the high-flow management practice had a drive energy of 7.1 MJ, a pump energy of 56.7 MJ, and a seasonal system energy requirement of 63.8 MJ. These values are the seasonal values to grow a ¼ circle, approximately 0.36 hectares, of cabbage.

Utilizing a low-flow management practice translates into a 37% decrease in system energy requirements over the course of the growing season. This reduction in energy requirements is beneficial when utilizing a power system that has a restriction on seasonal energy output.

5.1.4 Yield measurements

Cabbage heads were harvested at each of the twelve sampling sites spaced throughout the test field (Figure 4.7). Recorded measurements were taken from the harvested samples prior to full crop development due to a hail storm that occurred on August 23, 2006 that caused outer leaf degradation (Figure 4.23). Sampling was done August 24 but was restricted to a number of sites due to saturated soil conditions causing access problems. A second sampling occurred on August 28, when the field had dried allowing sampling of all sites. During each sampling event, 10 cabbage heads were weighed and recorded from each site; with an average plant area of 0.35 m^2 the sample area was approximately 3.5 m^2.

Above ground mass of each plant was disregarded, because the hail caused a reduction in the outer leaf area and values were not representative of the true weights of undamaged plants. Outer leaves protected the cabbage head from damage and mass reduction; it was agreed that head weights would be used in water and energy use efficiency calculations as these values are a realistic value of marketable weight.

The average head weights between each management practice had no statistically significant difference (at the 95% confidence level), with the low-flow management producing an average head weight of 1.91 kg compared to 1.89 kg for the high-flow management (Table 5.5). Similar yields being produced with different application depths suggests that the excess water is not being utilized beneficially by the crop and therefore is being lost directly to evaporation, deep percolation or run-off.

Table 5.5: Cabbage head yield weights (kg) from sample sites under proposed irrigation management practices

Date	1	2	3	10	11	12	94 LPM	4	5	6	7	8	9	370 LPM
August 24, 2006	1.65	1.96	1.81	--	2.01	--	**1.86**	1.71	1.74	1.76	--	2.01	--	**1.81**
August 28, 2006	1.86	2.16	1.82	1.96	2.22	1.74	**1.96**	2.13	2.20	1.64	1.95	1.97	1.96	**1.98**
Avg. Head Weight (kg)	**1.76**	**2.06**	**1.82**	**1.96**	**2.12**	**1.74**	**1.91**	**1.92**	**1.97**	**1.70**	**1.95**	**1.99**	**1.96**	**1.89**

Sampling of four sites was not completed on August 24, 2006 due to moisture in field due to hail storm prevented field accessibility for sampling.

To identify exactly how a crop is utilizing water and energy under a management practice, measurements must be quantified into an efficiency value.

5.2 Data Analysis

Water use efficiency and energy use efficiency were selected as the methods to evaluate each management practice and to quantify the data obtained from field tests. Water use efficiency is an identifier of how well a management practice performed and where energy use efficiency is generally related to water use. Because the system being evaluated is dependent on a constrained power supply, energy use efficiency is included in the analysis to determine how the proposed BMP affects system energy use.

5.2.1 Water Use Efficiency

Water use efficiency was calculated, for each of the twelve sampling sites (Figure 5.5), as the ratio of average head weight (wet) of cabbage sampled over the depth of water consumed or lost from the system as per the water balance equations [Eq. 4.4].

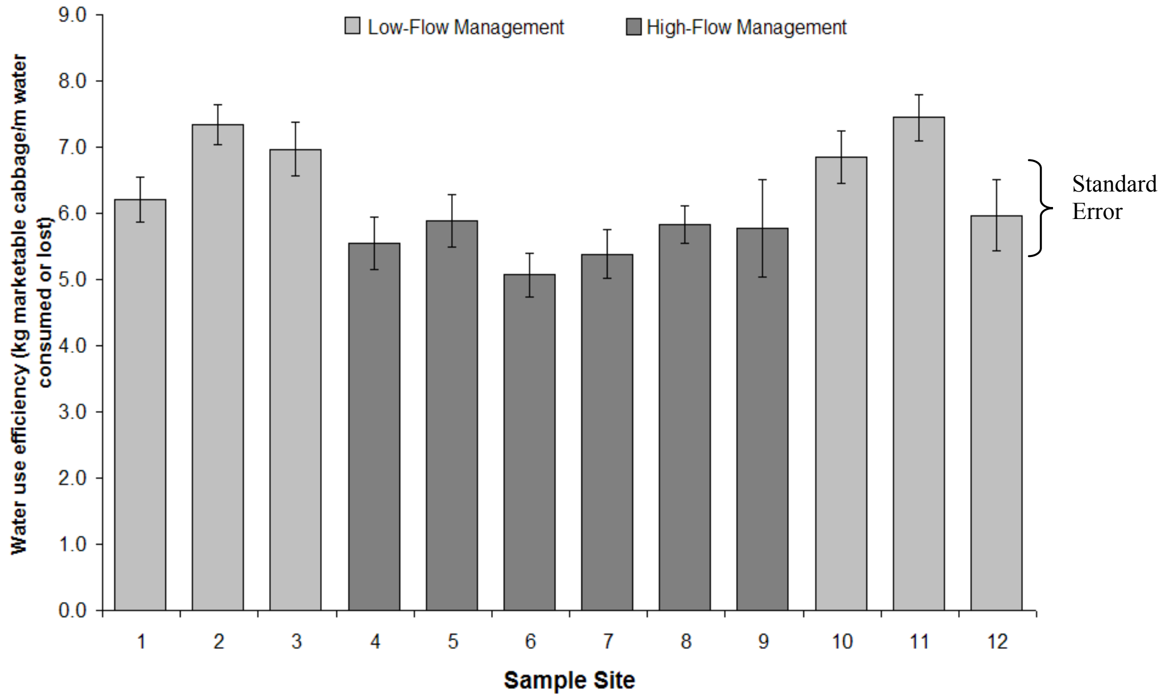

Figure 5.5: Water use efficiency of irrigation management practices for cabbage production with Greenfield solar powered mini-pivot

The average water use efficiency of the low-flow management practice was measured as being 6.8 kg marketable weight for every meter of water consumed or lost. The high-flow rate management practice had an average water use efficiency of 5.6 kg m^{-1}. The 1.2 kg m^{-1} difference amounts to a 21 % increase in water use efficiency when converting from a high-flow to a low-flow management practice. These efficiency values are based upon a plant spacing of 460 mm x 760 mm or 0.35 m^2 given for each plant. Water use efficiency values, based on this plant spacing, could also be represented as 19.4 kg and 16 kg marketable weight for every cubic meter of water consumed/lost for low-flow and high-flow management practices respectively.

The difference in yield production was minimal, with the average head weight between each management method differing by approximately one percent. It therefore can be suggested that because each crop differed by only water application practices, the excess water loss experienced in the high-flow management practice was not beneficial to plant growth. The possible causes for water loss include excess ponding causing increased surface evaporation, potential run-off and evaporation caused by a decrease in application efficiency. Ponding was visually observed during high-flow application system operation, creating an increased potential for pre-infiltration evaporation or increased runoff. This is supported by Kay and Abo Ghobar (1990) who demonstrated that application rate directly affects volume of run-off, depending on soil texture.

Altering the time of application by varying between day time and evening-night irrigations may have also been a contributing factor for the difference in water consumed or lost. Day time irrigation, associated with the high-flow management practice, had a lower value of water use efficiency compared to the low-flow management practice, which had irrigation events were scheduled primarily in the evening and night. How each aspect of the BMP affected WUE could not be quantified because of the scope of this study; further research is required to determine how each component of the proposed BMP would individually influence WUE.

From the resulting research data and supporting literature review it can be suggested that the proposed low-flow management practice is a more beneficial management practice, in terms of improving water use efficiency by definition, compared to the current high-flow management practice employed at CSIDC.

5.2.2 Energy Use Efficiency

Energy use efficiency of each system was determined by quantifying the total seasonal energy required by the drive and pump systems for the total area that was produced by the high-flow or low-flow BMP package. The potential marketable production was equal to the average head weight of a sample site multiplied by the total potential plants available within each area under the specified BMP. Based on a field area of 3560 m^2, for each BMP, and a plant area of 0.35 m^2 there is potential for approximately 10200 plants. This value ignored spray paths and assumes the entire field was planted with cabbage. Using this value of 10200 plants, the average cabbage head weight of each sample site (Table 5.5) and the seasonal energy requirements of each management practice (Table 5.3 and Table 5.4), the energy use efficiency for each sampling site was determined (Figure 5.6).

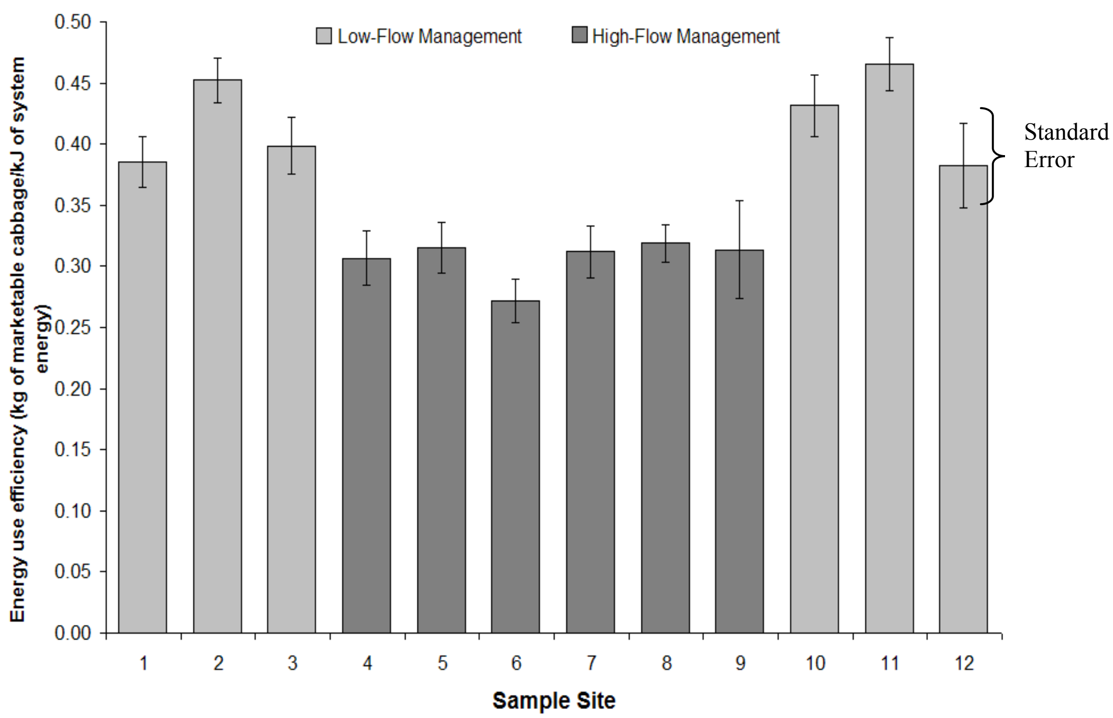

Figure 5.6 Energy use efficiency of irrigation management practices for cabbage production with Greenfield solar powered mini-pivot

Energy use efficiency follows a similar trend as water use efficiency, with a greater statistical difference represented between each management practice. The average energy use efficiency of the low-flow management practice is equal to 0.42 kg of marketable weight produced for every kilo joule of energy required by the system. This is an increase of 35 % over the energy use efficiency of a high-flow management practice averaging 0.31 kg kJ^{-1}.

The difference in efficiency is a result of increased pumping volume to compensate for differences in water use efficiency as well as the increased energy loss, through friction, when pumping water at higher-flow rates. To supply this additional water to the field, the total pumping volume as well as the irrigation duration increased, resulting in increased energy usage. Another possible cause for the difference in energy use efficiency was the variation in friction loss values between each system. Friction loss, the energy loss from water through friction with the pipe walls, increase as the volumetric flow rate through a constant pipe diameter increases. To compensate for this loss the initial pumping head must increase to insure sufficient pressure at the end sprinkler nozzle resulting in an increase in power and energy requirements for the system.

5.3 System Potential and Recommended Use

The solar drive pivot system located in Outlook, Saskatchewan is the first of its kind in Canada (Zimmatic Canada 2006). It is important to identify the potential use of this type of system, as an energy alternative, with regards to vegetable production.

To identify the potential uses of these systems, the constraints and characteristics of the operating environment first must be established. As an introductory analysis of the potential for these systems, the constraints and scenarios were simplified to create a general understanding. The key aspects of the environment taken into account during this analysis consisted of:

i) Crop type – crop type selected was a cabbage crop with a spacing of 460 mm x 760 mm.

ii) Soil type – three soil types including Sand, Loam and Clay soil were selected to give a broad range of possible field composition.

iii) Irrigated area – the irrigated area was dependent on the length of the system, assuming the entire field was planted to cabbage; calculations were based on a standard 33.5 m span length. It was determined, for pumping requirements, that system length would not exceed three towers as energy requirements made longer systems unreasonable.

iv) System location - irrigation system location, with respect to the water source, is important in determining the required pumping head and resulting energy requirements of the water delivery system.

v) Solar production/PV cell output – panel sizing and selection is dependent on potential daily solar panel energy production and system energy requirements.

With these key aspects identified, general guidelines for system selection can be established to identify the potential of implementing this type of system into production of high value crops.

5.3.1 Crop type

Crop type was limited to vegetables because the capital cost of these systems limits production to high value per acre crops. Cabbage was selected because of its high water demand and ability to be grown in the cool short growing seasons experienced in the Canadian prairies. Many other cool climate vegetable crops would also work well with this type of system, but to minimize the scope cabbage was only looked at in this analysis.

In irrigation design, pivot and supply systems are selected to ensure sufficient water is supplied to meet peak crop demands during the growing season. Peak crop demands, for cabbage, can be determined by calculating the peak sustainable evapotranspiration (ET) of the crop during growth. ET can be calculated knowing the maximum ET of a reference crop in combination with a crop coefficient (Allen et al. 1998). In this project a grass reference crop was employed for predicting water requirements of cabbage produced in the prairies. Irrigation management and irrigation system sizing is important when crop water requirements are at peak levels and therefore a mid-season crop coefficient, representing a period of maximum water demand, was utilized. System size and resulting irrigated area must be restricted; because the end tower velocity is constant the system must be design such that water can be applied to sufficiently keep up with potential evapotranspiration. From data presented by Maulé et al. (2006), a value of 6 mm day^{-1} was assumed as a maximum sustainable potential ET_o. This is not the maximum value observed, but it is an ET value that was sustainable for a sufficient period of time, 4 to 7 days. This was combined with a crop coefficient for cabbage at peak growth of 1.05 (BCMAFF 2001), the reference crop has a constant coefficient of 1.00. It therefore can be assumed that the maximum sustainable evapotranspiration for cabbage is equal to 6.3 mm day^{-1}.

5.3.2 Soil type

Soil water storage, related to soil type, has an effect on irrigation system selection. Soil characteristic will determine the amount of water to apply with each irrigation event and the resulting days between irrigation events (Table 5.6). The time between irrigation events for this project was referred to as the duration of an irrigation cycle. The duration of an irrigation cycle, time between consecutive irrigation event starts, is important to determine the water requirements per application and sizing of the solar panel to ensure that system energy demands are met.

Table 5.6: Irrigation scheduling requirements to meet peak cabbage crop water demands for the climate of the Outlook, SK. region depending on soil type

Soil Property	Clay	Loam	Sand
Field Capacity (mm of water /mm of soil)	0.38	0.24	0.15
60 % - 70 % of F.C. Range (mm/mm)	0.25 – 0.27	0.14 – 0.17	0.09 – 0.105
Allowable Depletion (mm)	55	39	24
Days between irrigation event starts (ET = 6.3 mm/day)	9 days (8.7)	6 days (6.2)	4 days (3.8)

*Assumed 460 mm rooting depth
Soil data taken from information presented by Warrick (2002)

System flow rate should be adjusted with soil type, as infiltration rate will change as soil type changes. To simplify this analysis, a constant system flow rate of

232 lpm per hectare was used; this value is comparable to the system flow rate used by the low-flow management practice that was previously developed.

5.3.3 Irrigated area

Irrigated area of a centre-pivot irrigation system is dependent on the number of towers and the resulting radial length. For this analysis, the system was confined to three towers with a standard tower length of 33.5 m with the first tower measuring 35.4 m. System length and the resulting irrigated area, shown in figure 5.7, were used in determining the system flow rate.

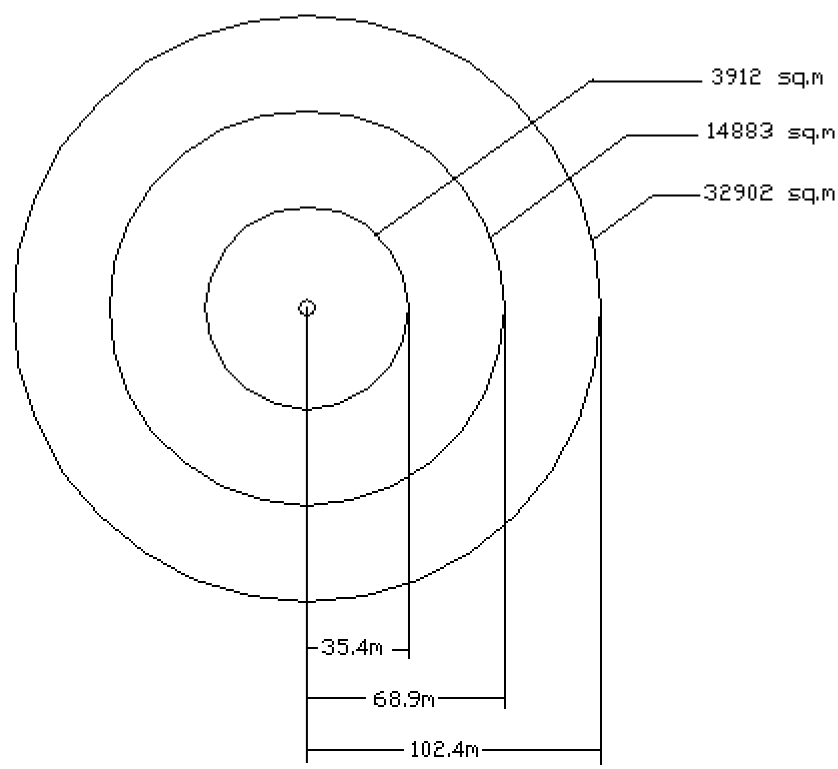

Figure 5.7 Span length and resulting irrigated area of Greenfield miniature pivot

Knowing the irrigated area, based upon the number of towers selected, and the standard system flow rate of 232 LPM per hectare, the total flow rate is calculated for each configuration. Total flow rate for a one tower system is approximately 25 lpm (1.5 m^3 hr^{-1}), increasing exponentially to 94 lpm (5.7 m^3 hr^{-1}) and 208 lpm (55 m^3 hr^{-1}) for two and three tower systems respectively.

5.3.4 System location

The pivot location with respect to a source of irrigation water is required to determine pumping pressure requirements. Specifically, the elevation difference between the water source and the pivot system (Figure 5.8) is used to determine the required pumping head to apply water at the required system pressure. Pumping head or total head is the pressure required by a pump to overcome elevation head differences (static head) and friction losses while meeting minimum sprinkler operating pressure head (Lundstrom 1989). A broad range of possible pumping head requirements will be looked at in this analysis. In general, individual systems will vary by flow rate, which is dependent on the length of the system, and by the pumping head required to deliver water at the specified flow rate. Knowing these two aspects will allow an irrigation producer/dealer to estimate the operating requirements and select the power system.

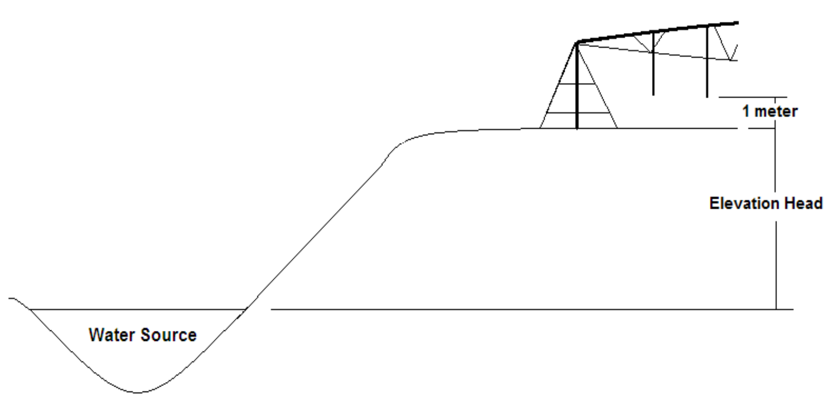

Figure 5.8: Elevation head of a centre pivot irrigation system with respect to the water source

5.3.5 System Power and Energy Requirements

System power and energy requirements can be estimated by estimating the power and energy requirements of the drive and pump systems. This analysis will be conducted similarly to energy use efficiency for the test field, although it will require identification of; a) power requirements by each pivot system configuration and b) resulting power requirements by the pumping system, depending on pumping head and flow rate requirements.

Pivot power requirements can be broken down into two components: a) the power required for moving the system around the fixed pivot point, and b) the power required to operate the current regulator and other control systems. Power demand of each pivot system, depending on the number of towers, is shown in Figure 5.9. Two tower system data was collected from in-field tests and averaged over the full range of system operation limits. The in-field test data was used to estimate the power draw of a one and three tower miniature system, due to the lack of available systems for testing. Individual tower operation data was isolated from the two tower in-field test data; this isolated data was used to estimate the operational power draw that would occur with a single tower miniature solar pivot.

Estimating the power draw of a three-tower system required extrapolation of the one- and two-tower power draw data. Knowing the operating characteristics of a centre pivot irrigation system, in a three-tower setup, the end, middle and first towers operate 100 %, 66 % and 33 % of the irrigation event respectively, when pivot is operating at 100 %. The power draw of a three-tower miniature pivot can be estimated using this concept and available data. The two functions displayed in Figure 5.9 relate the power requirements of the entire system and the power requirements of the drive system independent of the control systems. It is important to isolate these values as the current regulators and control systems require power during irrigation and recharge periods, where the drive system is drawing power only during irrigation events. Therefore, constant power draw of the current regulator and control systems must be accounted for when determining the total energy requirements of the irrigation system during and between irrigation events.

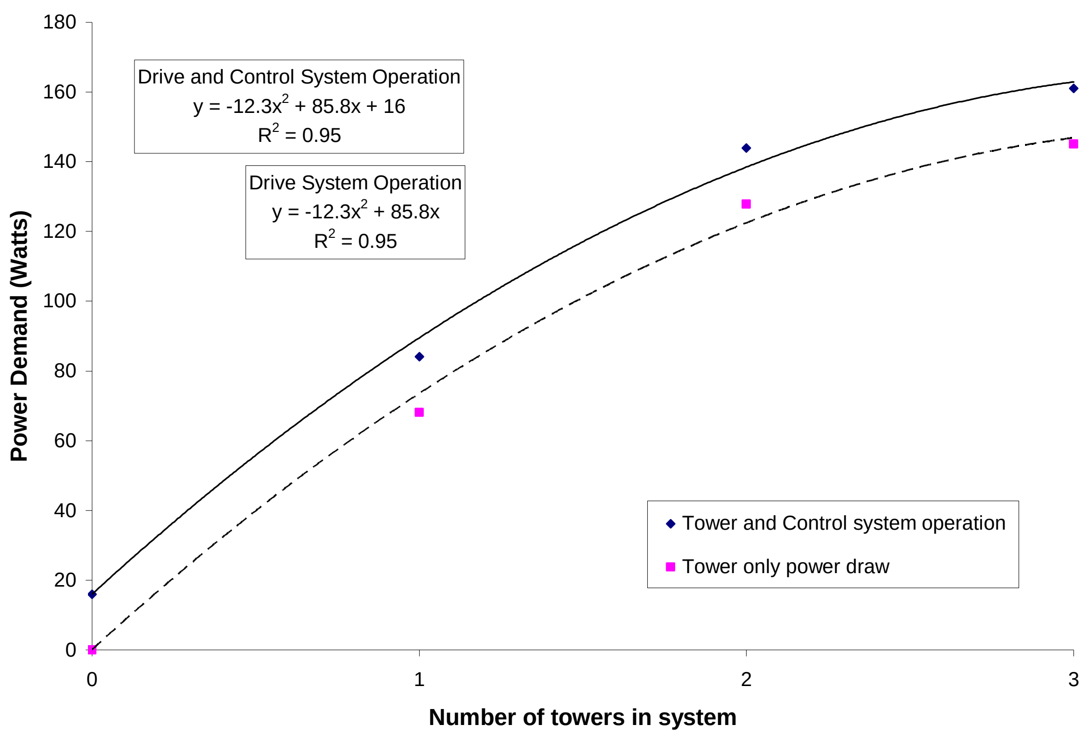

Figure 5.9: Power requirements of Greenfield mini-pivot drive and control system for a one-, two- and three-tower system setup

The total drive energy required for each irrigation event can be determined knowing the power demand of each configuration and the time required to complete a full circle (assuming 100% timer setting). Knowing the estimated power draw of each system (Figure 5.9), the travel distance of the end tower, and the end tower velocity (Table 4.2), total drive energy requirements can be determined.

Sample Calculation (3 tower system):

From Table A7:

Power Draw of Drive System (towers only) = 147 Watts

End tower travel distance = 634 m

Full circle time, traveling at 0.91 m/min = 697 min

Total drive energy requirements = 147 Watts x 693 min x 60 s/min

= 6,148,000 J

= 6.1 MJ

Total drive energy requirements for each system configuration are equal to 1.0 MJ, 3.4 MJ and 6.1 MJ for 1, 2 and 3 towers respectively. Once again these values are predicted from measured data and further measurements would be recommended if a 1 tower and 3 tower systems become available for further research.

Energy requirements of the pumping systems can be calculated using Bernoulli's extended equation [Eqn. 4.6], modified to utilize total volume applied rather than the volumetric flow rate of the system

$$E_{pump} = \frac{(\rho \cdot g \cdot h \cdot V)}{0.50} \tag{5.2}$$

where:

E_{pump} = energy requirements of the pump (joules),

ρ = density of fluid pumped (kg m^{-3}),

h = pumping head (m),

g = acceleration due to gravity (kg $m^{-2} \cdot s^{-1}$),

V = total volume applied per irrigation event (m^3).

A value of 0.50 was included for pumping efficiency. At low flow rates it is common to see poor efficiencies ranging from 0.20 to 0.60 due to the small impeller size (Goulds 2006).

Recalling Bernoulli's extended equation [Eq. 4.6], fluid density (ρ) is generally accepted as 1000 kg/m^3, acceleration due to gravity (g) is equal to 9.81 kg/m^2·s and, therefore, equation 5.2 can be further simplified:

$$E_{pump} = 19620 \cdot (h) \cdot (V) \tag{5.3}$$

This equation was used in system analysis for evaluation of pumping requirements, depending on the pumping head (h) and the total volume applied per irrigation event (V). An irrigation event, for this project, is the application of water during one full rotation of the centre pivot.

Application volume requirements, per irrigation event, are dependent on the irrigated area and the application depth of each irrigation event depending on the soil type (Table 5.7).

Table 5.7: Total pumped volume required by each application (m^3/application), depending on soil type and proposed pivot length

# of Towers / Soil Type	1	2	3
Clay	250	952	2106
Loam	164	625	1382
Sand	109	417	921

Note: These values are dependent on a PET = 6.4 mm/day and an average assumed application efficiency of 90%.

Pumping head will vary from system to system, depending on the location of a suitable water source; therefore a range of pumping heads were included in calculations in an attempt to evaluate multiple scenarios. A range of 6 – 21 m of head (58.78 – 205.74 kPa) at a 0.75 m interval was used. Pivot and control system energy requirements (E_{I+C}), of each irrigation event and resulting down time between irrigation events, can be determined as follows

$$E_{I+C} = E_I + 1.6 \times 10^{-5} MW \cdot (t_I) \quad (5.4)$$

where:

E_{I+C} = Pivot and control system energy requirements (MJ),

E_I = pivot drive requirements per irrigation event, full revolution, (MJ),

P_C = power requirements of current regulator and control system,

= 1.6×10^{-5} MW (16 W)

t_I = time between irrigation starts (seconds).

The pivot drive requirements (E_I) of each irrigation event, previously determined (Figure 5.9), were equal to 1.0 MJ, 3.4 MJ and 6.1 MJ for a 1, 2 and 3 tower irrigation system respectively. The control system energy requirements had a constant power draw of 16 Watts during pivot operation and system downtime. The time between irrigation starts (t_I), in seconds, is dependent on the soil type and resulting water storage properties. Sand has the shortest average time between starts, 4 days (345600 s), where Loam was 6 days (518400 s) between starts and Clay had the highest storage capacity resulting in 9 days (777600 s) between starts.

The total system energy requirements ($E_{Irr.cycle}$), per irrigation cycle, can be determined by combining the pivot and control system energy requirements per irrigation cycle with the energy requirements of the pump per application, shown by

$$E_{Irr.cycle} = E_{pump} + E_{I+C} \tag{5.5}$$

Note: An irrigation cycle is the time duration between consecutive irrigation event starts, referring back to Table 5.6, the irrigation cycle duration for clay, loam and sand was equal to 9 days, 6 days and 4 days respectively.

The resultant total system energy requirement for each irrigation cycle was calculated, using equation 5.5, for each combination of system length and soil type over the defined range of pumping head. Calculated values are shown in Table 5.8. Knowing the total system energy requirements of each irrigation cycle and the cycle duration, the required energy production of the PV array must be determined.

Table 5.8: Total system energy requirements per irrigation cycle for proposed solar powered mini-pivot and pump system

		Total system energy requirements (MJ) per irrigation cycle								
Pumping Head		1 Tower			2 Tower			3 Tower		
kPa	m	Sand	Loam	Clay	Sand	Loam	Clay	Sand	Loam	Clay
58.78	6.00	19.4	28.6	42.9	58.0	85.3	127.9	120.0	177.1	266.5
66.13	6.75	21.0	31.0	46.6	64.2	94.5	141.9	133.6	197.4	297.4
73.48	7.50	22.6	33.4	50.2	70.3	103.7	155.9	147.2	217.8	328.4
80.83	8.25	24.2	35.8	53.9	76.4	112.9	169.9	160.7	238.1	359.4
88.17	9.00	25.8	38.3	57.6	82.6	122.1	183.9	174.3	258.4	390.4
95.52	9.75	27.4	40.7	61.3	88.7	131.3	198.0	187.8	278.8	421.4
102.87	10.50	29.0	43.1	64.9	94.8	140.5	212.0	201.4	299.1	452.4
110.22	11.25	30.6	45.5	68.6	101.0	149.6	226.0	214.9	319.4	483.4
117.56	12.00	32.2	47.9	72.3	107.1	158.8	240.0	228.5	339.8	514.4
124.91	12.75	33.8	50.3	76.0	113.2	168.0	254.0	242.0	360.1	545.4
132.26	13.50	35.4	52.7	79.7	119.4	177.2	268.0	255.6	380.4	576.4
139.61	14.25	37.0	55.1	83.3	125.5	186.4	282.0	269.1	400.8	607.3
146.96	15.00	38.6	57.6	87.0	131.7	195.6	296.0	282.7	421.1	638.3
154.30	15.75	40.2	60.0	90.7	137.8	204.8	310.0	296.2	441.5	669.3
161.65	16.50	41.8	62.4	94.4	143.9	214.0	324.0	309.8	461.8	700.3
169.00	17.25	43.4	64.8	98.1	150.1	223.2	338.0	323.3	482.1	731.3
176.35	18.00	45.0	67.2	101.7	156.2	232.4	352.0	336.9	502.5	762.3
183.69	18.75	46.6	69.6	105.4	162.3	241.6	366.1	350.4	522.8	793.3
191.04	19.50	48.2	72.0	109.1	168.5	250.8	380.1	364.0	543.1	824.3
198.39	20.25	49.8	74.5	112.8	174.6	260.0	394.1	377.5	563.5	855.3
205.74	21.00	51.4	76.9	116.4	180.7	269.2	408.1	391.1	583.8	886.3

5.3.6 Photovoltaic cell output

The quantity of PV cells required to ensure that the energy used by the irrigation system is replenished by the next irrigation event, can be determined knowing the average daily PV cell output during peak growing conditions. The 160 W_p array's power output was measured and logged throughout the season using voltage and current transducers (Figure 4.19), during irrigation events and in-field tests. On a day with minimal cloud cover the power production function of the PV cell was observed as bell or sinusoidal in shape (Figure 5.10).

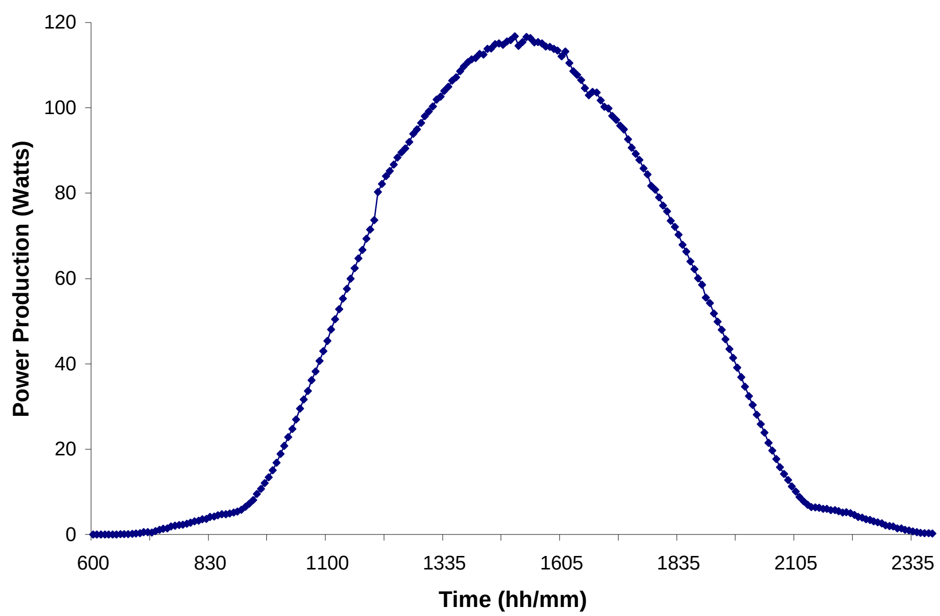

Figure 5.10: Photovoltaic power production curve for 160 W_p panel located at CSIDC on June 27, 2006

On the function presented in Figure 5.11, sunrise and sunset were the first and last significant curve change at approximately 0900 h and 2130 h respectively; there is some solar production while the sun is not fully above the horizon and the sky is partially illuminated.

Using the collected data a function of solar array production can be created to estimate the total daily energy production of the array of this size under clear sky illumination. Clear sky production was used in calculations, relating to the period of greatest ET, which is the basis of irrigation system design.

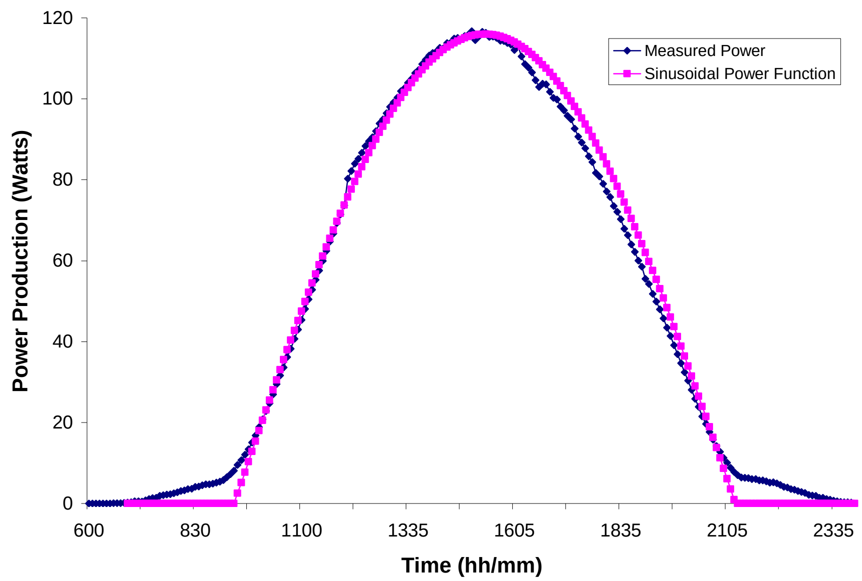

Figure 5.11: 160 Watt-peak solar array sinusoidal power production function related to measured solar array power data, Outlook June 27, 2006

The developed sinusoidal function developed from the collected data is represented by

$$P_{Array} = 116 \cdot \sin\left(\frac{t_e}{13500}\right) \tag{5.6}$$

where:

P_{Array} = Instantaneous power produced by the solar array (Watts)

t_e = time elapsed (seconds) where at initial production t_e = 0 seconds and production continues until t_e = 42300 seconds

It can be estimated, for this analysis, knowing the sinusoidal power production function of the 160 Watt-peak PV cell located at CSIDC and the operational time total cloud free day solar energy production is equal to 3.13 MJ. This value is a sample of only one time period and location. Further analysis of these systems involving different regional locations as well as increasing the number of clear day samples should be completed to get a better estimate of solar energy production. For this analysis the value of 3.13 MJ was used to represent cloud free day solar energy production, noting that the resulting guidelines are generalized for the sample period and should be further investigated in future research.

5.3.7 Guidelines for potential use

Panel size selection is dependent on the energy requirements of the irrigation system during an irrigation cycle, the duration of the irrigation cycle and the recharge efficiency of the battery system.

An average recharge efficiency of 85% is a commonly used factor for lead-acid battery packs (Stevens and Corey 1996). For simplicity, it can be stated that every 1 joule of energy produced by the solar panel will result in approximately 0.85 joules of energy available to the irrigation system or for battery recharge. This may result in an over-estimate of panel size. During operation, a one to one transfer of energy between the solar panel and the irrigation system, during active watering, is a closer representation. Over-estimating the panel size may compensate for factors such as partial cloud cover, debris on the panel surface or other unforeseen efficiency losses.

Assuming transfer of energy from the panels to the system is 85% efficient and knowing the total system energy requirements for an irrigation cycle ($E_{IrrCycle}$) as well as the irrigation cycle duration ($t_{IrrCycle}$), in days, the required daily energy output of the PV cell array (E_{pv}) can be determined by

$$E_{pv} = \frac{\left(\dfrac{E_{IrrCycle}}{t_{IrrCycle}}\right)}{0.85} \tag{5.7}$$

The resulting panel energy output requirements for all stated system lengths, soil types and pumping heads are presented in Table 5.9. Note that panel sizing is not affected by soil texture; soil texture will change the pumping volume per event but the irrigation cycle duration varies accordingly resulting in similar daily energy production requirements for all soil types.

Table 5.9: Required daily PV cell energy output to meet proposed mini-pivot and pump system energy demands

		PV cell energy output requirements to meet system demand (MJ/day)								
Pumping Head		1 Tower			2 Tower			3 Tower		
kPa	m	Sand	Loam	Clay	Sand	Loam	Clay	Sand	Loam	Clay
58.78	6.00	5.7	5.6	5.6	17.1	16.7	16.7	35.3	34.7	34.8
66.13	6.75	6.2	6.1	6.1	18.9	18.5	18.6	39.3	38.7	38.9
73.48	7.50	6.6	6.6	6.6	20.7	20.3	20.4	43.3	42.7	42.9
80.83	8.25	7.1	7.0	7.0	22.5	22.1	22.2	47.3	46.7	47.0
88.17	9.00	7.6	7.5	7.5	24.3	23.9	24.0	51.3	50.7	51.0
95.52	9.75	8.1	8.0	8.0	26.1	25.7	25.9	55.2	54.7	55.1
102.87	10.50	8.5	8.4	8.5	27.9	27.5	27.7	59.2	58.6	59.1
110.22	11.25	9.0	8.9	9.0	29.7	29.3	29.5	63.2	62.6	63.2
117.56	12.00	9.5	9.4	9.5	31.5	31.1	31.4	67.2	66.6	67.2
124.91	12.75	9.9	9.9	9.9	33.3	32.9	33.2	71.2	70.6	71.3
132.26	13.50	10.4	10.3	10.4	35.1	34.8	35.0	75.2	74.6	75.3
139.61	14.25	10.9	10.8	10.9	36.9	36.6	36.9	79.2	78.6	79.4
146.96	15.00	11.4	11.3	11.4	38.7	38.4	38.7	83.1	82.6	83.4
154.30	15.75	11.8	11.8	11.9	40.5	40.2	40.5	87.1	86.6	87.5
161.65	16.50	12.3	12.2	12.3	42.3	42.0	42.4	91.1	90.5	91.5
169.00	17.25	12.8	12.7	12.8	44.1	43.8	44.2	95.1	94.5	95.6
176.35	18.00	13.2	13.2	13.3	45.9	45.6	46.0	99.1	98.5	99.6
183.69	18.75	13.7	13.7	13.8	47.7	47.4	47.9	103.1	102.5	103.7
191.04	19.50	14.2	14.1	14.3	49.5	49.2	49.7	107.1	106.5	107.7
198.39	20.25	14.7	14.6	14.7	51.4	51.0	51.5	111.0	110.5	111.8
205.74	21.00	15.1	15.1	15.2	53.2	52.8	53.3	115.0	114.5	115.9

The values presented in Table 5.9 are the required daily energy production values and must be converted into rated peak watt production when selecting a PV cell array. In section 5.3.6 it was determined that a 160 Watt-peak rated photovoltaic cell had a daily energy production value (E_{160Wp}) equal to 3.13 MJ under cloud free conditions.

Using a simple ratio calculation we can estimate the solar array peak watt rating (P_{rated}) depending on the daily energy requirements of the solar system using

$$P_{rated} = E_{pv} \cdot \frac{P_{rated(160W_p)}}{E_{160W_p}} \tag{5.8}$$

where:

P_{rated} = Solar array peak-watt rating (Watts),

E_{pv} = Required daily energy output of the PV cell array (MJ),

$P_{rated(160Wp)}$ = *160 W*, rated watts of a 160 W_p solar array

E_{160Wp} = *3.31 MJ,* daily cloud-free energy production of 160 W_p solar array located at CSIDC, Outlook SK.

Utilizing this formula, Figure 5.12 was developed to display the required rated peak-watt array for the scope of evaluated irrigation scenarios.

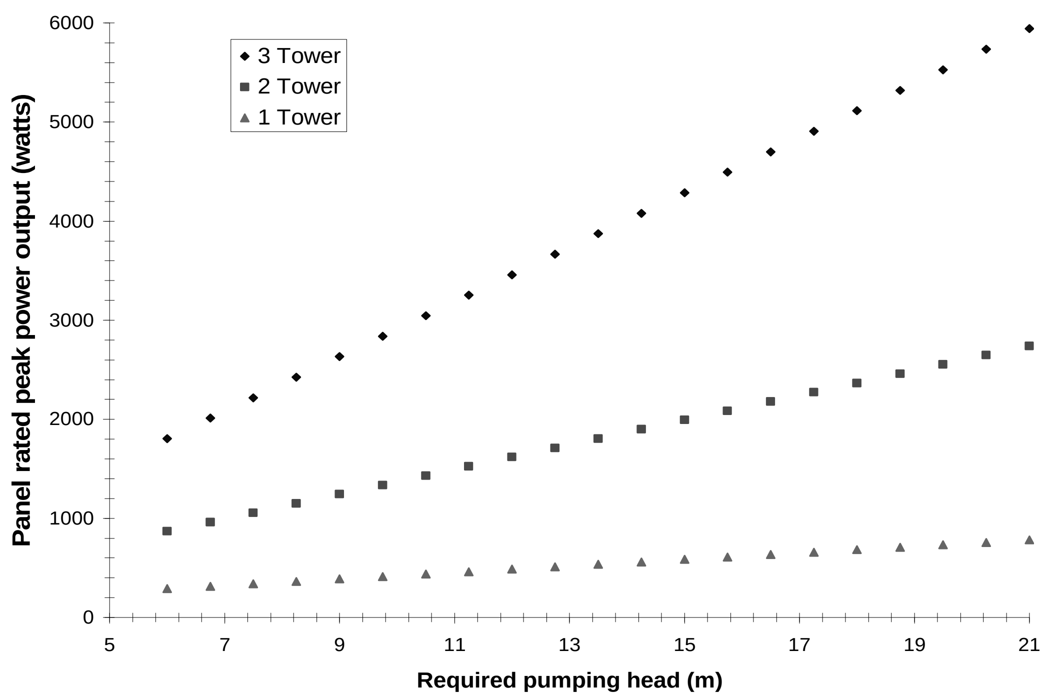

Figure 5.12: Required solar array peak-watt rating to meet power requirements of various irrigation scenarios for Outlook, SK.

The 16o Wp PV array located in Outlook, SK has an approximate surface area of $4m^2$ so although capital cost may not be a concern if price continues to come down, available area could be of concern; with a 6000 Wp panel requiring approximately 150 m^2 of area for construction. As PV cells technology advances so too will the efficiency of theses cells allowing for more energy production from a reduced surface area.

6.0 CONCLUSIONS

6.1 System Management

During the 2006 growing season there were statistical differences in water and energy use efficiencies between low-flow and high-flow management practices. Water use efficiency was improved using a low-flow management practice applying water during the evening and night hours over the high-flow management practice with irrigation applications occurring during the daytime hours. This resulted in reduced water volumes required producing similar yield.

Energy use efficiency was increased in the low-flow management practice over the high-flow management practice. This was a result of increased water requirements in the high flow system associated with lower water use. As water use efficiency decreased, additional water was required to compensate for losses that were not beneficial to plant growth. To supply this additional water to the field, the total pumping volume, as well as the irrigation operating duration, increased resulting in increased energy usage. Another possible cause for the difference in energy use efficiency was the variation in friction loss values between each system. Friction loss, the energy loss from water through friction with the pipe walls, increases as the volumetric flow rate through a constant pipe diameter increases. To compensate for this loss, the initial pumping head must increase to ensure sufficient pressure at the end sprinkler nozzle which therefore results in increased power and energy requirements for the system.

It can be concluded that the proposed low-flow management practice is a better or 'best' management practice compared to the current high-flow management practice employed by CSIDC.

One benefit observed with the high-flow management system was the increase in application uniformity over that of the low-flow system. This is dependent on the nozzling requirements and nozzle availability of the irrigation system. The closer the coefficient of uniformity of an irrigation system is to 100 percent, the more uniform the application depth is over the entire field. This ensures every plant receives the same amount of water with each irrigation application. The high-flow management system had higher application uniformity, due to over watering patterns near the pivot point experienced with the low-flow system. Over watering near the pivot point could cause increased ponding, run-off losses, evaporation and potential washout of crops and disease development. As these systems are relatively new, manufacturers may develop a broader range of available nozzle sizes to prevent this problem from occurring.

6.2 System Potential

Introductory calculations showed that the PV array and battery system, located at CSIDC in Outlook, Saskatchewan, is sufficient for the current pivot system. However, it has insufficient power production to operate a pump in combination with the pivot, although this is not required because this system currently operates on a pressurized supply line.

Calculations were completed for a range of irrigation system lengths, one to three towers, and a variety of required pumping heads to determine the possibility of developing an entirely solar powered irrigation system for small scale situations isolated from the electric grid. Although PV systems have a high capital cost, if kept to a small scale with low-pumping requirements, these systems can be economic for production of high value crops, such as cabbage. Systems must be kept small because the pumping power requirements grow exponentially with system length resulting in large requirements for photovoltaic arrays and battery banks.

Referring to the values presented by Carlson 1989, the pricing required to make PV cells competitive with combustion generators was 3 U.S. dollars per rated peak-watt; currently PV cell prices have been observed, depending on order volume, to have dropped to between 3 and 5 U.S. dollars per rated peak watt (www.ecobusinesslinks.com). This value will continue to reduce with increases in production, with the introduction of thin-filmed solar cells being produced at costs less then 1 U.S. dollars per rated peak watt (Nanosolar 2006). Although PV systems are currently not as cost efficient as combustion generator systems, possible increases in panel availability, panel efficiency and escalating petroleum costs may result in PV systems becoming more affordable than the alternative in the future.

7.0 RECOMMENDATIONS

When utilizing a solar powered mini-pivot, it is recommended to employ a low-flow management system with irrigation events scheduled during the evening or night to minimize evaporative losses. Employing a 94 lpm application system over the current 370 lpm application system, located at CSIDC in Outlook, Saskatchewan, produces an increase in water use efficiency of 21% and energy use efficiency of 35%. This increase in efficiencies will translate into water/energy savings and in turn reduce the operating cost and capital cost as smaller volume pumps and reduced power systems are required.

High-flow application systems are beneficial for uniform water application throughout the field and in reducing operating times. Although high-flow systems had an increase in the number of irrigation events, the seasonal operating time was reduced as water was applied at an increased rate. Reduced operating times can be beneficial in specific agricultural applications, though centre pivot systems can operate for extended periods of time without supervision and therefore operating time is not a high priority to most irrigators.

Solar power irrigation systems have potential in the small-scale production of high value crops in areas where producers have a sufficient supply of water lack accessibility to the electrical grid. More specifically these type of producers involve locally operated market gardens, turf producers and u-pick operations that are most commonly located near a major city but lack the infrastructure commonly associated with large scale irrigation districts. As these systems utilize a renewable resource with zero exhaust emissions, society today may pay a premium for crops produced with 'green' power. Although studies or surveys should be conducted to support this proposition, environmentally friendly crop production in today's society may be a lucrative one. These systems lack the moving components associated with combustion generators reducing overall labour requirements.

Currently, the miniature pivot in Saskatchewan utilizes PV cells to power the pivot drive system solely and an alternative power system for the pump. PV systems are currently manufactured to operate only the pivot system and are a tested viable method to accomplish this task. Preliminary testing and general calculations have shown that a pivot/pump combined system may be operated with a PV array. Further testing on various lengths of centre pivots, sizing of PV array, location of array and increased solar energy generation data should be done to ensure that these systems can be sustained over the length of a growing season in a variety of locations throughout Canada.

PV systems are still more costly than current combustion generating systems but if the price of petroleum continues to increase and the efficiency and production cost of PV cells continue to decrease, solar systems may become a more economical alternative in a broader range of situations. Solar powered irrigation systems are a promising alternative to combustion generators and should be further studied to identify the situations that will most efficiently utilize this emerging application of technology.

The next logical step would be to conduct economic studies to identify in what agricultural situations, i.e. market gardens, turf production and small scale farms, is this technology best suited for and what events need to occur, i.e. rise in oil prices and a drop in PV cell cost, for these situations to make economic sense. This technology has made advances over past decades and the future looks as if solar technology will continue to be in demand as the demand for energy continues to grow.

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9.0 APPENDIX A:

DATA

Table A1: Volumetric soil moisture content measurements from sampling sites within test plot, top 150 mm of soil

	Volumetric Moisture Content (mm/mm)													
Sample	1	2	3	4	5	6	7	8	9	10	11	12	94 LPM	370 LPM
02-Jun-06	0.22	0.17	0.13	0.22	0.14	0.14	0.18	0.14	0.15	0.21	0.18	0.20	0.18	0.16
07-Jun-06	0.18	0.17	0.16	0.16	0.18	0.17	0.18	0.16	0.15	0.20	0.18	0.18	0.18	0.17
13-Jun-06	0.24	0.21	0.26	0.25	0.23	0.25	0.22	0.21	0.22	0.21	0.20	0.23	0.22	0.23
22-Jun-06	0.30	0.37	0.31	0.29	0.24	0.28	0.26	0.23	0.24	0.28	0.24	0.26	0.29	0.26
28-Jun-06	0.26	0.24	0.21	0.19	0.23	0.22	0.21	0.21	0.21	0.23	0.23	0.20	0.23	0.21
04-Jul-06	0.19	0.15	0.17	0.15	0.18	0.16	0.15	0.14	0.16	0.14	0.17	0.18	0.17	0.16
12-Jul-06	0.25	0.27	0.26	0.29	0.24	0.25	0.15	0.19	0.22	0.22	0.20	0.22	0.24	0.23
17-Jul-06	0.17	0.14	0.16	0.17	0.14	0.23	0.12	0.11	0.15	0.12	0.16	0.14	0.15	0.15
24-Jul-06	0.31	0.17	0.33	0.22	0.27	0.21	0.18	0.19	0.19	0.26	0.21	0.20	0.25	0.21
01-Aug-06	0.16	0.18	0.24	0.15	0.19	0.20	0.15	0.18	0.18	0.16	0.21	0.18	0.19	0.17
08-Aug-06	0.15	0.17	0.16	0.19	0.16	0.13	0.10	0.12	0.12	0.14	0.13	0.13	0.15	0.14
14-Aug-06	0.22	0.29	0.24	0.22	0.22	0.23	0.23	0.21	0.25	0.23	0.24	0.25	0.25	0.23
21-Aug-06	0.16	0.20	0.18	0.15	0.16	0.14	0.17	0.18	0.16	0.19	0.14	0.22	0.18	0.16
29-Aug-06	0.27	0.24	0.26	0.21	0.22	0.27	0.20	0.17	0.21	0.23	0.20	0.19	0.23	0.21

Table A2: Volumetric soil moisture content measurements from sampling sites within test plot, 150 mm – 300 mm soil depth

	Volumetric Moisture Content (mm/mm)													
Sample	1	2	3	4	5	6	7	8	9	10	11	12	94 LPM	370 LPM
27-Jun-06	0.34	0.33	0.31	0.30	0.32	0.30	0.30	0.33	0.30	0.31	0.31	0.32	0.32	0.31
04-Jul-06	0.33	0.32	0.30	0.30	0.31	0.29	0.29	0.33	0.30	0.30	0.31	0.32	0.32	0.30
12-Jul-06	0.33	0.32	0.31	0.29	0.30	0.28	0.28	0.33	0.29	0.30	0.30	0.32	0.31	0.29
17-Jul-06	0.32	0.30	0.28	0.28	0.29	0.26	0.27	0.32	0.27	0.28	0.28	0.31	0.30	0.28
24-Jul-06	0.31	0.31	0.29	0.27	0.28	0.24	0.25	0.32	0.26	0.27	0.28	0.30	0.30	0.27
01-Aug-06	0.32	0.29	0.28	0.27	0.27	0.22	0.24	0.32	0.26	0.26	0.28	0.30	0.29	0.26
08-Aug-06	0.31	0.29	0.29	0.26	0.27	0.22	0.23	0.30	0.25	0.26	0.27	0.28	0.28	0.26
14-Aug-06	0.32	0.30	0.31	0.29	0.30	0.26	0.26	0.32	0.29	0.29	0.30	0.31	0.31	0.29
22-Aug-06	0.30	0.27	0.29	0.26	0.27	0.21	0.22	0.31	0.26	0.26	0.27	0.29	0.28	0.26
29-Aug-06	0.31	0.30	0.31	0.29	0.30	0.26	0.26	0.31	0.28	0.28	0.29	0.30	0.30	0.28

Table A3: Volumetric soil moisture content measurements from sampling sites within test plot, 300 mm – 600 mm soil depth

	Volumetric Moisture Content (mm/mm)													
Sample	1	2	3	4	5	6	7	8	9	10	11	12	94 LPM	370 LPM
27-Jun-06	0.32	0.31	0.30	0.29	0.31	0.30	0.30	0.32	0.29	0.30	0.30	0.33	0.31	0.30
04-Jul-06	0.31	0.30	0.29	0.29	0.30	0.29	0.29	0.32	0.29	0.29	0.30	0.32	0.30	0.30
12-Jul-06	0.31	0.30	0.30	0.28	0.30	0.29	0.29	0.31	0.28	0.29	0.29	0.32	0.30	0.29
17-Jul-06	0.30	0.29	0.28	0.28	0.29	0.27	0.27	0.31	0.27	0.27	0.29	0.31	0.29	0.28
24-Jul-06	0.30	0.28	0.28	0.27	0.28	0.26	0.26	0.30	0.26	0.27	0.28	0.30	0.29	0.27
01-Aug-06	0.29	0.27	0.28	0.27	0.28	0.25	0.24	0.30	0.26	0.26	0.27	0.29	0.28	0.27
08-Aug-06	0.28	0.27	0.28	0.26	0.27	0.24	0.24	0.30	0.25	0.25	0.27	0.28	0.27	0.26
14-Aug-06	0.29	0.28	0.30	0.28	0.29	0.26	0.24	0.30	0.27	0.28	0.29	0.30	0.29	0.27
22-Aug-06	0.28	0.26	0.28	0.26	0.27	0.24	0.22	0.29	0.25	0.25	0.27	0.29	0.27	0.26
29-Aug-06	0.29	0.28	0.30	0.28	0.29	0.26	0.23	0.30	0.27	0.27	0.28	0.30	0.29	0.27

Table A4: Change in soil water storage (ΔS) for sampling sites and proposed irrigation management practices

	1	2	3	4	5	6	7	8	9	10	11	12	94 LPM	370 LPM	Date of Sample
Top 150 mm															
$s_{initial}$ (%)	22	17	13	22	14	14	18	14	15	21	18	20	18	16	Jun-02
s_{final} (%)	27	24	26	21	22	27	20	17	21	23	20	19	23	21	Aug. 29
ΔS (mm)	**8**	**12**	**20**	**-2**	**12**	**20**	**2**	**4**	**9**	**3**	**3**	**-2**	**7**	**7**	
150 – 300 mm															
$s_{initial}$ (%)	34	33	31	30	32	30	30	33	30	31	31	32	32	31	Jun-27
s_{final} (%)	31	30	31	29	30	26	26	31	28	28	29	30	30	28	Aug. 29
ΔS (mm)	**-4**	**-4**	**-1**	**-2**	**-3**	**-6**	**-7**	**-2**	**-3**	**-4**	**-3**	**-3**	**-3**	**-4**	
300 – 600 mm															
$s_{initial}$ (%)	32	31	30	29	31	30	30	32	29	30	30	33	31	30	Jun-27
s_{final} (%)	29	28	30	28	29	26	23	30	27	27	28	30	29	27	Aug. 29
ΔS (mm)	**-8**	**-10**	**-1**	**-5**	**-7**	**-12**	**-20**	**-6**	**-8**	**-7**	**-5**	**-8**	**-6**	**-10**	
ΔS (mm) Total	**-4**	**-1**	**19**	**-9**	**2**	**2**	**-25**	**-5**	**-2**	**-8**	**-5**	**-13**	**-2**	**-6**	

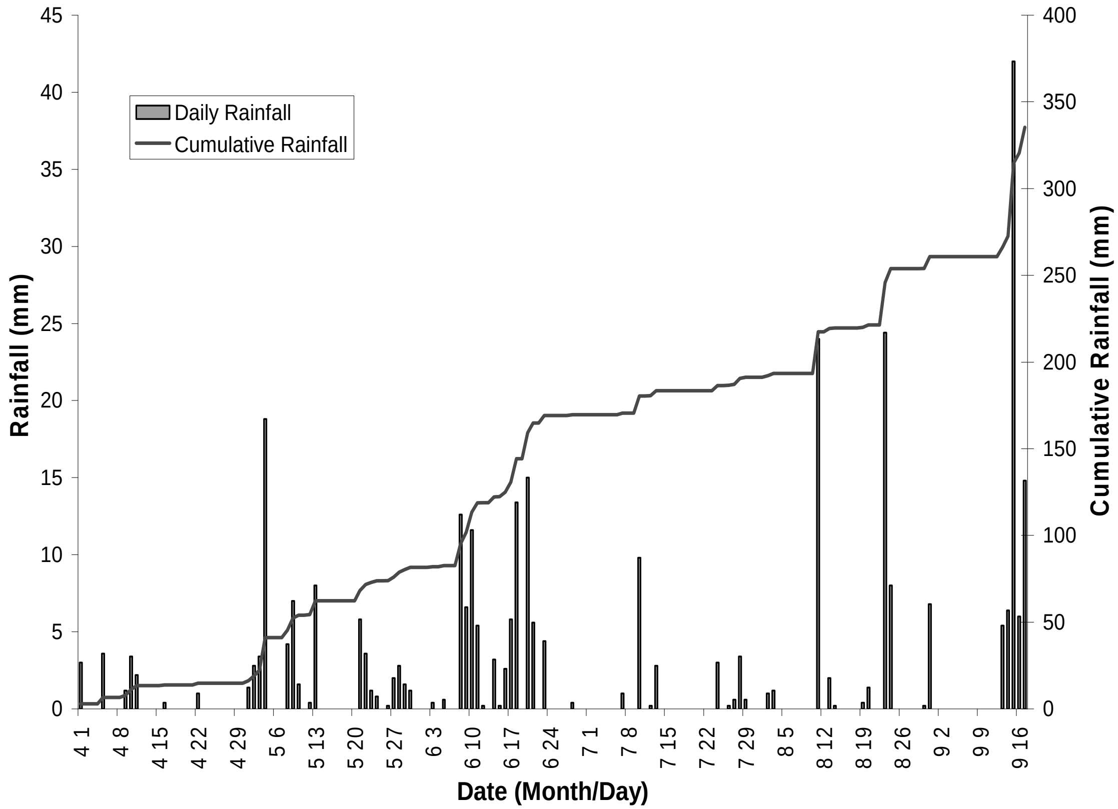

Figure A1: Seasonal rainfall event and cumulative rainfall data for CSIDC, Outlook Saskatchewan 2006 (Environment Canada 2006)

Table A5: Calculated water use efficiency (WUE) from sample sites and proposed irrigation management practices for irrigated cabbage head production

Sample	Irrigation (mm)	Total Precipitation (mm)	SWS Change (mm)*	Consumption / Losses (mm)	Average Head Weight (kg)	WUE (kg / m)
1	107	279	-4	283	1.76	6.2
2	107	279	-1	281	2.06	7.3
3	107	279	19	261	1.82	7.0
4	165	337	-9	346	1.92	5.6
5	165	337	3	335	1.97	5.9
6	165	337	2	335	1.70	5.1
7	165	337	-25	362	1.95	5.4
8	165	337	-5	342	1.99	5.8
9	165	337	-2	339	1.96	5.8
10	107	279	-8	287	1.96	6.8
11	107	279	-5	284	2.12	7.4
12	107	279	-13	292	1.74	6.0
94 LPM	**107**	**279**	**-2**	**281**	**1.91**	**6.8**
370 LPM	**165**	**337**	**-6**	**343**	**1.89**	**5.6**

* Change in soil water storage (SWS) was measured using gravimetric and neutron probeto a depth of 600 mm between June 2 and August 29

Table A6: Calculated energy use efficiency (EUE) from sample sites and proposed irrigation management practices for irrigated cabbage head production using a Greenfield two-tower solar powered centre pivot

Sample	Pivot Energy (kJ)	Pump Energy (kJ)	Total Energy (kJ)	Average Head Weight (kg)	kg / 1/4 Pivot Area*	EUE (kg / kJ)
1	10567	35867	46434	1.76	17901	0.39
2	10567	35867	46434	2.06	21012	0.45
3	10567	35867	46434	1.82	18513	0.40
4	7078	56654	63732	1.92	19584	0.31
5	7078	56654	63732	1.97	20094	0.32
6	7078	56654	63732	1.70	17340	0.27
7	7078	56654	63732	1.95	19890	0.31
8	7078	56654	63732	1.99	20298	0.32
9	7078	56654	63732	1.96	19992	0.31
10	10567	35867	46434	1.96	19992	0.43
11	10567	35867	46434	2.12	21573	0.46
12	10567	35867	46434	1.74	17748	0.38
94 LPM	**10567**	**35867**	**46434**	**1.91**	**19457**	**0.42**
370 LPM	**7078**	**56654**	**63732**	**1.89**	**19533**	**0.31**

* kg produced under a 1/4 Pivot Area is based on a planting density of 18" x 30" and a 1/4 pivot area of 0.88 acreas (approximately 10200 plants)

Table A7: Operating Characteristics of one-, two- and three tower Greenfield solar powered miniature centre pivot irrigation systems

# Towers	Irrigated Area, m^2 (acres)	End Tower Travel Distance, m	Recommended Flow rate m^3/hr (U.S. GPM)	Full-Circle Time @ 0.914 m/min, min (hrs)	Power Draw of Drive System, Watts
1	3903 (1.0)	212	1.5 (6.8)	232 (3.9)	74
2	14875 (3.7)	423	5.7 (25)	463 (7.7)	122
3	32903 (8.1)	634	12.5 (55)	693 (11.6)	147

Table A8: Energy required by pumping system per irrigation event for proposed solar powered mini-pivot systems

Pumping Head		1 Tower			2 Tower			3 Tower		
		Energy required by pump (MJ) per irrigation event								
kPa	**m**	**Sand**	**Loam**	**Clay**	**Sand**	**Loam**	**Clay**	**Sand**	**Loam**	**Clay**
58.78	6.00	12.8	19.3	29.4	49.1	73.6	112.1	108.4	162.7	247.9
66.13	6.75	14.4	21.7	33.1	55.2	82.8	126.1	122.0	183.0	278.9
73.48	7.50	16.0	24.1	36.8	61.4	92.0	140.1	135.5	203.4	309.9
80.83	8.25	17.6	26.5	40.5	67.5	101.2	154.1	149.1	223.7	340.9
88.17	9.00	19.2	29.0	44.1	73.6	110.4	168.1	162.6	244.0	371.9
95.52	9.75	20.9	31.4	47.8	79.8	119.6	182.1	176.2	264.4	402.9
102.87	10.50	22.5	33.8	51.5	85.9	128.8	196.1	189.7	284.7	433.9
110.22	11.25	24.1	36.2	55.2	92.0	138.0	210.1	203.3	305.0	464.8
117.56	12.00	25.7	38.6	58.9	98.2	147.2	224.1	216.8	325.4	495.8
124.91	12.75	27.3	41.0	62.5	104.3	156.3	238.1	230.4	345.7	526.8
132.26	13.50	28.9	43.4	66.2	110.5	165.5	252.2	243.9	366.1	557.8
139.61	14.25	30.5	45.9	69.9	116.6	174.7	266.2	257.5	386.4	588.8
146.96	15.00	32.1	48.3	73.6	122.7	183.9	280.2	271.1	406.7	619.8
154.30	15.75	33.7	50.7	77.3	128.9	193.1	294.2	284.6	427.1	650.8
161.65	16.50	35.3	53.1	80.9	135.0	202.3	308.2	298.2	447.4	681.8
169.00	17.25	36.9	55.5	84.6	141.1	211.5	322.2	311.7	467.7	712.8
176.35	18.00	38.5	57.9	88.3	147.3	220.7	336.2	325.3	488.1	743.8
183.69	18.75	40.1	60.3	92.0	153.4	229.9	350.2	338.8	508.4	774.7
191.04	19.50	41.7	62.7	95.6	159.5	239.1	364.2	352.4	528.7	805.7
198.39	20.25	43.3	65.2	99.3	165.7	248.3	378.2	365.9	549.1	836.7
205.74	21.00	44.9	67.6	103.0	171.8	257.5	392.2	379.5	569.4	867.7

Table A9: Required rating, peak-watts, for solar arrays to meet proposed mini-pivot and pump system energy demand

		Peak-Watt Rating of solar array for system to operate								
Pumping Head		1 Tower			2 Tower			3 Tower		
feet	m	Sand	Loam	Clay	Sand	Loam	Clay	Sand	Loam	Clay
58.78	6.00	294	289	289	881	863	863	1822	1792	1798
66.13	6.75	318	314	314	974	956	958	2028	1998	2007
73.48	7.50	343	338	339	1067	1049	1052	2234	2204	2216
80.83	8.25	367	363	364	1160	1142	1147	2440	2410	2425
88.17	9.00	391	387	389	1253	1235	1241	2645	2615	2634
95.52	9.75	416	412	413	1346	1328	1336	2851	2821	2843
102.87	10.50	440	436	438	1440	1421	1430	3057	3027	3052
110.22	11.25	464	460	463	1533	1514	1525	3263	3233	3261
117.56	12.00	489	485	488	1626	1608	1619	3468	3439	3470
124.91	12.75	513	509	513	1719	1701	1714	3674	3644	3679
132.26	13.50	537	534	537	1812	1794	1808	3880	3850	3889
139.61	14.25	562	558	562	1905	1887	1903	4085	4056	4098
146.96	15.00	586	583	587	1999	1980	1997	4291	4262	4307
154.30	15.75	610	607	612	2092	2073	2092	4497	4468	4516
161.65	16.50	635	631	637	2185	2166	2186	4703	4673	4725
169.00	17.25	659	656	662	2278	2259	2281	4908	4879	4934
176.35	18.00	683	680	686	2371	2352	2375	5114	5085	5143
183.69	18.75	708	705	711	2464	2445	2470	5320	5291	5352
191.04	19.50	732	729	736	2557	2538	2564	5526	5497	5561
198.39	20.25	757	753	761	2651	2631	2659	5731	5702	5770
205.74	21.00	781	778	786	2744	2724	2753	5937	5908	5979

10.0 APPENDIX B:

SOILS REPORT

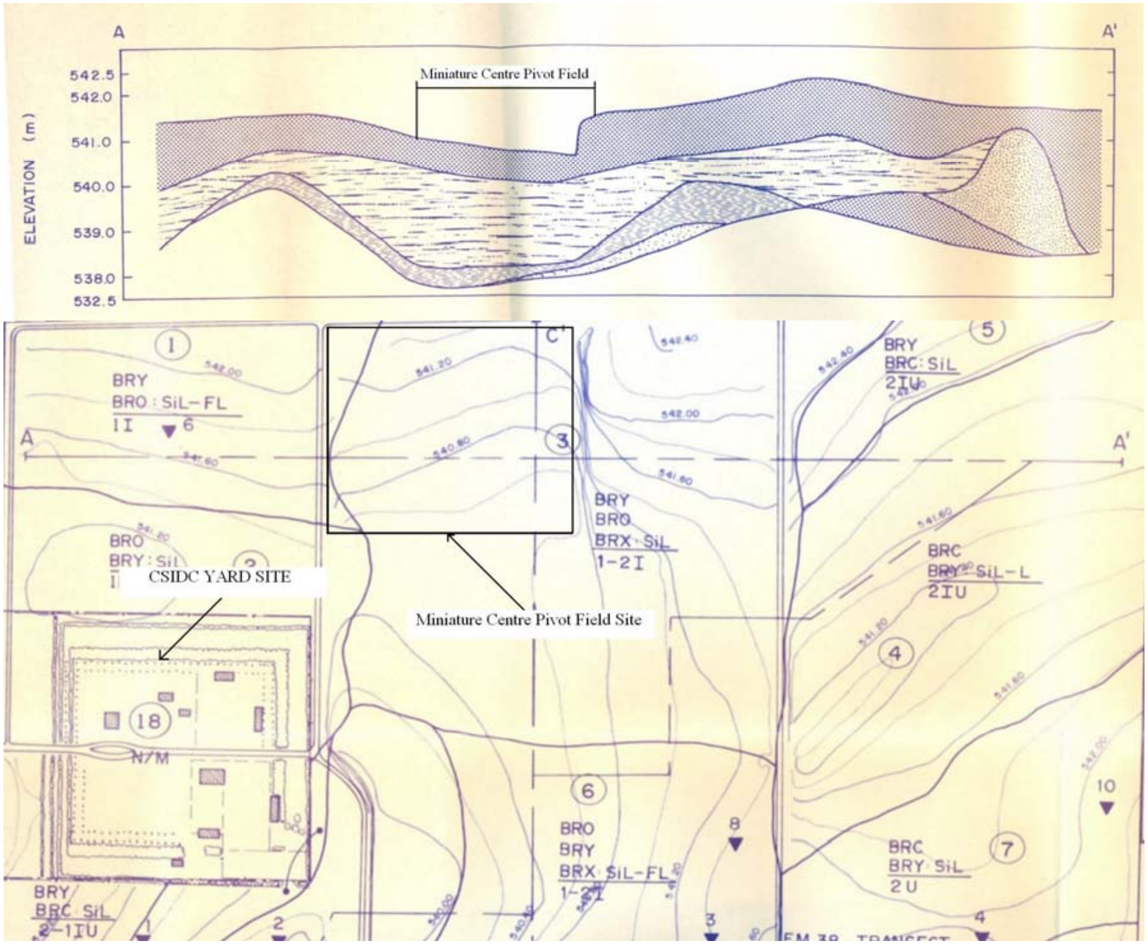

Figure A2: Soils map of miniature centre pivot field site and cross-section, adapted from Stushnoff and Acton 1978.

<u>**Soil Report:** Prepared by Stushnoff and Acton 1978</u>

Area No. 3

Dominant Series (Comprises > 40% of the map unit): Calcareous Bradwell, Ap greater than 20cm thick.

Significant Series (Comprises > 15% but < 40% of the map area): Regosolic Bradwell

Inclusions (Comprises < 15% of the map area): Saline Bradwell

Surface Texture: Silt Loam

Slope Class: Level (0 – 5% slope) to Nearly Level (0.5 – 2% slope)

Surface Expression: Inclined (a sloping unidirectional surface with a generally constant slope not broken by marked irregularities).

Salinity: Non-saline to moderate (0 – 8 dS/m)

Material Composition
Thin to very thin, medium textured lacustrine sediments overlying a moderately fine- to fine-textured material. Glacial till may occur at 2 – 3m (Stushnoff and Acton 1978).

Explanation
This area consists of well- and moderately well-drained calcareous Bradwell soils with Ap horizons greater than 20 cm thick. Significant areas of regosolic Bradwell soils occur where the soil profile has been removed and mixed into adjacent soil areas. Saline Bradwell inclusions occur at the Base of the dyke (eastern most side of field). Sub-soils are usually saline below 1.3m (Stushnoff and Acton 1978).