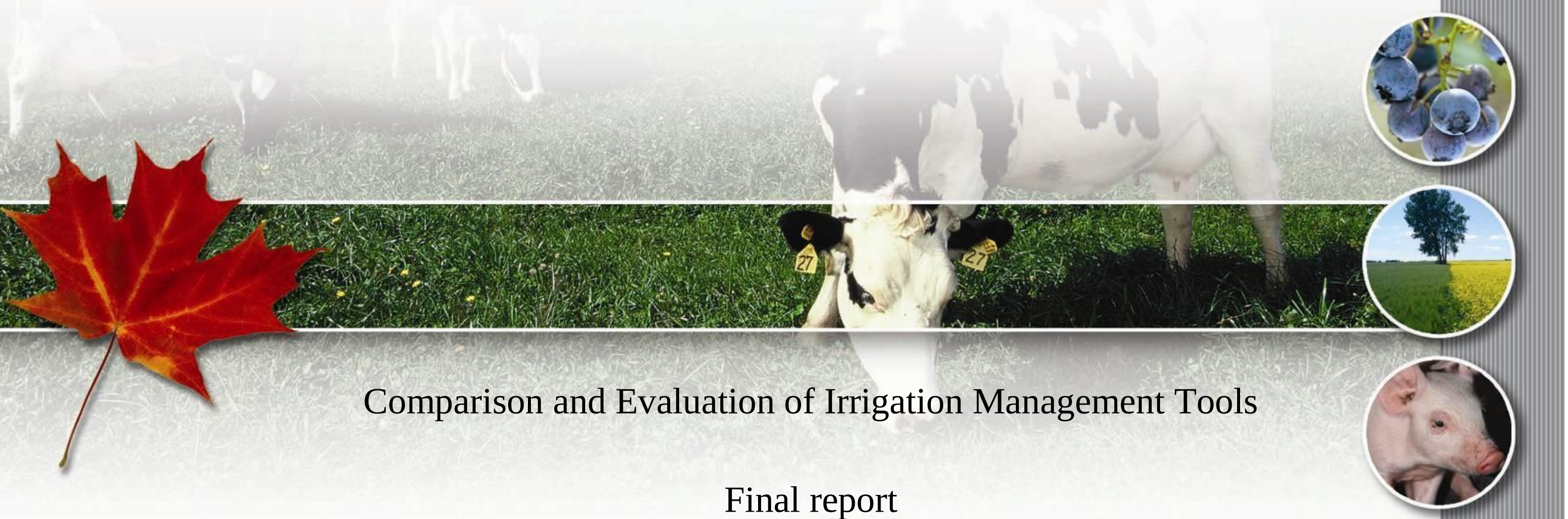

Comparison and Evaluation of Irrigation Management Tools

Final report

Report presented to the:

Conseil pour le développement de l'agriculture
du Québec (CDAQ)

CDAQ Project # 6712
IRDA Project # 901 017

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Institut de recherche
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CDAQ
CONSEIL POUR
LE DÉVELOPPEMENT DE
L'AGRICULTURE DU QUÉBEC

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Agriculture and Agri-Food Canada (AAFC) is committed to working with industry partners. The opinions expressed in the current document are those of the applicant and are not necessarily shared by the AAFC or CDAQ.

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SUMMARY

During the 2012 and 2013 growing seasons, the water budget irrigation method (also known as the water balance method or the chequebook method) was studied and compared to two other irrigation management tools: tensiometers and reflectometers. Specifically, the performance of a software program developed in British Columbia, the Landscape Irrigation Scheduling Calculator (LISC), was evaluated in Quebec. The software was used to generate daily estimates of soil water content, using evapotranspiration values retrieved from a weather station that was part of the AgWeather network or located on the farm.

The irrigation management tools were compared as to their ability to detect a specific threshold for irrigation, which was set at 50% of the available water storage capacity (AWSC). Irrigation scheduling with tensiometers was used as the reference, since tensiometers measure soil water content directly. In the summer of 2012, the LISC was evaluated without overriding the software's default values, and it did not perform well: very few of its predicted dates matched those scheduled with the aid of the other tools. Later, the software was enhanced to allow the defaults to be replaced by values based on physical characterization of the soil at the experimental sites. In 2012, a second simulation was run for one site using this customized data, and it showed that the software would have performed much better in 2012 if the customized scenario had been available for the experiment, matching more of the actual irrigation dates. In 2013, the enhanced version was used, and its performance was comparable to the other irrigation management tools.

Compared to the 2012 season, there were fewer irrigation events in 2013, which made it possible to evaluate the overall performance of the water budget method during seasons with high and low evapotranspiration demand, respectively. It was observed that the water budget calculator performs better during a season in which evapotranspiration demand is low, as in 2013. The volume of water used when irrigation was scheduled based on the enhanced version of the water budget calculator was at most 20% higher than with tensiometers, for the Deschambault site in 2012 and for all the sites in 2013.

In order to manage irrigation effectively, producers must be able to anticipate how much water the crops will need. For that purpose, the software evaluated in this project has a clear advantage over the other tools used in the experiment. By incorporating an estimate of the soil water content and weather forecasts, the software predicts how much water the crops will need in the next few days. This capability is particularly important for large-hectarage crops.

Although the results indicate that the water budget method is not as precise as the tensiometer method, a hybrid approach would be preferable, as it would combine the advantages of both methods.

1 Introduction

For optimal irrigation management, water must be applied at the right times and according to plant needs, soil characteristics and weather conditions. Few agricultural producers use measuring instruments to determine when to trigger irrigation. Instead, they generally base that decision on a visual examination of the crop and on the hand-feel method of estimating soil moisture, which often leads to inefficient water management and entails a risk of non-point-source pollution. For example, Giroux and Sarrasin (2011) sampled wells supplying water for human consumption, located on or near potato producers' property, in five Quebec regions. They found that the water in 69% of the 77 wells sampled contained pesticides. The same study reported that the water in 40% of the wells sampled had nitrate concentrations higher than the standard for drinking water. Although the study did not establish a direct link between irrigation and non-point-source pollution, its conclusions illustrate the connection between non-point-source pollution and the movement of water through the soil.

Tools exist that can measure the situation in the fields in real time in order to determine when to irrigate; tensiometers are a good example. For crops with very high revenues per hectare (e.g., strawberries, raspberries, highbush blueberries), it is worth making significant investments in measuring equipment in order to manage irrigation in real time. But for extensive crops that are irrigated by sprinklers or have much lower revenues per hectare, it may not make sense for producers to invest in a large number of measuring instruments. In such cases, the water budget method, which takes precipitation and the evapotranspiration of the crop into account, is often a good solution. With that in mind, the Irrigation Industry Association of British Columbia, under the supervision of Ted van der Gulik of the B.C. Ministry of Agriculture, used the water budget approach to develop the Landscape Irrigation Scheduling Calculator, a user-friendly computer program available on a website. Users enter information about crop parameters and the type of irrigation, and the software uses it, together with weather data, to schedule the approximate time for the next irrigation event. With the cooperation of the B.C. government and Ted van der Gulik, the software was tested in Quebec. The model shows great promise because of its accessibility and the fact that it can be adapted to different irrigation systems. However, a model that is based primarily on weather data and only estimates the soil water content could lead to sizeable systematic error in the scheduling of irrigation dates.

Potatoes are a good example of an irrigated high-hectarage crop. From 2001 to 2012, the number of hectares of irrigated potatoes in Quebec increased considerably, from 3,260 to 5,300 ha (BPR Consulting Group, 2003; Bergeron, 2012). Various studies of water management in potato irrigation have been carried out in recent years in the Quebec City area and elsewhere in Canada. Trials conducted in Quebec have shown that excess water reduces yield (Boivin and Landry, 2008; Boivin et al., 2008). From both an environmental and economic point of view, the optimal time to trigger irrigation is when soil moisture content is at 50% of the available water storage capacity (Boivin and Landry, 2011).

A hybrid approach that uses the water budget calculator to schedule irrigation but also incorporates a limited number of real-time measurements of soil moisture content would make it possible to manage larger areas more efficiently by combining the advantages of both approaches. In addition, unlike drip systems, which are stationary, sprinkler systems (booms, pivot, guns, etc.) are generally more time-consuming to use because the system must be moved from one field to another and the speed of movement during application is limited). Therefore, with sprinkler systems, knowing a few days in advance which fields will need to be irrigated is a definite advantage. Lastly, the LISC does not allow the user to correct possible systematic error in the scheduling, but that could be done with a hybrid approach by using quantitative measurements taken in the field.

1.1 Overall objective

The overall objective was to improve irrigation management in order to maximize economic and environmental gains.

1.2 Specific objectives

- Evaluate the performance of the Landscape Irrigation Scheduling Calculator.
- Compare and evaluate different irrigation management tools.
- Evaluate a hybrid approach to irrigation management (water budget and real-time measuring instruments)
- Anticipate the crop's irrigation requirements a few days in advance.
- Do an economic assessment of the irrigation management methods tested.

2 Materials and methods

2.1 Experimental sites

Two experimental sites were located in fields where extra-fine green beans and potatoes, respectively, were being grown by two commercial producers, Les Jardins Ducharme at Sainte-Mélanie (46.10 ºN, 73.50 ºW) and La Ferme Sylvain Tarte (Groupe Gosselin Production FG) at Lanoraie (46.01 ºN, 73.2 ºW), both in the Lanaudière region of Quebec. The third site was located at the experimental farm run by the Institut de recherche et de développement en agroenvironnement (IRDA) at Deschambault in the Quebec City region (46.67 ºN, 71.916881 ºW). The soils in which the experimental plots were established belong to the Uplands series at Sainte-Mélanie, the Lanoraie series at Lanoraie and the Chicot series at Deschambault. Soil textures were determined using a soil texture classes triangle (Figure 1) and particle-size analyses performed in a laboratory.

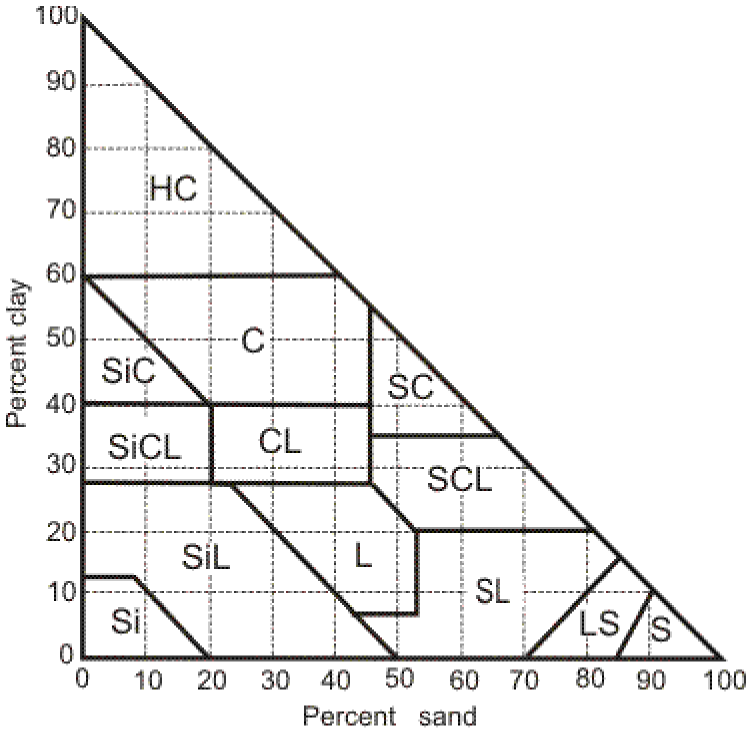

Figure 1. Soil texture classes triangle (Agriculture Canada, 2002).

2.2 Crops and field operations

Two of the three sites were planted with potatoes. These two sites were located at Deschambault (cv. Goldrush) and Lanoraie (cv. Russet Burbank). The third site, located at Sainte-Mélanie, was planted with extra-fine green beans (cv. Denver and Anger). At the Lanoraie and Sainte-Mélanie sites, the trials were carried out under commercial production conditions using the producer's own system for tilling, planting, fertilizing and phytosanitary treatments. At the Deschambault site, the field operations were supervised by the IRDA team.

2.3 Treatments

The three sites were used to compare up to three irrigation management tools. The threshold established for an irrigation event was 50% of the available water storage capacity. Three tools were compared:

T1 –Water budget (WB) calculator developed in B.C.;
T2 – Water budget calculator plus scheduling adjustments with tensiometers;
T3 – Water budget calculator plus scheduling adjustments with reflectometers (Deschambault site only).
There was also an unirrigated control plot.

The duration of an irrigation event is determined based on the crop rooting depth and the soil moisture content at the time when irrigation is triggered. This prevents water from being wasted outside the root zone.

2.4 Experimental plots

The experimental plots at the Lanoraie and Sainte-Mélanie sites were arranged in a randomized block design with 4 blocks and 3 treatments, for a total of 12 experimental plots per site (Figure 2, Figure 3). At the Deschambault site, an extra treatment was added in which reflectometers were used to schedule irrigation. Consequently, that site had 4 blocks and 4 treatments, for a total of 16 plots (Figure 4).

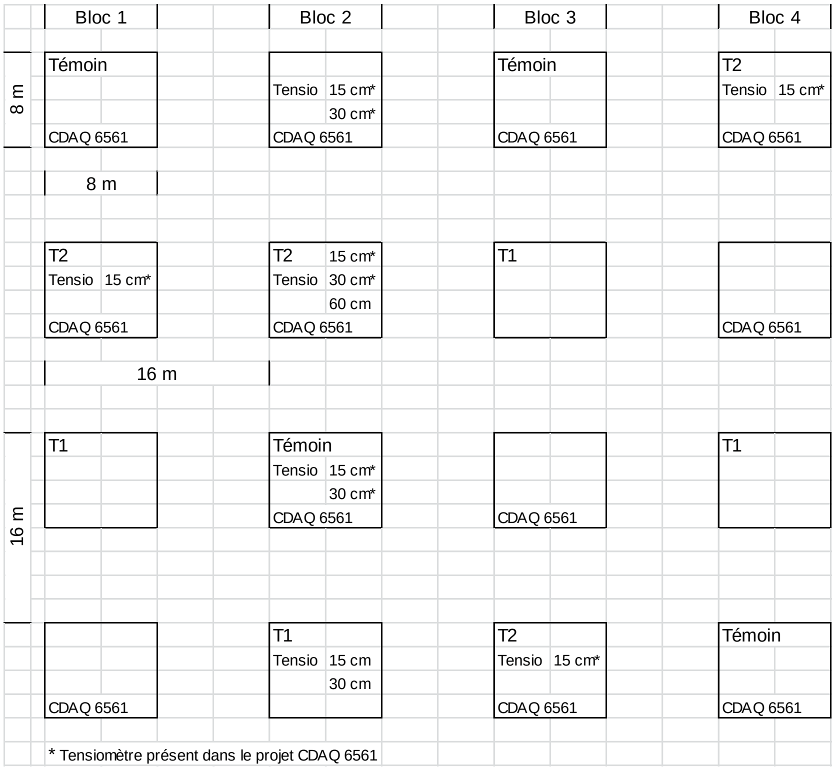

Figure 2. The Sainte-Mélanie plots.

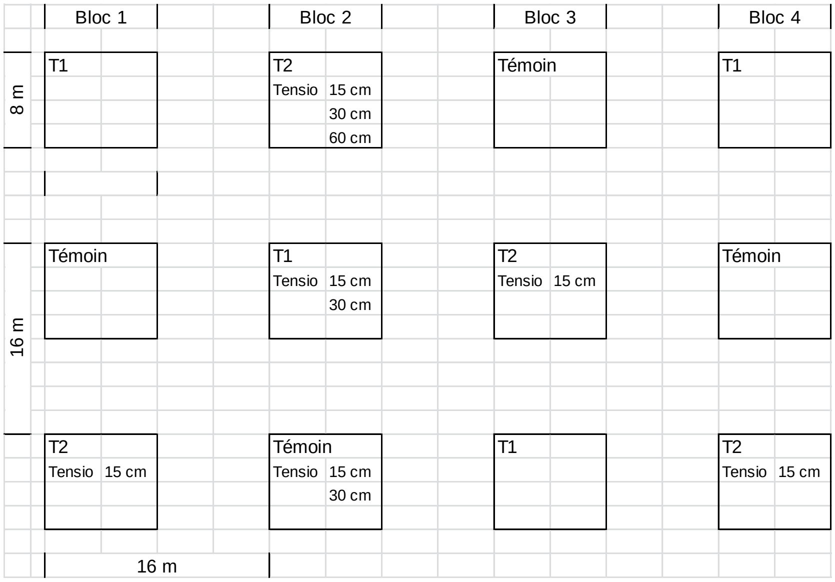

Figure 3. The Lanoraie plots.

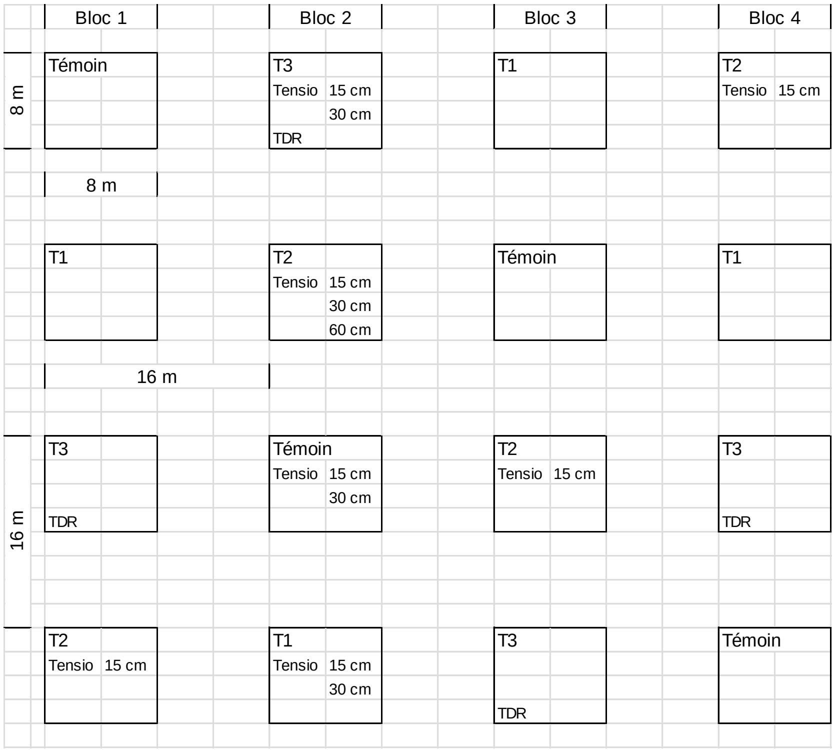

Figure 4. The Deschambault plots.

2.5 Data collection

2.5.1 Physicochemical characterization of soils

Soil analyses were conducted on composite samples taken from the 0–20-cm soil layer in all the blocks at the three experimental sites. The soils were sieved to 2 mm, then air-dried at 21 ºC. Particle size was determined using the six-point hydrometer method followed by sand sieving (Gee and Bauder, 1986). The $\mathrm{pH}_{\mathrm{water}}$ was measured using a 1:1 soil/water ratio (CPVQ, 1988). The total organic matter (OM) content was measured using the Walkley–Black wet oxidation method (Allison, 1965). The total Kjeldahl nitrogen was determined by colorimetric analysis using a Technicon auto-analyzer (McGill and Figueiredo, 1993). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and aluminum (Al) were extracted using a Mehlich-3 solution (Tran and Simard, 1993) and subjected to optical ICP analysis. Samples of undisturbed soil were also taken in each of the blocks and were used to plot soil water desorption curves (Topp et al., 1993). At the Deschambault site, this characterization was performed only in 2012, as the 2013 trials were carried out in the same plots. At the commercial farm sites, the characterization was performed in both spring 2012 and spring 2013, because the plots were in different locations the second year.

2.5.2 Weather conditions

Rainfall was measured throughout the season (section 0) using HOBO RG3-M rain gauges. The ambient air temperature and relative humidity were measured with HOBO Pro v2 (model U23-001) dataloggers. Weather stations at each of the sites were used to measure the temperature and relative humidity (HC2-S3, Campbell Scientific), solar radiation (LI-200SZ, LI-COR), wind speed and direction (Young 05103-10 wind monitor) and rainfall (TE525WS, Campbell Scientific) (Annex, Photograph 1). The data was recorded hourly with a CR1000 datalogger (Campbell Scientific). A weather station (Base RF, Hortau) was set up at the Deschambault site.

2.5.3 Soil water tension and volumetric water content in the experimental plots

Soil water tension (matric potential) was measured throughout the project with Hortau tensiometers (TX3 and TX80) (Photograph 2) in order to manage the irrigation events. Each of the tensiometer treatment (T2) plots was equipped with a tensiometer at a depth of 15 cm. In addition, at each site, all of the treatments in one block (Block 2) were equipped with tensiometers at depths of 15 cm and 30 cm. Lastly, in one plot at each site (the T2 plot in Block 2) a tensiometer was installed at 60 cm. All of the data was recorded in real time on a computer using Hortau's Irrolis-Light (version 1.9, version 3) software, to be used for analysis of each of the irrigation treatments. For the reflectometer treatment at the Deschambault site, water applications were managed based on readings of the volumetric water content of the soil taken with wireless soil-water probes (CWS655, Campbell Scientific) (Photograph 3). The measurements were recorded and saved by a datalogger (CR1000) every 15 minutes.

2.5.4 Growth stages and plant leaf canopies

For the extra-fine green beans, beginning the week after seeding, the growth stages and the plant leaf canopies were monitored on a weekly basis. For the potato plants, the growth stages were monitored only at Deschambault, in all the plots. Plant leaf canopies were not measured for the potato crops at either site. Growth stages were monitored by observing the plants in a predetermined 1.4-m section at the same location within each plot. The growth stages that were monitored—germination, leafing, flowering and fruiting—were taken from the *Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie* (BBCH) scale (Zadoks et al., 1974). Each stage was divided into sub-stages and was evaluated based on the proportion observed in the section where the measurements were taken. For the green beans, the same section was used to calculate the canopy coverage. A photograph was taken of a section of three adjacent rows of plants. Then the photograph was processed (ImageJ, National Institutes of Health) to isolate the green colour of the leaves and calculate the percentage of the plot area covered by the leaf canopies (Photograph 4 and Photograph 5). The same section was photographed once a week to track the plants' growth rate.

2.5.5 Dry matter content of the plants and preliminary harvesting of potatoes

For the extra-fine green beans, beginning the week after seeding, the plants' dry matter content was measured biweekly. Five consecutive plants in a predetermined location within the plot were harvested, dried at 105 °C, and weighed. At the sites planted with potatoes, tubers were harvested during the season: on July 16 and 23, 2012, at Deschambault and on July 25 and 30, 2013, at Lanoraie. In each plot, the tubers produced by three plants in the same row were dug up. The tubers were weighed individually. The dry mass of the above-ground portion of the plant was determined by drying the plants at 105 °C, then weighing them.

2.5.6 Yield and quality

A final harvest was carried out at each of the sites in order to measure the total and marketable yields and the quality of the crop. For the potato sites, the harvest involved digging up the tubers from a 4-m section (in some cases, two 2-metre sections) in each of the two centre rows of each plot. The potatoes were graded. The total and marketable yields (grade: Canada No. 1 excluding undersized potatoes measuring 1.9 cm to 4.1 cm in diameter; long: Canada No. 1 excluding undersized potatoes less than 5.1 cm in diameter) were determined. The tubers were also rated for quality and examined for common scab (*Streptomyces scabies*). The degree of common scab infestation was rated using a method developed at MAPAQ's Les Buissons research station (Otrysko et al., 1984). The scab index calculated by this method uses a weighting factor ranging from 1 to 5, which takes into account both the extent of the damage and the type of symptoms observed on the potatoes. Twenty-five tubers (Canada No. 1) were selected at random from each of the harvested batches. Each of the tubers was categorized based on the severity of the damage observed (in ascending order of severity: surface lesions, raised lesions, coalesced lesions, or pitted lesions) and the surface area of the tuber that was damaged (0%–trace, trace–5%, 5%–20%, 20%–40%, > 40%). The total number of tubers per category was then calculated. The appropriate weighting factor was applied to each of the categories, based on the combination of severity and extent of damage. The scab index is calculated by multiplying the number of tubers in a category by the category's weighting factor, then dividing that number by the total number of tubers rated. All of the tubers harvested were also examined for rhizoctonia infestation (*Rhizoctonia solani*), and an evaluation grid was used to assign a weighting factor. Like the common scab index, the rhizoctonia index uses a weighting factor ranging from 1 to 5 that takes into account both the extent of the damage and the type of symptoms observed on the tubers. Lastly, specific gravity was measured based on a sub-sample of 3 kg of tubers per plot. First, the sub-sample was weighed (weight in air). The tubers were then immersed in water and weighed again (weight in water). The specific gravity of the tubers was calculated as follows:

$$\text{Specific gravity} = \text{Weight in air} / (\text{Weight in air} - \text{Weight in water}).$$

At the green bean site, in each plot, the plants from four 0.5-m sections, selected to provide a representative sample, were harvested. First the plants were weighed fresh, then all the beans were removed from the plants and weighed fresh. The plants were dried at 105 °C and weighed again. A 700-g subsample of beans from each plot was prepared, made up of harvested beans. The beans in each subsample were grouped by diameter (< 5 mm, 5 to 6.5 mm, > 6.5 mm) and weighed, after which the subsamples were reassembled. Each subsample was then cooked in a pressure cooker for 180 seconds, with the time measured from the moment when the internal pressure reached 81.4 kPa. After cooking, 100 g of beans were randomly selected from each subsample and checked for stringiness (by means of a traction test), and 500 g were used to determine the seed/pod ratio (each pod was opened and the seeds were removed, the seeds and the pods were weighed separately, and the ratio was calculated).

3 Results and analysis in light of the study's specific objectives

3.1 Evaluation of the Landscape Irrigation Scheduling Calculator

3.1.1 Performance of the software

Irrigation management based on the water budget (WB) model, using the Landscape Irrigation Scheduling Calculator developed in B.C., was explored during the 2012 and 2013 growing seasons.

The Landscape Irrigation Scheduling Calculator is a software program that produces a theoretical estimate of soil water content. The software has an intuitive, easy-to-use interface (Figure 5; Photograph 6, 7 and 8). To run a simulation, the user creates a "project" in four simple steps. Step 1 involves selecting the crop to be irrigated. Based on that selection, the software inserts the default values for the rooting depth at maturity, the availability coefficient (the portion of water stored in the soil that is readily available to the plant) and the crop coefficient (k_c). These coefficients will be discussed in greater depth in the following sections. Step 2 deals with the soil cross-section. Here, the user identifies the soil textures by depth. The software then assigns a theoretical value for the maximum amount of water that the soil can hold (field capacity). It is also possible to enter a value for field capacity manually. In Step 3, information concerning the irrigation system, such as the type of system and the spacing and flow rate of emitters, is entered in order to calculate the quantity of water to be applied to the soil during irrigation events. In the fourth and final section, the calculator generates the irrigation schedule, based on all of the factors from the first three steps plus evapotranspiration data. In Quebec, the evapotranspiration data comes from a network of 250 weather stations whose data is validated and made available on the AgWeather Quebec website.[5] The crop's evapotranspiration is determined using the data from the weather station closest to the site, which is retrieved directly by the calculator.

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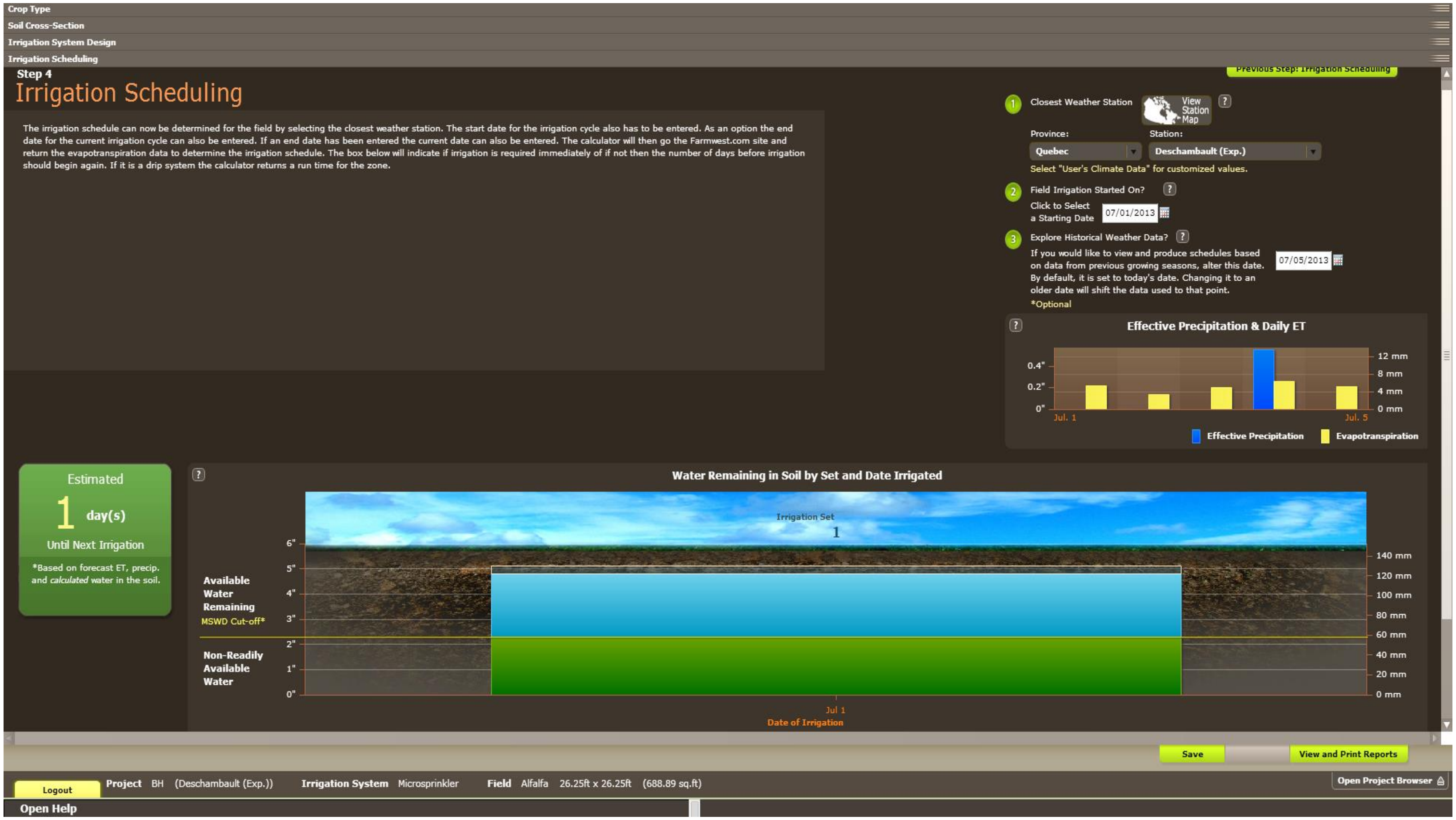
[5] http://www.agrometeo.org/?lang=en



Step 4

Irrigation Scheduling

The irrigation schedule can now be determined for the field by selecting the closest weather station. The start date for the irrigation cycle also has to be entered. As an option the end date for the current irrigation cycle can also be entered. If an end date has been entered the current date can also be entered. The calculator will then go the Farmwest.com site and return the evapotranspiration data to determine the irrigation schedule. The box below will indicate if irrigation is required immediately of if not then the number of days before irrigation should begin again. If it is a drip system the calculator returns a run time for the zone.

1 Closest Weather Station

Province: Quebec

Station: Deschambault (Exp.)

Select "User's Climate Data" for customized values.

2 Field Irrigation Started On?

Click to Select a Starting Date: 07/01/2013

3 Explore Historical Weather Data?

If you would like to view and produce schedules based on data from previous growing seasons, alter this date. By default, it is set to today's date. Changing it to an older date will shift the data used to that point. 07/05/2013

*Optional

Estimated 1 day(s) Until Next Irrigation

*Based on forecast ET, precip. and *calculated* water in the soil.

Project BH (Deschambault (Exp.))

Irrigation System Microsprinkler

Field Alfalfa 26.25ft x 26.25ft (688.89 sq.ft)

Figure 5. One of the steps in the Landscape Irrigation Scheduling Calculator interface.

3.1.2 Technological variability of evapotranspiration values

Evapotranspiration consists of two separate physical processes: evaporation and transpiration. Evaporation is the physical process by which liquid water is transformed into water vapour in the atmosphere. Transpiration also changes liquid water into water vapour. It involves the movement of water from the soil through a plant toward the leaf canopy. The water vapour is then released into the atmosphere through the plant's stomata.

Estimates of the evapotranspiration of a crop can be obtained by using weather station data and mathematical equations. Generally, the weather data used are air temperature, solar radiation, relative humidity and wind speed, all of which must be measured using instruments. Many factors can affect the quality of weather data from a station, including the quality of the components or the calibration or design of the equipment. This means that the difference between two measurements of the same parameter taken from two instruments in the same environment may be sizeable or even critical.

In order to use the water budget method effectively, it is essential to obtain a reliable evapotranspiration value every day. Imprecision in the evapotranspiration value could introduce inaccuracies into the water budget calculations and result in mistiming of irrigation events. In addition, when the software calculates the available water storage capacity, it uses a default value. If that value is lower or higher than the real value, it will introduce an error for every day of the simulation. Cumulatively, those errors may cause the software to schedule irrigation earlier or later than it should. Either error is detrimental to sound irrigation management.

To assess this variability, two weather stations—one acquired from Campbell Scientific and the other from Hortau—were installed at the Deschambault site, less than 10 metres apart. Since the distance between the two stations would not have caused significant differences in the measurements of weather data, both should theoretically have calculated similar values for evapotranspiration (Figure 6 and Figure 7). The 2012 observations show a similar overall trend, but with variability in certain specific values: there were more values close to zero from the Hortau station. The values close to zero are probably reading errors and should not be used in the water budget calculations. The data from the Hortau station also had a wider range between the minimum and maximum values. In 2013, wide variations were observed in the maximum evapotranspiration values.

The quality of the data from the Campbell weather station was monitored throughout the season. When evapotranspiration values are checked against those from neighbouring weather stations, outliers can be eliminated. The differences observed between the two stations can probably be explained by this fundamental difference in the monitoring of the data. Monitoring data quality is extremely important in order to ensure the model's precision.

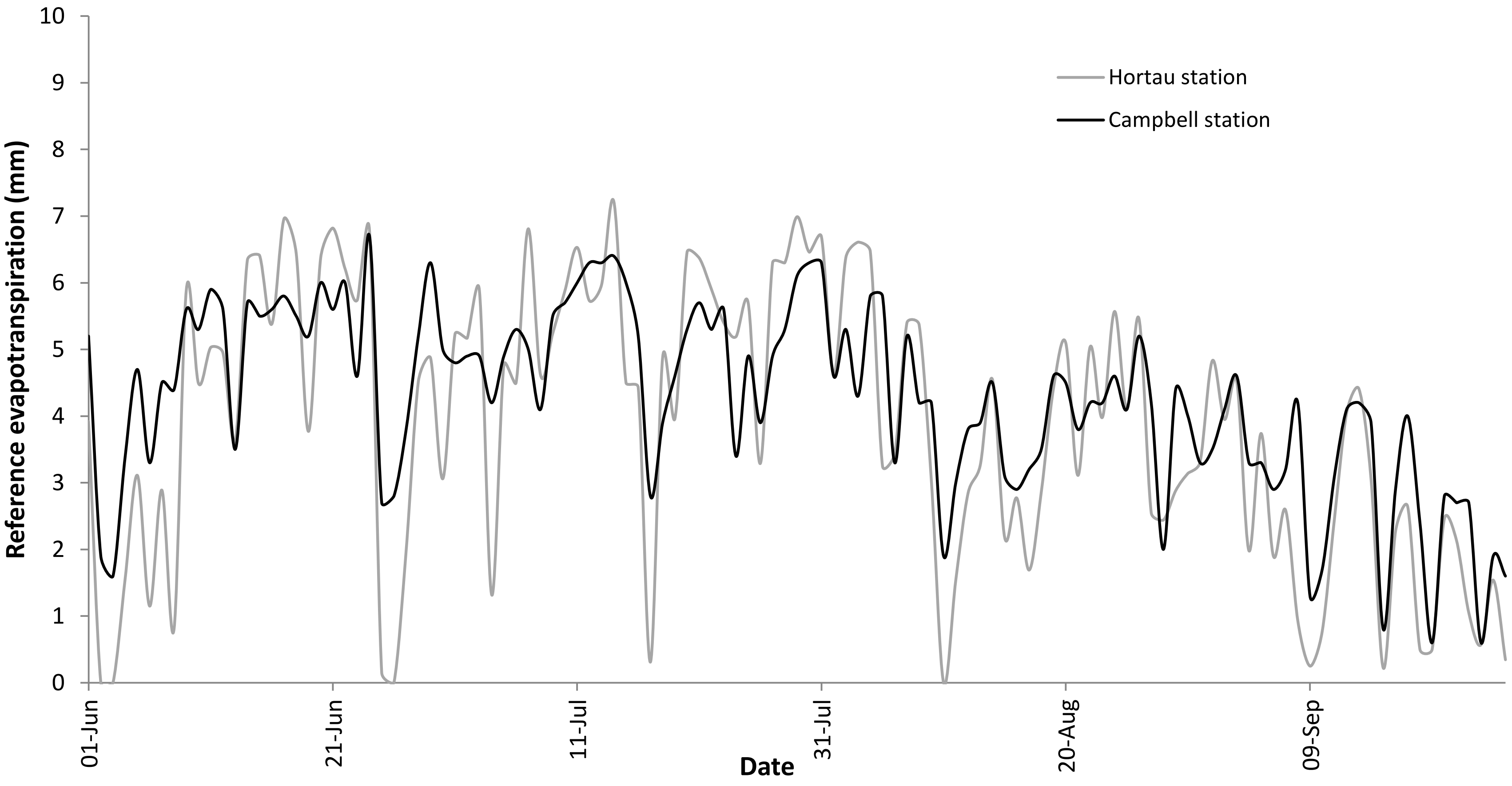


Figure 6. Daily evapotranspiration measured by the two weather stations at the Deschambault site, 2012 season.

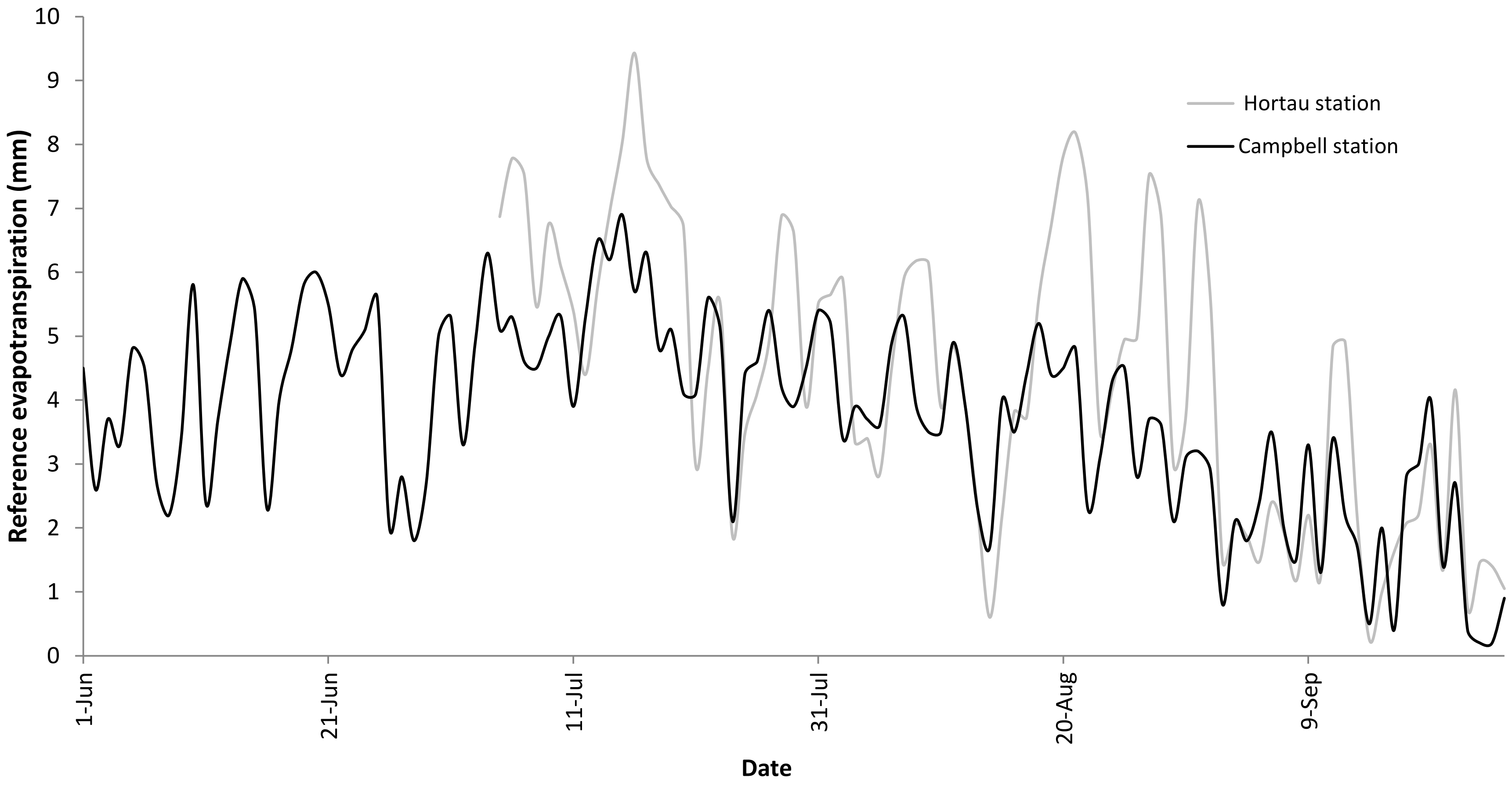


Figure 7. Daily evapotranspiration measured by the two weather stations at the Deschambault site, 2013 season.

3.1.3 Spatial variability of evapotranspiration values

To establish a precise irrigation schedule, the software must monitor soil moisture content daily. The total volume of water lost from the soil is calculated using the potential evapotranspiration value from the weather stations. Because each weather station records the conditions in its specific location, the evapotranspiration value is based on those conditions. Is the water budget method still effective when the weather station is not located near the field to be irrigated? This question can be answered by comparing the evapotranspiration data measured by the weather stations located within a 30-km radius of the Deschambault experimental site (Figure 8 and Figure 9). The method for determining the potential evapotranspiration values is based on empirical equations whose parameters are obtained from the weather station data. The official formula used by the automatic weather stations (Deschambault Campbell, St-Alban, Ste-Anne-de-la-Pérade, Ste-Catherine-de-la-Jacques-Cartier) is the Penman–Monteith equation (Equation 1), while a station where the data is recorded manually (Deschambault manual) uses the Baier–Robertson equation (Equation 2). Within a 30-km radius, the potential evapotranspiration values calculated with the weather station data are very similar. In addition to local variations in potential evapotranspiration, part of the variation in measurements may be due to the equipment (calibration, type of equipment, installation, etc.). There is very little difference between the potential evapotranspiration values from the two weather stations at the Deschambault site, even though they were calculated using two different formulas. Monitoring the data quality may have helped ensure greater uniformity between the two sets of values produced by the two formulas. Although statistical tests were not performed, it appears that those differences would cause only slight changes to the irrigation schedule. The consequences are therefore considered minimal or even negligible.

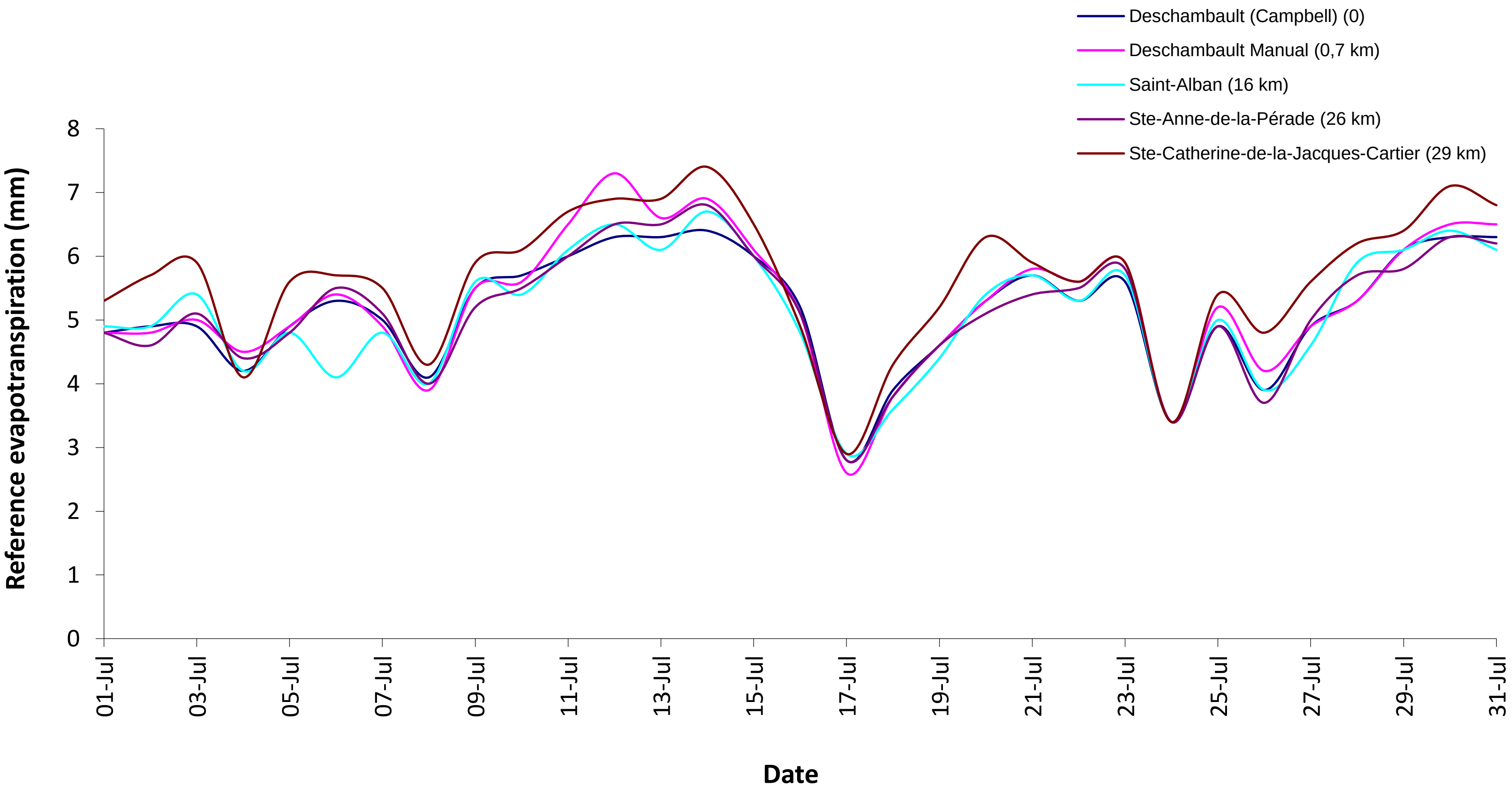


Figure 8. Evapotranspiration values calculated using data from the weather stations within 30 km of the Deschambault site, 2012 season.

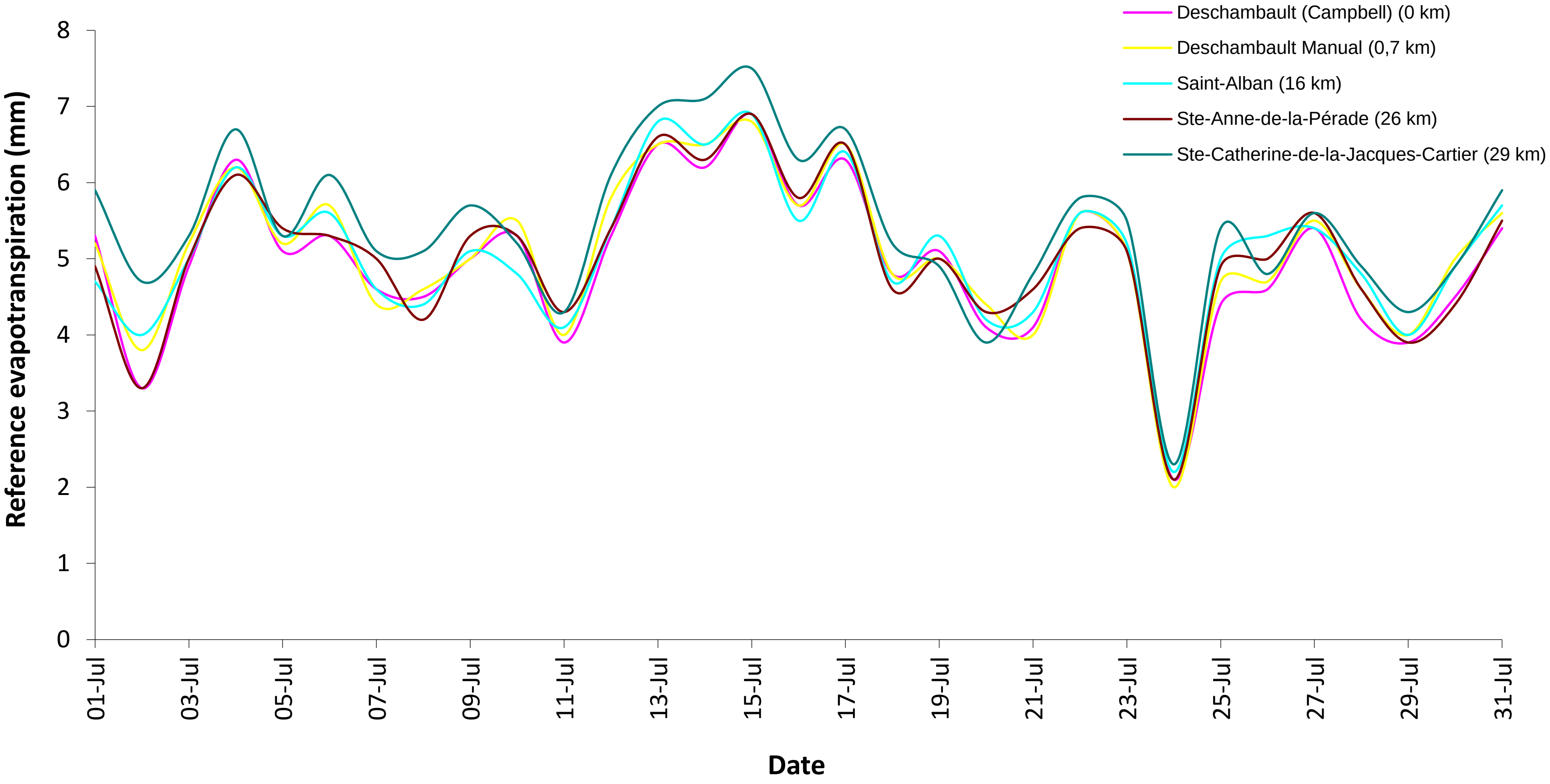


Figure 9. Evapotranspiration values calculated using data from the weather stations within 30 km of the Deschambault site, 2013 season.

3.1.4 Setting irrigation thresholds

Effective irrigation begins with establishing irrigation thresholds that take the specific growing conditions of the crop into account and enable the producer to maintain soil moisture at an ideal level. Establishing an irrigation threshold is an essential step, no matter what method is used to monitor soil moisture content during the growing season. Soil characterizations were performed for the experimental plots in order to identify the conditions under which the trials were conducted and gather the data required to establish irrigation thresholds for each of the sites (Table 1). The soils in the study were all quite coarse-textured (sandy loam to sand) and had an organic matter content between 1.9% and 3.6%. Desorption curves were plotted in a laboratory (Figure 10 and Figure 11) and interpreted in order to characterize the soil and establish the irrigation threshold for the treatments.

Table 1. Physiochemical characteristics of soil in the experimental plots

Season	Experimental site	Crop and cultivar	Predominant soil texture	Organic matter (%)	pH_{water}
2012	Deschambault	Potatoes, Goldrush	Sandy loam	2.5	n/a
	Lanoraie	Potatoes, Russet Burbank	Sand	2.1	5.3
	Sainte-Mélanie	Extra-fine green beans, Denver	Loamy sand	3.6	n/a
2013	Deschambault	Potatoes, Goldrush	Sandy loam	2.5	n/a
	Lanoraie	Potatoes, Russet Burbank	Sand	1.9	n/a
	Sainte-Mélanie	Extra-fine green beans, Anger	Sand	3.1	n/a

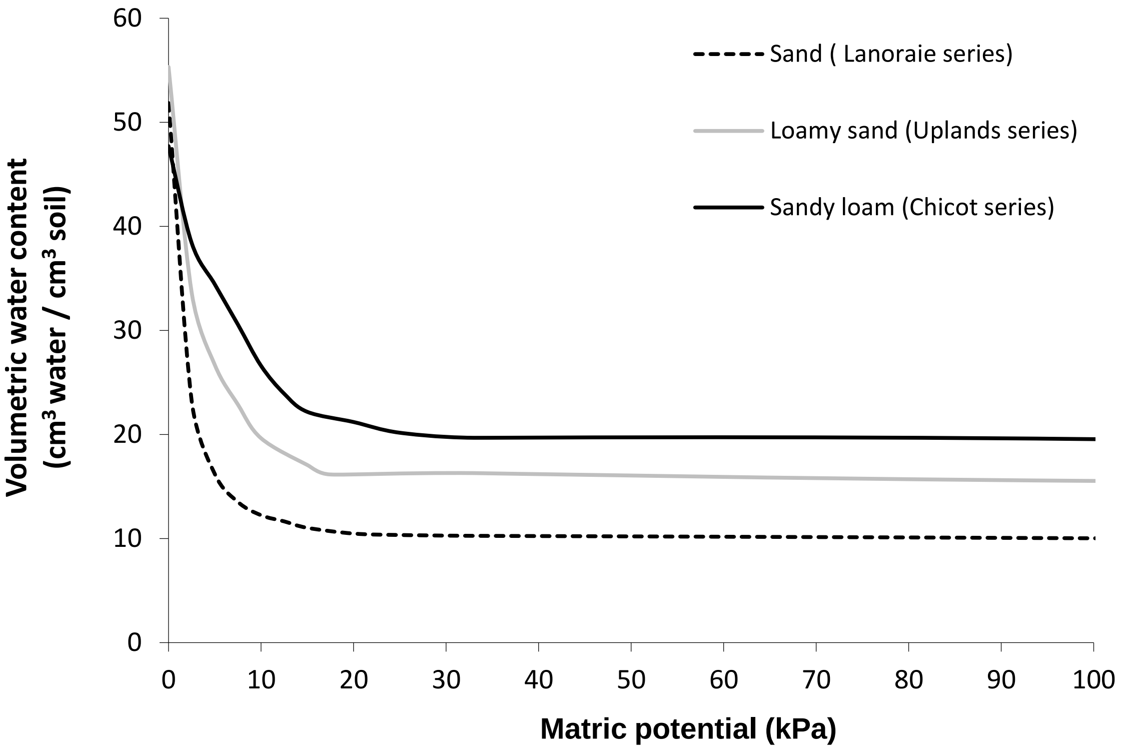


Figure 10. Soil water desorption curves for the three sites, 2012 season.

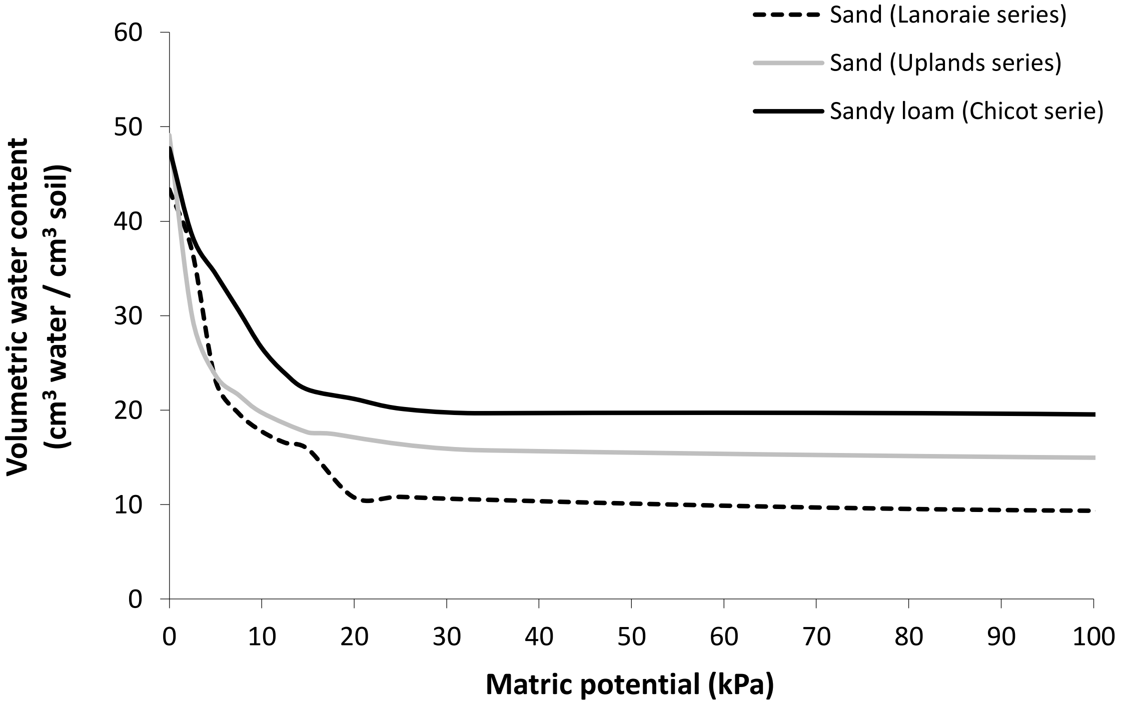


Figure 11. Soil water desorption curves for the three sites, 2013 season.

3.1.5 Managing irrigation schedules with the software

When the user enters data, the software provides default values based on a number of important factors. To evaluate how well the default values would perform, a simulation was run with the software in which none of the defaults was overridden. Then a customized scenario was created by replacing the default values with others that more closely reflected the specific characteristics of the crop and the soil. The customized scenario (Table 10) is a theoretical reference for demonstrating the model's precision. Note that the customized scenario was not actually tested in summer 2012; the simulation was performed after the fact. Lastly, the two scenarios were compared with the real irrigation dates based on the tensiometer treatment (Figure 12). During the summer of 2012, based on the tensiometer treatment, there were five irrigation events, which occurred on July 10, 13, 21, 25 and 30. The tensiometer treatment was used as a reference, since the irrigation events were based on the actual water content of the soil. The theoretical irrigation events scheduled by the water budget method were then compared with the actual events based on the tensiometers. The simulation using the software's default values would have triggered seven irrigation events; the customized scenario would have triggered six. In both simulations, the software overestimated the number of irrigations required, compared to scheduling based on tensiometer readings. It is also interesting to look at whether the dates calculated by the simulations and those based on the tensiometer readings match. In that respect, the customized scenario clearly performed better, matching four out of the tensiometer treatment's five irrigation dates. The simulation using the default values matched only one date.

In 2013, a customized scenario was run for each site. Equivalent irrigation thresholds were set so that the three tools (water budget software, tensiometers and reflectometers) would maintain the soil moisture content at 50% of the total available water storage capacity. That did not happen with the default scenario. A physical characterization of the soils was performed with the aid of desorption curves, which made it possible to calculate the available water storage capacity. The irrigation threshold, set in accordance with the soil type and the management tools, is a numerical value beyond which the crop is considered to be water-stressed. For example, for the Lanoraie site in 2013, total available water storage capacity was calculated as 50 mm of water available for a depth of 30 cm. The rooting depth was set at the same value used for the tensiometer treatment. Therefore, the irrigation threshold was set at 25 mm (50% of the total available water storage capacity). At the Sainte-Mélanie site during the 2013 season, the performance of the two treatments—water budget (Figure 13) and tensiometer (Figure 14)—was similar. With both treatments, two irrigation events were scheduled in July: on July 13 and 27 with the water budget treatment and on July 16 and 28 with the tensiometer treatment. The water budget calculator moved the first irrigation event forward by three days, but the July 27 event was just one day early. It is logical to conclude that the software was slightly overestimating the crop's evapotranspiration on the dates before July 13. That overestimation could be corrected by using new crop coefficients based on the current growth stage rather than monthly values. Crop coefficients will be discussed in detail in section 3.1.8.

At the Deschambault site during the 2013 season, the water budget method produced good results. The irrigation dates based on the water budget (July 13 and July 30) (Figure 15) were close to those based on the tensiometers (July 16 and July 30) (Figure 16). On July 13 the water budget calculator moved the ideal irrigation date forward. However, by the date of July 16 identified by the tensiometer method, the irrigation threshold had been exceeded by a day or two. Therefore, the date calculated by the LISC was quite close to the correct one.

Because there were fewer irrigation events in 2013 than in 2012, there were fewer opportunities to evaluate the overall performance of the water budget calculator. However, under low-evapotranspiration conditions, the water budget calculator's estimates of soil water content were quite acceptable.

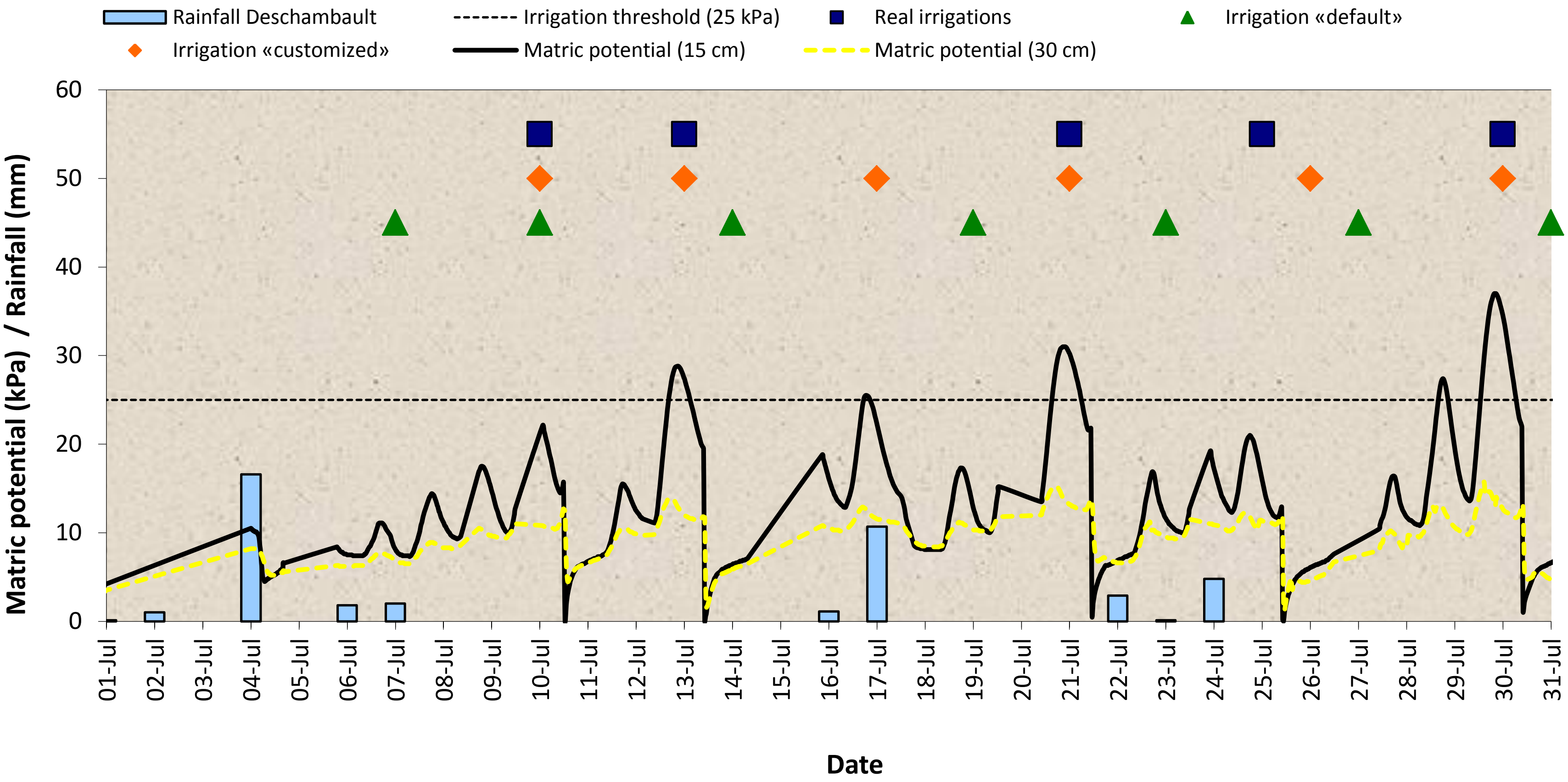


Figure 12. Tensiometer readings, real irrigation dates and dates from the LISC simulations, Deschambault site, 2012 season.

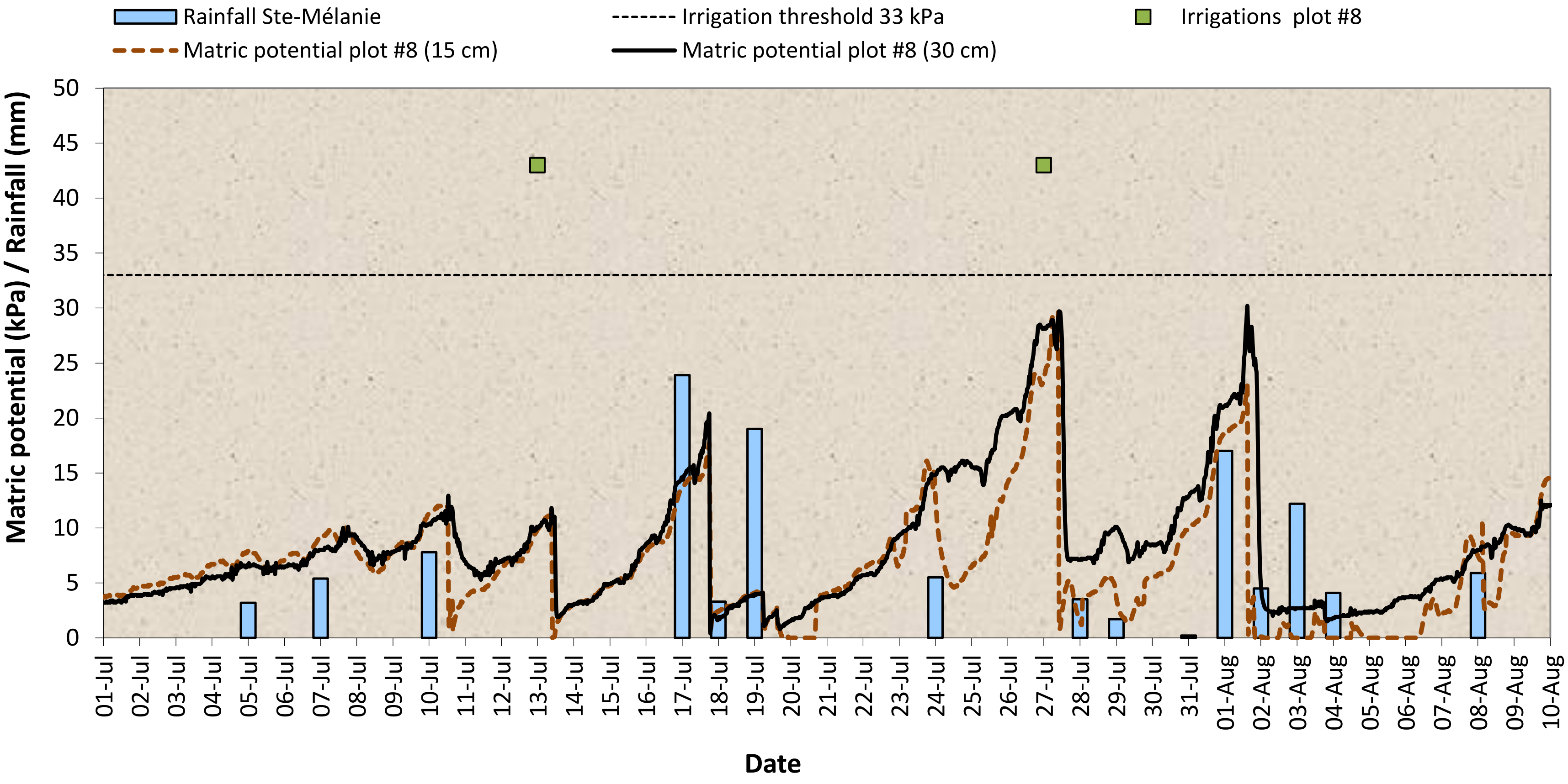


Figure 13. Tensiometer readings and irrigation dates from the LISC simulation, Sainte-Mélanie site, 2013 season.

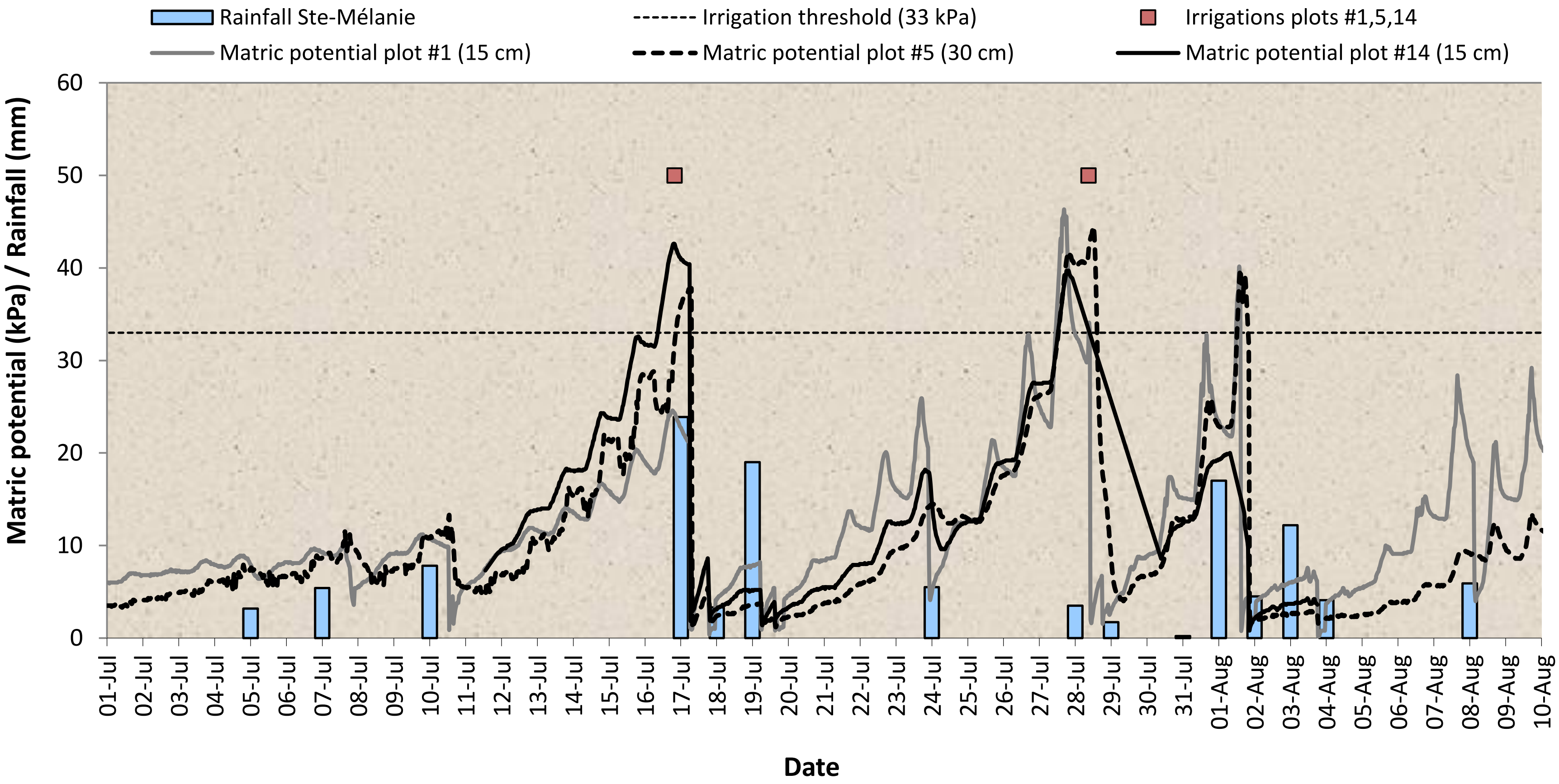


Figure 14. Tensiometer readings and irrigation dates based on them, Sainte-Mélanie site, 2013 season.

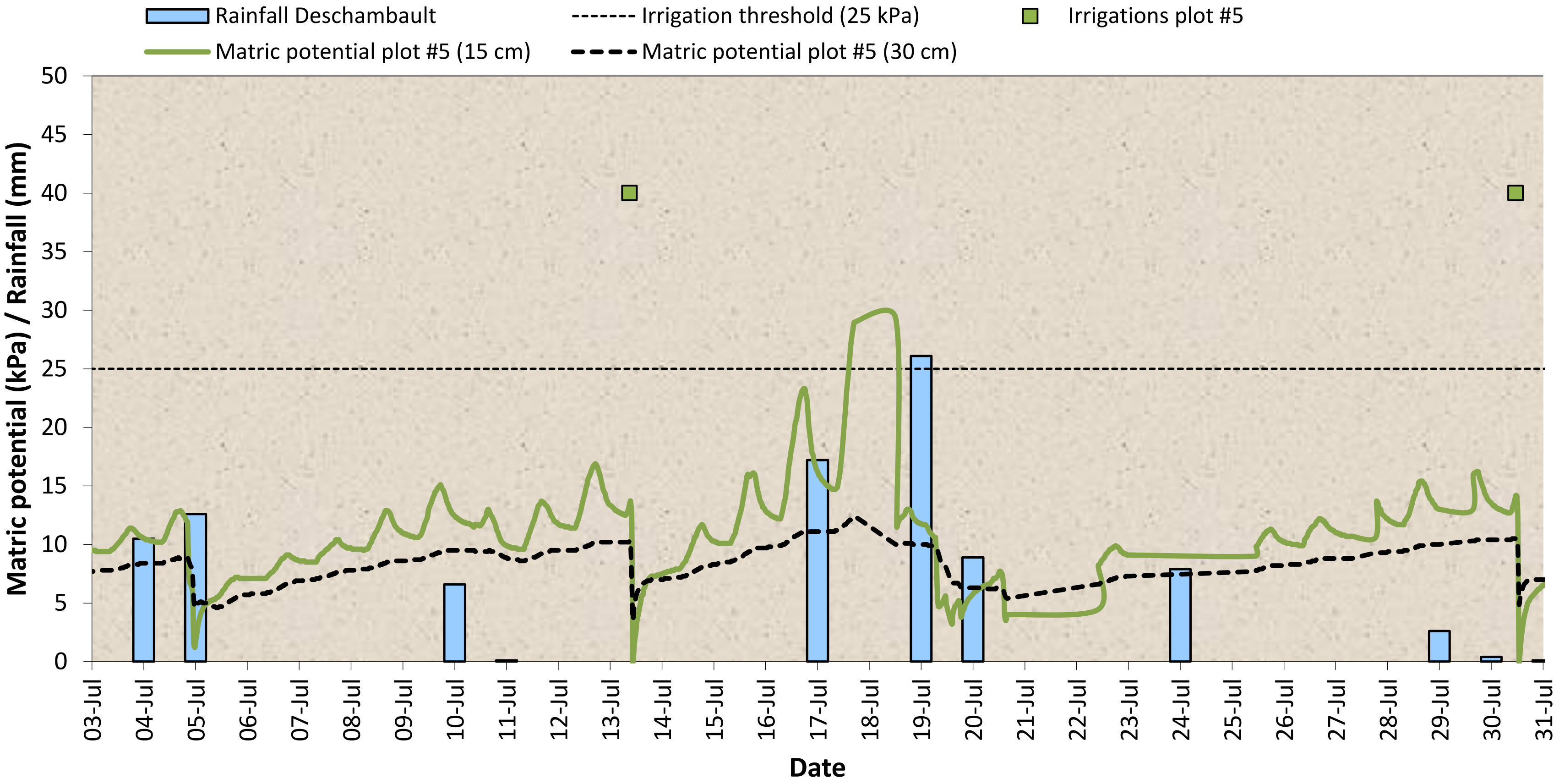


Figure 15. Tensiometer readings and irrigation dates from the LISC simulation, Deschambault site, 2013 season.

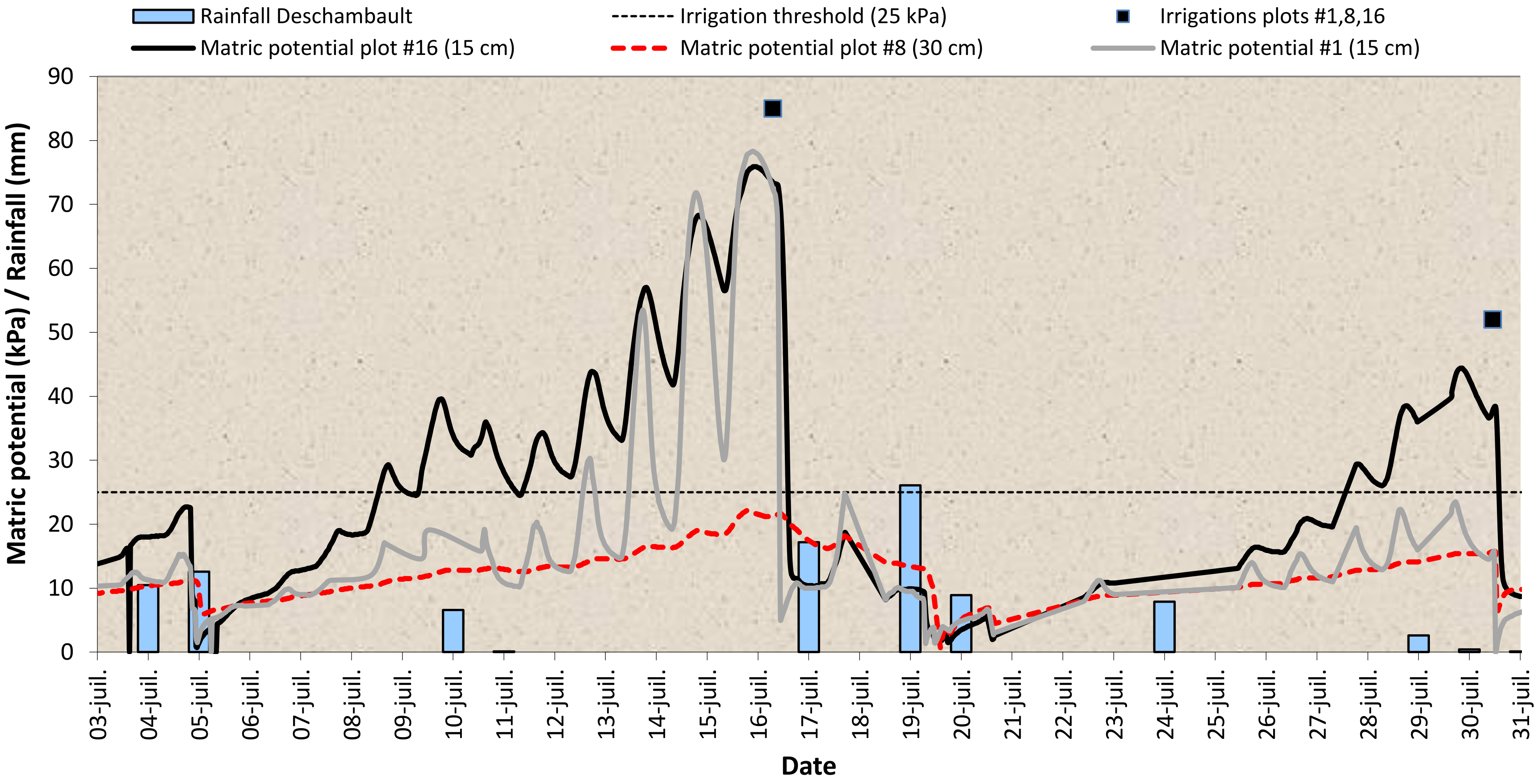


Figure 16. Tensiometer readings and irrigation dates based on them, Deschambault site, 2013 season.

3.1.6 Comparison of water volume applied

The aim of irrigation management is generally to replenish the available water storage capacity in order to replace water lost through evapotranspiration. For each site, the volume of the available water storage capacity was determined based on desorption curves and the specific characteristics of the crop. The duration of irrigation was also adjusted so that the available water storage capacity would be replenished with every irrigation event. The volume of water applied by irrigation and the amount of precipitation are shown in Table 2. The volume applied in July varied considerably between treatments and between years. The total amount of water applied was proportional to the number of irrigation events. The amount of water applied per irrigation event remained constant: it was about 22 mm at Deschambault, 16 mm at Sainte-Mélanie and about 20 mm at Lanoraie. However, that was the gross measurement. Only a certain proportion of the water applied is absorbed by the soil; the rest evaporates during application. The proportion lost to evaporation varies depending on the conditions during application (wind, leaf canopy cover, temperature, humidity, etc.). In 2012, the volume of water that would have been applied at Deschambault based on the enhanced water budget simulation was 20% higher than with the tensiometer treatment. In 2013, the volumes calculated by the water budget method were almost the same as those based on the tensiometer treatment, for both Sainte-Mélanie and Deschambault. At the Lanoraie site in 2013, the volume of water used based on the water budget method was 16% higher than that based on the tensiometer readings.

Table 2. Average water application, by treatment, in July and August of 2012 and 2013.

Season	**Site**	**Soil**	**Treatment and precipitation**	**Cumulative water application**		
				Number of irrigation events	**Total depth of water (mm)**	**Volume of water (l/ha)**
2012	Deschambault*	Sandy loam	Water balance (default)	7	150	1,500,000
			Customized water budget scenario*	6	128	1,280,000
			Tensiometers	5	106	1,060,000
	Sainte-Mélanie	Loamy sand	Customized water budget scenario	n/a	n/a	n/a
			Tensiometers	6	97	970,000
	Lanoraie	Sand	Customized water budget scenario	n/a	n/a	n/a
			Tensiometers	9	183	1,830,000
2013	Deschambault	Sandy loam	Customized water budget scenario	2	42	420,000
			Tensiometers	2	42	420,000
	Sainte-Mélanie	Sand	Customized water budget scenario	2	33	330,000
			Tensiometers	2	28	280,000
	Lanoraie**	Sand	Customized water budget scenario	7	142	1,420,000
			Tensiometers	6	122	1,220,000

*July 2012 only.
**July 2013 only.

3.1.7 Yield

The average yields of the crops studied were compared by treatment (Table 3, Table 4, Table 5). Yields were also broken down based on the grades and categories used for extra-fine green beans and potatoes. As mentioned previously, there was no significant difference in the irrigation thresholds between the water budget treatment and the tensiometer treatment. In other words, those two treatments were carried out under the same conditions and received very similar quantities of water.

The proportion of extra-fine green beans measuring between 5 mm and 6.5 mm in diameter was higher for the irrigated treatments than for the unirrigated control, in both years of the project. In 2012, the final harvest for all treatments was completed on the same date, and the results indicate that the different treatments probably caused the beans to mature on different dates. For extra-fine green beans, the timing of the harvest is determined a few days in advance depending on the stage of maturity, and even a few days could make a difference in the diameter of the pods. Had the crops from different treatments been harvested on different days, it might have been easier to compare yields. Specifically, the beans from the control plots could have been harvested a few days earlier in order to synchronize the growth stages. As it was, the tensiometer-treatment plots had an average yield 38.2% higher than that of the control plots. In 2013, no difference in maturity date was observed between the treatments.

Potato yields at Deschambault for the 2012 season were very similar for the different treatments. The difference between the lowest yield (control) and the highest (reflectometers) is about 10%. There was no notable difference between treatments in marketable yield: the percentage of rejected tubers ranged from 12.4% for the tensiometer treatment to 14.5% for the control. In 2013, there was little or no difference in yield between treatments. Marketable yields were also the same for all treatments.

At Lanoraie in 2012, the yield from the control plots was slightly higher than for the tensiometer treatment. However, the marketable yield was higher for the tensiometer treatment: 82.6% of the total yield versus 69.7% for the control. In 2013, the water budget method produced the highest total yield of the three treatments. However, the proportion of marketable potatoes was much lower than with the tensiometer treatment: for the tensiometer treatment, the marketable yield was 69.9% of the total yield; for the water budget treatment, it was just over 50%.

There are probably several reasons for the differences in yield observed between the 2012 and 2013 seasons. One of the most likely is the marked difference in weather conditions: in 2012, the growing season was hot and dry, whereas in 2013 there was a cold, rainy spring. The high rainfall in the spring of 2013 may have caused leaching of nitrogen and a substantial delay in growth.

Table 3. Tuber yield potential and quality by treatment and season, Sainte-Mélanie.

Season	**Treatment**	**Average yield (t/ha)**	**Diameter (%)**			**Seed / pod ratio (%)**	**DM of beans (g)**	**DM of beans (g)**
			< 5 mm	5 - 6.5 mm	> 6.5 mm			
2012	Water budget	19.4	13.2	83	3.4	5.1	191	323.9
	Tensiometer	19.6	12.2	82	4.6	4.1	188.7	339.4
	No irrigation (control)	12.1	19.6	72.9	6.5	6.9	149.8	256.9
2013	Water budget	9.6	3.6	63.	28.5	4.2	109.9	170.1
	Tensiometer	10.4	3.4	62.4	31	5	123.6	177.3
	No irrigation (control)	10.2	2.1	52.3	41.5	4.7	115.1	158.5

Table 4. Tuber yield potential and quality by treatment and season, Deschambault.

Season	**Treatment**	**Average yield potential (t/ha)**	**Grade**								**Specific gravity**
			Canada No. 1 medium		Canada No. 1 large		Jumbo		Rejected (small)		
			(t/ha)	(%)	(t/ha)	(%)	(t/ha)	(%)	(t/ha)	(%)	
2012	Water budget	41.9	34.2	81.4	1.8	4.3	0.2	0.5	5.7	13.5	1.0725
	Tensiometer	41.9	34.9	83.3	1.5	3.6	0.2	0.5	5.2	12.4	1.0725
	Time domain reflectometer	42.7	34.8	81.2	1.9	4.5	0.0	0.0	6.0	14.1	1.0728
	No irrigation (control)	38.9	30.8	79.0	2.0	5.2	0.4	1.0	5.7	14.5	1.0668
2013	Water budget	29.7	16.5	55.7	0	0	0	0	13.2	44.3	n/a
	Tensiometer	33.1	16.7	50.4	0	0	0	0	16.4	49.6	n/a
	Time domain reflectometer	29.4	16.4	55.7	0	0	0	0	13.0	44.3	n/a
	No irrigation (control)	32.5	17.9	55.1	0	0	0	0	14.6	44.9	n/a

Table 5. Tuber yield potential and quality by treatment and season, Lanoraie.

Season	Treatment	Average yield potential (t/ha)	Grade						Specific gravity
			Canada No. 1 medium		Canada No. 1 large		Rejected (small)		
			(t/ha)	(%)	(t/ha)	(%)	(t/ha)	(%)	
2012	Water budget	49.3	42.4	85.9	0	0	6.9	14.1	1.0734
	Tensiometer	43.9	36.3	82.6	0	0	7.6	17.4	1.0724
	No irrigation (control)	44.3	30.9	69.7	0	0	13.4	30.3	1.0672
2013	Water budget	45.9	21.3	46.4	1.9	4.2	22.7	49.4	n/a
	Tensiometer	43.9	25.8	58.7	4.9	11.2	13.2	30.1	n/a
	No irrigation (control)	43.7	20.3	46.5	1.3	2.9	22.1	50.6	n/a

3.1.8 Crop coefficients

Crop coefficients (k_c) are essential to the water budget method. They make it possible to replace the evapotranspiration value generated by the weather station (ET_o) with the crop evapotranspiration value (ET_c), which takes the specific characteristics of the crop into account. Factors that affect k_c include leaves' resistance to evaporation, crop height, roughness and reflectivity of the leaves, percentage of the soil covered by the crop's leaf canopy, and root development (Allen et al., 1998). Note that the ET_c value produced by the software is a value for evapotranspiration under normal conditions—i.e., it is assumed that the crop is grown under conditions favouring optimal productivity. Therefore, ET_c is valid only when crops are healthy and well fertilized and are grown in a soil whose water content maximizes their productivity. In addition, the k_c values have not been validated under Quebec production conditions and, if used unthinkingly, they could become a considerable source of error in the water budget method. The Landscape Irrigation Scheduling Calculator uses crop coefficients that can only be adjusted monthly. That approach does not allow the user to make the best use of the water budget method. The parameters affecting the value of k_c are physical parameters that change with the plants' growth stage. If k_c is changed in the calculator based on the crop's growth stages, the crop's evapotranspiration value may shift away from the default (Figure 17). If the value of k_c causes an overestimation of the evapotranspiration value at the beginning of the season, that will result in an inaccurate estimate of the soil moisture content at the beginning of the simulation. Similarly, overestimating evapotranspiration at the end of the season could trigger extra irrigation events. Figure 17 illustrates this perfectly. For example, on June 15, the difference between the default value and the modified value was approximately 25 mm. If the water budget simulation had been started at the very beginning of the season, that 25-mm difference might have triggered an additional irrigation event. It is important to remember that the water budget method is cumulative. Consequently, even small discrepancies between the values may eventually cause serious inaccuracies in the budget. If k_c is replaced with a k_c value that takes the growth stage into account, it would be possible to analyze variability between sites and between growing seasons. An early or late seeding, a short growing season or any change that affects the growth stage at a given time could enhance the analysis if the software is able to incorporate them.

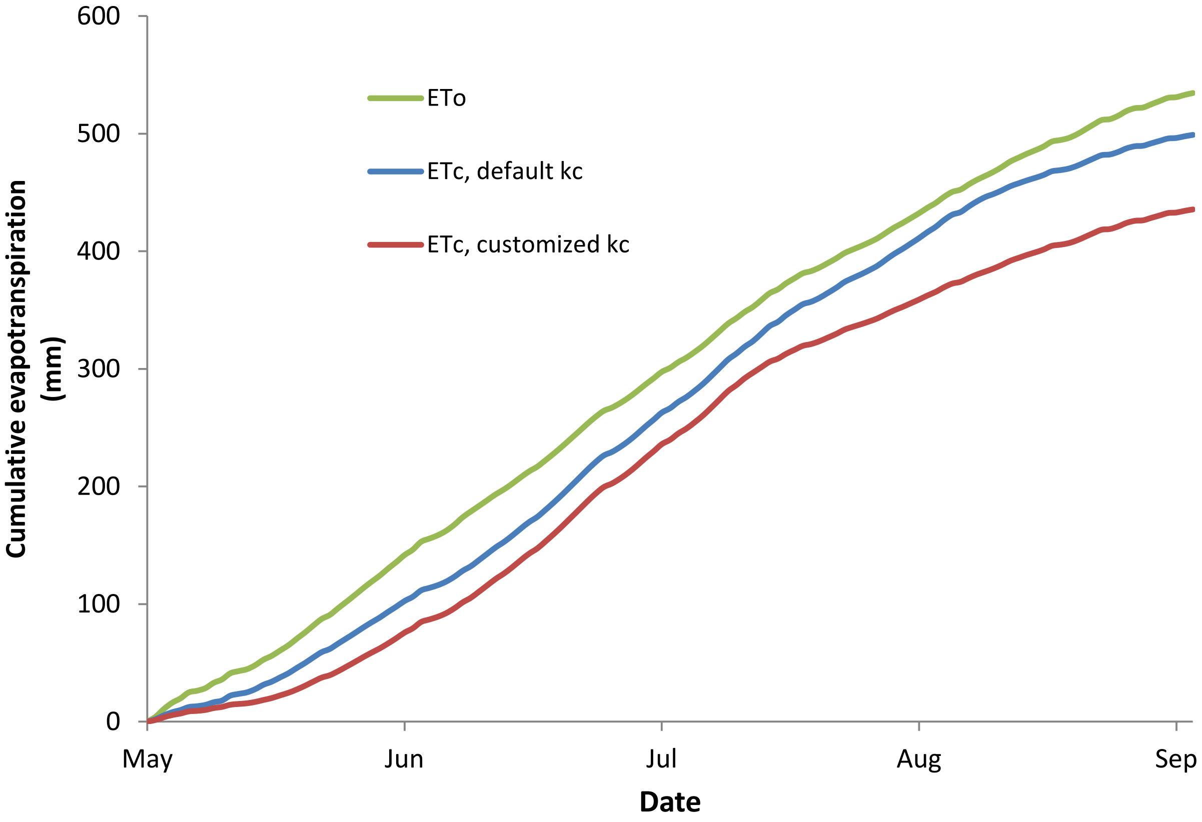


Figure 17. Effect of K_c on evapotranspiration, Deschambault site, 2012 season.

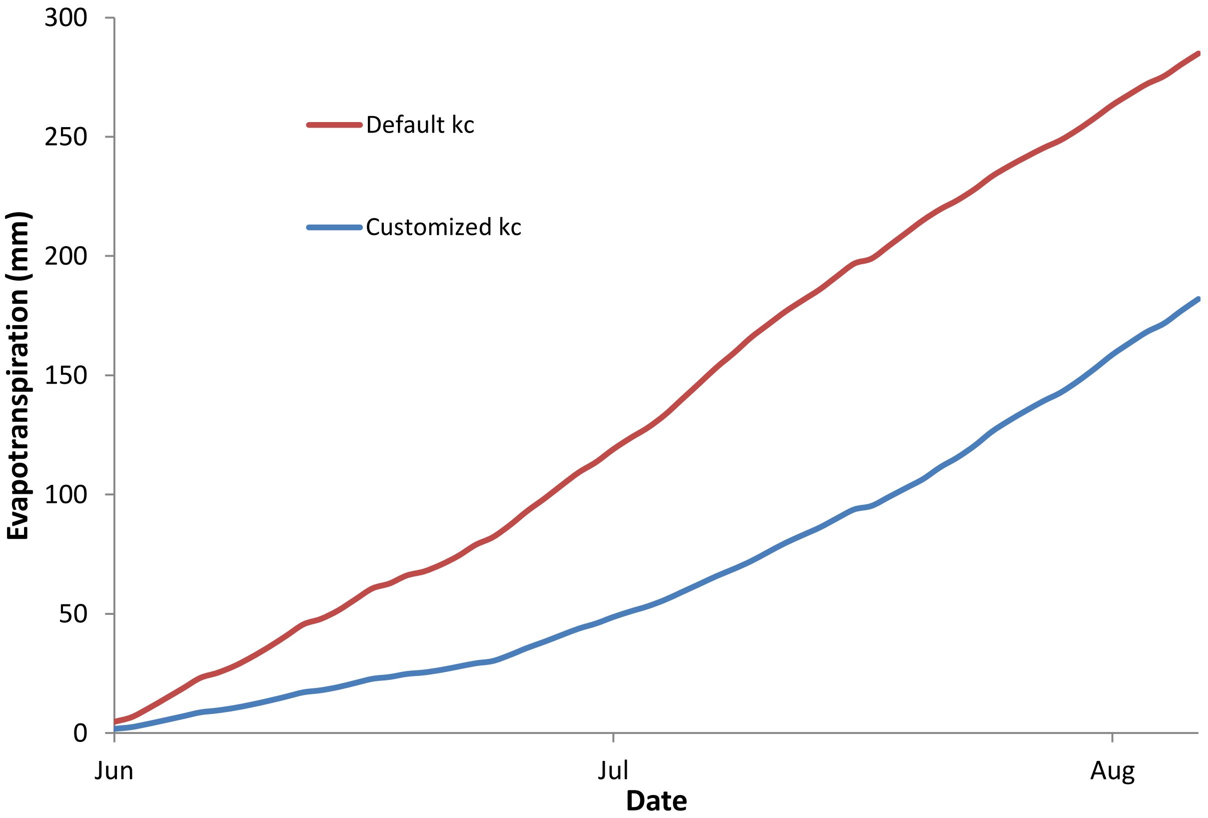


Figure 18. Cumulative evapotranspiration (mm), Sainte-Mélanie, 2013 season.

3.1.9 Growth stages

The irrigation management tools analyzed and compared in this study all require an overall understanding of the crop's growth stages. That knowledge makes it possible to calculate the total available water storage capacity based on the rooting depth at various stages, and to determine the k_c value to use (if k_c is being modified). In the extra-fine green bean experimental plots only, specific growth stages were monitored using the BBCH scale. The growth stages monitored were germination, leaf development, flowering and fruiting. Their timing was measured in days after seeding (DAS) (Table 6). No differences were observed between the treatments.

Table 6. Timing of growth stages for each treatment, Sainte-Mélanie, 2012 season.

Season	**Cultivar**	**Soil**	**Seeding date**	**Treatment**	**2 leaves unfolded**	**1 leaflet unfolded**	**2+ leaflets unfolded**	**Full flowering: 50% of flowers open**	**1st pods visible**	**50% of pods at final length**
					Days after seeding (DAS)					
2012	Denver	Loamy sand	June 27	Water budget	8	n/a	22	45*	50	65
				Tensiometer	8	n/a	22	45*	50	58
				No irrigation (control)	8	n/a	22	42	50	58
2013	Anger	Sand	June 10	Water budget	n/a	22	30	39*	42	n/a
				Tensiometer	n/a	22	30	39*	42	n/a
				No irrigation (control)	n/a	22	30	39*	42	n/a

* Estimated value.

For the green bean crops, the DAS for the different treatments was very similar. The only notable difference was for the growth stages when 50% of the pods had reached their final length: in 2012, it took 7 days longer for the water budget treatment than for the other two treatments. The difference is very difficult to explain, since the plants that received the water budget treatment and those that received the tensiometer treatment were grown under much the same conditions.

At the Deschambault site, the growth stages were determined with the aid of photographs taken weekly. No significant differences between the treatments were observed. The results shown in Table 7 are representative of the growth stages observed for all experimental plots (across all treatments).

Table 7. Timing of growth stages of Goldrush potatoes at the Deschambault site.

Season	Cultivar	Soil	Date				
			Seeding	100% emergence	Hilling	Full flowering	Senescence
2012	Goldrush	Sandy loam	May 15	June 4	June 19	July 12	August 10
2013	Goldrush	Sandy loam	May 28	June 25	July 10	July 26*	August 19

*Estimated date.

3.2 Comparing irrigation management tools

Some irrigation management tools take measurements directly; others calculate indirect measurements. The tensiometers and reflectometers used in this project take measurements directly from the soil, while the water balance method calculates soil moisture content based on indirect measurements. Indirect measurements are less precise than direct measurements, but a hybrid model combining the two methods should be precise enough to schedule irrigation events accurately. Instruments that take direct measurements can be used initially as references to validate the hybrid model. Obviously, each instrument has advantages and disadvantages that help and hinder the hybrid model. Since reflectometers are not yet well suited for use in irrigation management, tensiometers currently have the highest potential for reducing imprecision and ensuring the best possible calculation of soil water content.

The relationship between tensiometer and reflectometer data can be graphed to produce soil water desorption curves (Figure 19 and Figure 20). The overall trend of these curves is similar to that of the desorption curves produced in the laboratory, but the field values for volumetric water content (VWC) are different for the same soil water tension values. It may be that the soil in the plots was coarser-textured than the samples analyzed in the lab, or that calibrating the sensors after the experiment would have brought the desorption curves based on field measurements closer to the laboratory curves. In addition, since the reflectometer reading was not taken at the same depth as the tensiometer reading due to the technical limits of the instrument, the relationship between the two values should be interpreted with caution. Given the current limits of the equipment, it is impossible to manage irrigation properly with wireless reflectometers.

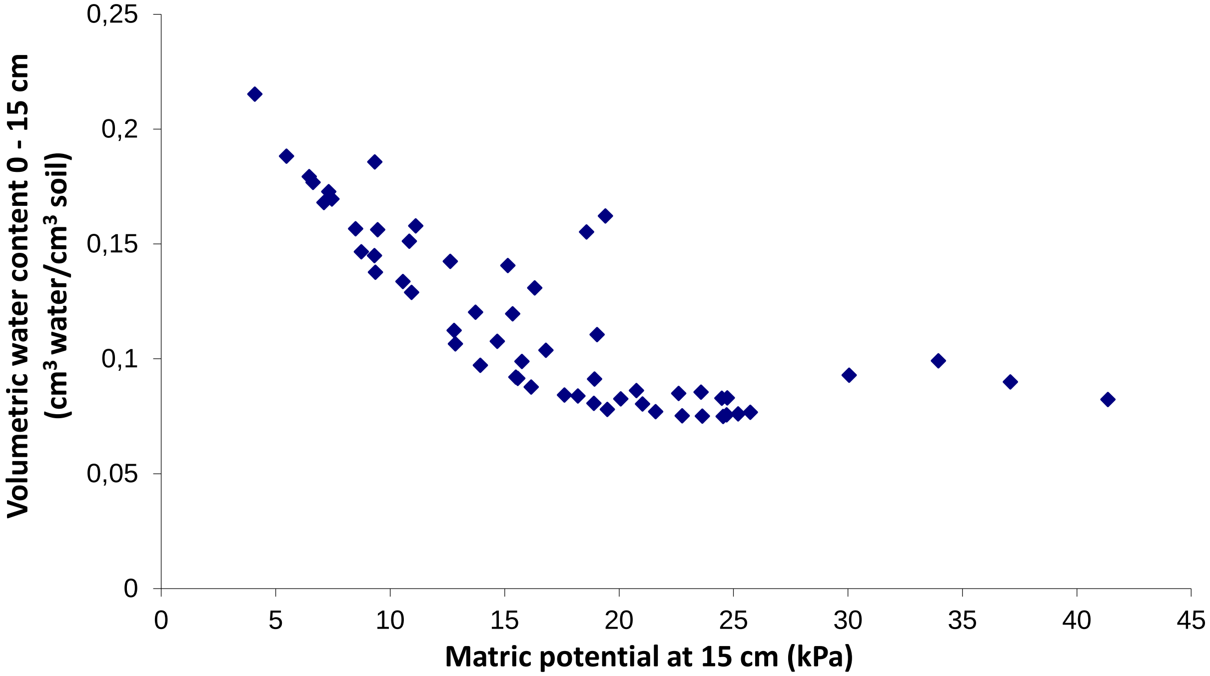


Figure 19. Soil water desorption curve based on field measurements, 2012 season.

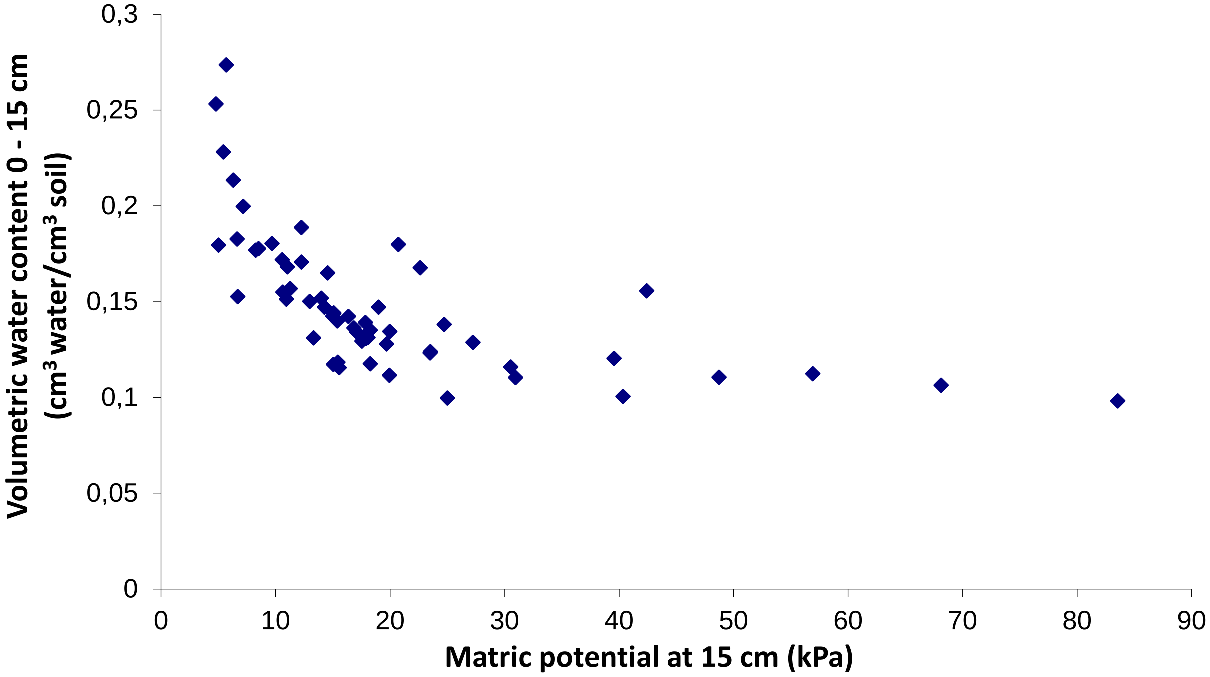


Figure 20. Soil water desorption curve based on field measurements, 2013 season.

The LISC is a widely available tool that has the advantage of being simple and user-friendly. It can be adjusted to all types of mineral soils, and it is easy to use the default values or replace them with customized values. The interface also incorporates weather forecasts in order to schedule irrigations over the next few days. That is a clear advantage over some other software programs that do not have this function. However, the current version of the LISC is not as precise as reflectometers and tensiometers. The version that was tested in this study does not always save customized parameters, which means that, for every simulation, the user must start the process over again from the beginning. However, those are small inconveniences that can be corrected. Also, the calculator does not maintain a history of irrigation events or of soil moisture content at given times. Such a capability would be very useful for displaying overall trends in soil moisture content. The LISC is compared to the two other tools in Table 8.

Table 8. Comparison of the three irrigation management tools

Tool	**Advantages**	**Disadvantages**	**Cost**	**Applications**
Water budget calculator (LISC)	• Simple to use • Available for many crops • Incorporates weather forecasts • Managing extensive crops	• Default settings need improvement • Some bugs in the software • No history • Requires proximity to a weather station	$	Irrigation management for entire fields
Tensiometers	• Reliable readings • Can measure horizontal and vertical movement of water • Datalogging is possible	• Need a large number of devices to calculate the soil moisture content of a field • Not suitable for heavy soils • Fragile • Equipment could impede field operations	$ to $$$	Irrigation management for small plots or entire fields
Reflectometers	• Reliable readings • Robust design • Long-term reliability of equipment	• Calibration is a complex, meticulous process • Needs to be connected to a lot of other equipment in order to work well • Equipment could impede field operations • Not suitable for irrigation management	$$$	Research

3.3 Evaluating a hybrid approach to irrigation management (water budget plus real-time measurements)

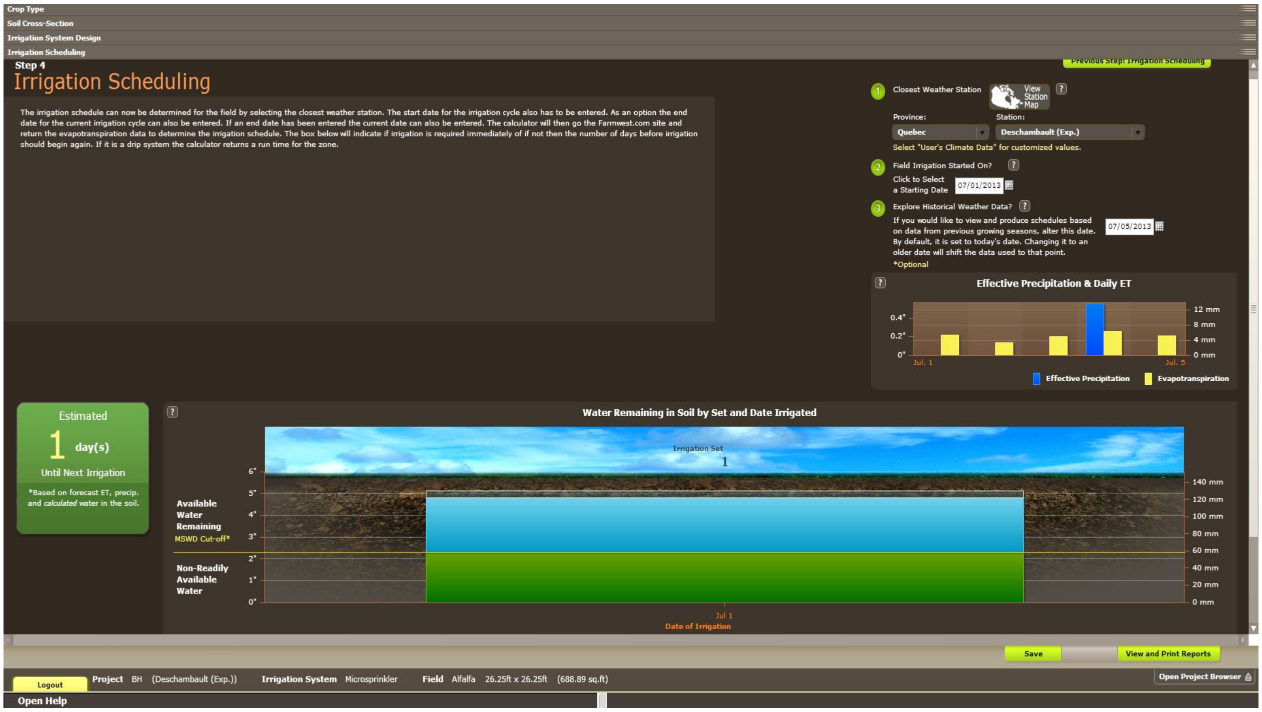
The advantage of a hybrid approach that combines water budgeting and direct measurements of soil water content lies in its ability to manage water applications efficiently. As discussed previously, except for the tensiometer treatment, it is impossible to tell from the results whether the different management tools negatively affected the yields of the crops being studied. However, since tensiometers take real-time quantitative measurements of soil moisture, they are still the reference. A difference in yield between treatments could be due to a different irrigation threshold, that is, the inability to correctly detect when 50% of the available water storage capacity has been reached. Since the threshold is the same for all the tools, irrigation events should be triggered simultaneously for all treatments. The post-hoc analysis of the water budget method and the theoretical demonstration of irrigation dates showed that the threshold of 50% of available water storage capacity was not reached at the same time with all treatments. However, the results also demonstrate that, once the water budget software is calibrated properly, it is possible for it to perform almost as well as the reference method.

Over time, the water budgeting software accumulates many small errors that can lead to a sizeable discrepancy between the theoretical and real soil water contents. Therefore, tensiometer readings would be useful for correcting the estimate of soil water content. A number of factors can produce these discrepancies, including the crop coefficient (k_c), the rooting depth at maturity, the total available water storage capacity, the availability coefficient for irrigation water, rainfall, the soil water content at the beginning of the simulation, and errors associated with the method of calculating $ET_{o.}$ As mentioned previously, the crop coefficients (k_c) generated by the software are monthly, which means that the growth stage of the crop is taken into account only indirectly. It is certainly possible to modify the value of k_c based on observations in the field, but it should be possible to achieve even greater precision—especially for crops that mature quickly, like extra-fine green beans—by enabling the user to vary k_c regardless of the month.

3.4 Anticipating crops' water requirements

For integrated irrigation management, it is important to be able to anticipate crops' water requirements in order to plan field operations efficiently. Irrigation management tools are an important source of information for anticipating water requirements.

As long as the precision of the water budgeting calculations can be relied on, the LISC is unparalleled. Using current evapotranspiration data, total available water storage capacity and the weather forecast for the next few days, the software calculates the number of days until the next irrigation (Figure 21).



Step 4

Irrigation Scheduling

The irrigation schedule can now be determined for the field by selecting the closest weather station. The start date for the irrigation cycle also has to be entered. As an option the end date for the current irrigation cycle can also be entered. If an end date has been entered the current date can also be entered. The calculator will then go the Farmwest.com site and return the evapotranspiration data to determine the irrigation schedule. The box below will indicate if irrigation is required immediately of if not then the number of days before irrigation should begin again. If it is a drip system the calculator returns a run time for the zone.

1 Closest Weather Station

Province: Quebec

Station: Deschambault (Exp.)

Select "User's Climate Data" for customized values.

2 Field Irrigation Started On?

Click to Select a Starting Date: 07/01/2013

3 Explore Historical Weather Data?

If you would like to view and produce schedules based on data from previous growing seasons, alter this date. By default, it is set to today's date. Changing it to an older date will shift the data used to that point. 07/05/2013

*Optional

Estimated 1 day(s) Until Next Irrigation

*Based on forecast ET, precip. and *calculated* water in the soil.

Project BH (Deschambault (Exp.)) Irrigation System Microsprinkler Field Alfalfa 26.25ft x 26.25ft (688.89 sq.ft)

Figure 21. Estimating the number of days until the next irrigation date, using the Landscape Irrigation Scheduling Calculator.

This function is one of the software's greatest strengths, as the user can see at a glance the next few dates on which irrigation must take place. Of course, the user must repeat the process day after day to check for changes in the weather forecast and see whether the number of days until the next irrigation event is still valid.

The software's strength at accurately predicting the need for irrigation in the next few days is a definite advantage with extensive crops irrigated by means of large-scale sprinkler systems (e.g., boom, gun). Because these types of systems irrigate only part of the total hectarage at one time, they require good planning in order to apply water when the crops need it. Water budgeting is a planning tool that can respond to both practical equipment-related considerations and the real needs of the crops.

With tensiometers, it is also possible to anticipate a crop's irrigation needs, but the process requires much more time and experience on the part of the user. The history of the soil moisture content for the previous few days can be used to estimate when the crops will need to be irrigated again. This process can be illustrated by the tensiometer treatment at Sainte-Mélanie in 2013 (Figure 22). On July 10, rainfall caused a substantial decrease in the tensiometer reading at 15 cm (a value close to 0 indicates saturation) and a slight decrease in the reading at 30 cm. The soil was therefore considered to be at or near field capacity on July 12, 24 hours after the event. Water was applied on July 17, the fifth day after field capacity was reached. In that situation, there was no precipitation between the field capacity date and the irrigation date, which made the estimation easier. But how valid is this process when small amounts of precipitation occur between the field capacity date and the irrigation date? An analysis of the following irrigation date (July 28) can be used to answer that question. The plot was irrigated on July 17, then received a few rainfalls and reached field capacity on July 20 or 21. Looking only at the number of days between field capacity and the pre-established irrigation threshold would have resulted in irrigation being scheduled on July 25 or 26. But on those dates, the soil moisture content was high enough that irrigation was not required. The rainfall on July 24, although light, increased the interval by 5 days. To take the effect of rain into account when scheduling irrigation, the user must note the soil moisture content on July 26 and look for an equivalent value in the history. The value from July 15 is quite similar, and the interval between July 15 and the irrigation date of July 17 is 2 days. If the interval before the second irrigation event is corrected to about 2 days, it would occur on July 28 (2 days after July 26).

Anticipating the need for irrigation with the tensiometer method requires a great deal of experience and observation. As with the water budget method, the calculations must be checked and updated every day. Clearly, the estimates produced using this method are approximations in current growing conditions. Consequently, any factor that alters crop evapotranspiration could substantially change the anticipated timing. For that reason, the anticipated dates are temporary and must be monitored carefully. In addition, without past tensiometer readings from the same field planted with the same crop, it is impossible to extrapolate in order to schedule the first irrigation date of the season.

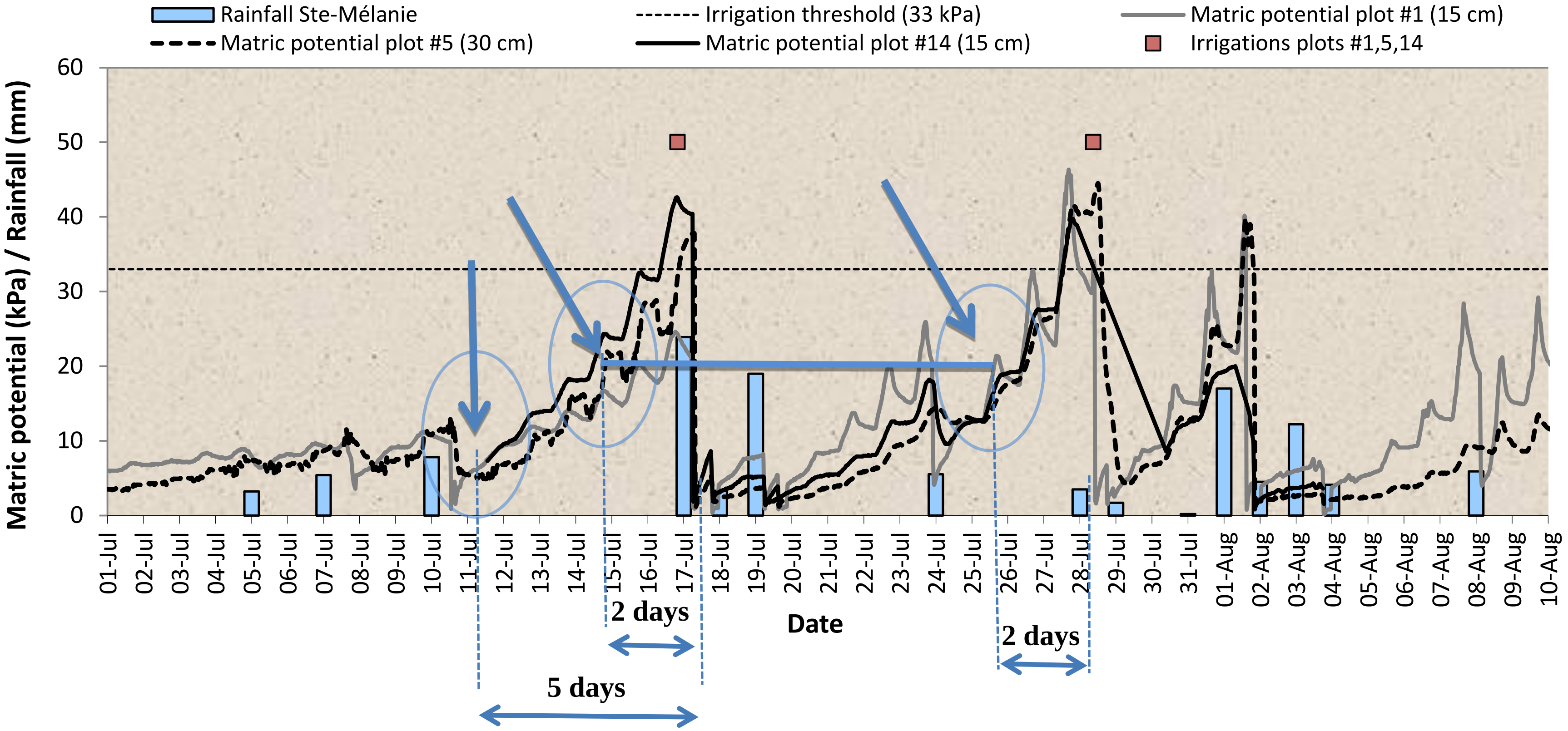


Figure 22. Scheduling the number of days between irrigations with the tensiometer method, Sainte-Mélanie, 2013 season.

3.5 Economic assessment of the irrigation management methods

For purposes of comparison, various irrigation management tools and their acquisition costs are shown in Table 9. The list of manufacturers and models is not exhaustive, but it does include the main pieces of equipment used during this project, as well as some popular equipment sold by specialized retailers. The weather stations listed all have wireless communication modules that enable users to receive information from the station over long distances. For tensiometry, three models are listed: one has wireless communication capability (Hortau TX3 web) and the others are read manually (Soilmoisture and Irrometer).

Table 9. Prices for irrigation management equipment

Method / equipment	Manufacturer /model[6]	Description	Price[7] ($ CAN)
Water budget / Weather station	*WatchDog*® 2900ET	Modules and measuring equipment	1,925
		Software	343
		Communication system	1,300
		Data hosting (1-year contract)	457
		Mounting base	116
		Total	4,141
	HOBO®	Modules and measuring equipment	2,973
		Software	111
		Communication system	Included
		Data hosting (2-year contract)	370
		Mounting base	393
		Total	3,847
	Hortau®	Modules and measuring equipment	4,790
		Software	Included
		Communication system	6,715
		Data hosting (1-year contract)	765
		Mounting base	395
		Total	12,665[8]
Tensiometry / Tensiometer	Hortau® TX3 web	Module	3,129
		Sensors (2)	1,190
		Data hosting (1-year contract)	765
		Total	5,084
	Soilmoisture® JetFill	Tensiometer 30 cm	194
	Irrometer®	Tensiometer 30 cm	133

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[6] WatchDog® is a registered trademark of Spectrum Technologies Inc. HOBO® is a registered trademark of Onset Computer Corporation. Hortau® is a registered trademark of Hortau Inc. Soilmoisture is a registered trademark of Soilmoisture Equipment Corp.

[7] Prices in effect in January 2014, not including taxes, installation and transport.

[8] Price from 2012.

4 Conclusion

Water budgeting is certainly not a new irrigation method, but the software evaluated in this project gives the user considerable flexibility and control. However, the user must be familiar with soil characteristics, both those entered into the software and those generated by it. Although water budgeting is not as precise as the tensiometer method, its low cost makes it indispensable for large areas under irrigation. The LISC is less precise under weather conditions that are likely to cause water stress, and it would overestimate by about 20% the number of irrigation events required to maintain the soil moisture content at a target value during a drier summer. Nevertheless, the water budget calculator was able to schedule the irrigation events on irrigation dates similar to those obtained using tensiometry, within a few days before the optimal time. In addition, water budgeting is more effective than subjective methods like the hand-feel method or the one-inch-of-water-per-week rule for estimating soil moisture content. Whichever method is used to manage irrigation, characterization of soil physical properties is essential. It makes sense to take advantage of the strengths of both the water budgeting method and tensiometry. A hybrid approach in which data generated by the water budget calculator are validated by a few direct tensiometer readings would be a good compromise between cost and precision, and it would take full advantage of the user's judgment while supporting it with quantitative data.

5 Suggested improvements to the software

5.1 Saving the data

Improvement is needed in the software's ability to save data entered in projects. A number of times, the calculator did not save the values that were entered, which meant that for each simulation, all the parameters had to be checked and the desired values had to be re-entered.

5.2 Resetting the available water storage capacity

The interface could also be improved by adding a reset button for the available water storage capacity. That way, the user could reset the balance to zero without having to insert irrigation events on fictitious dates in order to fully replenish the AWSC. Such a button would be a great help in a hybrid approach if the direct measuring instruments suggested resetting the balance to zero.

5.3 User's climate data

The ability to modify the evapotranspiration values retrieved from the weather station is a useful function, but it is not fully developed in the current version of the software. In order to take advantage of this function, the user must enter new evapotranspiration and precipitation values for the desired dates. As shown in the preceding sections, the variability of evapotranspiration values from neighbouring weather stations is negligible. In addition, the quality of the evapotranspiration values was monitored to ensure that they were reliable. However, precipitation is a much more variable parameter, and local precipitation can easily go unnoticed. Many producers already own a rain gauge. It would be handy to be able to use just the precipitation values from the farm in combination with the evapotranspiration values from the nearest weather station. To make that possible, the evapotranspiration and precipitation parameters would simply need to be separated in the "User's climate data" function.

5.4 Irrigation schedule

In a simulation, the user must enter the date of the last irrigation event. The time is not taken into account in this step. The way in which the calculator uses this data—adding the effect of the irrigation to the water balance and subtracting the day's evapotranspiration—could lead to errors. For example, if water is applied at the end of the day, the available water storage capacity should be completely replenished the next day. However, that is not the case. To get around this problem, the user must enter the time of the previous irrigation event to modify the calculation, if need be.

5.5 Available water storage capacity (AWSC)

In situations where the irrigation date is not scheduled correctly, the water budgeting software creates a serious bias in the calculation of soil moisture content. For example, if Soil X has a total available water storage capacity of 40 mm, with an irrigation threshold of 50% of the available water storage capacity, the AWSC equals 20 mm. The calculator subtracts the evapotranspiration and adds the effective precipitation for the day to the plant's available water storage capacity. When 50% of the available water storage capacity is exhausted, the plant is considered to be water-stressed, and its real evapotranspiration is no longer the same as the value generated by the weather station. Evapotranspiration data from the weather station are theoretical values based on the soil being at field capacity. But the software continues to subtract evapotranspiration from the available water storage capacity. In reality, when a plant is water-stressed, evapotranspiration decreases. To correct this problem, a new coefficient should be added to adjust the evapotranspiration value. A coefficient, K_s, already exists that can be used to adjust evapotranspiration values under conditions of water stress (Allen et al., 1998). Or, in the interests of simplicity, the following changes could be made to the calculator:

- An irrigation event that provides a volume of water equivalent to the irrigation threshold could fully replenish the AWSC, regardless of the soil moisture content calculated by the software.
- The software could stop subtracting evapotranspiration values once the irrigation threshold has been crossed.

5.6 Crop coefficients

In its current form, the software uses monthly crop coefficients. As discussed in section 4.1.8, the coefficients should take into account the crop's growth stage and the percentage of leaf canopy coverage, which are major components of the crop coefficient. The model's precision could also be improved by using coefficients that change gradually rather than by category.

5.7 Mulch and ground cover

The software does not take into account crops grown under mulch or ground cover. It would be helpful to add this variable, since many crops are planted using these techniques. An adjustable coefficient for effective rainfall should also be added, as it is a very important element to consider for crops grown under mulch.

5.8 History

Efficient irrigation management also involves analyzing the irrigation dates and the volumes of water used during the growing season. Adding a “History” module would make it possible to archive the data so that comparisons could be made between seasons. A well-designed archive could become a very useful tool.

5.9 Weather station updates

The date and time when the software received the last update from the weather station it is linked to could be displayed during the simulations. That information is essential to the decision-making process, but at this point it is not available.

5.10 Revision of the French version of the calculator

There are still some nomenclature errors in the interface. It should be carefully revised to bring the French version up to the level of the original.

6 Dissemination of the results

- IRDA website: http://www.irda.qc.ca, since April 2011.
- Information day: “Gestion de l’eau en horticulture” [Water management in horticulture], organized by MAPAQ-DRCN and RLIO, held on February 27, 2013, in Ste-Famille, Île d’Orléans.
- Information day: “La nutrition hydrique et minérale de la pomme de terre : une gestion unifiée pour augmenter la productivité!” [Water and mineral supply for potatoes: unified management to increase productivity], organized by IRDA, held on November 29, 2013, in Quebec City.

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8 Annex

8.1 Penman–Monteith equation

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} V_2(e_s - e_a)}{\Delta + \gamma(1 + C_d V_2)}$$

Equation 1. Penman–Monteith equation (American Society of Civil Engineering, 2005)

Where

ET_o: reference evapotranspiration [mm $jour^{-1}$],
R_n: net solar radiation at crop surface [MJ m^{-2} $jour^{-1}$],
G : soil heat flux density [MJ m^{-2} $jour^{-1}$],
T: average daily temperature at a height of 2 m [°C],
V_2: wind speed at a height of 2 m [m s^{-1}],
C_n: constant that changes depending on the size of the plants (900 for small; 1,600 for large),
C_d: constant that changes depending on the size of the plants,
e_s : saturation vapour pressure [kPa],
e_a: actual vapour pressure [kPa],
$e_s - e_a$: saturation vapour pressure deficit [kPa],
Δ: slope vapour pressure curve [kPa $°C^{-1}$],
γ: psychrometric constant [kPa $°C^{-1}$].

8.2 Baier–Robertson equation

$$ET_p = -5.39 + 0.157\, T_{max} + (T_{max} - T_{min}) + 0.00457 R_a$$

Equation 2. Baier–Robertson equation (Baier and Robertson, 1965)

Where

ET_p: potential evapotranspiration [mm $jour^{-1}$],

T_{max}: maximum daily air temperature [°C],

T_{min}: maximum daily air temperature [°C],

R_a : extraterrestrial radiation [cal/cm^2j].

8.3 Parameters used in the water balance calculator

Table 10 shows the default parameters and those used in the scenario customized for the Deschambault site.

Table 10. Default and customized parameters used for the water budget scenarios

Parameter		Default	Customized
Crop		Potatoes	Potatoes
Rooting depth at maturity		0.61 m	n/a
Availability coefficient		0.35	0.5[9]
Crop coefficients	May	0.5	0.35
	June	0.8	0.65
	July	1.1	1.1
	August	1.1	0.8
	September	0.75	0.75
	Off season	0.5	0.5
Available water storage capacity		73.2 mm[10]	86 mm[11]
Maximum application rate		3.35 mm/h	21.8 mm/h
Maximum soil water deficit		25.6 mm	43 mm

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[9] Equivalent to the threshold of 50% of the ASWC.

[10] Based on a rooting depth of 61 cm.

[11] Based on a rooting depth of 30 cm.

8.4 Photographs

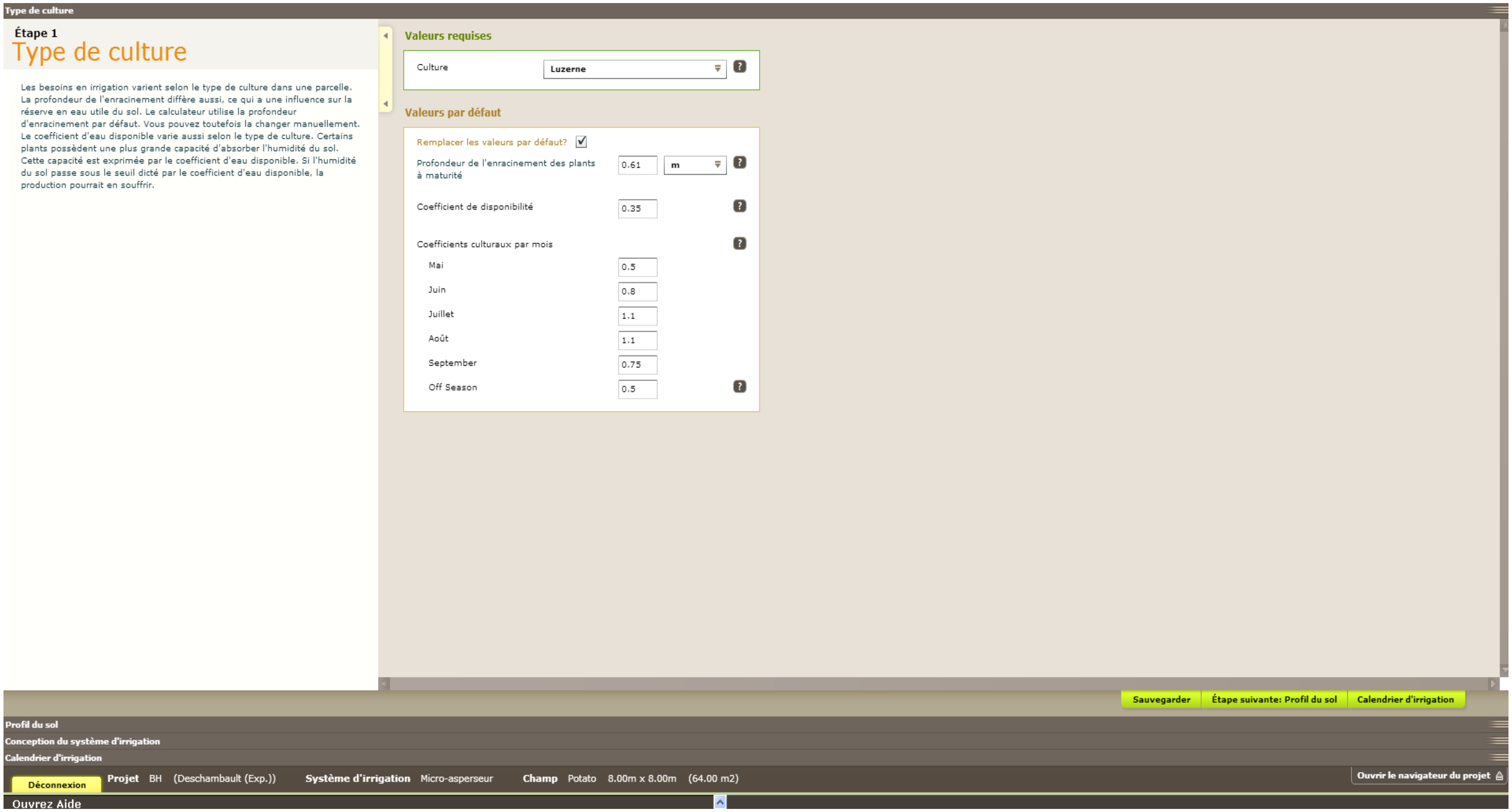
Photograph 1. Complete weather station.


Photograph 2. Hortau tensiometer (TX3 model).

Photograph 3. Wireless time domain reflectometer (TDR)(for illustrative purposes only).

Photograph 4. Unprocessed image of plant leaf canopies.

Photograph 5. Processed image of plant leaf canopies (middle row).



Type de culture

Étape 1

Type de culture

Les besoins en irrigation varient selon le type de culture dans une parcelle. La profondeur de l'enracinement diffère aussi, ce qui a une influence sur la réserve en eau utile du sol. Le calculateur utilise la profondeur d'enracinement par défaut. Vous pouvez toutefois la changer manuellement. Le coefficient d'eau disponible varie aussi selon le type de culture. Certains plants possèdent une plus grande capacité d'absorber l'humidité du sol. Cette capacité est exprimée par le coefficient d'eau disponible. Si l'humidité du sol passe sous le seuil dicté par le coefficient d'eau disponible, la production pourrait en souffrir.

Valeurs requises

Culture: Luzerne

Valeurs par défaut

Remplacer les valeurs par défaut? ☑

Profondeur de l'enracinement des plants à maturité: 0.61 m

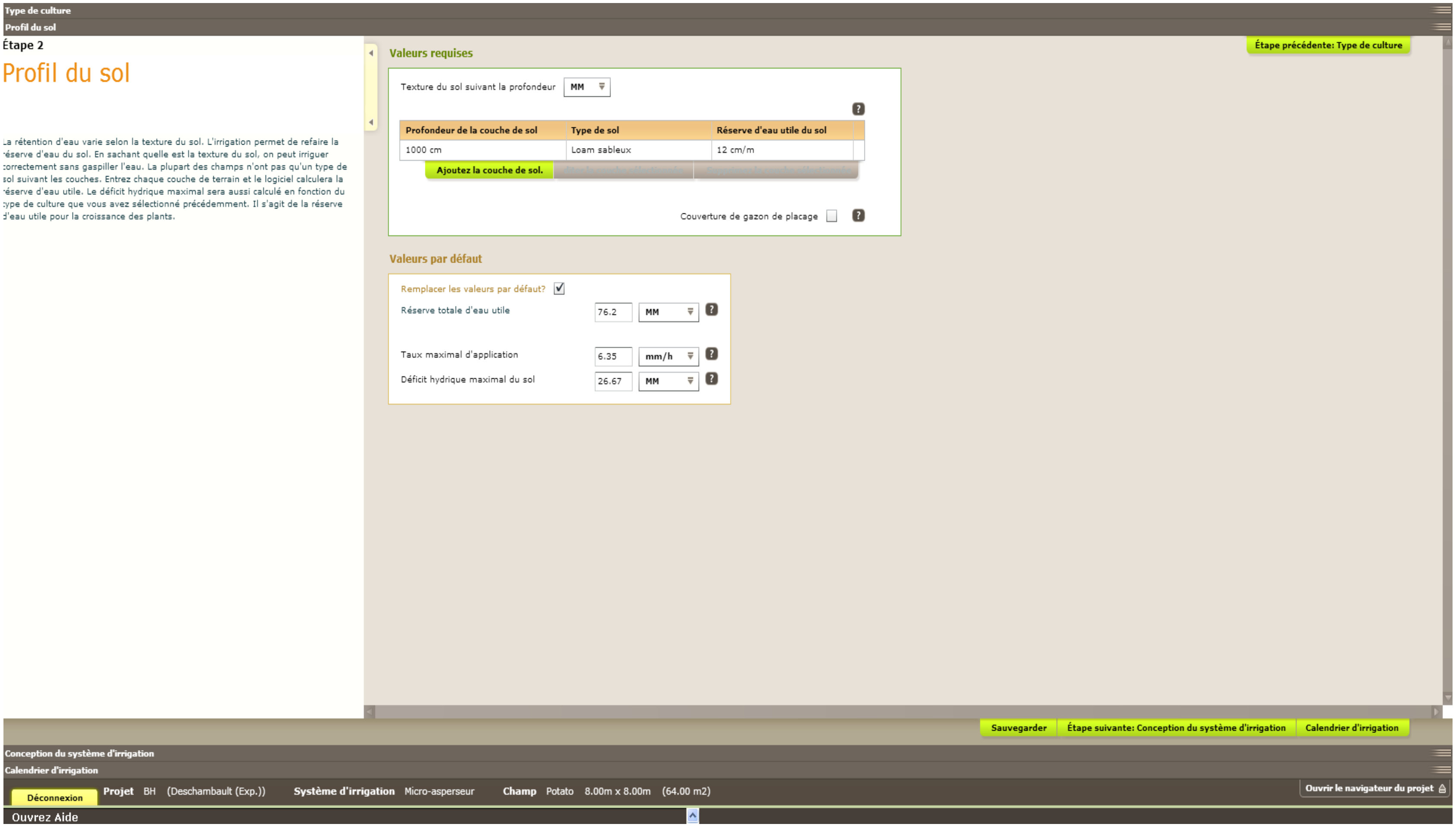
Coefficient de disponibilité: 0.35

Coefficients culturaux par mois

Mai	0.5
Juin	0.8
Juillet	1.1
Août	1.1
September	0.75
Off Season	0.5

Projet BH (Deschambault (Exp.)) Système d'irrigation Micro-asperseur Champ Potato 8.00m x 8.00m (64.00 m2)

Photograph 6. Step 1 of the LISC interface: crop, availability coefficient and crop coefficients.



Étape 2

Profil du sol

La rétention d'eau varie selon la texture du sol. L'irrigation permet de refaire la réserve d'eau du sol. En sachant quelle est la texture du sol, on peut irriguer correctement sans gaspiller l'eau. La plupart des champs n'ont pas qu'un type de sol suivant les couches. Entrez chaque couche de terrain et le logiciel calculera la réserve d'eau utile. Le déficit hydrique maximal sera aussi calculé en fonction du type de culture que vous avez sélectionné précédemment. Il s'agit de la réserve d'eau utile pour la croissance des plants.

Valeurs requises

Texture du sol suivant la profondeur: MM

Profondeur de la couche de sol	Type de sol	Réserve d'eau utile du sol
1000 cm	Loam sableux	12 cm/m

Couverture de gazon de placage ☐

Valeurs par défaut

Remplacer les valeurs par défaut? ☑

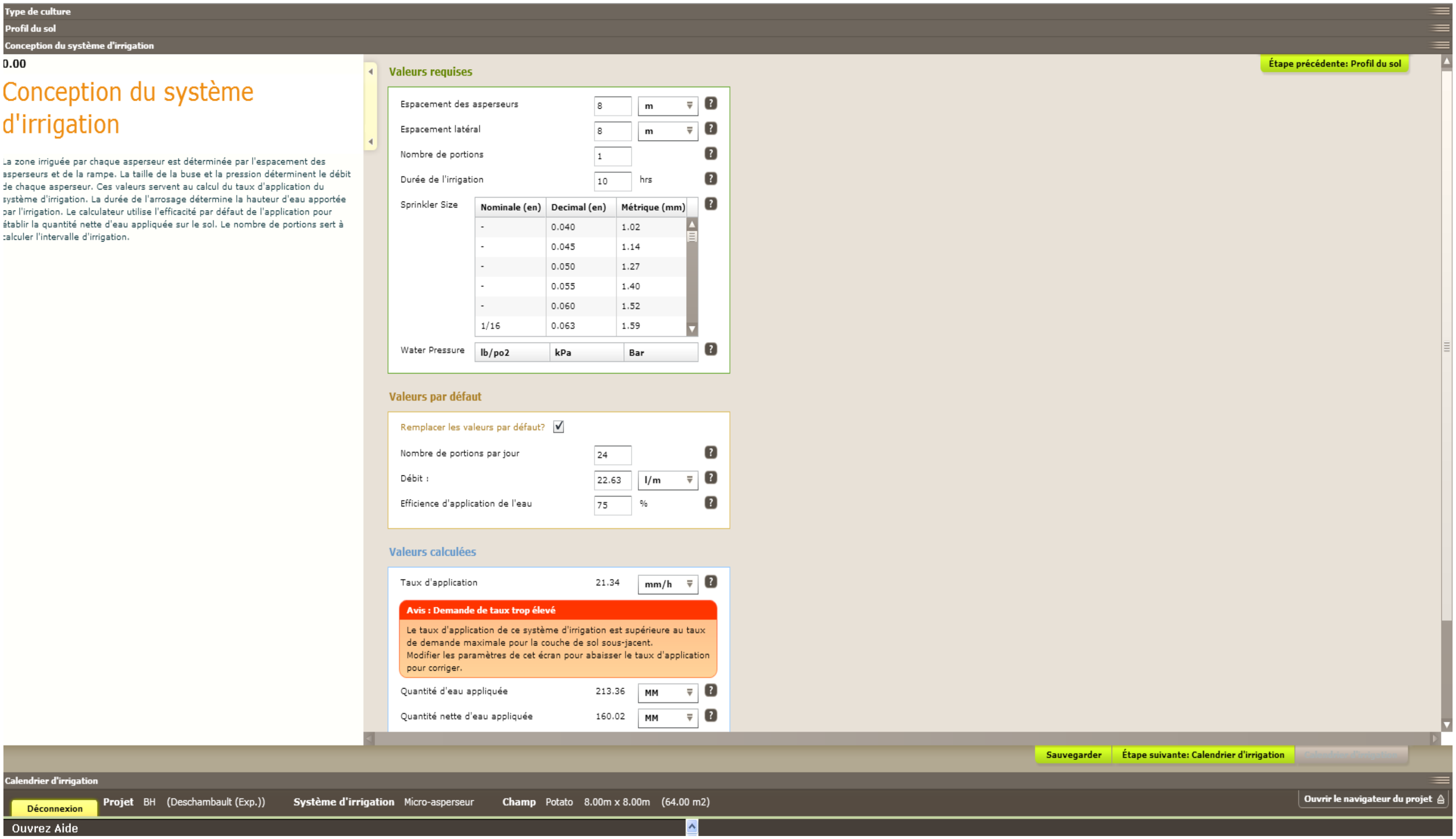
Réserve totale d'eau utile: 76.2 MM

Taux maximal d'application: 6.35 mm/h

Déficit hydrique maximal du sol: 26.67 MM

Projet BH (Deschambault (Exp.)) **Système d'irrigation** Micro-asperseur **Champ** Potato 8.00m x 8.00m (64.00 m2)

Photograph 7. Step 2 of the LISC interface: determining the available water storage capacity.



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Conception du système d'irrigation

La zone irriguée par chaque asperseur est déterminée par l'espacement des asperseurs et de la rampe. La taille de la buse et la pression déterminent le débit de chaque asperseur. Ces valeurs servent au calcul du taux d'application du système d'irrigation. La durée de l'arrosage détermine la hauteur d'eau apportée par l'irrigation. Le calculateur utilise l'efficacité par défaut de l'application pour établir la quantité nette d'eau appliquée sur le sol. Le nombre de portions sert à calculer l'intervalle d'irrigation.

Valeurs requises

Espacement des asperseurs	8	m
Espacement latéral	8	m
Nombre de portions	1	
Durée de l'irrigation	10	hrs

Sprinkler Size

Nominale (en)	Decimal (en)	Métrique (mm)
-	0.040	1.02
-	0.045	1.14
-	0.050	1.27
-	0.055	1.40
-	0.060	1.52
1/16	0.063	1.59

Water Pressure

lb/po2	kPa	Bar

Valeurs par défaut

Remplacer les valeurs par défaut? ☑

Nombre de portions par jour	24	
Débit :	22.63	l/m
Efficience d'application de l'eau	75	%

Valeurs calculées

Taux d'application	21.34	mm/h

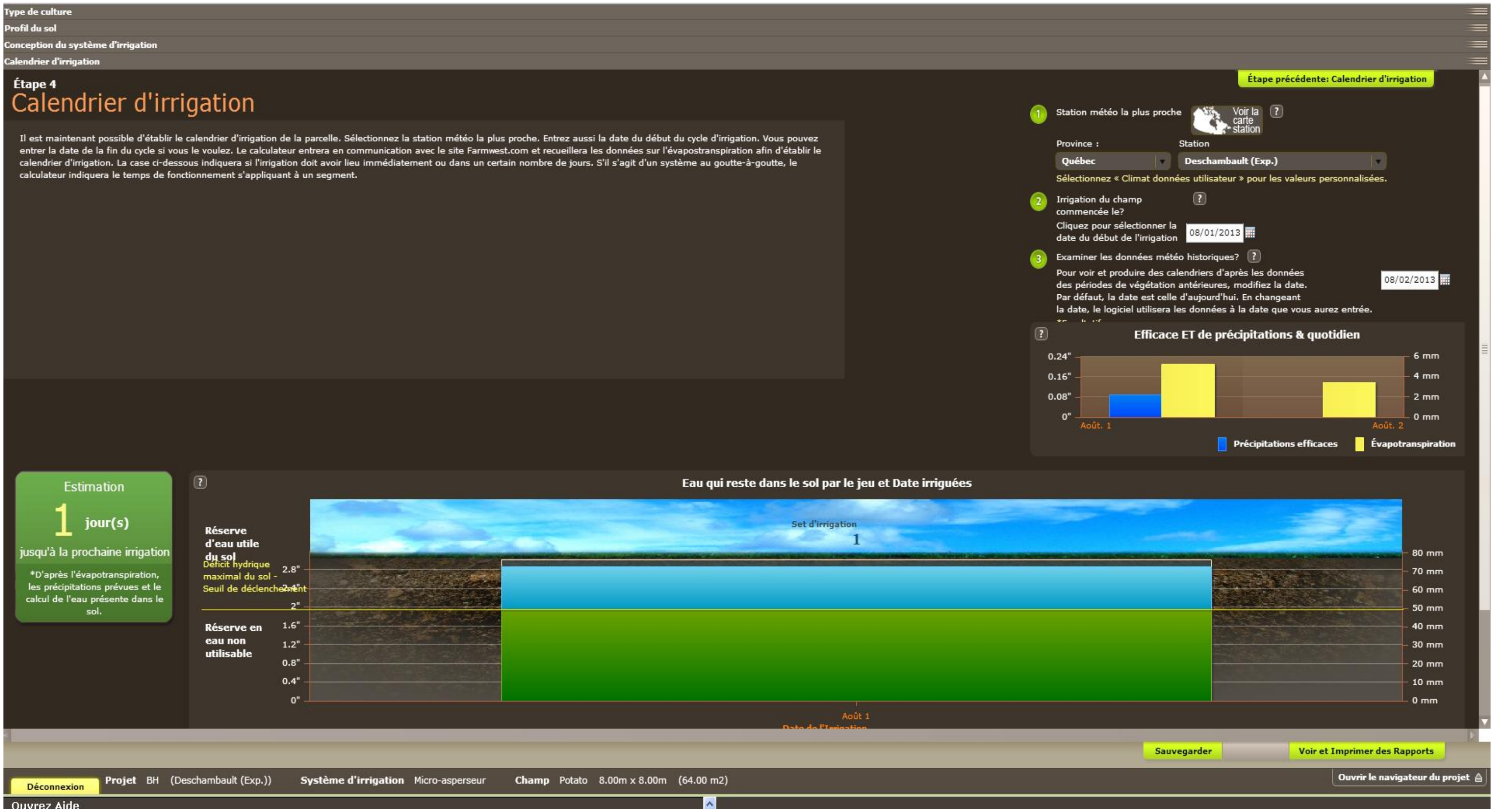
Avis : Demande de taux trop élevé

Le taux d'application de ce système d'irrigation est supérieure au taux de demande maximale pour la couche de sol sous-jacent.
Modifier les paramètres de cet écran pour abaisser le taux d'application pour corriger.

Quantité d'eau appliquée	213.36	MM
Quantité nette d'eau appliquée	160.02	MM

Projet BH (Deschambault (Exp.)) **Système d'irrigation** Micro-asperseur **Champ** Potato 8.00m x 8.00m (64.00 m2)

Photograph 8. Step 3 of the LISC interface: irrigation system design.



Étape 4

Calendrier d'irrigation

Il est maintenant possible d'établir le calendrier d'irrigation de la parcelle. Sélectionnez la station météo la plus proche. Entrez aussi la date du début du cycle d'irrigation. Vous pouvez entrer la date de la fin du cycle si vous le voulez. Le calculateur entrera en communication avec le site Farmwest.com et recueillera les données sur l'évapostranspiration afin d'établir le calendrier d'irrigation. La case ci-dessous indiquera si l'irrigation doit avoir lieu immédiatement ou dans un certain nombre de jours. S'il s'agit d'un système au goutte-à-goutte, le calculateur indiquera le temps de fonctionnement s'appliquant à un segment.

1. Station météo la plus proche

Province : Québec

Station : Deschambault (Exp.)

Sélectionnez « Climat données utilisateur » pour les valeurs personnalisées.

2. Irrigation du champ commencée le?

Cliquez pour sélectionner la date du début de l'irrigation: 08/01/2013

3. Examiner les données météo historiques?

Pour voir et produire des calendriers d'après les données des périodes de végétation antérieures, modifiez la date. Par défaut, la date est celle d'aujourd'hui. En changeant la date, le logiciel utilisera les données à la date que vous aurez entrée. 08/02/2013

Estimation

1 jour(s)

jusqu'à la prochaine irrigation

*D'après l'évapotranspiration, les précipitations prévues et le calcul de l'eau présente dans le sol.

Projet BH (Deschambault (Exp.)) **Système d'irrigation** Micro-asperseur **Champ** Potato 8.00m x 8.00m (64.00 m2)

Photograph 9. Step 4 of the LISC interface: weather data and irrigation scheduling

Photograph 10. Tilling the soil before planting at the Deschambault site, May 15, 2012.

Photograph 11. Seeding the plots at the Deschambault site, May 15, 2012.

Photograph 12. Experimental plots at the Deschambault site, June 13, 2012.

Photograph 13. Experimental plots at the Deschambault site, July 4, 2012.

Photograph 14. Experimental plots at the Deschambault site, July 26, 2012.

Photograph 15. Sprinklers running at the Deschambault site, summer 2012.

Photograph 15. Sprinklers running at the Deschambault site, summer 2012.

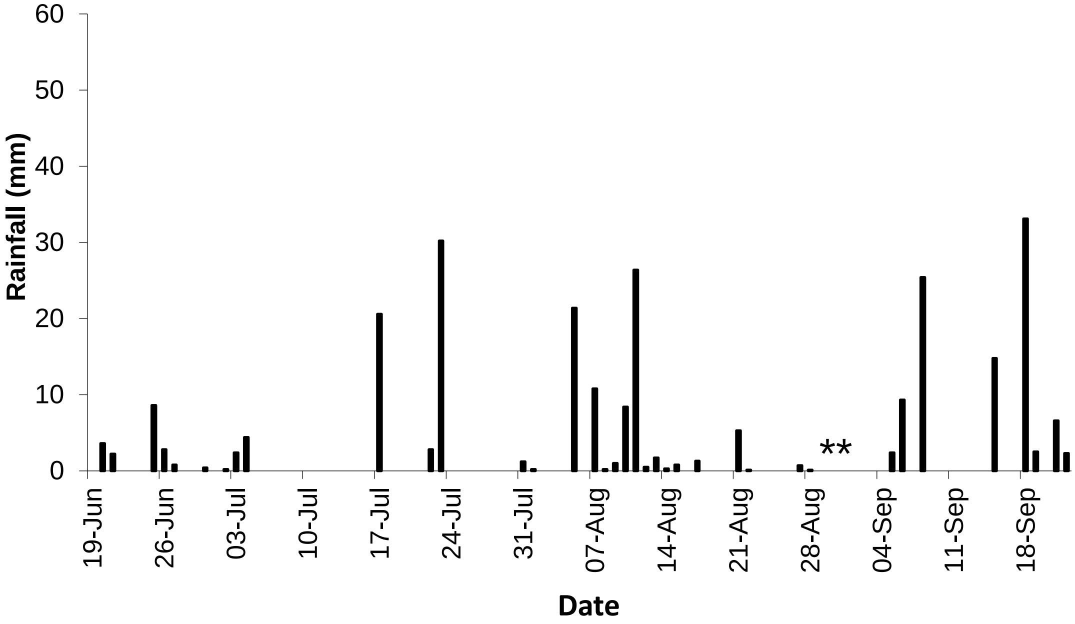
Photograph 16. Weather stations at the Deschambault site, summer 2012.

Photograph 17. Senescent plants at the Deschambault site, August 20, 2012.

Photograph 18. Harvest at the Lanoraie site, October 5, 2012.

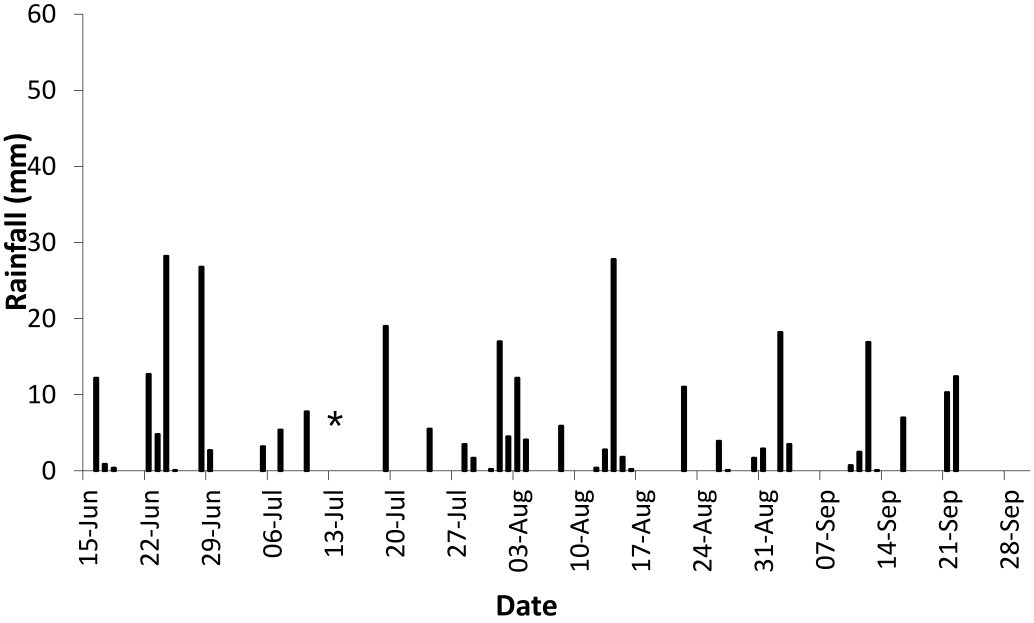
Photograph 19. Field of extra-fine green beans at the Sainte-Mélanie site, August 31, 2012.

8.5 Rainfall



** No data for August 31 and September 1.

Figure 23. Precipitation (mm) measured at the Sainte-Mélanie site, 2012 season.



*No data for July 18.

Figure 24. Precipitation (mm) measured at the Sainte-Mélanie site, 2013 season.

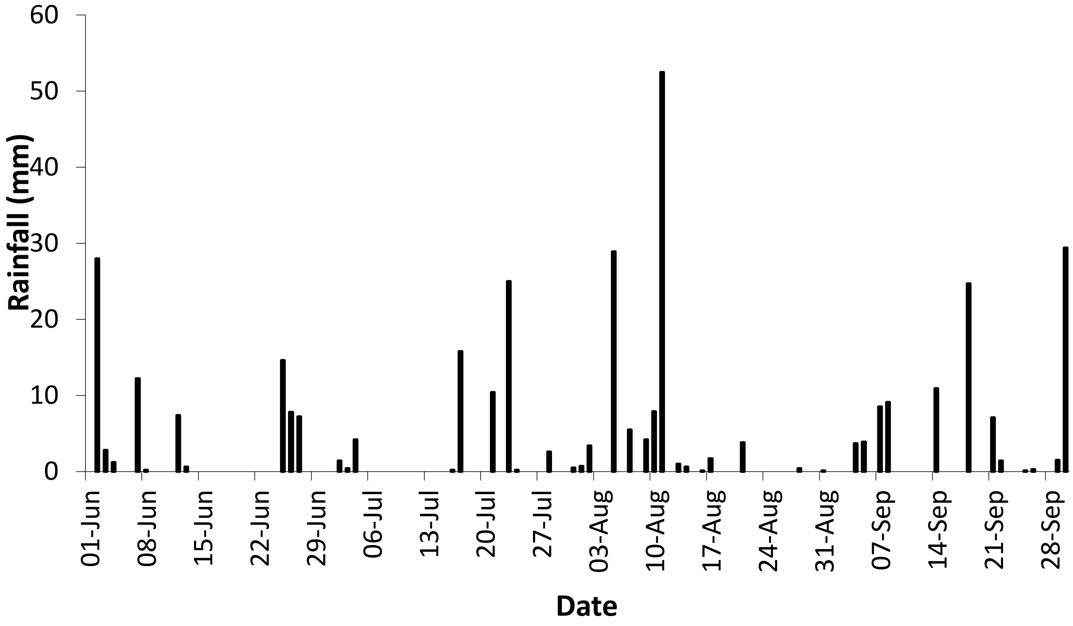


Figure 25. Precipitation (mm) measured at the Lanoraie site, 2012 season.

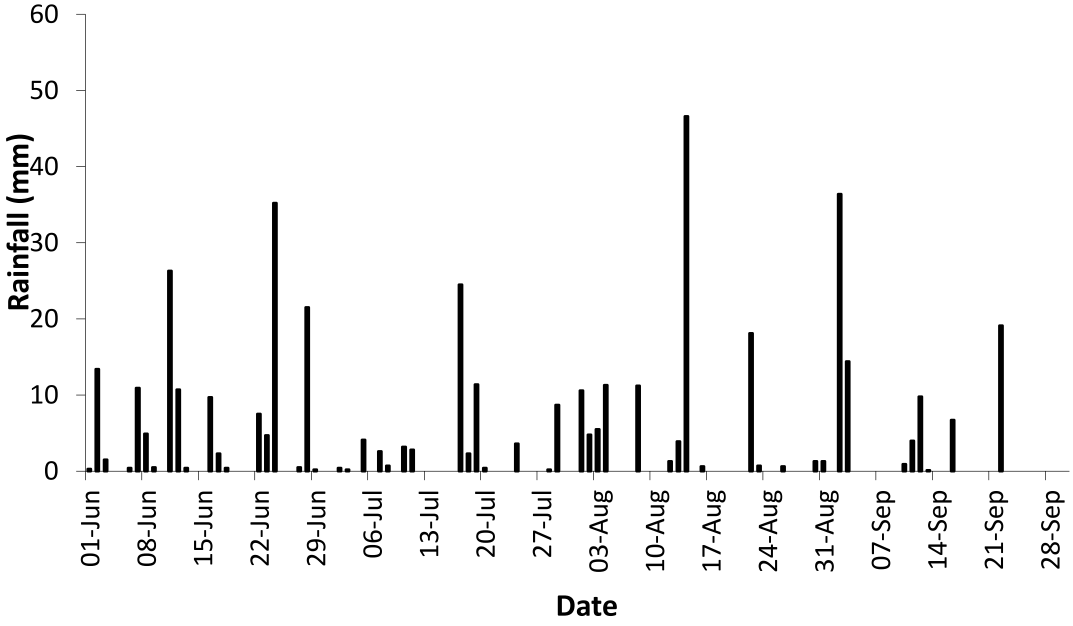


Figure 26. Precipitation (mm) measured at the Lanoraie site, 2013 season.

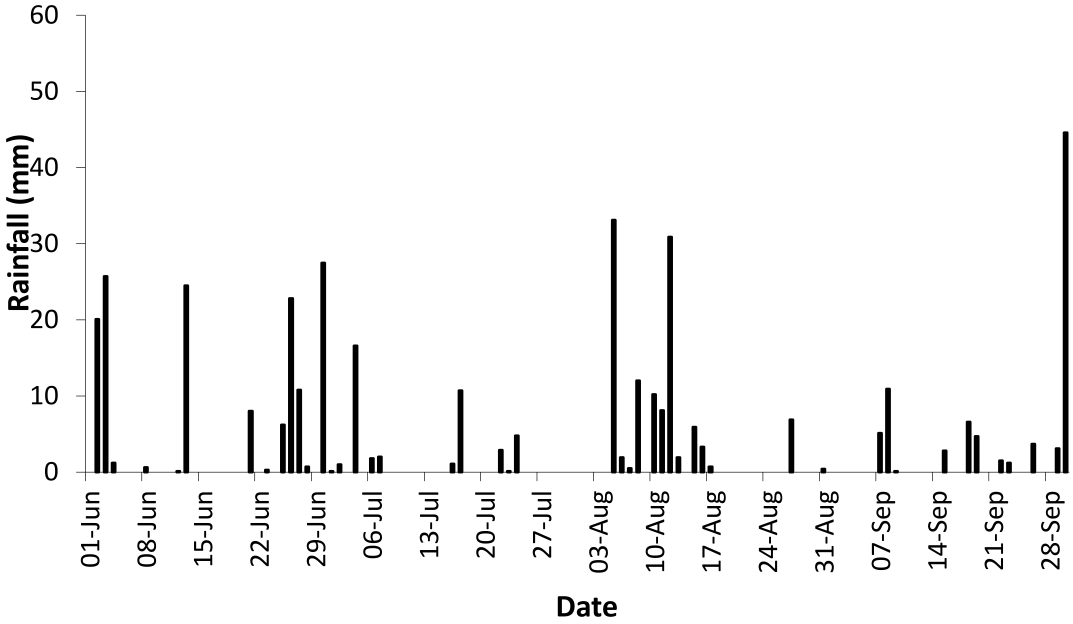


Figure 27. Precipitation (mm) measured at the Deschambault site, 2012 season.

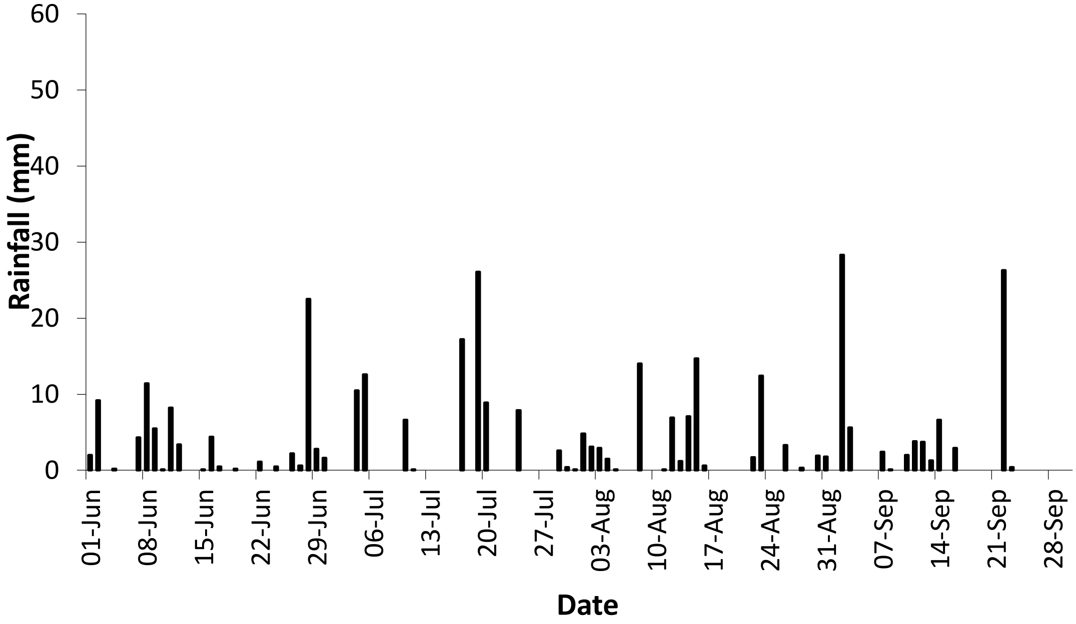


Figure 28. Precipitation (mm) measured at the Deschambault site, 2013 season.