Groundwater contribution to irrigated potato production in the Canadian Prairies

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Abbas, H. and R. Sri Ranjan. 2015. **Groundwater contribution to irrigated potato production in the Canadian Prairies**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **57**: 1.13-1.24. Potato is a moisture sensitive crop with soil water deficit/excess causing yield reduction. In Southern Manitoba, potato producers are experiencing wetter and drier conditions within the soil profile during the growing season leading to poor quality and inconsistent yields. The objective of this study was to compare the effect of groundwater contribution under overhead irrigation and no-irrigation treatments; on water availability within the potato root-zone and potato yield in a fine sandy loam soil in Southern Manitoba. Data on precipitation, irrigation depth, soil water content by depth, and potato yield were collected during the 2013 and 2014 growing seasons to assess the impact of groundwater contribution on potato production, water table depth, and volumetric soil water content. Although, the overhead-irrigated plots had a marginally higher yield, the difference was not statistically significant compared to the control in both years. Potato yields from both treatments were significantly negatively correlated with the average groundwater depth. A water balance analysis was conducted within the root-zone during rainy and rain-free periods, which showed that groundwater contribution might have met some of the crop water demand. The deeper the groundwater table the lower the upward flux to the root-zone from the water table which shows that groundwater level had a significant influence on potato yield. High yield even under non-irrigated conditions shows the importance of upward migration of water from the shallow groundwater table. Since upward flux is a major contributor to potato water uptake, the quality of groundwater should be monitored to ensure the quality of potatoes. **Keywords.** Groundwater level, overhead irrigation, potato root-zone, potato yield, soil water content, upward flux.

La pomme de terre, une culture sensible à l'eau, voit ses rendements réduits lors de sécheresse ou de saturation du sol. Dans le sud du Manitoba, les producteurs observent, durant la saison de croissance, des conditions du profil de sol qui varient d'humides à sèches entraînant ainsi des récoltes variables et de piètres qualités. L'objectif de cette étude était de comparer les effets de la contribution de la nappe phréatique, avec ou sans irrigation par aspersion, sur la disponibilité de l'eau dans la zone racinaire des plants et le rendement en pommes de terre d'un sol de loam sableux fin du sud du Manitoba. Des données sur les précipitations, les profondeurs de sols irrigués et les teneurs en eau en fonction de la profondeur ont été recueillies durant les saisons de croissance de 2013 et 2014. À l'aide de ces données, l'impact de la contribution de la nappe phréatique sur la production, de la profondeur de la nappe et de la teneur en eau volumétrique du sol a été évalué. Bien que les parcelles irriguées par aspersion offraient un rendement marginalement plus élevé que les témoins, cette différence n'était pas statistiquement significative pour les deux saisons. Les rendements en pommes de terre des deux traitements avaient une corrélation négative avec la profondeur moyenne de la nappe phréatique. Une analyse du bilan en eau a été réalisée dans la zone racinaire durant des périodes pluvieuses et sans pluie. Celle-ci a démontré que la contribution de la nappe phréatique aurait comblé une partie des besoins en eau des plants. Plus la nappe phréatique était profonde, plus faible était l'écoulement ascendant vers la zone racinaire indiquant une influence significative de la nappe phréatique sur les rendements en tubercules. Des rendements élevés, même dans les conditions sans irrigation, ont confirmé l'importance de la migration ascendante de l'eau provenant de la nappe phréatique peu profonde. Comme l'écoulement ascendant contribue de manière importante à l'apport en eau des plants, la qualité de l'eau souterraine devrait faire l'objet d'un suivi pour s'assurer de la qualité des pommes de terre. **Mots clés:** niveau de la nappe phréatique, irrigation par aspersion, zone racinaire des pommes de terre, rendement en pommes de terre, teneur en eau du sol, écoulement ascendant.

INTRODUCTION

The demand for potatoes (*Solanum tuberosum* L.) is increasing at a greater rate as compared to many other food crops such as rice, wheat, and maize (corn). (Fabeiro et al. 2001). The average annual diet of a global citizen includes about 33 kg of potato (FAO 2009). The total world production of potato is reported as 3.24 x 10^8 MT. China is the world's largest potato producer with an annual production of 7.48 x 10^7 MT. Canada contributes 4.42 x 10^6 MT to the world's total potato production, of which Manitoba contributes 9.86 x 10^5 MT from an area of 33,000 ha (Agriculture and Agri-Food Canada 2007). Canada is the largest exporter and the second largest producer of processed potatoes in the world (USDA 2004). Furthermore, the potato industry in Canada contributes about $6.4 billion in both direct and indirect income as well as generates 33,000 jobs for the individuals living in Canada (Potato Innovation Network 2007). The cool and humid climatic conditions of Manitoba make it very favorable for growth and development of potato, which is emerging as one of the major cash crops. Manitoba is the second largest potato-producing province after Prince Edward Island in Canada. The contribution of Prince Edward Island in Canada's total potato production is about 27% while Manitoba's contribution is about 19% (Statistics Canada 2009). Manitoba's potato production had increased from 286,000 tonnes (t) to 986,000 t (19% of Canada's

production) from 1982 to 2007 with an increase in potato-seeded area from 20,000 ha to 33,000 ha (Statistics Canada 2007). However, Manitoba's potato area decreased to 28,328 hectares, due to delays in planting (Agriculture and Agri-Food Canada 2013).

Major factors affecting potato yield include climatic conditions, crop rotation, tillage management, production practices, including seed piece spacing (Rex 1991), irrigation management (Ahmadi et al. 2010; Unlu et al. 2006; Ojala et al. 1990), and nutrient management (Ierna et al. 2011; Alva et al. 2012; Stark et al. 1993). Of all these factors, irrigation management is one of the most important factors that decide the total tuber yield. Harris (1978) reported that as compared to the non-irrigated conditions, every 10 mm increment in the water supply could increase the yield by 1 t/ha. World's average water demand for potato crop varies from 450 to 800 L/kg of tuber dry matter depending on the environmental conditions such as precipitation, temperature, relative humidity, solar radiations, and wind velocity. (Wright and Stark 1990). Potatoes have a shallow root-zone with 85% of root length within the upper 0.3 m soil layer (Opena and Porter 1999). In soils having low water holding capacity, the potato crop needs more water during periods of high evapotranspiration (ET) (Ojala et al. 1990). Numerous irrigation trials in different parts of the world have shown that potato is a moisture sensitive crop (Ierna et al. 2011; Onder et al. 2005; Yuan et al. 2003; Fabeiro et al. 2001). Both the deficit and the excess of soil moisture within the potato root-zone cause reduction in potato yield (Western Potato Council 2003). The sparse and shallow root system (0.5-0.6 m), and the fast stomatal closure at a relatively high soil moisture compared to other shallow rooted crops, make it less tolerant to water deficit (Harris 1992). With increasing soil moisture deficit, photosynthesis and transpiration rates decrease very rapidly in potatoes compared to other crops (Hang and Miller 1986). There is a threat of potato tuber stunting, if the stress condition is sustained for a long time (Ojala et al. 1990). Harris (1978) reported that to obtain high yield the soil water content should not be lower than 50% of maximum available water (difference between field capacity and permanent wilting point) within the potato root-zone during the tuber initiation stage. In order to meet the ET losses and to maintain a maximum capillary pressure of 25 kPa, the average daily water requirement for growing potatoes is 3-5 mm (Marutani and Cruz 1989).

The total growing season of potato could be divided into five stages i.e. (1) sprout development, (2) vegetative growth, (3) tuber initiation, (4) tuber bulking, and (5) maturation stage. The effect of water extremes (excess or deficit) on tuber yield is different at different growth stages (Opena and Porter 1999). An adequate supply of soil moisture is crucial at all stages but soil moisture stress during the tuber initiation and bulking stages limits the yield (Jefferies and Mackerron 1993). Water stress at tuber initiation and early bulking stages suspends the potato growth for some time after which it resumes. It leads to a reduction in marketable potato yield by increasing tuber malformations. Mid-bulking is the most critical stage of potato growth. Water stress at this stage causes a reduction in tuber size and total yield (Ojala et al. 1990).

Depending on environmental conditions, soil type, and cultivar, the water requirement of potato crop falls between 350 and 500 mm throughout the growing season in different parts of the world (Sood and Singh 2003). This requirement is partially fulfilled by precipitation whereas the deficit is met through artificial means i.e. supplemental irrigation. There are no specific guidelines available for supplemental irrigation depth because of the wide diversity of rainfall patterns, temperature, and soil conditions under which potatoes are grown (Silver et al. 2011). Potato receives an average of 90 mm as supplemental irrigation in Manitoba (Western Potato Council, 2003). Silver et al. (2011) reported that the variability of crop yield caused by inconsistent rainfall might be decreased by supplemental irrigation. Supplemental irrigation caused an increase in tuber yield of two potato cultivars in New Brunswick but the response varied with sites and climatic conditions (Belanger et al. 2000). Self-propelled mobile irrigation systems e.g. sprinkler/spray irrigation with center pivot or linear move, and rain gun systems are generally used for irrigating the potato crop in Southern Manitoba. The potato producers in Southern Manitoba have been facing poor product quality and inconsistent yield due to the great variability of field moisture regime (MASC 2010). Excessive precipitation and/or supplemental irrigation can contribute to a rise in the water table elevation and eventually lead to adverse effect on root-zone aeration. Therefore, the presence of water table at the recommended depth below the ground surface is important.

In areas where the groundwater table is shallow, there is a potential for upward water flux to meet part of the crop water demand. Contribution of shallow groundwater to the plant roots (subsurface irrigation) may reduce the required volume of water applied through overhead irrigation. Depth of groundwater from the ground surface, growth stage, and daily ET are the main factors controlling the amount of shallow groundwater contribution to the plant roots (Ayars et al. 2006). Ayars and Schoneman (1986) reported the contribution of upward flux of water from the water table located at 1.7 m depth below the ground surface to meet the needs of increased ET in cotton crop. They further attributed the increase in water table depth from 1.7 m to 2.1 m to the contribution of water from groundwater to the plant roots. During periods of high ET, Wallender et al. (1979) reported 60% contribution of groundwater to meet the cotton crop water demand from water table present at 1.5 m depth. Pratharpar and Qureshi (1998) found that water table present at less than 1.5 m depth could meet ET demand and decrease surface irrigation requirements by up to 80% without compromising crop yield. Soppe and Ayars (2003) found groundwater contribution up to 40% of daily safflower crop water needs

met by upward flux from the water table located at 1.5 m depth. Kahlown et al. (1998) found a significant groundwater contribution towards plant roots from water table depths less than 1.0 m compared to water table depths exceeding 2 or 3 m. Shallow groundwater contribution to the plant roots plays an important role in the water balance within the plant root-zone. However, groundwater quality should be adequate to achieve the high yield goals. The main objective of this study was to determine the impact of groundwater contribution under supplemental irrigation and no irrigation treatments on water availability within the potato root-zone and potato yield in Manitoba.

MATERIALS AND METHODS

Study site

A two-year study (2013-2014) was conducted in Southern Manitoba, 3-km south of Winkler (49° 10`N Lat., -97$^o$ 56`W Long., 272-m elevation) in the rural municipality of Stanley to compare the effect of two water management treatments: Irrigated (IR) and Non-Irrigated (NI), on tuber yield and water uptake. In the first year of study (2013) the experimental location was at the Canada Manitoba Crop Diversification Center (CMCDC) farm while the second year of the study was conducted at the Hespler Farm site one km west (2014).

Climatic conditions

The climate of study a rea is dry and cold in winters whereas summers are hot and frequently dry (Natural Resources Canada 1957). The growing season in this area usually starts in May and lasts up to the end of August. Harvesting is done by mid-September. The average summer temperature typically ranges from 12 to 22 °C, while average temperature range for winters is -15 to -25 °C. Winkler receives an annual average precipitation of 533 mm. However, the growing season receives 342 mm precipitation in the form of rainfall (Environment Canada 2013).

Soil type

Soil characteristics of both study areas are given in Table 1. The soil characteristics i.e. soil type, soil texture, and drainable porosity are similar at both sites.

Experimental Design

In 2013, the field area of 1.2 ha (2.97 ac) was divided into six equal plots of approximately 0.2 ha (0.49 ac) with dimensions of 44.6 m X 40.3 m. In 2014, an area of approximately 1.29 ha (3.19 ac) was divided into six equal plots with dimensions of 50 m X 44 m. The field plots were replicated three times with Randomized Complete Block Design (RCBD). All the plots were planted with potatoes. In 2013, water was applied using a linear move irrigation system and in 2014 a rain gun irrigation system was used for the irrigated treatments, which also received rainfall. The selection of the irrigation system was dependent on what was available at the site. The irrigation water was pumped from a reservoir established and maintained by a group of local farmers who captured and stored the spring snowmelt runoff. The three non-irrigated plots only received rainfall in both years. Soil moisture contents and soil water tension were measured in each plot at 0.2, 0.4, 0.6, 0.8 and 1.0 m depths from the ground surface, throughout the growing season using C-probe and Watermark sensors, respectively. The soil water tension measured using tensiometers were used only to trigger irrigation events in 2013 at the CMCDC site. However, in 2014 at the Hespler site the weather data was used in irrigation decisions to replenish the water lost by ET. Observation wells were installed in the center of each plot to continuously measure the depth to the groundwater table. In the 2013 study site, each plot had a tile drainage system. The spacing between the drains was 11.1 m and depth from ground surface was kept as 0.9 m.

Table 1. Soil Characteristics of study areas.

Study Site	Sand	Silt	Clay	Field Capacity	Permanent Wilting Point
	%	%`	%	%	%
CMCDC Farm	70	19	11	28	11.6
Hespler Farm	67.7	20.8	11.5	31.2	14.7

Instrumentation and data collection

Water level sensors (WLS) (Solinst Levelogger Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) were used to monitor the groundwater level in each plot throughout the season. These sensors were set to take a reading at half an hour intervals. These sensors were hung inside the piezometers installed at the center of each plot. The piezometers were made from 2.5 m long steel pipes with an inner diameter of 41 mm. In order to avoid any hindrance to farming operations, such as hilling and spraying, all the piezometers were installed along the crop rows. In order to monitor the local groundwater flow, observation wells were also installed in the surrounding plots of the experimental field. The piezometers were manually installed using a soil auger. Manual readings of ground water level were also taken using a water level sensing tape as a check. A barometric pressure sensor (Solinst Barologger Gold) was used for subsequent barometric correction of the water level sensor data.

Volumetric soil moisture contents and soil temperature were monitored using capacitance/frequency domain probes (C-probe) (Model EC-5, Decagon Devices, Inc., Pullman, Wash.) continuously throughout the growing season. These probes were installed at five different depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) in the center of each plot. The C-probe provided real time soil moisture and soil temperature data through the Weather Innovations Network (WIN) website. Logging interval was 15 minutes. Soil water tension (kPa) was monitored at five depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) by Watermark sensors (Spectrum Technologies, Inc. WatchDog 1000 Series) installed at the center of each plot.

Precipitation, temperature, wind speed, relative humidity and solar radiation data were collected continuously on site on a daily basis through the Manitoba Ag Weather Network station located on site (Spectrum Technologies, Inc. Weather Station 2000 Series). The reference evapotranspiration (ET_o) was computed using the Penman-Montieth method. In 2013, the irrigation water was applied using a linear move (LM) irrigation system (O3000 Orbitor, Nelson Irrigation Corporation, Walla Walla, WA). The linear move irrigation system was tested according to ASAE standards for uniformity of application prior to the critical growth stage i.e. mid to late June. In 2014, the irrigation water was applied using a travelling gun irrigation system.

The stage of plant growth, rooting depth, and evapotranspiration were the main factors considered in determining the depth of irrigation (mm). Allowable depletion for the irrigated plots was based on 25% of the available water (difference between field capacity and permanent wilting point) being lost as ET. This trigger point corresponded to a soil matrix tension of 25 kPa. Irrigation application was triggered when the tensiometer reading exceeded 25 kPa at any of the 0.2, 0.4, 0.6 m soil depths in the irrigated plots. Volume of irrigation was based on % volumetric depletion integrated over the depth of the root-zone (600 mm). Field capacity (FC) was determined using C-probes by saturating the soil soon after installation (Jensen et al. 1990). Irrigation nozzles were manually turned on/off to ensure no irrigation outside of the selected plot boundaries. Irrigation application rates were measured by in-field rain gauges. The irrigation rate was adjusted to meet the daily ET demand of the potato crop.

The seedbed was prepared by tilling in early May. Fertilizer (N, P, K and S) rates for the study area were based on soil test results. Immediately after broadcasting fertilizers, all the plots were cultivated to incorporate fertilizer with a chisel plough. All the plots were fertilized equally, and based on "very high" target yield to ensure that nutrients are not limiting. The cultivar used in this study was Russet Burbank, a commonly grown cultivar in Manitoba. Hilling/ridging was done by power hiller to stabilize the stems of potatoes against wind effects. Berming was done along the plot boundaries following hilling operations to minimize overland flow of surface water between plots and from outside the study area. Seed spacing between the rows was kept at 0.91 m (36 in.) whereas within row seed spacing was maintained at 0.36 m (14 in.). Planting was done mechanically on May 17th in 2013 and on May 13th in 2014. Fungicides were applied on a weekly basis. However, herbicides and insecticides were applied when needed.

This research was designed to address the question from the farmers on how to manage the irrigation at different stages of growth to attain maximum tuber yield in areas having shallow groundwater. Therefore, the final tuber yield was used as the outcome in the statistical analyses to evaluate the impact of growth stage specific water table depths. At maturity, potatoes were flailed and harvested on three 20 m length strips per plot. Potatoes were harvested using a single row potato digger and collected in burlap bags, separated by treatments, and weighed in the field. Harvesting was done on September 26th in 2013 and September 25th in 2014. Final yield and growth stage specific water table depth data were analyzed by comparing means of treatments of same year using Student's t-test at the 0.05 significance level (JMP software, Ver. 8, SAS Institute, Inc., Cary, N.C.). The relationship between stage specific average water table depth and the final potato yield for 2013 (CMCDC Farm) and 2014 (Hespler Farm) growing seasons was determined using regression analysis (MS Excel, Ver. 2010, Microsoft Corporation).

RESULTS AND DISCUSSION

Weather conditions at the site

The 2013 growing season (May to September) received 12% higher rainfall (389 mm) compared to the 30-year average (342 mm). During this period the average T_{max} was 23.6 ^oC and T_{min} was 10.2 ^oC. However, the 2014 growing season was comparatively drier with a total precipitation of 262 mm (26 % less than the 30-year average) and an average T_{max} of 23 ^oC, and T_{min} of 9.5 ^oC. On average, the potato crop in Manitoba needs 90 mm of supplemental irrigation (Western Potato Council 2003). Using eleven irrigation events, a relatively higher (130 mm) than normal supplemental irrigation was applied during the 2013 growing season. In 2014, overhead irrigation was carried out five times, with a total application of 95 mm.

In the beginning of the growing season (sprout development and vegetative growth stages), supplemental irrigation was not required in both years because rainfall was sufficient to meet the crop water demand. In 2013, total precipitation for the month of May was reported as 144 mm. The supplemental irrigation was done, when needed, from 29 June to 20 August (53 days) in 2013, which coincided with the tuber initiation and tuber bulking stages. During this period, total rainfall depth was reported as 120.6 mm. The total amount of supplemental irrigation was considerably higher than the average annual moisture deficit of 90 mm during this year. Since the tuber bulking stage experienced a number of days with > 25 ^oC, higher than normal supplemental irrigation was needed. During the months of May, June and September the potato crop was sustained by the moisture received through rainfall.

In the 2014 growing season, a 30-day dry period from 23 July (tuber initiation stage) to 21 August (tuber bulking stage) with only 14.6 mm rainfall resulted in the need for supplemental irrigation. The tensiometer readings fell below 25 kPa during several days because rainfall was not adequate to meet the crop water demand. During this period, supplemental irrigation was applied to the irrigated treatment, through five irrigation events to replenish the losses from evapotranspiration (ET). Although 2014 was a

Table 2. Potato tuber yields for overhead irrigated and non-irrigated treatments.

Treatment	2013 Yield		2014 Yield	
	MT/ha	SE	MT/ha	SE
Overhead Irrigated	51.2 a	1.09	62.9 a	1.77
Non-irrigated	50.0 a	1.62	61.7 a	4.26

comparatively drier year, lower mean temperature during the critical growth stages of tuber initiation (18.8 ^{o}C) and tuber bulking (18.0 ^{o}C), lowered the ET demand. A total of 97.7 mm rainfall received during critical growth stages and contribution of shallow groundwater to the plant roots decreased the need for irrigation. The irrigated period spanned over the tuber initiation and tuber bulking stages in both years. Since the potatoes do not need as much water during the maturation stage (Rowe 1993), no supplemental irrigation was applied during this stage.

Potato Yield

The total growing season lasted about 135 days in both years. Average potato yield in the non-irrigated plots were lower compared to the irrigated plots in both years, although the differences were statistically not significant (Table 2). Better availability of water within the potato root-zone resulted in a comparatively higher yield in the irrigated treatment. In 2014, yields were higher than in 2013 across both treatments. Several factors including change in the study location, weather conditions, and initial groundwater levels may be attributed to the higher yield in the 2014-growing season.

Depth to the groundwater table

As observation wells were also installed in the surrounding plots of the experimental field to monitor the local groundwater gradient, no significant groundwater flow to the surrounding plots occurred in both treatments during both growing seasons. Table 3 shows the seasonal average water table depth from the ground surface for both years. The analysis of variance showed a significant difference in the depth to water table between the treatments within the years.

Potato tuber yield from both treatments was significantly negatively correlated with the average groundwater depth during each of the three important potato growth stages i.e. tuber initiation, tuber bulking, and maturation stage in both years (Fig. 1). Although the water table depth was significantly negatively correlated with the potato yield during all the three stages, the tuber

Table 3. Average daily water table depth from the ground surface over the growing season for overhead irrigated and non-irrigated treatments.

Treatment	Seasonal Average Ground Watertable Depth (m)	
	2013	2014
Overhead Irrigated	1.69 a	1.10 a
Non-irrigated	1.77 b	1.03 b

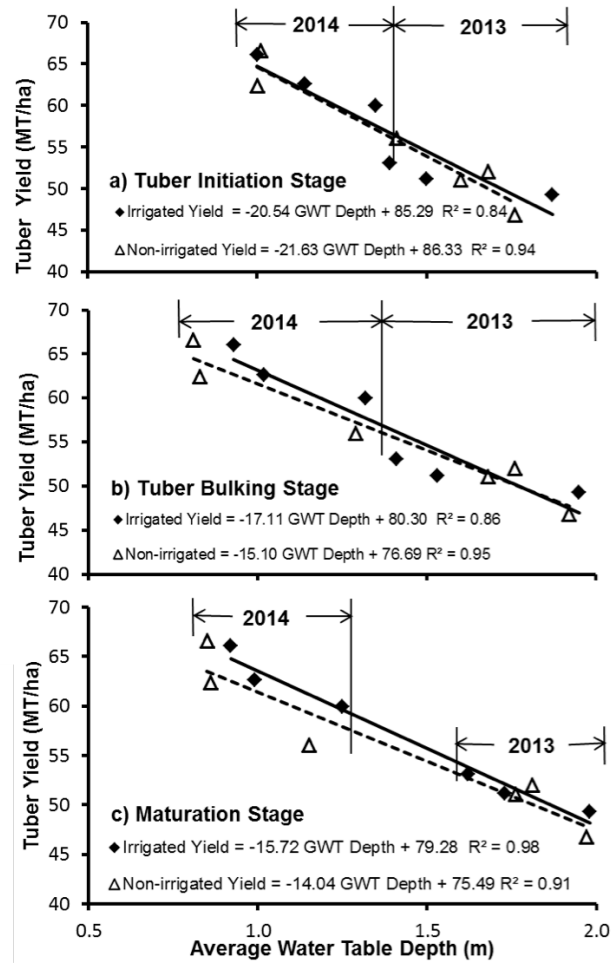

Fig. 1. Relationship between stage specific average water table depth and potato yield for 2013 (CMCDC Farm) and 2014 (Hespler Farm) growing season. (Continuous and dashed lines correspond to irrigated and non-irrigated treatment, respectively.)

initiation stage was influenced the greatest. This shows that the tuber initiation stage is the most critical stage, among all the potato growth stages, with respect to the moisture availability and moisture deficit at this stage has the greatest impact on total yield. The deeper the water table, lower the potential for the supply of water to the root-zone by upward flux. In the 2013 growing season (CMCDC farms), the water table depth was lower as compared to the 2014-growing season (Hespler farms). Therefore, in 2014, yields were higher than in 2013 across both treatments. Water table depth from the ground surface was responsive to the recharge events (rainfall and/or supplemental irrigation).

Water table response in 2013

Figure 2 shows the variations in water table depth from the ground surface as an average for the three replicates in relation to the recharge events (precipitation and overhead irrigation) in 2013. The first supplemental irrigation was

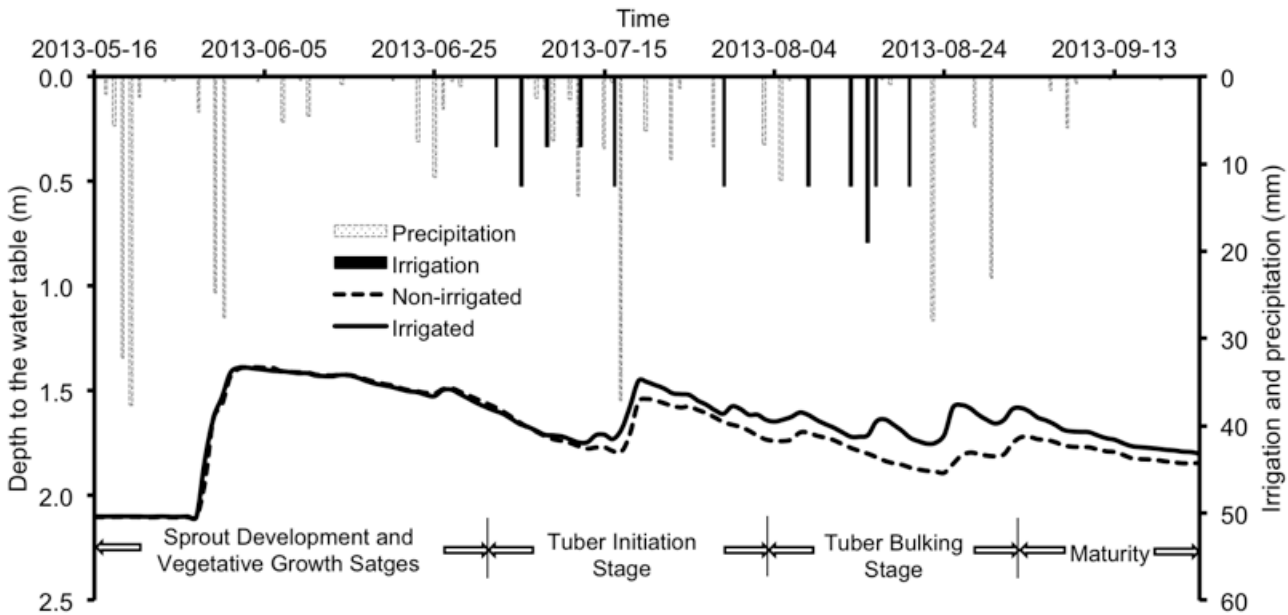

Fig. 2. Water table depth, precipitation, and irrigation amounts in 2013.

applied on 02 July 2013. Ground water level in both treatments remained the same prior to the third irrigation event. After 12 July 2013, the water table depth in the non-irrigated treatment began to increase while it remained the same until the rainfall event on 16 July 2013 in the irrigated treatment. Water table depth in the non-irrigated treatment remained below the water table depth in the irrigated treatment from 12 July 2013 to 25 September 2013 as a result of upward flux of groundwater to meet the plant water requirement in the non-irrigated treatment.

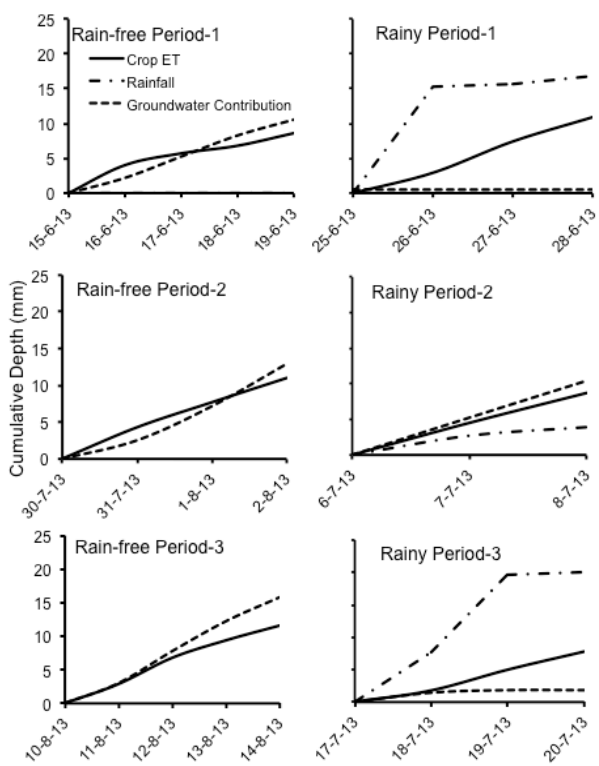

Fig. 3. Cumulative groundwater contribution to the non-irrigated treatment during rain-free and rainy periods in 2013.

Total precipitation during the 2013-growing season was reported to be 389 mm. An adequate water supply through rainfall events may have increased the unsaturated hydraulic conductivity between the unsaturated soil profile and the saturated zone (water table). The rainfall may have contributed sufficient moisture within the potato root-zone leading to a lower uptake from the groundwater table. However, during the rain-free periods, soil layers below the plant roots may have dried out leading to a change in the hydraulic gradient. This hydraulic gradient may have pulled up the water from the water table to replenish the soil moisture within the root-zone. This upward migration of groundwater towards the plant roots resulted in the lowering of the groundwater level in the non-irrigated treatment more than the irrigated treatment, commensurate with plant water needs. In order to verify this scenario, three rain-free and three rainy periods at different growth stages were selected from the non-irrigated treatment to analyze the contribution of groundwater towards ET and the resultant crop water demand (CWD). The ET was calculated specifically for the potato crop at the study location.

Figure 3 shows the cumulative contribution of groundwater to the root-zone in the non-irrigated treatment during the three rain-free and rainy periods along with the corresponding cumulative crop ET. The initial value of each period was taken as zero to calculate the cumulative values for the subsequent days within each period. Groundwater table elevation was found to be responsive to the crop ET. Generally, the water table elevation declined with an increase in crop ET confirming the contribution

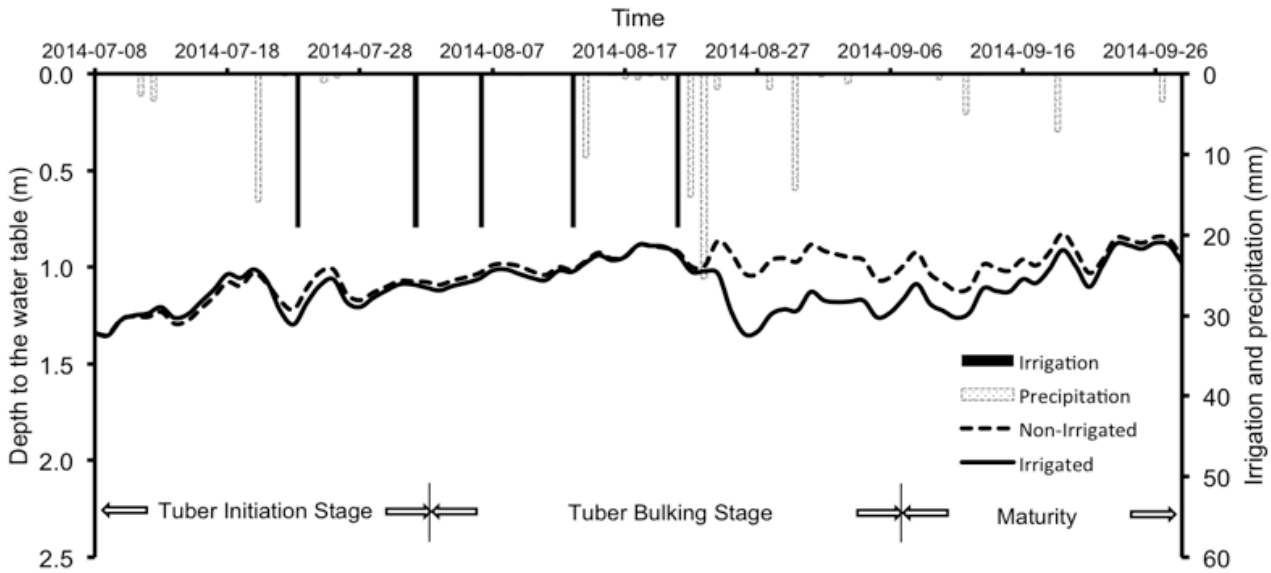

Fig. 4. Water table depth, precipitation, and irrigation amounts in 2014.

from the shallow groundwater table. The lowering of the ground water table may be attributed to the upward migration of water during the dry periods. The groundwater contribution was calculated by multiplying the drop in water table elevation by the drainable porosity (25%) to develop the graphs presented in Figs. 3 and 5. It should be noted that the drainable porosity was calculated based on tile outflow measurements made in previous years when there was sufficient rainfall to cause tile outflow. The total tile outflow resulting from a specific rainfall event was converted to depth, which was then divided by the drop in the water table elevation soon after the specific rainfall event to calculate the drainable porosity. This calculation was repeated for different rainfall/outflow events to obtain an average drainable porosity for this field. The 2013 growing season did not have any tile outflow because the water table was below the depth of the tile. During the rainy periods, the depth of rainfall was recorded as 16.8, 4.1, and 20.1 mm, respectively. The groundwater table did not contribute to the potato root-zone during the rainy period 1 because adequate depth of water from rainfall replenished the crop water demand. A very small contribution of groundwater was observed during the rainy period 3 characterized by minimal change in the water table elevation. However, during the rainy period 2, only 4.1 mm rainfall depth resulted in the upward migration of groundwater to meet the crop water demand with the consequent drop in the water table elevation.

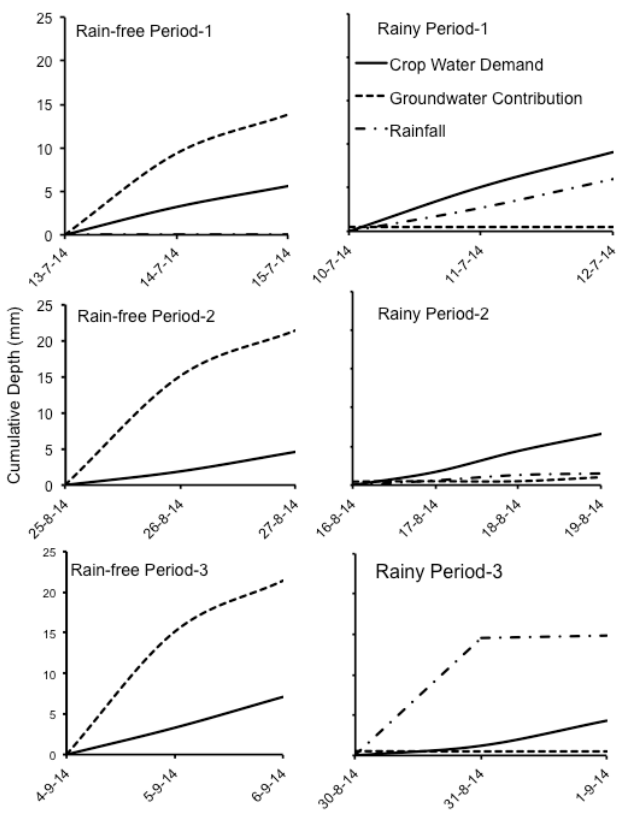

Fig. 5. Cumulative groundwater contribution to the irrigated (IR) treatment during rain-free and rainy periods in 2014.

Water table response in 2014

Figure 4 shows the variation in water table depth from the ground surface as an average for the three replicates in relation to the recharge events (precipitation and overhead irrigation) in 2014. During the 2014 growing season, the water table remained below the level of tile drains and as a result no tile flow was observed. During tuber initiation, and tuber bulking stages, the irrigated plots received a total of 95.2 mm supplemental irrigation over five irrigation events to meet the crop ET.

Regardless of the supplemental irrigation, the groundwater level in the non-irrigated plots remained very close to the groundwater level in the irrigated plots until

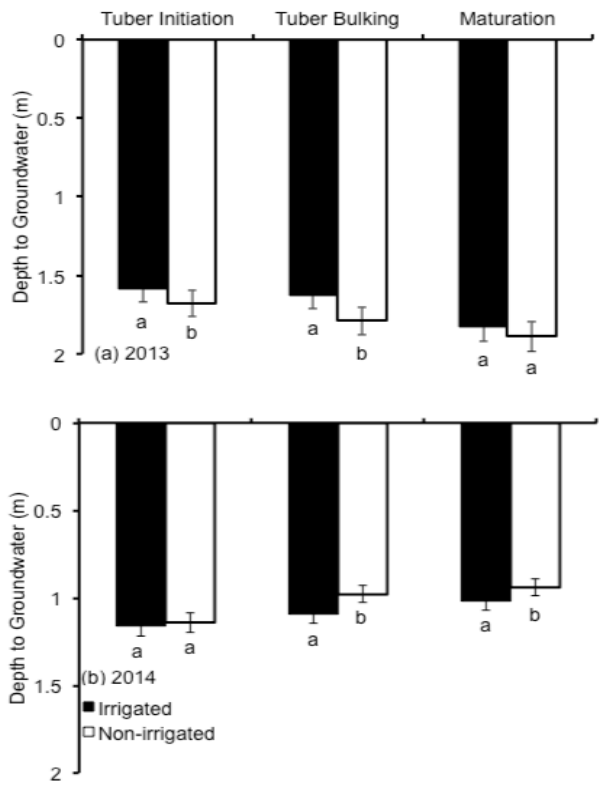

Fig. 6. Growth stage specific average water table depth. (Different letters indicate significant (p = 0.05) difference between treatments within the growth stages and years.)

the middle of tuber bulking stage indicating that the water applied through irrigation was used by the plant. Until the middle of tuber bulking stage there was no change in watertable elevation as wells as no drainage outflow indicating there was no loss through upward migration or through the drains. The low water content of the soil beneath the root-zone could have acted like a capillary barrier preventing the upward movemnet of water. A 30-day dry period from August 25 to September 25 (mid bulking to maturation stage) with only 30.9 mm rainfall did not increase the water content of the unsaturated zone in the non-irrigated plots. However, in the irrigated plots the addition of water improved the hydraulic conductivity of soil beneath the root-zone allowing upward migration from the water table resulting in the lowering of the watertable in the irrigated plots. A decline in groundwater level in the irrigated plots starting from the middle of tuber bulking stage (08 August 2014), may have been due to contribution from the groundwater. The irrigated plots receiving supplemental water from the watertable, which had a salinity ranging from 2.4 to 3.8 dS/m, may not have helped attain higher yield due to osmotic stress compared to the non-irrigated plots suffering from water stress. Crop water demand is relatively higher at tuber bulking stage (Rowe 1993). The contribution of groundwater to the plant roots started to decrease and water table started to rise gradually as the growth stage proceeded towards maturation in late September 2014. In order to verify this scenerio, three rain-free and rainy periods were selected from the irrigated treatment at different growth stages to analyze the cumulative contribution of groundwater due to the change in crop ET.

Figure 5 shows the cumulative contribution of groundwater to the root-zone in the irrigated treatment during three rain-free and rainy periods along with the cumulative crop ET. Groundwater level was found to be responsive to crop ET. Generally, the water table elevation declined with an increase in crop ET confirming the contribution of shallow groundwater towards the plant roots. Lowering of the ground water table may be attributed to the upward migration of water during the dry periods. The average daily volumetric water content within the effective root-zone depth (0.6 m) during dry period 1, 2, and 3 were recorded as 0.19, 0.22, and 0.21 m^3 m^{-3}, respectively.

During the rainy periods, the depth of rainfall was recorded as 6, 1.5, and 14.8 mm during rainy period 1, 2 and 3, respectively. Groundwater did not contribute to the potato root-zone during the rainy periods 1 and 3 because an adequate depth of rainfall met the crop ET. However, only 1.5 mm rainfall depth during the rainy period 2 led to the upward migration of groundwater to meet the crop ET.

Growth Stage Specific Groundwater Levels

During the growing season of 2013, a statistically significant difference between irrigated and non-irrigated treatments was found in the groundwater table levels at the tuber initiation stage (p = 0.0006) and tuber bulking stage (p = 0.0001) (fig. 6). However, the difference was not significant at the maturation stage (p = 0.308). In 2014, the difference between groundwater levels in both of the treatments was not significant at tuber initiation stage (p = 0.320). However, a statistically significant difference was found in the groundwater levels at tuber bulking (p = 0.0001) and maturation stages (p = 0.020).

The 2014 growing season was comparatively drier with below average rainfall. During this season, 65% of the total seasonal rainfall occurred in the initial growth stages i.e. sprout development, vegetative growth, and tuber initiation. High rainfall events, during this period, led to a lower need for contribution from the groundwater table in both treatments. The difference between groundwater levels in both treatments was not significant at tuber initiation stage. During the tuber initiation stage, only 38.1 mm irrigation water was applied in the irrigated treatment in two irrigation events. The supplemental irrigation during tuber bulking and maturation stages precluded the need for contribution from the water table in the irrigated treatment. The total irrigation application of 95.2 mm as supplemental irrigation improved the hydraulic conductivity between the root-zone and the water table. It is assumed that the drier conditions in the non-irrigated treatment may have led to lower unsaturated hydraulic conductivity in the soil below the root-zone

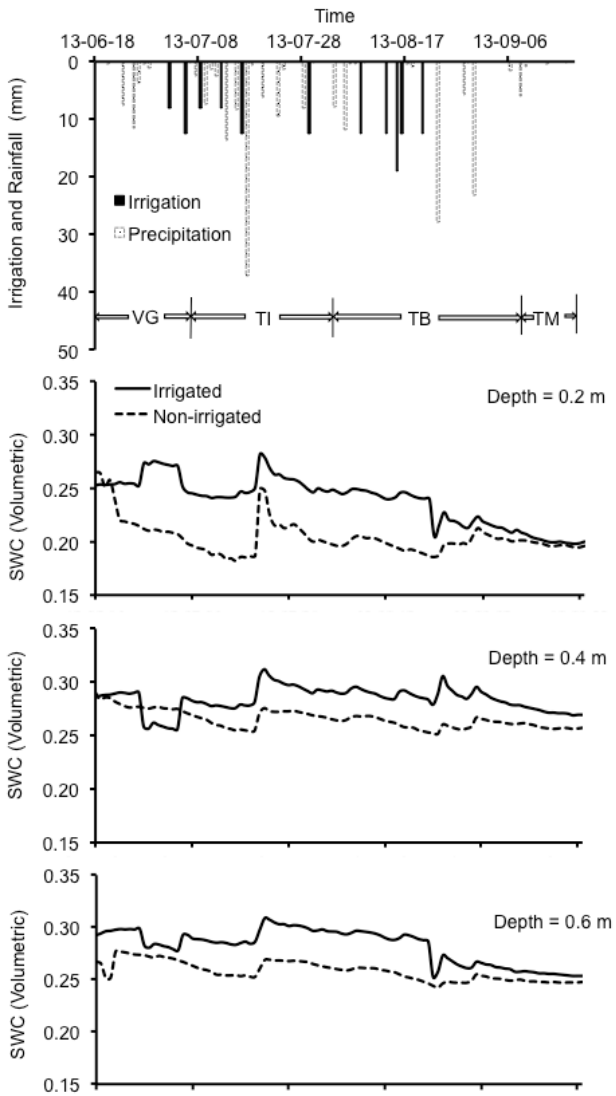

Fig. 7. Volumetric soil water content (SWC), precipitation, and supplemental irrigation in the 2013-growing season. (VG – Vegetative growth, TI – Tuber initiation, TB – Tuber bulking, TM – Tuber maturation)

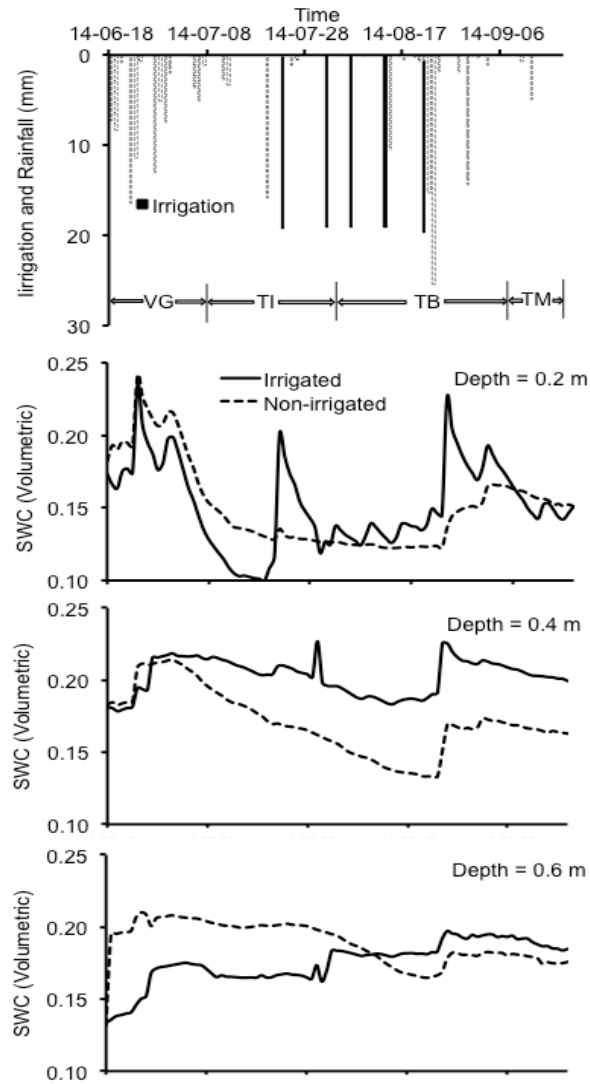

Fig. 8. Volumetric soil water content (SWC), precipitation, and supplemental irrigation in the 2014-growing season. (VG – Vegetative growth, TI – Tuber initiation, TB – Tuber bulking, TM – Tuber maturation)

which in turn may have resulted in a capillary barrier below the root-zone preventing contribution from the water table. Therefore, the difference between groundwater levels was significantly higher in the irrigated treatments during tuber bulking and maturation stages.

Soil water distribution within the effective root-zone

C-probes were used to continuously measure the water content at 0.2 m intervals within the top 1 m of the soil profile throughout the growing season. The daily average volumetric soil water contents (SWC) within the effective root-zone of potato (0 - 0.6 m) for the 2013- and 2014-growing seasons are shown in figs. 7 and 8, respectively. During the recharge event, the soil water content quickly increased in the top layer (0.2 m). However, the water redistributed into the deeper soil layers after each recharge event. Daily ET gradually depleted the top layer water content in the following days making this soil layer drier. Therefore, the deeper layers remained wetter than the surface layer. As a result, the unsaturated hydraulic conductivity of the soil would have increased within the root-zone and the soil profile below the root-zone.

Average soil water contents during the 2013- and 2014- growing season are given in Table 4 and 5, respectively. In the 2013-growing season, the soil water contents were significantly higher in the irrigated treatment as compared to the non-irrigated treatment at 0.2, 0.4, and 0.6 m depth during tuber initiation, tuber bulking, and maturation stages. Soil water content in both

Table 4. Average soil water content during the 2013-growing season at different growth stages. (Different letters beside the means indicate significant difference (p = 0.05) between the treatments by depth within each growth stage; IR – Irrigated, NI – Non-irrigated)

Growth Stage	Depth (m)					
	0.2		0.4		0.6	
	Treatment					
	IR	NI	IR	NI	IR	NI
Vegetative Growth	0.29 a	0.29 a	0.29 a	0.29 a	0.29 a	0.29 a
Tuber Initiation	0.29 a	0.26 b	0.29 a	0.26 b	0.29 a	0.26 b
Tuber Bulking	0.28 a	0.25 b	0.29 a	0.26 b	0.28 a	0.25 b
Maturation	0.26 a	0.25 b	0.27 a	0.26 b	0.26 a	0.25 b

treatments remained constant within the soil profile prior to the first irrigation event i.e. at vegetative growth stage in both treatments. Supplemental irrigation was applied during the tuber initiation, and tuber bulking stages in both years. The application of irrigation and precipitation increased the soil water content within the soil profile in the irrigated treatment. However, the non-irrigated treatment was receiving water from rainfall and shallow ground water table as a result of upward flux of groundwater to meet the plant water requirement.

In the 2014-growing season, soil water content in both treatments remained constant within the soil profile at the vegetative growth stage. First irrigation was applied in the late tuber initiation stage. There was no significant difference in soil water content at 0.2 m depth between both treatments. However, soil water content was significantly higher in the irrigated treatment at 0.4 m depth, and in the non-irrigated treatment at 0.6 m depth. It indicates that rainfall water accumulated within the root-zone of the non-irrigated treatment due to hydraulic barrier below the root-zone and did not infiltrate to the groundwater at tuber initiation stage. The soil water contents were significantly higher in the irrigated treatment as compared to the non-irrigated treatment at 0.2, 0.4, and 0.6 m depth during the tuber bulking stage.

High yield under dry conditions signifies the importance of upward migration of water from the shallow groundwater table. However, ground water quality may significantly affect the marketable yield and quality of potatoes. These results are in agreement with Cordeiro and Sri Ranjan (2012), who conducted a study in the same location to compare the yield of corn under no-irrigation and with overhead irrigation. They reported no statistical difference between the yields from the control treatment and treatments receiving the overhead irrigation. MASC (2013) reports also support these results. According to these reports, Southern Manitoba experienced good crops in 2012 despite the dry weather conditions. In a study conducted by Follett et al. (1974) in sandy loam soil under shallow water table conditions with corn crop, they reported good corn yield in the absence of supplemental irrigation.

CONCLUSIONS

This study investigated the impact of overhead irrigation on potato yield under Manitoba conditions during two consecutive years. A trend of higher potato yield was observed in irrigated plots compared to non-irrigated plots in both years, although the difference in yield was not statistically significant. Both treatments received moisture through natural precipitation i.e. rainfall. However, both treatments had the potential to receive supplemental moisture from the shallow groundwater table. Comparatively better potato yield in irrigated plots showed the importance of soil moisture supply through overhead irrigation at critical stages of development. The irrigation water supplied through overhead irrigation system was sufficient to meet the crop water demand.

Water demand of potato crop varies with the stage of growth. In the very beginning of the growing season (sprout development and vegetative growth stages), plant root density is small and the water uptake is also small. Plant root density rapidly increases as the plant

Table 5. Average soil water content during the 2014-growing season at different growth stages. (Different letters beside the means indicate significant difference (p = 0.05) between the treatments by depth within each growth stage; IR – Irrigated, NI – Non-irrigated)

Growth Stage	Depth (m)					
	0.2		0.4		0.6	
	Treatment					
	IR	NI	IR	NI	IR	NI
Vegetative Growth	0.20 a	0.20 a	0.20 a	0.20 a	0.20 a	0.20 a
Tuber Initiation	0.13 a	0.13 a	0.21 a	0.17 b	0.17 a	0.20 b
Tuber Bulking	0.16 a	0.14 b	0.20 a	0.15 b	0.19 a	0.18 b
Maturation	0.15 a	0.15 a	0.20 a	0.16 b	0.19 a	0.17 b

development proceeds from tuber initiation to tuber maturation stage. As the soil water within the root-zone is depleted during these stages, upward migration from the groundwater table is needed to meet the water demand in the absence of rainfall/irrigation. This upward water flux is seen as an increase in soil moisture in the deeper layers. Conducive hydraulic conductivity in the soil profile facilitated the upward water migration leading to a decline in the groundwater table. Therefore, the upward flux of groundwater to meet the crop water demand led to a lowering of the water table.

Shallow groundwater resources may significantly decrease the need for supplemental irrigation. Major natural sources of recharge to groundwater include rainfall and snowfall. These sources should be managed properly to make effective use of groundwater as a source for crop production. However, groundwater quality should be measured to ensure the quality is adequate to produce good quality potatoes. Facilitating the upward migration of water at the expense of marketable yield is not desirable.

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