water

MDPI

Article

Crop Water Deficit and Supplemental Irrigation Requirements for Potato Production in a Temperate Humid Region (Prince Edward Island, Canada)

Serban Danielescu [1,2,*], Kerry T. B. MacQuarrie [3], Bernie Zebarth [1], Judith Nyiraneza [4], Mark Grimmett [4] and Mona Levesque [1]

1 Fredericton Research and Development Centre, Agriculture and Agri-Food Canada 95 Innovation Rd., Fredericton, NB E3B 4Z7, Canada
2 Canada Centre for Inland Waters, Environment and Climate Change Canada, 867 Lakeshore Rd., Burlington, ON L7S 1A1, Canada
3 Department of Civil Engineering and Canadian Rivers Institute, University of New Brunswick, 17 Dineen Drive, Fredericton, NB E3B 5A3, Canada
4 Charlottetown Research and Development Centre, Agriculture and Agri-Food Canada, 440 University Avenue, Charlottetown, PE C1A 4N6, Canada
* Correspondence: serban.danielescu2@agr.gc.ca

Abstract: The global increase in potato production and yield is expected to lead to increased irrigation needs and this has prompted concerns with respect to the sustainability of irrigation water sources, such as groundwater. The magnitude, and inter- and intra-annual variation, of the crop water requirements and irrigation needs for potato production together with their impact on aquifer storage in a temperate humid region (Prince Edward Island, Canada) were estimated by using long-term (i.e., 2010–2019) daily soil water content (SWC). The amount of supplemental irrigation required for the minimal irrigation scenario (SWC = 70% of field capacity; 0.7 FC) was relatively small (i.e., 17.0 mm); however, this increased significantly, to 85.2 and 189.6 mm, for the moderate (SWC = 0.8 FC) and extensive (SWC = 0.9 FC) irrigation scenarios, respectively. The water supply requirement for the growing season (GS) increased to 154.9 and 344.7 mm for a moderately efficient irrigation system (55% efficiency) for the SWC = 0.8 FC and SWC = 0.9 FC irrigation scenarios, respectively. Depending on the efficiency and the areal extent of the irrigation system, the irrigation water supply requirement can approach or exceed both the GS and annual groundwater recharge. The methodology developed in this research has been translated into a free online tool (SWIB—Soil Water Stress, Irrigation Requirement and Water Balance), which can be applied to other areas or crops where an estimation of soil water deficit and irrigation requirement is sought.

Keywords: precision agriculture; hydroinformatics; irrigation efficiency; aquifer storage; hydrology tools; SWIB

Citation: Danielescu, S.; MacQuarrie, K.T.B.; Zebarth, B.; Nyiraneza, J.; Grimmett, M.; Levesque, M. Crop Water Deficit and Supplemental Irrigation Requirements for Potato Production in a Temperate Humid Region (Prince Edward Island, Canada). *Water* **2022**, *14*, 2748. https://doi.org/10.3390/w14172748

Academic Editor: Haijun Liu

Received: 12 August 2022
Accepted: 1 September 2022
Published: 3 September 2022

1. Introduction

Potato, the fourth most important food crop in the world [1], has seen a long-term global increase in both production and yield in the last several decades [2]. It is expected that the demand for potatoes will continue to increase in the future and this will result in increased irrigation needs, resulting in additional stress to the already limited water supply [3–5]. Hence, highly-managed deficit irrigation strategies and the increased efficiency of irrigation systems will be essential to help meet future challenges relative to potato production [3,5]. Potatoes are an important agricultural commodity for Prince Edward Island (PEI), Canada, with land in potato production representing about 14.4% of PEI's total farm area [6] and PEI production contributing more than 25% of Canadian potato production [7]. Currently, most of the potato crops in PEI are rain-fed; however, it is anticipated that the requirement for supplemental irrigation will intensify because of interest from farmers to compensate for the frequent crop water deficits [8–10]. Climate change may also lead to increased irrigation, both as land area irrigated and water amount, due to the anticipated amplification of the crop water deficit and the increased demand for greater crop yields in order to be competitive in global markets [9,11–13]. Because groundwater is the primary source for irrigation water in PEI, the possibility of increased irrigation has raised concerns about reducing baseflow to streams, depleting groundwater resources and increasing saltwater intrusion into the sandstone aquifer underlying the province [9,10,14].

Soil water deficit, defined as the difference between the amount of water the soil can hold (i.e., soil water content (SWC) at field capacity (FC)) and the actual amount of water present in the soil (i.e., actual SWC), is a key concept for estimating the water requirement for any given crop. The crop water requirement is defined herein as the amount of water needed to minimize the detrimental effects of the soil water deficit on crop growth. Supplemental irrigation can be used when the SWC provided naturally from precipitation does not satisfy the crop water requirement. Of the major world crops, potato is one of the most sensitive to water stress [1,15]. Water stress, which can manifest either as a result of soil water deficit (i.e., SWC below the optimal range) or soil water excess (i.e., SWC above the optimal range), can have significant adverse effects, for example, on tuber development and quality, and the incidence of diseases, when present even for a few consecutive days [1,13,15–17]. The recommendations for the optimal SWC for potatoes vary, but generally indicate that the SWC during most of the growing season (GS; late May to late October), and particularly during the tuber initiation and tuber bulking stages (early July to mid-September), should be maintained predominantly between 80 and 90% of FC, although values between 65 and 95% are sometimes suggested [18–20].

Investigations of the water deficit in PEI are limited, and there are only a few studies available in the literature for Atlantic Canada. For example, Bootsma et al. (2005) [21] estimated the average water deficit, expressed as the precipitation deficit and calculated based on differences between crop evapotranspiration and precipitation, to be between −25 mm (i.e., excess) and >150 mm for fields cultivated with soybean, corn and barley in various areas of Atlantic Canada between 1990 and 2000. Malekian et al. (2014) [22] used the Versatile Soil Moisture Budget (VSMB; [23]), calibrated using measured soil moisture data between 1998 and 1999, to develop a long-term simulation (1910–2001) at a grassed study site near Truro, Nova Scotia. They estimated that the soil water deficit was significant, with 40–50% of the days in July and August having a SWC below 50% of the soil available water capacity (defined as the difference between FC and wilting point). In PEI, Afzaal et al. (2020) [9] estimated and recognized the economic significance of water deficit for fields under potato production. In the respective study, the water deficit was calculated during each GS (June–October) between 2011–2017 as a monthly precipitation deficit. Although the monthly and seasonal values were not explicitly presented, it was estimated that the precipitation deficit, which occurred mostly between June and August, averaged 110 mm (±70 mm) for this three-month period and reached a maximum in July (i.e., ~60 mm). Jiang et al. (2021) [10] estimated the precipitation deficit between 2001 and 2018 for the potato plants in PEI and suggested that supplemental irrigation can be particularly beneficial in PEI in years with a high water deficit (i.e., 100–300 mm) during the GS (June to September). In the respective study it was found that the precipitation deficit (or excess) for the GS ranged between −97 (excess) and 295 mm (deficit), with an average of 81 mm. Studies focused on understanding the soil water deficit and supplemental irrigation requirements in the context of potato production in PEI are limited and to date have not been supported directly by in-field measurements such as the SWC and soil properties.

Determination of the soil water deficit as well as the supplemental irrigation requirements is important both for assessing the feasibility of irrigation practices (e.g., cost–benefit analysis) as well as for quantifying potential impacts of irrigation practices on the various sources of water (e.g., impact of irrigation on aquifer storage). The objective of this study was to estimate the magnitude, and inter- and intra-annual variation, of the soil water deficit and thus the irrigation requirements for potato production systems in PEI, under current climate conditions. In addition, considerations relative to SWC thresholds, the efficiency of the irrigation systems and areal extent of irrigation practices have been included for evaluating the supplemental irrigation requirements. Specifically, we quantified the soil water deficit using long-term (2010–2019) daily measurements of SWC in the root zone in conjunction with laboratory measurements of soil properties and used this information to estimate the irrigation requirements for a potato crop cultivated on a sandy loam soil considered to be representative for much of PEI. Then, we assessed the impact of various irrigation intensity practices as well as a range of irrigation system efficiencies on the irrigation water supply requirements. Finally, we assessed the potential impacts of irrigation water withdrawal on aquifer storage under several irrigation expansion scenarios. This research serves as a reference for developing field-based methodologies and guidelines relative to irrigation requirements and irrigation allowances based on soil moisture measurements. The soil moisture-based methodology developed in this study can easily be applied to other areas and crops where an estimation of soil water stress, supplemental irrigation requirements and the impact of irrigation on aquifer storage is sought via the freely available SWIB (Soil Water Stress, Irrigation Requirement and Water Balance) online tool that has been developed as part of this research [24].

2. Materials and Methods

2.1. Site Description

The site is located at the Agriculture and Agri-Food Canada Harrington Experimental Farm, about 11 km north of Charlottetown, PEI, and has an area of 2.3 ha (Figure 1). The field is located on a long gentle slope (3.4%), with the local topographic high about 50 m north-west of the site and a topographic low about 200 m from the eastern edge of the field, where a small creek flows perpendicular to the slope.

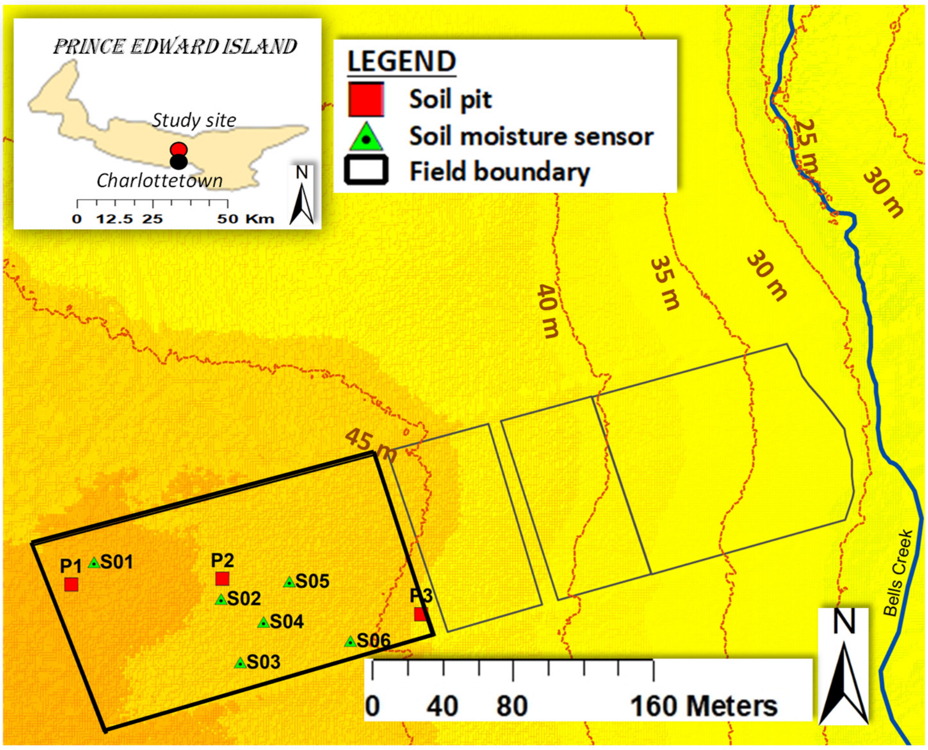

Figure 1. Soil monitoring and sampling locations at the study site. Inset: position of the study site in Prince Edward Island.

The climate in the area is cool, temperate humid. Based on the 1981–2010 Climate Normals for the Environment and Climate Change Canada Charlottetown weather station [25], average annual air temperature is 5.7 °C, with a minimum monthly average in

January (−7.7 °C) and the maximum monthly average in July (18.7 °C). The average annual precipitation is 1150 mm and includes 290 mm as snow. Precipitation is relatively uniformly distributed during the year, with the monthly average precipitation ranging from 75 to 100 mm. The snowpack can be significant, with an average maximum depth of 30 cm reached in February, and a subsequent significant snowmelt period between February and April.

The soils at the site, belonging to the Charlottetown soil association and developed on strongly acid fine sandy loam glacial till, have a sandy loam texture and are classified as an Orthic Humo-Ferric Podzol in the Canadian system of soil classification [26]. This soil, with properties similar to many other soils in PEI, is the soil with the largest extent at the provincial scale coverage and is representative of the soils used for potato production in much of PEI [26,27]. The Charlottetown association soils are dominantly well drained; however, the permeability contrast between the soil and the underlying glacial till can lead to the presence of transient perched water conditions for several days per year, especially following snowmelt [28,29]. The study site overlies an 8-m-thick layer of glacial till, which is underlain by a fractured sandstone aquifer; both the till and the bedrock are representative at the provincial scale [26,28,30]. The regional water table is located within the bedrock [28]. Annual groundwater recharge in PEI ranges between 400 and 500 mm and is minimal during the summer months [28,31,32].

The field has been under a three-year potato rotation as mandated by the provincial government [33]. The rotation implemented in the field since 2008 was common for PEI and consisted of potato (year 1), barley underseeded with red clover (year 2) and red clover (year 3). Similar to the common practice for the fields under potato production in PEI, none of the rotation phases received supplemental irrigation for the duration of this study. The field was typically planted with potatoes or barley in mid to late May and was harvested in late October for potatoes, and from mid-August to early September for barley. The red clover was cut one to three times during the summer and left in the field to increase soil organic matter content and was plowed in September or October. Potatoes were planted in 2011, 2014 and 2017. Barley underseeded with clover was planted in 2012, 2015, 2016 and 2018. The field was under clover in 2010 and 2013 and under a mix of grasses in 2019. The irregularities in rotation sequence were a result of adjusting the agricultural management of the potato rotation.

2.2. Soil Properties and Root Zone Depth

Soil samples were collected in October 2009 from three soil pits distributed throughout the study site (Figure 1). The soil pits were about 4 m (L) × 1.5 m (W) × 1 m (D) and extended to the bottom of the soil profile. The pits were dug using a small excavator and the extent, color, soil structure and drainage type for each soil horizon were determined in the field immediately after excavation. Disturbed samples were collected from each pit (1 per horizon × 3 horizons × 3 pits; ~150 g each). Undisturbed soil samples were collected from each pit (4 per horizon × 3 horizons × 3 pits) for subsequent laboratory analyses by using soil core rings (7.6 cm diam. × 7.6 cm height).

Disturbed soil samples were air-dried and passed through a 2 mm sieve. Soil texture was determined in duplicate using the pipette method following organic matter removal [34]. Soil organic carbon was determined by dry combustion [35] using a Vario Macro CN analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). Soil water retention curves were determined on undisturbed core samples using the method described by Rees and Chow (2005) [36]. SWC at matric potentials of −0.5, −5 and −10 kPa were measured on tension tables using the procedure described by Topp and Zebchuk (1979) [37], while for matric potentials of −33 and −100 kPa pressure plates were used. Water content at a matric potential of −33 kPa was considered to represent FC and FC was assumed to remain constant for the study period. Total porosity was determined using the method described in Hao et al. (2007) [38]. Upon completion of water retention and hydraulic conductivity analysis, the samples were oven dried at 105 °C and bulk density was calculated as the mass of dry soil divided by the total soil volume. Total porosity was calculated by assuming a particle density of 2.65 g cm^{-3}.

The potato root system (i.e., root zone depth) was considered to extend from the surface of the ground to a depth of 50 cm in accordance with the range of 45–60 cm suggested in the literature [1,16,39].

Representative values for the soil parameters for each horizon included in the root zone (i.e., horizons A and B) were obtained by averaging the values obtained for each parameter in the same soil horizon of each pit. Based on the average depth of the soil horizons in each pit, soil horizon A was considered to extend between 0 and 25 cm below ground surface, while horizon B extended from 25 to 50 cm below ground. The overall average value for the root zone for the study site as a whole was calculated as a depth-weighted average (Table 1). The soil properties as determined from field surveys and laboratory measurements were consistent across the study site for each horizon. The SWC at FC for the root zone was 29.1%, similar to the value of 27.9% reported by Carter (1987) [27] for the Charlottetown soil association.

Table 1. Soil properties at the study site [1].

Soil Horizon	Depth (cm)	Texture	Sand (%)	Clay (%)	Silt (%)	TP (%)	OM (%)	FC (%)
No. of samples/horizon	-	-	6	6	6	12	6	12
A	0–25	Sandy loam	59.5	11.5	29.1	49.6	3.15	32.7
B	25–50	Sandy loam	63.3	8.5	28.2	49.6	1.16	25.5
C	50–100	Sandy loam	60.0	11.0	29.0	42.8	0.31	20.7
Root zone average	0–50		61.4	10.0	28.6	49.6	2.15	29.1

Note: [1] TP—total porosity; OM—soil organic matter; FC—field capacity.

2.3. Soil Water Content

Soil water content, temperature and electrical conductivity were logged hourly at up to 6 locations between 2010 and 2019 using 5TE Decagon sensors connected to EM50 data loggers (METER Group, Pullman, WA, USA) (Figure 1). The sensors, which measure volumetric water content (VWC, m^3 m^{-3}) based on the dielectric properties of the soil, were placed at four or five depths at each location, with depths ranging from 5 cm to 80 cm below ground surface. At all locations sensors were installed at 10, 20 and 50 cm depths; however, the 5 cm and the 80 cm depths were available only at selected locations (i.e., 5 cm at S01 and S02; 80 cm at S03, S04, S05 and S06). The sensors were installed by auguring a 7.5-cm-diameter vertical hole to 1 m depth (i.e., bottom of the soil profile), and pushing the sensors (horizontally) into the walls of the hole at selected depths. The sensor cables were run underground through 2.5-cm-diameter PVC pipes (i.e., to protect from rodents) to data loggers, which were installed on 1 m vertical poles to prevent them from being covered by snow during the winter.

The 5-cm-depth SWC measurements were discarded as they were prone to errors due to their proximity to the soil surface, the influence of large macropores and/or plant material, as well as instability of readings over time due to changes in the packing of the topmost several centimeters of the soil. The SWC readings at 80 cm depth were used only for correction of data obtained from 10, 20 and 50 cm depth, as they were below the bottom of the root zone (i.e., 50 cm). Missing sensor data, due to instrument malfunction or removal of selected sensors (S02, S03, S04, S05) during planting and harvesting periods, were estimated using regressions with the sensors from the next available depth, or if these were not available, using regressions with sensors from the same depth at other locations. The 5TE sensors did not accurately measure SWC when the temperature of the soil approached or was below the freezing point (i.e., sensors showed a sudden drop in water content at the outset of the freezing period, followed by an equivalent rise in SWC at the conclusion of the respective period). For these cases, the data were corrected based on correlations with the greatest depth available (when this was not affected by freezing), or by offsetting the water content values with the equivalent of the drop in water content at the outset of the freezing period.

The SWC measured hourly at depths within the root zone (10, 20, 50 cm) was averaged for each day over all locations, to obtain a representative daily value for SWC in the root zone. In addition, daily SWC measurements were converted to millimeters equivalent depth of water column, to allow comparison with, or calculation of, other parameters (e.g., total precipitation, crop water deficit, irrigation water supply). The conversion was achieved by multiplying the VWC ($m^3\ m^{-3}$) by the thickness of root zone (i.e., 0.5 m).

All daily SWC values were subsequently integrated over monthly, GS (including tuber initiation and bulking stages) and annual periods. In addition, a representative year for all crops as well as for each phase of the rotation was developed by averaging the SWC values for any given day in all the years when the respective crop was present in the field (e.g., Jan. 1 of the representative year for the potato crop was obtained by averaging SWC values on Jan. 1 in each of the years when the potato was planted).

Precipitation data used in this study were obtained from Environment and Climate Change Canada Charlottetown weather monitoring station [40].

2.4. Soil Water Deficit and Excess

Soil water deficit was considered present when the SWC was below FC, while soil water excess was considered to be present when SWC was greater than FC. Additional SWC thresholds (i.e., 70%, 80% and 90% of FC) were chosen based on recommended optimum ranges of SWC for potato production [18–20] to allow examination of the severity (i.e., temporal extent and magnitude) of soil water deficit for the potato rotation phase. In addition, for the potato phase, the water deficit and water excess were calculated as presence/absence (i.e., values of 1 or 0) as well as equivalent water height (mm) by using the thickness of the root zone and the difference between measured water content and FC, for the resulting SWC ranges of values (i.e., <70% FC, <80% FC, <90% FC).

2.5. Supplemental Irrigation Water Requirement

The supplemental irrigation water requirement was calculated for the potato phase as the daily amount of water required to maintain SWC at or above the three SWC thresholds defined above (i.e., 70% FC, 80% FC and 90% FC) to represent minimal, moderate and extensive irrigation strategies, respectively. In this study it was assumed that the plant water consumption needs were constant when SWC was lower than the respective thresholds. Based on the average planting and harvesting data for the monitoring period, the growing season (GS) for the potato was defined as 25 May to 30 October (159 days). Within this period, by extrapolating the extent of various potato growth stages suggested in the literature [41,42], the tuber initiation and tuber bulking stages were considered to occur between July 1 and September 17 (78 days). Similar to the water deficit, the supplemental irrigation requirement was calculated as presence/absence, and as actual equivalent water height (mm), for both the GS and the tuber initiation and bulking stages for each of the three scenarios. In order to obtain the volume of water required per hectare ($m^3\ ha^{-1}$), the values expressed as equivalent water height (mm) were multiplied by 10.

For each of the thresholds specified above, the daily supplemental irrigation water requirement for the potato crop was calculated using the methodology illustrated in Figure 2. The supplemental irrigation (IR) was triggered only on the days when the measured SWC was lower than the thresholds (THR) mentioned above. For the respective days, the SWC was adjusted ($SWCA_t$) to be equal to the specified threshold ($SWCA_t$ = THR). For the following day, the adjusted SWC was calculated using the adjusted SWC for the previous day and the difference in measured SWC between the two days ($SWCA_{t+1} = SWCA_t + (SWC_{t+1} - SWC_t)$) and the resulting soil moisture was checked against the SWC threshold. This routine was applied repeatedly for the full duration of the GS. For the purpose of this study, it was assumed that, regardless of the irrigation method, the irrigation water changed the SWC within the timestep of the calculation (i.e., day).

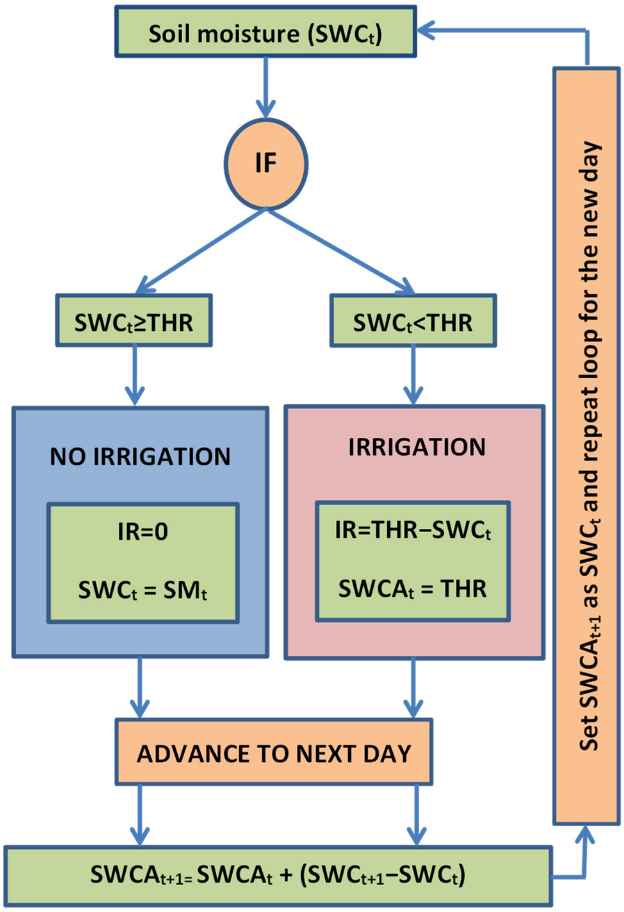

Figure 2. Calculation procedure for determining irrigation requirement (SWC_t, measured SWC on day t; THR, SWC threshold for triggering irrigation; IR, irrigation requirement; $SWCA_t$, adjusted SWC on day t; $SWCA_{t+1}$, adjusted water content on day t + 1; SWC_{t+1}, measured SWC on day t + 1).

The water supply requirement for the potato crop was calculated using the supplemental irrigation requirement multiplied by the irrigation efficiency coefficients available in the literature (i.e., water supply requirement = supplemental irrigation requirement x irrigation efficiency coefficient). Efficiency data for PEI irrigation systems are not available; however, irrigation efficiency review studies suggest that the overall efficiency can range from 20 to 90% [43–45], with significant variability in each of the efficiency subcomponents (e.g., storage, transportation, application), depending on factors such as the type of irrigation system, the materials used for the irrigation system, the crop, the soil properties and climatic conditions. For the purpose of this analysis, three irrigation system efficiencies were considered: (1) high (i.e., 90%), (2) moderate (i.e., 55%) and (3) low (i.e., 20%).

The methodology for calculating the soil water deficit, irrigation requirements and the impact of irrigation practices on aquifer storage were integrated into SWIB (Soil Water Stress, Irrigation Requirement and Water Balance), an online customizable tool programmed in PHP 7.4, which has cross browser compatibility and is freely available to the larger public (Danielescu et al., 2021) [24]. SWIB allows users to estimate daily water stress (either as water deficit or water excess), crop irrigation requirements and the impact of irrigation on aquifer storage, together with a series of water balance components, using user-provided daily soil moisture, precipitation and evapotranspiration time series. SWIB allows for testing of irrigation scheduling and efficiency scenarios based on user-defined growing and irrigation seasons, thresholds for soil moisture and water losses. The tool integrates tabular and graphical visualization options and export functions via a streamlined interface.

3. Results and Discussion

3.1. Soil Water Deficit and Excess

When the entire study period and all crops were considered, the average SWC was 26.9%, with an average of 23.8% for the GS and 29.3% outside of the GS, with similar averages for the years when the field was cultivated with potatoes (i.e., 27.4% multi-annual average, with an average of 23.6% for the GS and 30.3% for OGS). For the entire study period, when the average for all crops was considered, the SWC from January to April was close to soil FC, averaging 29.7%, likely in response to a mix of driving factors such as the presence of the snow cover for most of the period, low air and soil temperature and reduced evapotranspiration (Figure 3, Table S1 in Supplementary Material). At the onset of the GS, SWC decreased from an average SWC of 26.9% in May to a minimum of 21.6% in August in response to reduced precipitation for July and increased evapotranspiration, which reaches its maximum in July [9,46]. The SWC then increased over time from September to December in response to decreased ET and increased precipitation, when the average SWC in December of 29.7% was close to FC.

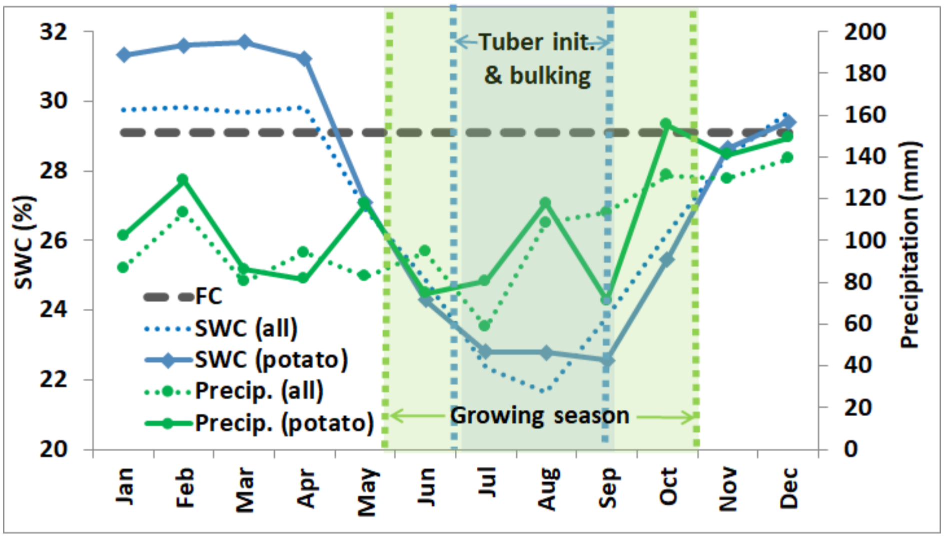

Figure 3. Field capacity (FC) and monthly averages for soil water content (SWC) and precipitation for potato and for all crops for the representative year.

SWC shows similar general trends when only the years when potato was cultivated were considered (Figure 3), with maximum differences of up to 1% during the growing season and up to 2% outside of the growing season compared to the average of all crops and regardless of the larger differences in monthly precipitation (e.g., up ~40 mm in September). The minimum SWC for the potato phase was reached during the critical growth stages of tuber initiation and bulking, when SWC had an average value of 22.8%. The GS SWC varied somewhat among years with a minimum value of 21.7% in 2012 (barley) and a maximum value of 25.3% in 2019 (clover). Each of the rotation phases showed SWC in both low and high range of values in separate years (Figure 4, Table S2) and paired t-tests conducted on growing season monthly SWC averages for each crop indicate that the crop species did not have a statistically significant impact on SWC (i.e., p-values of 0.312, 0.912 and 0.710 for barley vs. clover, barely vs. potato and potato vs. clover, respectively).

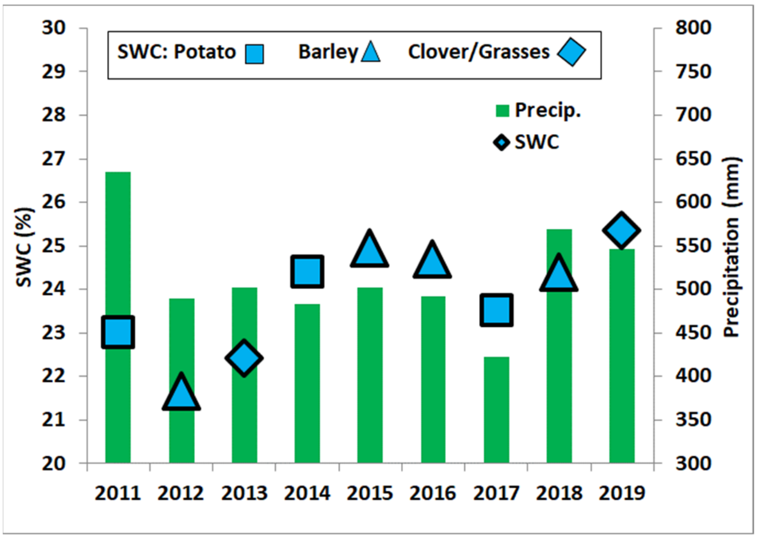

Figure 4. Average soil water content (SWC) and precipitation for each growing season during the study period (Note: 2010 growing season data [incomplete] not included).

For potatoes, on average, the SWC during the GS was below 0.7 FC, 0.8 FC, 0.9 FC and FC on 19, 75, 132 and 154 days, respectively. The number of days during the GS with SWC in various deficit intervals varied widely among years (Figure 5). Notably, July and August were the months with the largest soil water deficit, with 98.4% of the days below 90% FC, 60.8% of the days below 80% of FC and 7.5% of the days below 70% FC. Overall, these findings suggest that during the GS, and particularly during the most critical stages of potato development (i.e., tuber initiation and bulking stages; 1 July–17 Sep; 78 days) the crops were regularly exposed to soil water deficit, with the natural SWC regime unable to satisfy the crop water requirements. Soil water excess was a rare occurrence during the potato GS, with SWC above FC on only 3% of the days (Figure 5). These occurrences of excess water occurred in response to significant rainfall events, and the presence of excess water typically persisted only for short periods of time (typically 1–2 days).

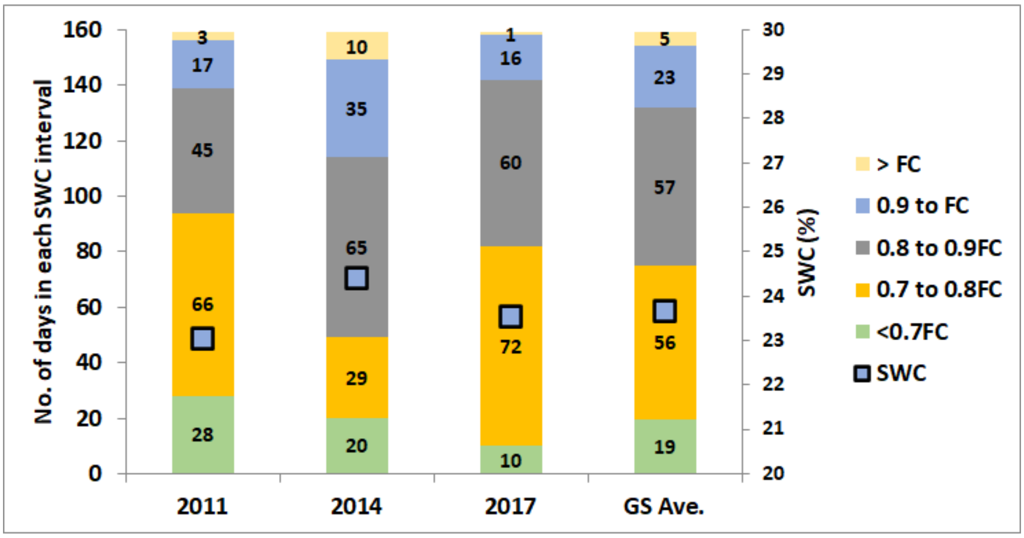

Figure 5. Number of days with soil water content (SWC) in each SWC interval for each potato growing season.

3.2. Crop Water Requirement and Supplemental Irrigation

The potato crop water requirement, representing the sum of the daily amounts of water required to maintain the SWC at levels that are optimal for the potato plant's development, were calculated for both the critical tuber growth stages (i.e., tuber initiation and tuber bulking) and GS using the same thresholds as for the soil water deficit (Figure 6). For the potato crop, the average number of days for which irrigation was required during the GS varied widely depending on the SWC threshold (i.e., 0.7 FC, 0.8 FC or 0.9 FC) selected for triggering supplemental irrigation. The number of days was 99.7 for the extensive irrigation scenario (SWC = 0.9 FC), 60.0 for moderate irrigation (SWC = 0.8 FC) and only 15.7 for minimal irrigation (SWC = 0.7 FC). The corresponding amount of water required for supplemental irrigation for each scenario was 189.6 mm (SWC = 0.9 FC), 85.2 mm (SWC = 0.8 FC) and 17.0 mm (SWC = 0.7 FC), respectively (Table 2). As a volume of irrigation water required per unit area, the above values translate to 1896 m^3 ha^{-1} (SWC = 0.9 FC), 852 m^3 ha^{-1} (SWC = 0.8 FC) and 170 m^3 ha^{-1} (SWC = 0.7 FC). The number of days that required supplemental irrigation during the tuber initiation and tuber bulking stages also varied widely, at 57.0 days for SWC = 0.9 FC, 38.0 days for SWC = 0.8 FC and 7.7 days for SWC = 0.7 FC, with the volume of irrigation water required estimated as 124.1 mm (SWC = 0.9 FC), 64.7 mm (SWC = 0.8 FC) and 8.2 mm (SWC = 0.7 FC), respectively. The irrigation required during tuber initiation and bulking varied with the irrigation scenario, and represented 65.5% for SWC = 0.9 FC, 76.0% for SWC = 0.8 FC and 48.7% for SWC = 0.7 FC of the total GS irrigation, showing that the bulk of the irrigation is most needed during these critical stages of plant growth, particularly for the more intensive irrigation scenarios. The significantly lower percentage for the SWC = 0.7 FC scenario is related to the extremely low levels of irrigation required, and hence to the increased sensitivity of the calculations (e.g., an increase of 3 mm in irrigation during tuber initiation and bulking will result in a ~20% increase in the relative contribution of irrigation during the tuber initiation and bulking stages).

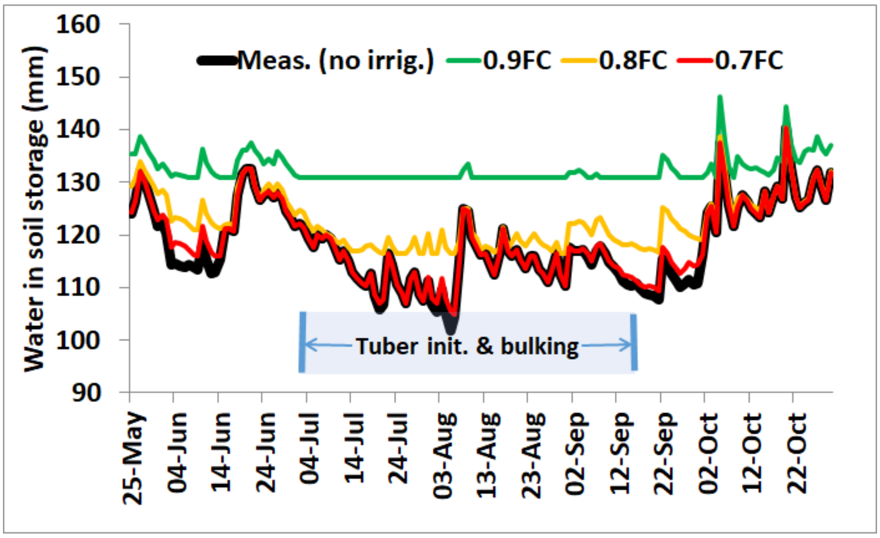

Figure 6. Multi-year daily averages of soil water storage for the potato GS under no irrigation (i.e., Meas. no irrig.) and three supplemental irrigation scenarios.

Table 2. Irrigation requirements (mm) for the growing season and tuber initiation and bulking stages based on multi-year daily averages for the study period (2010–2019).

	SWC = 0.9 FC	SWC = 0.8 FC	SWC = 0.7 FC
	Growing Season (25 May–30 October; 159 Days)		
Irrigation Days	**99.7**	**60.0**	**15.7**
Irrigation Efficiency			
100%	189.6	85.2	17.0
90%	210.7	94.6	18.8
55%	344.7	154.9	30.8
20%	948.0	425.9	84.8
	Tuber initiation and tuber bulking (1 July–17 September; 78 Days)		
Irrigation Days	57.0	38.0	7.7
Irrigation Efficiency			
100%	124.1	64.7	8.2
90%	137.9	71.9	9.2
55%	225.7	117.6	15.0
20%	620.7	323.5	41.2

The irrigation requirement during the GS showed significant variation from year to year (Figure 7), regardless of the irrigation scenario selected. For example, for the extensive irrigation scenario (SWC = 0.9 FC), the supplemental irrigation requirement ranged between 125.5 and 302.9 mm, while for the moderate irrigation scenario (SWC = 0.8 FC), this ranged between 56.6 and 135.5 mm. The minimal irrigation scenario showed very low amounts of irrigation required, i.e., between 12.2 and 19.4 mm. The amount of irrigation water required was well correlated with SWC for the extensive and moderate scenarios (R2 = 0.67); however, it showed very little correlation for the minimal irrigation scenario (R2 = 0.03). These findings suggest that it would be more appropriate to assess the irrigation requirement as much as possible in real time (e.g., by triggering irrigation events based on SWC measurements) as opposed to applying a similar irrigation volume each year, based on generic recommendations for the respective crop and geographical area. The amount and scheduling of supplemental irrigation based on SWC allows for adjusting the irrigation rates based on the water needs of the crop on a daily basis as opposed to precipitation deficit [9,10], which uses a monthly basis, and this would result in more accurate and appropriate supplemental irrigation estimates.

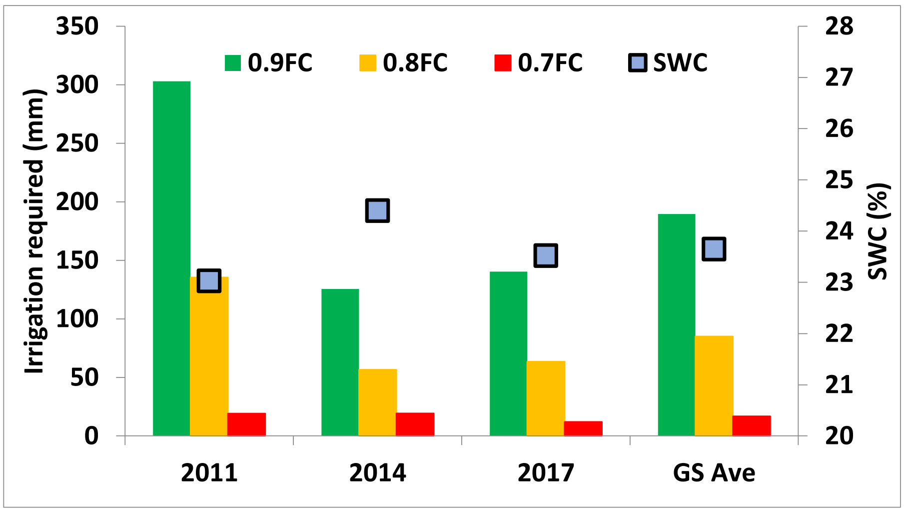

Figure 7. Potato supplemental irrigation requirement for the various irrigation scenarios for each growing season during the monitoring period (Note: 2010 growing season data [incomplete] not included).

The monthly distribution of the irrigation requirement for the growing season reached its maximum in August, with July only slightly lower, regardless of the scenario (Figure 8), thus suggesting that the maximum water stress occurs during tuber initiation and bulking.

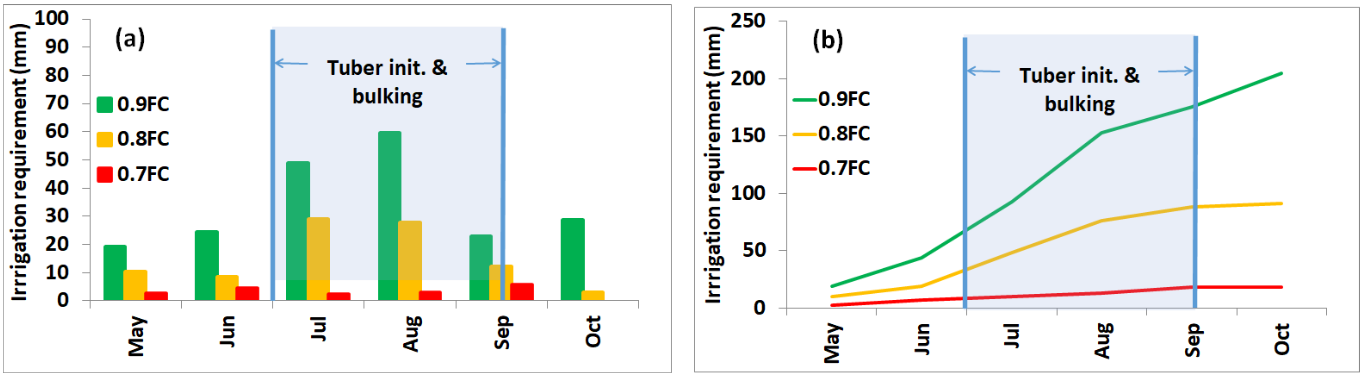

Figure 8. Monthly supplemental irrigation requirement for the various scenarios for each month (**a**) and cumulative (**b**) for the representative potato growing season.

The relative contribution of the GS supplemental irrigation from the total amount of water received by the crop was 27% for the SWC = 0.9 FC scenario, 14.2% for the SWC = 0.8 FC scenario and 3.2% for the SWC = 0.7 scenario, while for the tuber initiation and bulking stages, their relative contribution was 35.6, 22.4 and 3.5%, respectively. These results are largely consistent with results from other studies, which suggest that irrigation can provide between 10% in humid regions and 90% in arid regions of the water needed for crop production [1]. Even limited amounts of irrigation can be beneficial to potato production as previous studies have shown that a change of 10% or less in the amount received via irrigation has quantifiable effects, relative to potato yield, tuber quality, incidence of disease, etc. [8,13,17,47]. As shown in Table 2, the irrigation requirement for maintaining the SWC throughout the GS under the minimal irrigation scenario was very small. Therefore, although the analysis of the economic implications of using supplemental irrigation is outside of the scope of this study, this would suggest that under the minimal irrigation scenario the potential benefits resulting from improvements in the potato crop (e.g., tuber quality, tuber yield) might be counterbalanced by the installation and operation costs of the irrigation system. Under the moderate and extensive irrigation scenarios, the amount of water needed for satisfying the crop water requirement is more substantial, and hence the feasibility of irrigation practices should be analyzed in more detail.

The estimated irrigation water requirements obtained in this study, for example, considering the moderate or extensive irrigation practices (Figure 7), were similar to the range presented in the two PEI-based studies identified that included estimations of the water deficit. In the study conducted by Afzaal et al. (2020) [9] in 2018 and 2019, between 150 and 240 mm of water was applied for the entire GS (June–October) in order to maintain SWC above 60% of FC. However, Afzaal et al. (2020) [9], who estimated the irrigation requirements based on the water deficit calculated using the differences between evapotranspiration and precipitation (i.e., precipitation deficit), had only four to five irrigation events per GS, and a threshold for triggering irrigation as well as soil properties that were different to those used in this study. Jiang et al. (2021) [10] used census data to study the relationship between precipitation, water stress (deficit or excess) and potato yield at the PEI scale between 2001 and 2018, and found that, for example, between 2011 and 2018, the precipitation deficit averaged 81 mm for the GS (June–September) and ranged between 51 mm in 2011 and 136 mm in 2017, while recognizing that the authors could not evaluate if the soil moisture levels would have been maintained at optimum levels if irrigation amounts equivalent to the precipitation deficit would have been applied. While these estimates are in a similar range with the results presented in this study, as well as the results presented in Afzaal et al. (2020) [10], a direct comparison is challenging as the methodologies involved were different and might include different time periods, location of the study site and meteorological stations used, as well as a different length of the growing season used in the analysis.

The efficiency of the irrigation system, including the efficiency of the entire system or efficiency related to specific components (e.g., transportation, distribution, application), needs to be considered when estimating the actual amount of water that would be required for ensuring that the crop requirements are met (i.e., irrigation water supply). Table 2 shows that the three irrigation efficiencies assumed in this study (90%, 55% and 20%), can result in significantly increased amounts of water required for the irrigation system in comparison with the actual crop water requirement (i.e., shown on the 100% efficiency row). For example, for a low efficiency (20%) system, the irrigation water supply reached 948 mm for the GS, with 620 mm required during the tuber initiation and tuber bulking stages when irrigation was used for maintaining SWC at 90% of FC. However, for the increased irrigation system efficiency (i.e., 90%), the GS water supply requirement dropped to between 18.8 and 210.7 mm, with only from 9.2 to 137.9 mm required during the tuber initiation and bulking stages. The irrigation water supply requirement was highly variable when considering each year of the study period (Tables S3 and S4) and showed a significant increase in the water supply requirement in years with low SWC. For example, for the moderate SWC scenario (SWC = 0.8 FC) and an irrigation system with a moderate efficiency (i.e., 55%), the average water supply requirement for the tuber initiation and bulking stages was 117.6 mm; however, it ranged between 54.7 mm in 2014 (SWC = 23.7%) and 204 in 2011 (SWC = 22.1%).

Irrigation water can be supplied from various sources including both surface water (i.e., retention ponds, streams, lakes) and groundwater. Sourcing irrigation from groundwater is of particular interest for PEI because of the potential for reducing baseflow to streams, depleting groundwater resources and increasing saltwater intrusion into the unconfined aquifer underlying the province [9,14]. Average annual groundwater recharge in PEI is ~400 mm yr^{-1} (4000 m^3 ha^{-1}) and typically shows a seasonal pattern with a significant recharge event in the spring, minimal recharge during the summer months and a secondary, sometimes absent, event in the fall [28,31,32]. Several combinations of irrigation intensity and efficiency scenarios, in conjunction with the areal extent of the irrigation practices, have the potential to considerably impact the aquifer storage in potato production areas (Table 2, Tables S5 and S6). For example, the average irrigation water supply requirement for an area with 25% of the land irrigated using a moderate irrigation scenario (SWC = 0.8 FC) with a highly efficient irrigation system (i.e., 90% irrigation efficiency) is the equivalent of 9.7% of the annual groundwater recharge. This estimate is within the range reported by Jiang et al. (2021) [10], the only identified study that attempts to link supplemental irrigation to aquifer storage in PEI, who found that between 2001 and 2018, supplemental irrigation could use between 2.6% and 23% of the annual aquifer recharge in the Wilmot River watershed, a watershed where it was estimated that 31% of the land mass was irrigated. Under the same moderate irrigation scenario (SWC = 0.8 FC), the irrigation requirement would be equivalent to 29.0% of the annual groundwater recharge if 75% of the land in potato production was irrigated. When a moderate irrigation scenario (SWC = 0.8 FC) is used with a low efficiency irrigation system (i.e., 20% efficiency), the respective irrigation requirements would be equivalent to 26.6% (25% of the land irrigated) and 79.9% (75% of the land irrigated) of the annual groundwater recharge, respectively. The above estimates suggest that the use of supplemental irrigation has the potential to result in significant depletion of aquifer storage, particularly over the summer when groundwater recharge is minimal. In extreme cases, such as a low efficiency irrigation system (i.e., 20%) extensive irrigation scenario (SWC = 0.9 FC; >50% of the land irrigated), the irrigation water requirement is equivalent to or surpasses the annual groundwater recharge, thus potentially resulting in long-term, sustained aquifer depletion in irrigated areas. In addition, the impacts of supplemental irrigation on aquifer storage can be exacerbated when the inter-annual variability of SWC is considered (Tables S2–S4).

4. Conclusions

Daily SWC data collected between 2010 and 2019 from a field under potato production located in Prince Edward Island, Canada, were used in conjunction with soil properties measured in situ, to estimate the magnitude, and inter- and intra-annual variation, of the soil water deficit and, consequently, the crop water requirements and irrigation needs while considering the impact of irrigation efficiency and areal extent of irrigation on water supply and aquifer storage. The study showed that in the years when potato was grown (i.e., 2011, 2014 and 2017), the soil water deficit reached maximum values during the months of July and August, a period that coincides with the tuber initiation and tuber bulking stages when the potato plant is most sensitive to water stress. This study demonstrates that depending on the combination of irrigation threshold, the efficiency of the irrigation system and the areal extent of the irrigation, the withdrawal of groundwater for irrigation can be significant when compared to groundwater recharge and can potentially result in the depletion of aquifer storage both during the GS and on an annual basis. These findings further suggest the need for integrated irrigation system–groundwater resource assessments in areas looking to expand the irrigation of potato crops.

The simple soil moisture-based methodology developed in this study can easily be applied to other areas where the estimation of soil water stress, supplemental irrigation requirements and impact of irrigation on aquifer storage is sought. The range of scenarios analyzed in this study suggests that the design of an irrigation system should be conducted thoroughly, with particular attention given to both the inter-annual and intra-annual variability in the soil water deficit, irrigation levels, efficiency of the irrigation system and the spatial extent of the irrigated area. While the study took place in Prince Edward Island, Canada, the methodology presented here can be applied without restriction to any field where irrigation is considered, via the online tool developed as part of this research.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14172748/s1, S1. Weather for the monitoring period; S2. Supplemental irrigation requirement for each year of the monitoring period (2010–2019); S3. Average supplemental irrigation requirement for various extents of irrigated areas; Table S1. Values for measured mean air temperature (T), total precipitation (TP), rain and soil water content (SWC) based on daily data for the study period (2010–2019); Table S2. Annual averages for measured mean air temperature (T), total precipitation (TP), rain and soil water content (SWC), based on daily data for the study period (2010–2019); Table S3. Supplemental irrigation requirement (mm1) for the various irrigation levels and efficiency scenarios for each GS during the monitoring period; Table S4. Supplemental irrigation requirement (mm1) for the various irrigation levels and efficiency scenarios during tuber initiation and bulking stages of each growing season during the monitoring period; Table S5. Volume of irrigation water required (m^3) during the average growing season for various areal extents of irrigated land; Table S6. Comparison between the volume of irrigation water required during the growing season and the annual groundwater recharge for various areal extents of irrigated land; Figure S1. Monthly total precipitation amounts for each of the study years (black line-multi-year monthly average).

Author Contributions: Conceptualization, S.D., K.T.B.M. and B.Z.; methodology, S.D., B.Z., J.N., M.G. and M.L.; software, S.D. and K.T.B.M.; validation, S.D.; formal analysis, S.D.; investigation, S.D., K.T.B.M. and B.Z.; resources, S.D., B.Z., J.N. and M.G.; data curation, S.D., M.G. and M.L.; writing—original draft preparation, S.D., K.T.B.M. and B.Z.; writing— S.D., K.T.B.M., B.Z., J.N., M.G. and M.L.; supervision, S.D., J.N. and M.G.; project administration, S.D., B.Z. and J.N.; funding acquisition, S.D., B.Z. and J.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Agriculture and Agri-Food Canada (AAFC) (grant numbers: SAGES #1459, GF2 #1029, GF2 #1199, GF2 #1538 and LL #J-002269).

Data Availability Statement: Data supporting the results of this study are available upon request from interested parties. As part of a separate effort, the methodology used in this study for calculating the daily crop water deficit, crop irrigation requirements and the impact of irrigation on aquifer storage based on measured daily soil moisture has been developed into an online tool (SWIB, Soil Water Stress, Irrigation Requirement and Water Balance online calculator). SWIB is free, does not require user registration and is available at https://portal.hydrotools.tech (accessed on 12 August 2022).

Acknowledgments: The authors would like to thank Sandy Jenkins, Taylor Main, Vernon Rodd, Lionel Stevens, Rick Allaby, Irene Power and Henry Roger, all from AAFC, who provided field and lab support for this study and to Sheng Li (AAFC) for providing valuable comments on a draft version of this paper. The authors would like to thank Alex Popa for his contributions to the development of the online interface of the SWIB tool. We would also like to extend our thanks to the reviewers of this manuscript for their helpful comments.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Stark, J.; Thornton, M.; Nolte, P. (Eds.) *Potato Production Systems*; Springer International Publishing: Berlin/Heidelberg, Germany, 2020; p. 635, ISBN 978-3-030-39156-0.
2. FAOSTAT. Crops and Livestock Products. 2022. Available online: http://www.fao.org/faostat/en/#data (accessed on 29 August 2022).
3. Haverkort, A.J.; Struik, P.C. Yield levels of potato crops: Recent achievements and future prospects. *Field Crops Res.* **2015**, *182*, 76–85. [CrossRef]
4. Levy, D.; Coleman, W.K.; Veilleux, R.E. Adaptation of potato to water shortage: Irrigation management and enhancement of tolerance to drought and salinity. *Am. J. Potato Res.* **2013**, *90*, 186–206. [CrossRef]
5. Evans, G.R.; King, B.A. Site-specific sprinkler irrigation in a water limited future. In Proceedings of the 5th National Decennial Irrigation Conference Proceedings, Phoenix Convention Center, Phoenix, AZ, USA, 5–8 December 2010. [CrossRef]
6. Prince Edward Island Department of Agriculture and Land (PEI DAL). Agriculture on Prince Edward Island. 2020. Available online: https://www.princeedwardisland.ca/en/information/agriculture-and-land/agriculture-pei (accessed on 15 April 2021).
7. Agriculture and Agri Food Canada (AAFC). Potato Market Information Review 2019–2020. 2020. Available online: https://www5.agr.gc.ca/eng/canadas-agriculture-sectors/horticulture/horticulture-sector-reports/potato-market-information-review-2019-2020/?id=1606246042832 (accessed on 18 April 2021).
8. Bélanger, G.; Walsh, J.; Richards, J.E.; Milburn, P.H.; Ziadi, N. Yield response of two potato cultivars to supplemental irrigation and N fertilization in New Brunswick. *Am. J. Potato Res.* **2000**, *77*, 11–21. [CrossRef]
9. Afzaal, H.; Farooque, A.A.; Abbas, F.; Acharya, B.; Esau, T. Precision irrigation strategies for sustainable water budgeting of potato crop in Prince Edward Island. *Sustainability* **2020**, *12*, 2419. [CrossRef]
10. Jiang, Y.; Ramsay, M.; Meng, F.; Stetson, T. Characterizing potato yield responses to water supply in Atlantic Canada's humid climate using historical yield and weather data: Implications for supplemental irrigation. *Agric. Water. Manag.* **2021**, *255*, 107047. [CrossRef]
11. Vigneault, H.; Paradis, D.; Ballard, J.-M.; Lefebvre, R. Numerical modelling of the evolution of groundwater nitrate concentrations under various Climate Change scenarios and agricultural practices for Prince Edward Island. In *Consequences of Climatic Changes on Contamination of Drinking Water by Nitrates on Prince-Edward-Island*; Savard, M., Somers, G., Eds.; Agriculture and Agri-Food Canada: Ottawa, ON, Canada, 2007; pp. 93–109.
12. Prince Edward Island Department of Environment, Energy and Climate Action (PEI DEECA). Climate Change and Island Agriculture. 2015. Available online: https://www.princeedwardisland.ca/en/information/communities-land-and-environment/climate-change-and-island-agriculture (accessed on 7 March 2021).
13. Wagg, C.; Hann, S.; Kupriyanovich, Y.; Li, S. Timing of short period water stress determines potato plant growth, yield and tuber quality. *Agric. Water. Manag.* **2021**, *247*, 106731. [CrossRef]
14. Prince Edward Island Department of Environment, Energy and Climate Action (PEI DEECA). Prince Edward Island Water—A Water Act Backgrounder. 2015. Available online: http://www.gov.pe.ca/photos/original/cle_bground.pdf (accessed on 18 March 2021).
15. Porter, G.A.; Opena, G.B.; Bradbury, W.B.; McBurnie, J.C.; Sisson, J.A. Soil management and supplemental irrigation effects on potato: I. Soil properties, tuber yield, and quality. *Agron. J.* **1999**, *91*, 416–425. [CrossRef]
16. Opena, G.B.; Porter, G.A. Soil management and supplemental irrigation effects on potato: II. Root growth. *Agron. J.* **1999**, *91*, 426–431. [CrossRef]
17. Jacques, M.M.; Gumiere, S.J.; Gallichand, J.; Celicourt, P.; Gumiere, T. Impacts of water stress severity and duration on potato photosynthetic activity and yields. *Front. Agron.* **2020**, *2*, 590312. [CrossRef]
18. van Loon, C.D. The effect of water stress on potato growth, development, and yield. *Am. Potato J.* **1981**, *58*, 51–70. [CrossRef]

19. Pavlista, A.D. *Potato Production Stages: Scheduling Key Practices*; UNL Coop. Ext. Circ. 1249; University of Nebraska–Lincoln: Lincoln, NE, USA, 1995.
20. Nuñez, J.; Haviland, D.R.; Aegerter, B.J.; Baldwin, R.A.; Westerdahl, B.B.; Trumble, J.T.; Wilson, R.G. *UC IPM Pest Management Guidelines: Potato*; UC ANR Publication 3463; University of California: Oakland, CA, USA, 2019; Available online: https://www2.ipm.ucanr.edu/agriculture/potato/harvest (accessed on 30 April 2021).
21. Bootsma, A.; Gameda, S.; McKenney, D.W. Potential impacts of climate change on corn, soybeans and barley yields in Atlantic Canada. *Can. J. Soil. Sci.* **2005**, *85*, 345–357. [CrossRef]
22. Malekian, R.; Gordon, R.; Madani, A.; Robertson, S. Evaluation of the Versatile Soil Moisture Budget model for a humid region in Atlantic Canada. *Can. Water. Resour. J.* **2014**, *39*, 73–82. [CrossRef]
23. Baier, W.; Boisvert, J.B.; Dyer, J.A. *The Versatile Soil Moisture Budget (VB) Reference Manual*; ECORC Contribution No. 001553; Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre (Canada): Ottawa, ON, Canada, 2000; pp. A1–D4.
24. Danielescu, S. SWIB (Soil Water Stress, Irrigation Requirement and Water Balance)—A Web Based Tool. Reference Manual. 2021. Available online: https://swib.hydrotools.tech (accessed on 20 June 2022).
25. Environment and Climate Change Canada (ECCC). Canadian Climate Normals for Charlottetown a Weather Station. 2021. Available online: https://climate.weather.gc.ca/climate_normals/index_e.html (accessed on 10 January 2021).
26. Agriculture Canada Research Branch (ACRB). *Soils of Prince Edward Island. Prince Edward Island Soil Survey*; Agriculture Canada Research Branch, Land Resource Research Centre: Ottawa, ON, Canada, 1998; p. 219, Contribution No. 83–54.
27. Carter, M.R. Physical properties of some Prince Edward Island soils in relation to their tillage requirement and suitability for direct drilling. *Can. J. Soil Sci.* **1987**, *67*, 413–487. [CrossRef]
28. Zebarth, B.J.; Danielescu, S.; Nyiraneza, J.; Ryan, M.C.; Jiang, Y.; Grimmett, M.; Burton, D.L. Controls on nitrate loading and implications for BMPs under intensive potato production systems in Prince Edward Island, Canada. *Groundw. Monit. Rem.* **2015**, *35*, 30–42. [CrossRef]
29. Lamb, K.; MacQuarrie, K.T.B.; Butler, K.; Danielescu, S.; Mott, E.; Grimmett, M.; Zebarth, B.J. Hydrogeophysical monitoring reveals primarily vertical movement of an applied tracer across a shallow, sloping low-permeability till interface: Implications for agricultural nitrate transport. *J. Hydrol.* **2019**, *573*, 616–630. [CrossRef]
30. Malenica, A. Evaluation of Nitrate Distribution and Matrix Storage Effects in a Dual Permeability Fractured Bedrock Aquifer with Heterogeneous Hydrochemistry. Master’s Thesis, Department of Engineering, University of Guelph, Guelph, ON, Canada, 2015; p. 164.
31. Francis, R. *Hydrogeology of the Winter River Basin, Prince Edward Island*; Department of the Environment: Charlottetown, PEI, Canada, 1989; p. 215.
32. Jiang, Y.; Nishimura, P.; van den Heuvel, M.R.; MacQuarrie, K.T.B.; Crane, C.S.; Xing, Z.; Raymond, B.G.; Thompson, B.L. Modeling land-based nitrogen loads from groundwater-dominated agricultural watersheds to estuaries to inform nutrient reduction planning. *J. Hydrol.* **2015**, *529*, 213–230. [CrossRef]
33. Prince Edward Island Department of Environment, Energy and Climate Action (PEI DEECA). Agricultural Crop Rotation Act. 2019. Chapter A-8.01. Available online: https://www.princeedwardisland.ca/sites/default/files/legislation/a-08-01-agricultural_crop_rotation_act.pdf (accessed on 28 June 2021).
34. Kroetsch, D.; Wang, C. Particle size distribution. In *Soil Sampling and Methods of Analysis*, 2nd ed.; Carter, M.R., Gregorich, E.G., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 713–725. ISBN 9780849335860.
35. Skjemstad, J.O.; Baldock, J.A. Total and Organic Carbon. In *Soil Sampling and Methods of Analysis*, 2nd ed.; Carter, M.R., Gregorich, E.G., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 225–227. ISBN 9780849335860.
36. Rees, H.; Chow, T.L. Impact of incorporated hay mulch on selected physical, chemical and microbiological properties of a loam soil in Atlantic Canada after five years of continuous potato production. *Can. J. Soil Sci.* **2005**, *85*, 161–172. [CrossRef]
37. Topp, G.C.; Zebchuk, W. The determination of soil-water desorption curves for soil cores. *Can. J. Soil Sci.* **1979**, *59*, 19–26. [CrossRef]
38. Hao, X.; Ball, B.C.; Culley, J.L.B.; Carter, M.R.; Parkin, G.W. Soil Density and Porosity. In *Soil Sampling and Methods of Analysis*, 2nd ed.; Carter, M.R., Gregorich, E.G., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 743–747.
39. Nair, A.; Lewis, D.; Lawson, V.; Iles, L.J.; Rodriguez-Salamanca, L. *Commercial Potato Production Guide. Report no. HORT 3044*; Iowa State University—Extension and Outreach: Ames, IA, USA, 2017; Available online: https://store.extension.iastate.edu/Product/Commercial-Potato-Production-Guide (accessed on 3 May 2021).
40. Environment and Climate Change Canada (ECCC). Daily Weather Historical Data for Charlottetown A Weather Station. 2020. Available online: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html (accessed on 15 September 2020).
41. Obidiegwu, J.E.; Bryan, G.J.; Jones, H.G.; Prashar, A. Coping with drought: Stress and adaptive responses in potato and perspectives for improvement. *Front. Plant Sci.* **2015**, *6*, 542. [CrossRef]
42. Da Ros, L.; Elferjani, R.; Soolanayakanahally, R.; Kagale, S.; Pahari, S.; Kulkarni, M.; Wahab, J.; Bizimungu, B. Drought-Induced Regulatory Cascades and Their Effects on the Nutritional Quality of Developing Potato Tubers. *Genes* **2020**, *11*, 864. [CrossRef]
43. Machibya, M.; Mdemu, M.; Lankford, B. *Tools for Irrigation Professionals and Practitioners—Draft Irrigation Efficiency and Productivity Manual*; DFID—RIPARWIN Project; Knowledge and Research KAR8064; Department for International Development: London, UK, 2004.
44. Perry, C. Efficient irrigation; inefficient communication; flawed recommendations. *Irrig. Drain.* **2007**, *56*, 367–378. [CrossRef]

45. Foster, S.S.D.; Perry, C.J. Improving groundwater resource accounting in irrigated areas: A prerequisite for promoting sustainable use. *Hydrogeol. J.* **2010**, *18*, 291–294. [CrossRef]
46. Danielescu, S. ETCALC: A unique online tool for estimation of daily evapotranspiration. Case study: Intercomparison of methods and precipitation deficit for Charlottetown, Canada (2010–2019). *Atmos. Ocean* **2022**. *accepted with revisions*.
47. Alva, A.K.; Moore, A.D.; Collins, H.P. Impact of Deficit Irrigation on Tuber Yield and Quality of Potato Cultivars. *J. Crop Improv.* **2012**, *26*, 211–227. [CrossRef]